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DETERMINISTIC MODELING OF STREAM WATER TEMPERATURES: DEVELOPMENT AND APPLICATIONS TO CLIMATE CHANGE EFFECTS ON FISH HABITAT

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Abstract

The effect of projected global climate change due to a doubling of atmospheric CO_2 on water temperatures in five streams in Minnesota is estimated using a deterministic heat transport model. The model calculates heat exchange between the atmosphere and the water and is driven by climate parameters and stream hydrologic parameters. The model is based on a finite difference solution of the unsteady heat advection–dispersion equation. An energy balance at the water surface accounts for the effects of air temperature, solar radiation, relative humidity, cloud cover and wind speed on the net rate of heat exchange through the water surface. The energy balance at the bottom of the stream requires modeling of diurnal heat exchange between water and streambed.

The model was calibrated against detailed measurements to account for seasonally variable shading and wind sheltering shown to be dependent on leaf cover of trees on stream banks. Measurements were made in 5 streams at 2 minute intervals over periods of up to 4 weeks. After calibration, accuracies of hourly and daily water temperature predictions over periods of several weeks are on the order of 0.2 to 1 °C.

The model is sensitive to each of the aforementioned weather parameters to different degrees. Sensitivity coefficients are calculated by two different methods which gave same order of magnitude results. The mean and/or the standard deviation of each of the weather parameters are combined with the sensitivity coefficients to establish the sensitivity of the model to each parameter. The sensitivity analysis showed that stream water temperature is most sensitive to air temperature and solar radiation.

Using climate projections from the GISS (Goddard Institute for Space Studies), GFDL (Geophysical Fluid Dynamics Laboratory) and OSU (Oregon State University) Global Circulation Models (GCM's) as input; stream temperature simulations predict a warming of freely flowing river reaches by 2.4°C to 4.7°C when atmospheric CO_2 doubles. In small shaded streams water temperatures are predicted to rise by an additional 6°C in summer if trees along stream banks should be lost due to climate change. These projected water temperature changes have significant consequences for survival and growth of fishes in different temperature guilds (cold–, cool– and warmwater fishes). A model developed by the USEPA, relating fish survival and fish habitat to water temperatures, was applied to make the first assessment. The simulation results obtained with the complete heat budget equations are also used to examine simplified water temperature/air temperature correlations.

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1. INTRODUCTION AND LITERATURE REVIEW

For more than a decade, a growing number of scientists have been warning about global warming which can be defined as the global increase of air temperature resulting from changes of the atmospheric chemistry. Judging from the past it is almost certain that the climate will change but when and by how much is still uncertain. One cause for the uncertainty is that the oceans act as a heat sink of immense capacity which will delay warming or cooling of the atmosphere to some unknown extent (NRC, 1982, 1983 and Waggoner, 1990). Other factors such as the change of the earth's vegetation cover play an indefinite role in controlling the extent of climate changes.

The cause of the feared climate change is the so called "greenhouse effect" due to the rise in atmospheric concentrations of carbon dioxide (CO_2), methane and other gases. This effect is well documented in publications by Bolin and Doos (1986), the NRC (1982, 1983) and Houghton et al. (1990).

The greenhouse gases are relatively transparent to most of the wavelengths in the incoming solar radiation (DeAngelis and Cushman, 1990). On the other hand, they absorb the long-wave radiation that is emitted from the warm earth surface resulting in warming of the earth atmosphere. Consequently, the higher the concentration of such "greenhouse gases", the higher the atmospheric temperature will be (NRC, 1982, 1983; Bolin and Doos, 1986; Wanner and Siegenthaler, 1988; Waggoner, 1990; Harrington, 1987; Schneider, 1989; NAS, 1988 and Houghton et al., 1989). Bolin and Doos (1986) and Waggoner (1990) estimated the increase of the atmospheric temperature to be on the order of 1.5 to 4.5 °C if atmospheric concentrations of CO_2 are doubled.

Such changes in the climate may have severe consequences. Of particular interest to us is that aquatic environments and resources, e.g., important fisheries may be disrupted (NRC, 1982, 1983; and Sibley and Strickland, 1985). This has led to anxious requests for information on effects and for ideas on possible mitigation or accommodation efforts.

Climatic factors are important correlates of productivity in aquatic ecosystems (Brylinsky, 1980). Fish are directly influenced by the temperature of their environment (Magnuson et al., 1990; Tonn, 1990; Graham and Orth, 1986; Taylor, 1988; Wangila and Dick, 1988; Baltz et al., 1987; Salvatore et al., 1987; Munson et al., 1980 and Coutant, 1990). Examples of the effects of climate change on fisheries production are given in Cushing and Dickson (1976). Meisner (1990) estimated the potential loss of thermal habitat for brook trout due to climate change. Frank et al. (1990) and Coutant (1990) expect a shift or an alteration of the geographic distribution of fish due to climate change.

The purpose of the research reported herein is to study the effects of projected global climate change on stream water temperatures in Minnesota, and consequences of this change for fish populations. The goal is accomplished through simulation of stream water temperatures using a complete heat budget model which includes the heat exchange between the stream water and the atmosphere as well as the stream water and the streambed. Brown (1969), Bowels et al. (1977), Delay and Seaders (1966), Edinger et al. (1968 and 1974), Jobson (1973 and 1977) and Raphael (1962) used similar heat budget models to predict water temperature in streams. Stream water temperature modeling can also be used as a first step in predicting the effect of man's activity on the aquatic ecosystem. Burt (1958), Delay and Seaders (1966) and Duttweiler (1962) studied the thermal effect of dams or the addition of heated effluents to rivers using modeling techniques. The effect of logging on stream water temperatures and temperature–related changes in the ecosystem can also be studied by modeling. Brown (1969) suggested applying such models to manage small municipal watersheds. He recommended the use of stream water temperature models to estimate the maximum stream exposure to solar radiation. Proper management would keep the stream water temperature cool enough so that algal blooms associated with warm water can be avoided.

Full heat budget models use information about the environment i.e. atmosphere and streambed surrounding the stream water to predict the amount of heat input or output to or from the stream water. The exchange of heat across the air–water interface is an important factor in determining the temperature of a water body (Edinger et al., 1968). Streambed heat flux is also important, especially in shallow streams (Brown, 1969, Jobson, 1977 and Bowles et al., 1977).

Stream water temperatures are mainly controlled by the ambient atmospheric conditions. Weather parameters such as air temperature, solar radiation, relative humidity, cloud cover, wind speed and barometric pressure play a main role in the heat exchange between the atmosphere and the stream water. MNSTREM is a computer program that solves the 1–D heat advection–dispersion equation and includes the heat exchange with the atmosphere. Each of the aforementioned weather parameters is used in the model to compute air–water heat exchange fluxes.

The model is more sensitive to some of the weather parameters than others. Sensitivity of the model to each of the weather parameters may be found by calculating the sensitivity coefficients.

To explore how stream water temperatures might be affected by climate change, an analysis of five representative streams in Minnesota was conducted. The five streams are the Straight River, the Baptism River, the Clearwater River, the Zumbro River and the Mississippi River (Fig. 1.1).

Minnesota was selected as a pilot area for the study because of the quality and accessibility of weather data dating back several decades, the availability of data relating to physical characteristics of streams, and the existence of a fishery resources data base. In addition, because of its northern latitude, Minnesota is expected to be strongly affected by global warming.

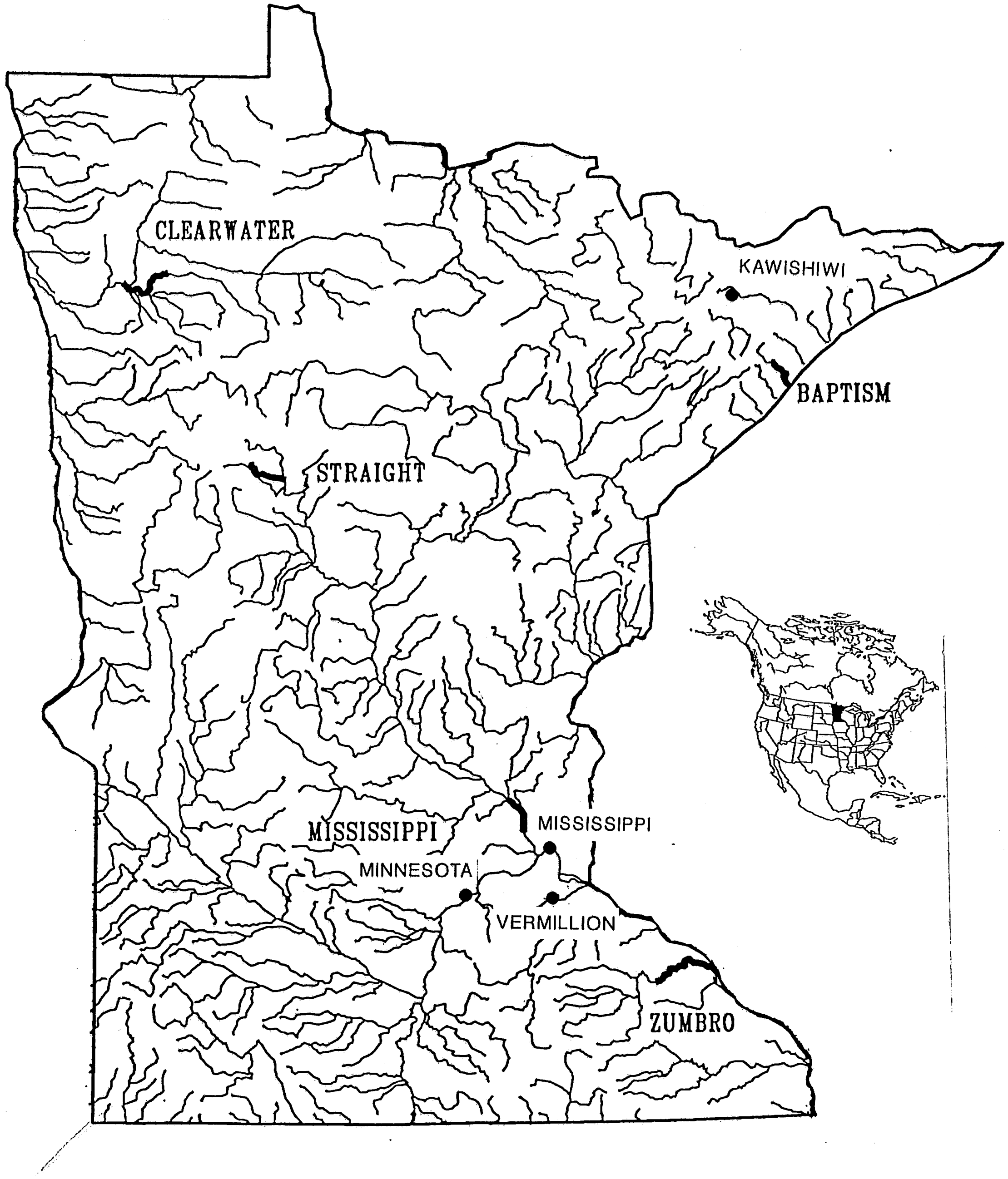


Figure 1.1. Location of selected streams for study of global climate change impacts.

The results of this analysis consist of changes projected for a variety of state stream types. The models, data bases, and assessment techniques employed can serve as templates for conducting analyses of impacts on other regions of the United States. The MNSTREM model was used to simulate stream water temperatures under four different climate change scenarios. The output of this model is in the form of 25-year daily average water temperatures in the period 1953 to 1979.

Habitat space for fish species is normally constrained by extreme temperatures. The USEPA Environmental Research Laboratory/Duluth has conducted laboratory tests and compiled data from many sources on fish sensitivities to water temperatures. Data relating distributions of 30 fish species to surface water temperatures are available.

The simulated stream water temperatures are interfaced with temperature sensitivity data for North American freshwater fishes to determine fish survival and growth conditions before and after climate change. Hence, the deterioration of fish habitat for certain species of fishes and the improvement for others are assessed in terms of temperature. The results indicate which fishes can be present in five different streams before and after climate change, and what growth conditions and yields can be expected. The importance of other factors to influence fish species distributions such as vegetation cover (shading), groundwater inflow (refuges) and reservoir releases are also analyzed. Not included in this study are changes in fish population due to secondary effects of climate change such as loss of food supply, invasion of predators and changes in flow regimes.

2. STREAM TEMPERATURE BEHAVIOR AND CONTROLS

Water temperatures in streams follow two cycles: A seasonal cycle and a diurnal cycle (Figs. 2.1 and 2.2). Records of measured stream water temperatures and air temperatures show that stream water temperature follows the air temperature closely on a seasonal scale. Diurnal cycles can be very dynamic depending on the stream depth (Appendix B). In the north central US, for example, stream water temperature can vary by as much as 8 °C between day and night (Fig. 2.2). Similar orders of magnitude have been reported and explained also for the Pacific northwest of the US (Brown, 1969).

Stream water temperature is controlled by the source of the stream water and heat inputs or losses. Only natural heating and cooling will be taken into consideration here, although effluent discharges (for example, from power plants) may also affect stream water temperature.

Streams can receive their water from springs, reservoirs (impoundments), lakes, wetlands, groundwater, tributaries, overland flow and precipitation. Different sources of stream water will likely have different stream temperatures. For example, the water released from a lake or a reservoir, as an example, has usually a temperature different than that of groundwater.

The significance of heat inputs and losses is illustrated in Fig. 2.3 which is a duplicate of Fig. 2.2, except that the water temperatures measured upstream are shifted by the hydraulic travel time. The two sets of curves in the figures should be identical if there were no heat exchange between the stream and its surroundings. The actual difference between the two curves is large and measures the heat input to the stream or the loss from it. Sources or sinks of heat are the atmosphere or the stream bed.

Heat exchange between the atmosphere and the stream include

(1) Heat input due to shortwave radiation from the sun (H_s),
(2) Heat loss and gain due to longwave radiation (H_l),
(3) Heat loss due to the evaporation of water from the water surface (H_e), and
(4) Convection of heat across the air–water interface (H_c).

The stream bed is a source or sink of heat. In previous studies the stream bed has often been neglected in the heat budget although Brown (1969) pointed out its significance in shallow streams. Herein the stream bed heat uptake or release will be considered since three of the five stream reaches studied are shallow.

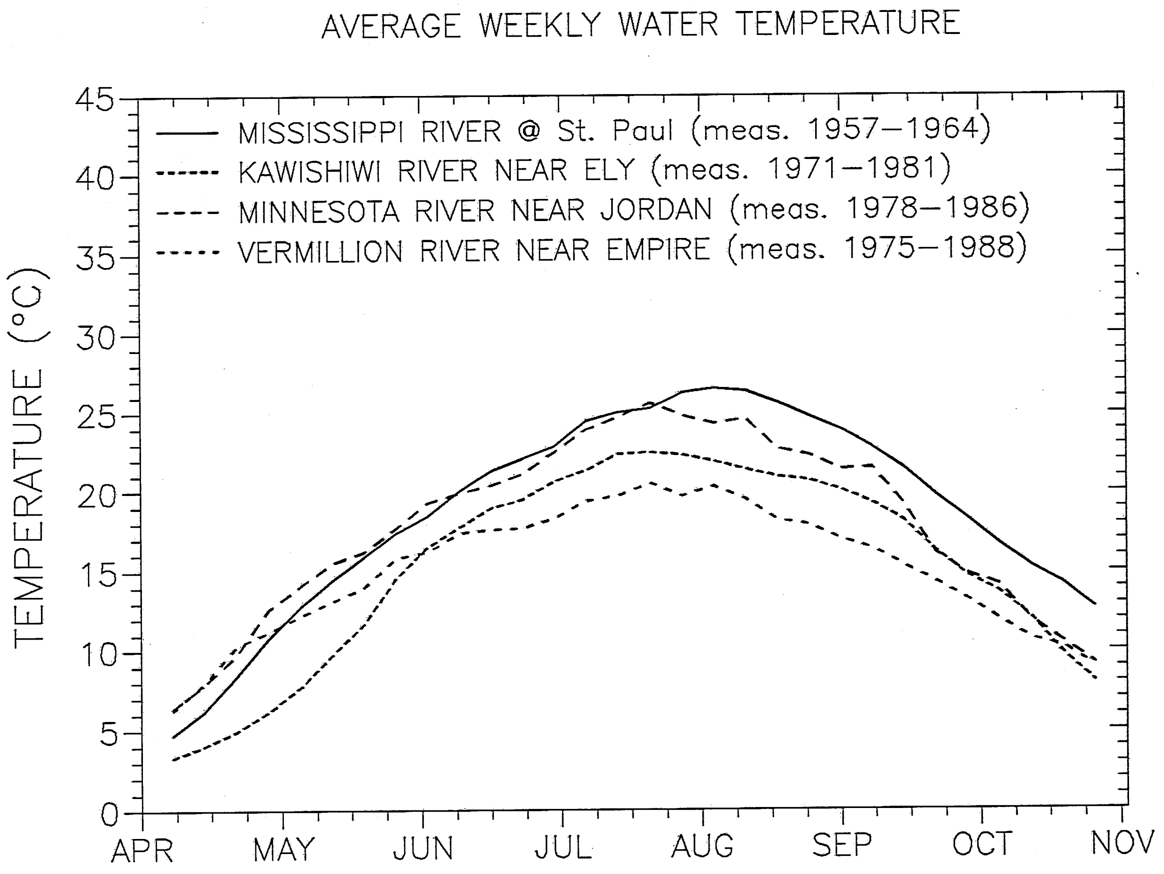


Figure 2.1. Examples of measured seasonal water temperature records.

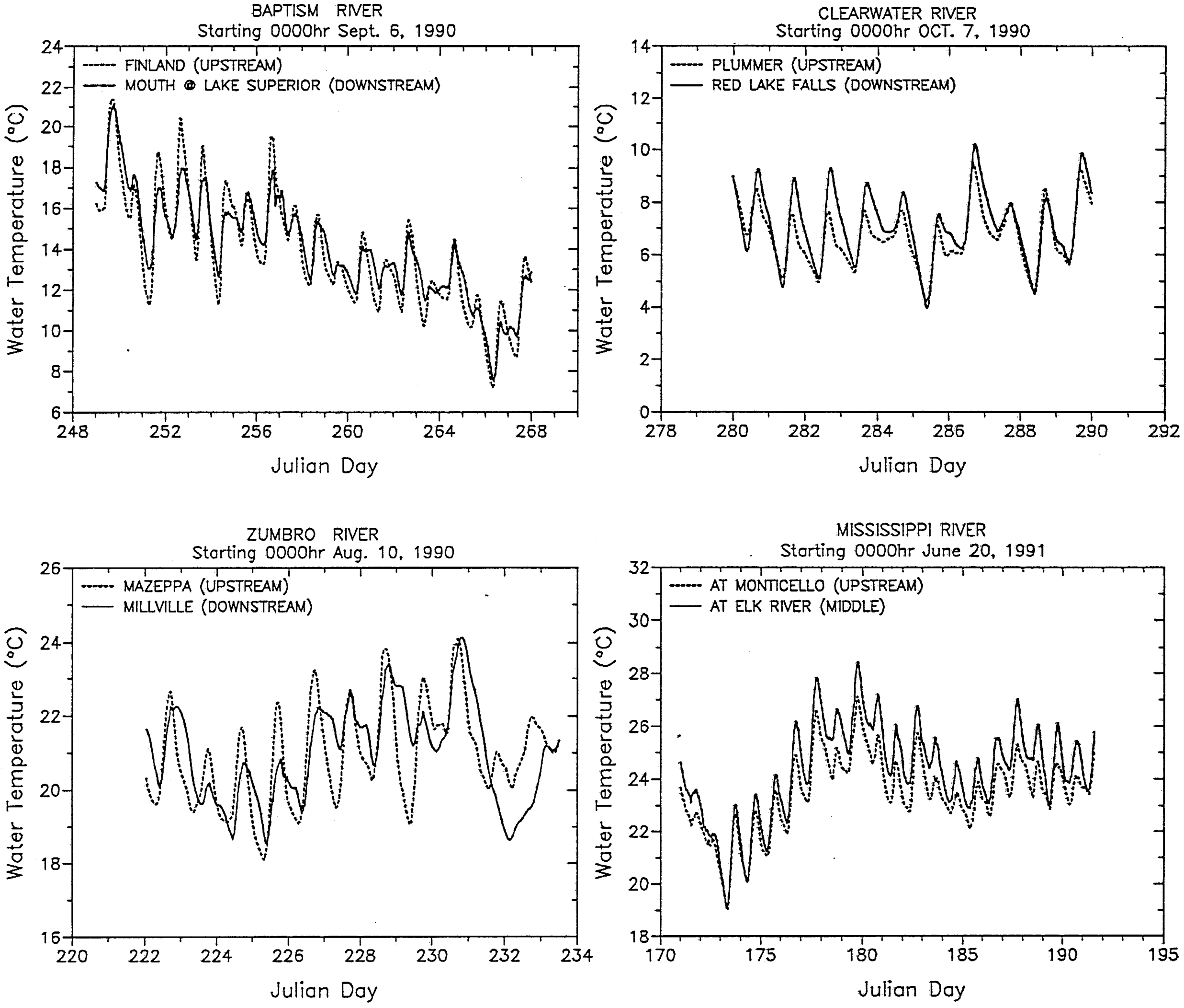
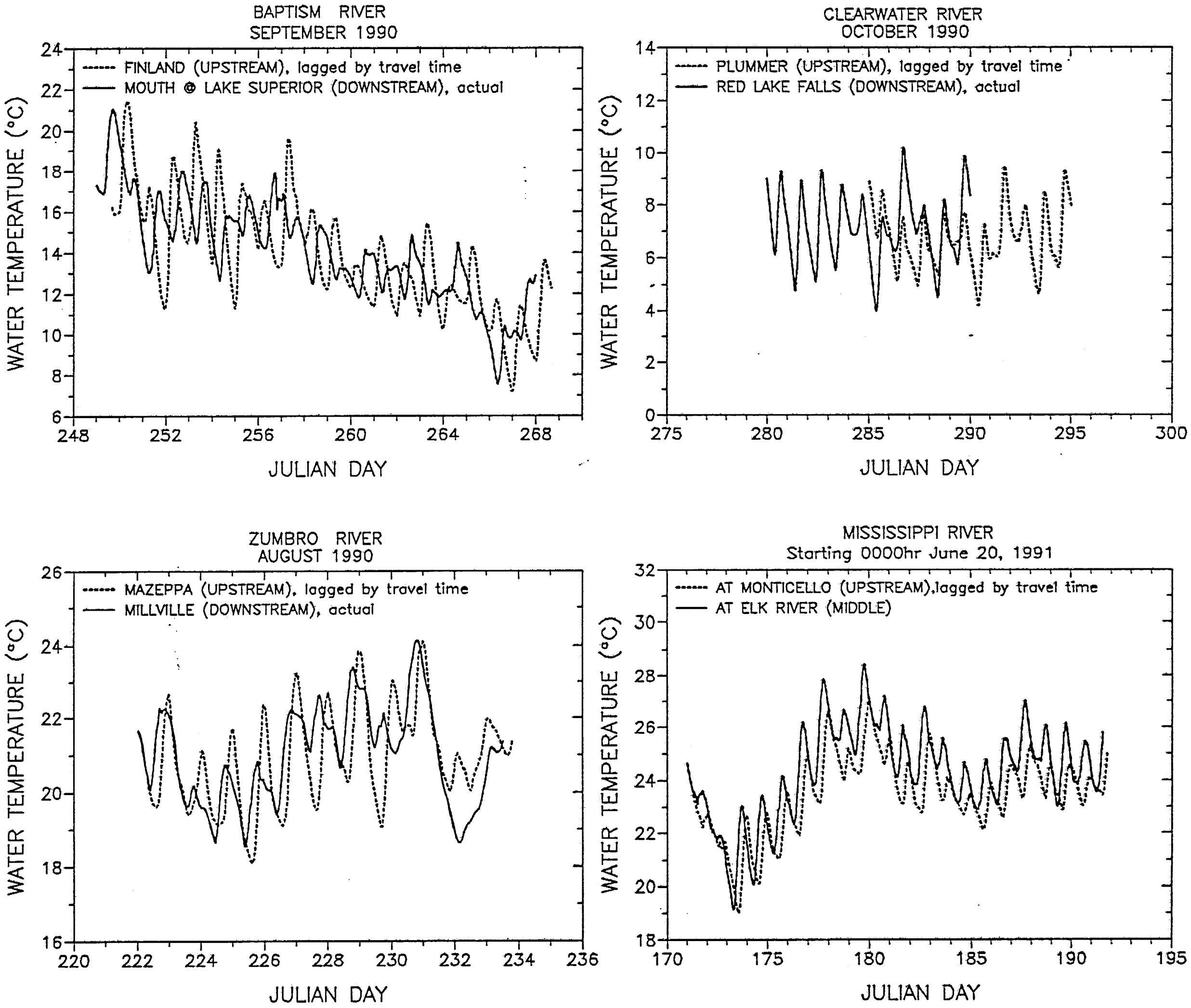


Figure 2.2. Example of measured water temperatures at the selected streams.

Figure 2.3. Measured water temperatures at the selected streams: Upstream temperatures are lagged by the travel time.



The atmospheric heat inputs and losses are directly related to weather parameters. Figures 2.4 and 2.5 represent air and water temperatures measured by the USGS (Stark, 1989) at the Straight River for the period from May 13, 1988 to Sept. 25, 1989. The seasonal cycle and a strong correlation between air and water temperatures are evident. The diurnal cycle of stream water temperature can be noticed clearly in the record for a six day period from June 1 to June 6, 1988 shown in Fig. 2.6. These diurnal cycles are directly related to the diurnal cycles of solar radiation and air temperature.

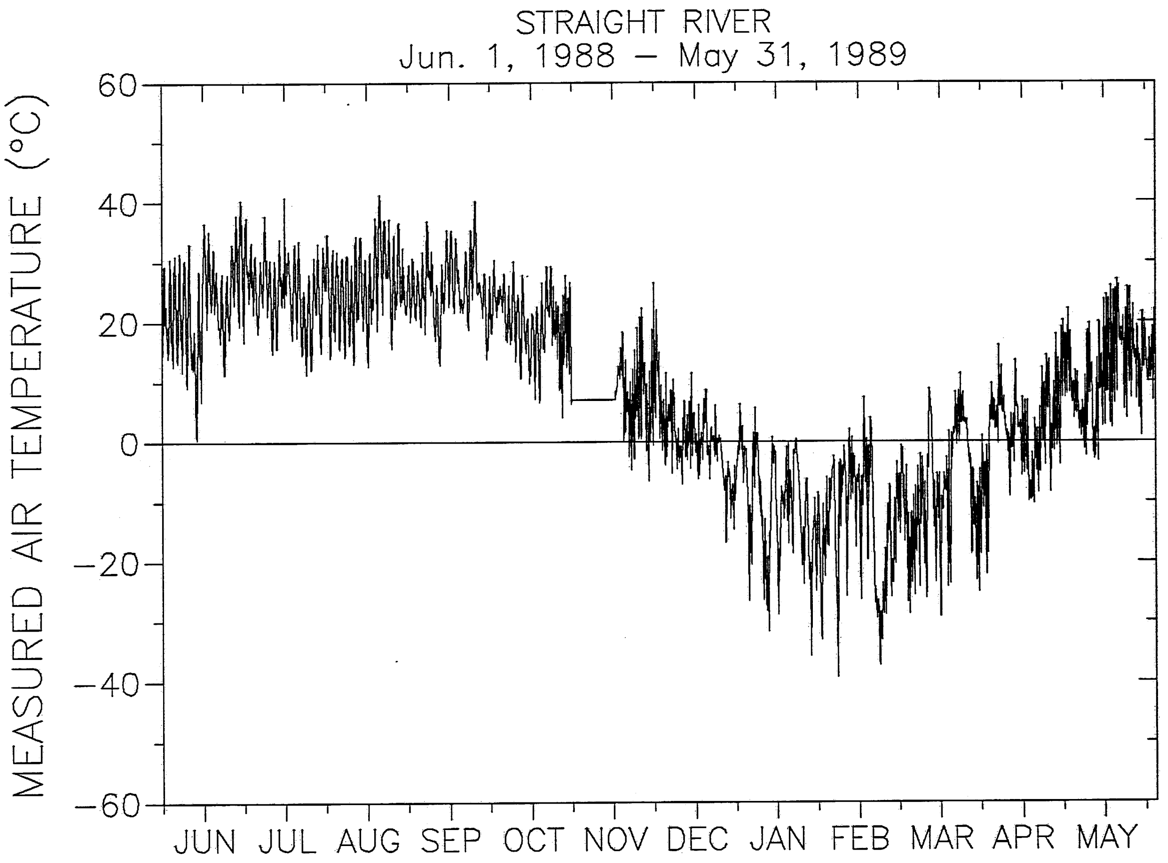


Figure 2.4. Measured air temperatures for the Straight River (data from MN–USGS).

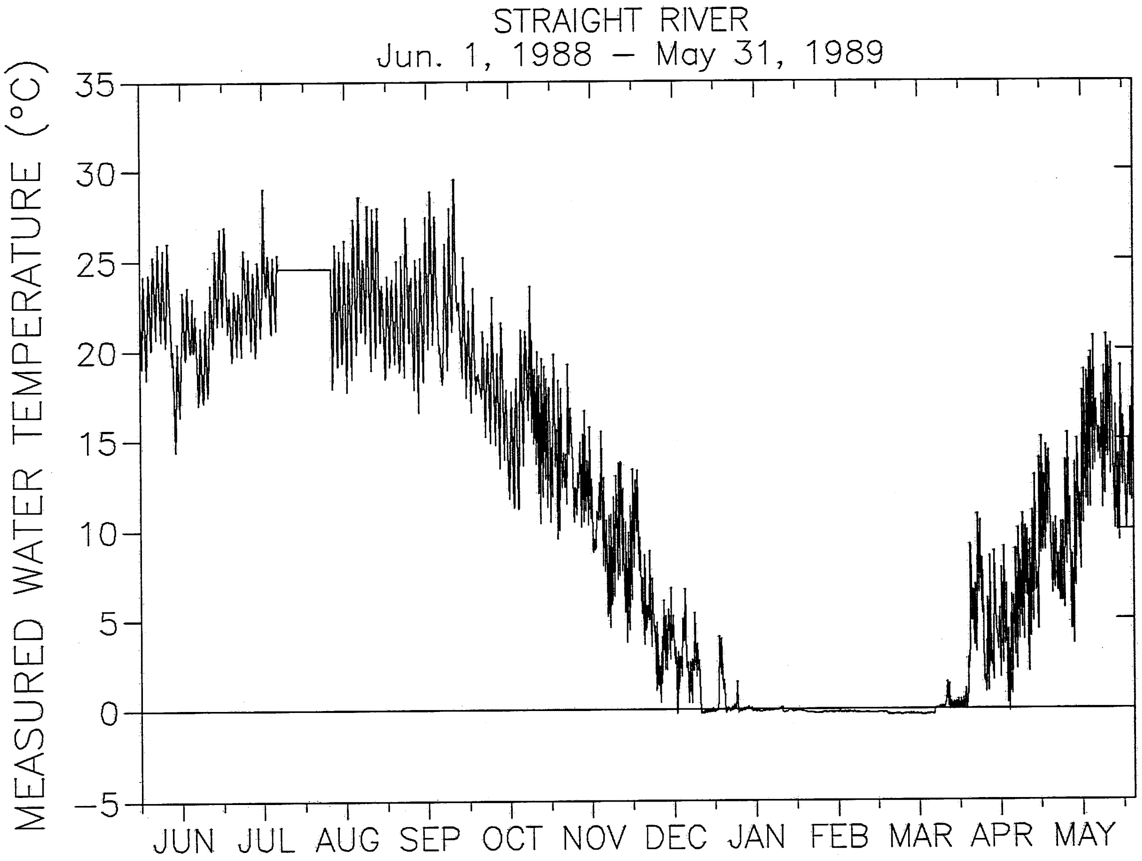


Figure 2.5. Measured water temperatures for the Straight River (data from MN–USGS).

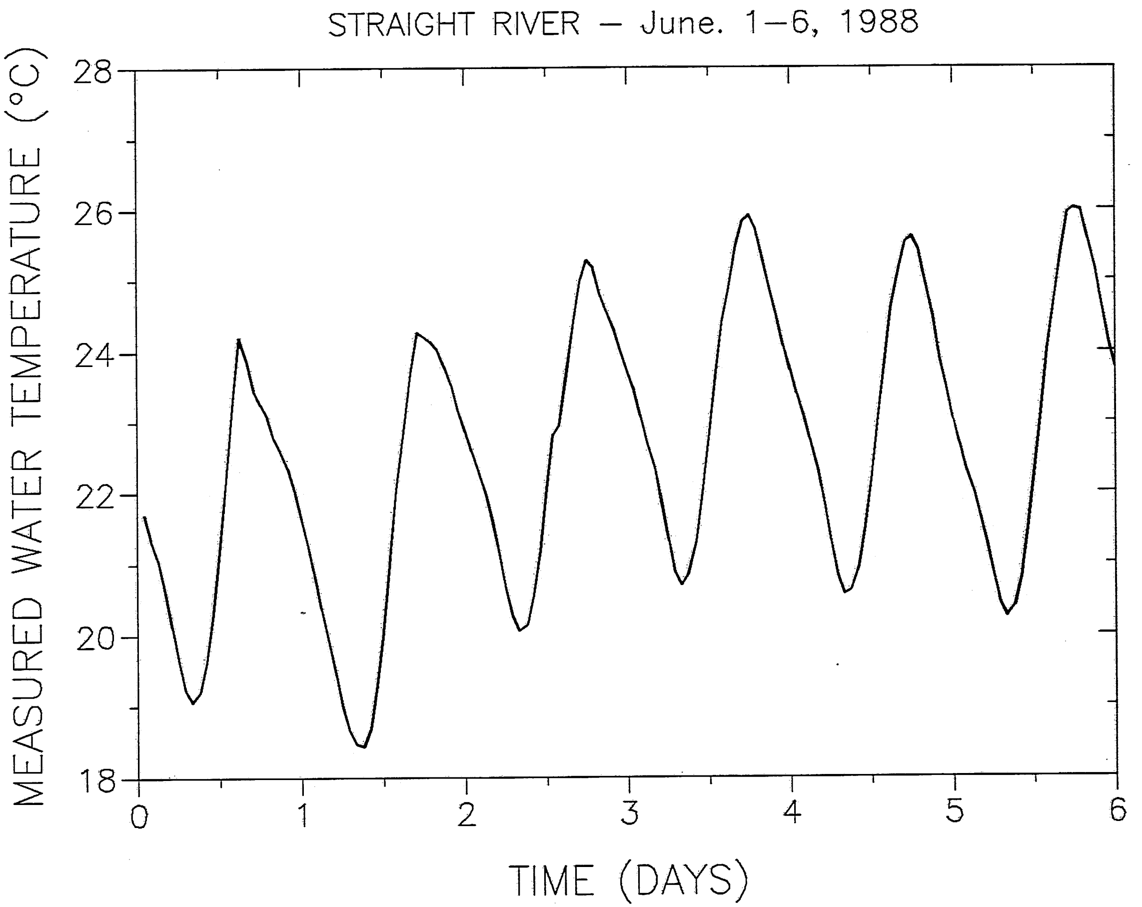


Figure 2.6. Measured water temperatures for the Straight River (data from MN–USGS).

3. MODEL OF STREAM WATER TEMPERATURE

The model used in this study is a modified version of the MNSTREM model (Stefan, Gulliver, Hahn and Fu, 1980). MNSTREM is a finite difference, implicit computer model for the simulation of the very dynamic channel water regime first developed to model water temperatures for the USEPA/Monticello Ecological Research Station (MERS) experimental channels. The model was extended to (1) calculate average daily water temperatures using daily weather data, and (2) to include streambed (sediment) heat flux into the heat budget. Previous applications had been for 3–hour time steps without heat transfer to the sediments. A summary of the model is as follows. A listing of the computer program is given in Appendix E.

3.1. Heat transport equations

Water temperature is calculated from the energy transport equation. When applied to an open channel of constant cross section and flow it takes the following form :

$$\frac{\partial T}{\partial t} = - U \frac{\partial T}{\partial x} + D_L \frac{\partial^2 T}{\partial x^2} + \frac{S}{\rho c_p h} \qquad (3.1a)$$

T is water temperature, x is distance downstream, t is time, D_L is a dispersion coefficient in the direction of flow (x–direction), S is a source or sink term which includes heat transfer with the surrounding environment, U is mean channel velocity, h is mean channel depth, ρ is the density of water and c_p is the heat capacity of water.

If stream cross–section and flow rate are variable, a more general form of equation 3.1a can be written as :

$$A \frac{\partial T}{\partial t} + \frac{\partial (QT)}{\partial x} = \frac{\partial}{\partial x} \left(A D_L \frac{\partial T}{\partial x} \right) + \frac{B\,S}{\rho c_p} \qquad (3.1b)$$

where A is the cross–sectional area, B is the channel surface width and Q is the stream flow rate. Equations (3.1a) and (3.1b) can also be used to predict water temperatures in streams that are well–mixed and have no significant transverse temperature gradients, i.e. main variation are along the main direction of the flow (longitudinal axis of the stream). Stream cross–sectional area and width must be adjusted according to the stream flow rate, which can be natural and uncontrolled and cover a fairly wide range throughout the year.

The source or sink term (S) expresses the heat transfer rate with the surrounding environment:

$$S = S_a + S_b \tag{3.2}$$

where

$$S_a = H_s - H_l - H_e - H_c \tag{3.3}$$

and

$$S_b = -k_b \frac{\partial T_b}{\partial z} \Big|_{z=0} \tag{3.4}$$

S_a is the net heat exchange rate between the water and the air (atmosphere). S_b is the net heat exchange between the streambed and the stream water, k_b is the thermal conductivity of the streambed material including any porewater, T_b is the streambed temperature and z is a vertical distance into the streambed. The temperature profile $T_b(z)$ of the streambed (rock or sediment) can be calculated by solving the 1–D unsteady heat conduction equation:

$$\frac{1}{\alpha}\frac{\partial T_b}{\partial t} = \frac{\partial^2 T_b}{\partial z^2} \tag{3.5}$$

where α is the thermal diffusivity of the streambed material. $T_b(z)$ is by solving equation (3.5) numerically using the implicit finite difference technique (Appendix C).

H_s is the net shortwave (solar) radiation. Essentially all shortwave radiation is from the sun. In this model solar radiation is a measured weather parameter and net shortwave radiation is expressed as the difference between measured incoming (H_{si}) and reflected (H_{sr}) radiation.

$$H_s = (H_{si} - H_{sr})\,(1\text{–}SF) \tag{3.6a}$$

or

$$H_s = H_{si}(1\text{–}r)\,(1\text{–}SF) \tag{3.6b}$$

where SF is the fraction of solar radiation that is blocked by the stream bank vegetation (shading) and r is the total reflectivity of the water surface. Anderson (1954) proposed an often used equation for total reflectivity of a water surface

$$r = A\,\alpha^B \tag{3.7}$$

where α is the solar angle in degrees, A and B are constants depending upon cloud cover.

If time increments of one day or greater are of interest, the relations of Koberg (1964) for Hsr are more appropriate. Brady, Graves, and Geyer (1969) calculated A and B as

$$A = 2.20 + \frac{C_r^{0.7}}{4.0} - (C_r^{0.7} - 0.4)^2/0.16 \tag{3.8}$$

and

$$B = -1.02 + \frac{C_r^{0.7}}{16.0} + (C_r^{0.7} - 0.4)^2/0.64 \tag{3.9}$$

where

$$C_r = 1 - H_{si}/H_{sm} = \text{"Cloudiness ratio"} \tag{3.10}$$

and H_{sm} is the solar radiation which would occur with clear skies.

H_l is the net longwave radiation and can be expressed as

$$H_l = \sigma\,(\epsilon_w T_s^4 - \epsilon_a T_a^4) \tag{3.11}$$

where T_s is the water surface temperature (°K), T_a is the air temperature (°K), ϵ_w is the long-wave emissivity of the water surface, ϵ_a is the emissivity of the atmosphere, and σ is the Stefan-Boltzman constant. For atmospheric emissivity without cloud cover, ϵ_{ac}, the Idso and Jackson (1969) formula will give accurate results

$$\epsilon_{ac} = 1 - 0.261 \exp\left[-7.77\text{x}10^{-4}\,T_a(^\circ C)^2\right] \tag{3.12}$$

The Bolz formula is then used to find ϵ_a.

$$\epsilon_a = \epsilon_{ac}\,(1 + K\,C_c) \tag{3.13}$$

where C_c is the fraction cloud cover, and K is a coefficient which depends upon cloud height. The coefficient K varies between 0.04 and 0.25. A TVA (1968) study recommends an average value of K = 0.17.

H_e is the evaporative heat transfer and may be expressed by the relation

$$H_e = \rho L(\text{Wftn})_z\,(e_{sw} - e_{az}) \tag{3.14}$$

where e_{az} is the vapor pressure of the air at height z, e_{sw} is the saturated vapor pressure at water surface temperature, Wftn_z is a wind function using wind velocity at height z, L is the latent heat of vaporization of water, and ρ is the density of water.

Saturation vapor pressure at any air temperature T(°K) may be computed over water by the Magnus–Tetons formula (see Murray, 1967).

$$e_s\ (\mathrm{mb}) = 6.1078 \exp\left[\frac{17.26939\ (T - 273.16)}{T - 35.86}\right] \tag{3.15}$$

Atmospheric vapor pressure is computed from relative humidity, RH

$$e_a = \frac{RH}{100}\, e_{sa} \tag{3.16}$$

The latent heat of vaporization is

$$L = 597.31 - 0.5631\ T_s \tag{3.17}$$

with L in cal/g and T_s in °C.

H_c is the convective heat transfer. According to Bowen (1926) it may be expressed as

$$H_c = 0.61\ \frac{P_a}{1000}\ \rho L\ (Wftn_z)\ (T_s - T_{az}) \tag{3.18}$$

where T_{az} is air temperature at a height z above the water surface, P_a is in mb and $(Wftn_z)$ is the same wind speed function as that for evaporative heat transfer (Eqn. 3.14). For more details about the wind function refer to Ryan and Harleman (1973) or Gulliver and Stefan (1986).

3.2. Numerical solution

Equation 1b is a one-dimensional, unsteady transport equation (in x-direction). A variety of numerical methods exist to solve this kind of differential equation. The finite difference approach was used in this case and it was formulated in a Crank–Nicholson implicit scheme as described in more detail by Stefan, Gulliver, Hahn and Fu (1980). The model could be run in two different modes: fully implicit or Crank–Nicholson implicit. There is a trade–off between the two methods. The fully implicit scheme always guarantees stable convergence. The Crank–Nicholson is more accurate but some oscillations could appear in the solution. Although the oscillations will eventually die out (Patankar, 1980) one could calibrate the model by changing the time or spatial increments to have a stable (non oscillatory) solution. Increasing the spatial increment or decreasing the time increment will increase the numerical diffusion which will dampen the oscillations in the solution. The time increment in the model is fixed and equal to 1–hour (3600 seconds). The spatial increment, on the other hand, can be varied to insure numerical stability. A spatial increment of 1000 ft was found to work well for the five streams modeled in this study.

In order to illustrate this, the model was used as a routing subroutine. The source term was set to zero and the upstream temperature was used as a signal to be routed and observed downstream. Figure 3.1 compares the computed signal (water temperature) at the downstream station using the fully implicit or the Crank–Nicholson implicit numerical schemes. The Crank–Nicholson showed to be more accurate than the fully implicit. Figure 3.2 shows that the spatial increment (Δx) should be at least 800 ft, in this specific case, to avoid oscillations in the solution.

The numerical solution requires initial and boundary conditions. The initial condition is the temperature profile along the modeled stream reach at the beginning of the simulation. It is obtained by specifying the upstream and downstream temperatures, which can be measured, calculated or assumed. The model will linearly interpolate between these two temperatures to find the entire profile. The boundary conditions consist of an upstream and a downstream boundary. The upstream boundary condition is the water temperature at the upstream site during the period of simulation. The downstream boundary condition is specified as a constant longitudinal gradient of temperature.

The upstream water temperature used as an upstream boundary condition is often not available. Two major scenarios of upstream boundary conditions can be considered in that case: A controlled upstream boundary, mainly by a lake or a reservoir, and a freely flowing stream which extends long enough in length to reach a quasi–steady state equilibrium temperature. For the freely flowing stream scenario, the water temperature simulated downstream will be a function of the weather parameters and the stream's mean depth only and it will be independent of the upstream water temperature. Figures 3.3 and 3.4 illustrate the freely flowing stream principle. Fig. 3.3 shows that the water temperature downstream is independent of the constant temperature imposed, as an upstream boundary condition, at the upstream station 30 miles away.

Fig. 3.4, on the other hand, represents longitudinal water temperature profiles along the stream reach at two different times. The profiles show that the stream water temperature becomes the same after travelling a distance far enough downstream from the imposed upstream boundary condition. This leads to the conclusion that the longitudinal temperature gradient is zero. Such a conclusion will result in a simplification of the governing equation (Eqn. 1b) and consequently in the model itself. The simplified equation will take the following form

$$A \frac{\partial T}{\partial t} = \frac{B\ S}{\rho c_p} \tag{3.19a}$$

or

$$\frac{\partial T}{\partial t} = \frac{S}{\rho c_p h} \tag{3.19b}$$

where h is the stream's mean flow depth.

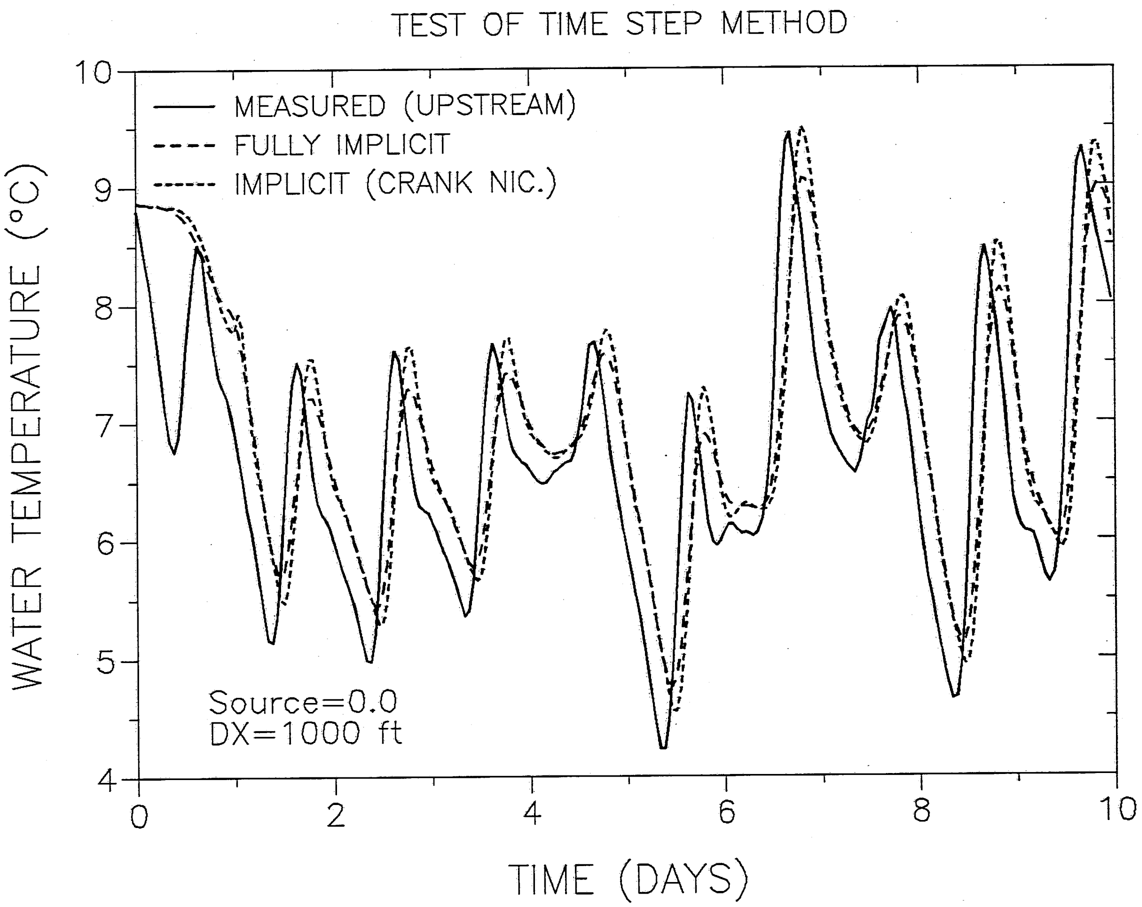


Figure 3.1. Comparison between fully implicit and Crank Nicolson implicit finite difference numerical solutions.

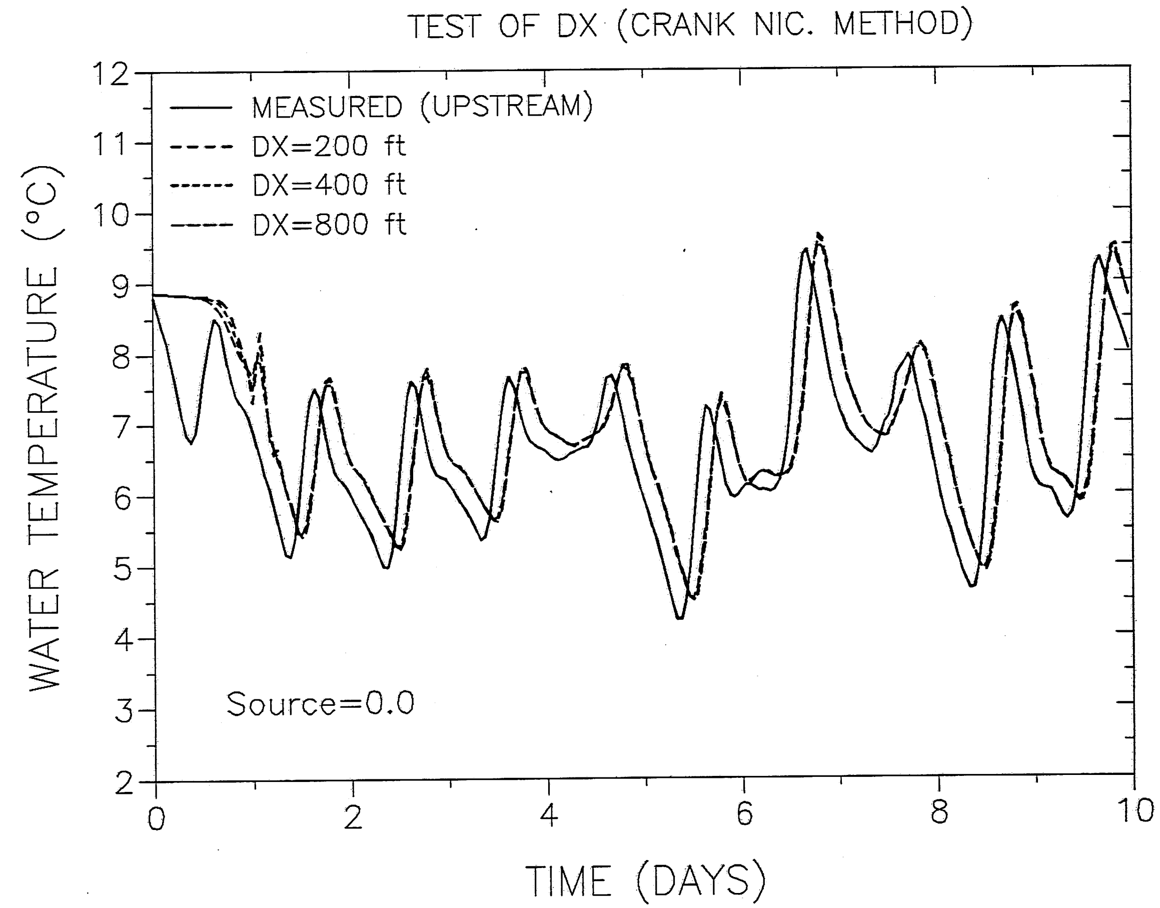


Figure 3.2. Comparison between model outputs for different spatial increments.

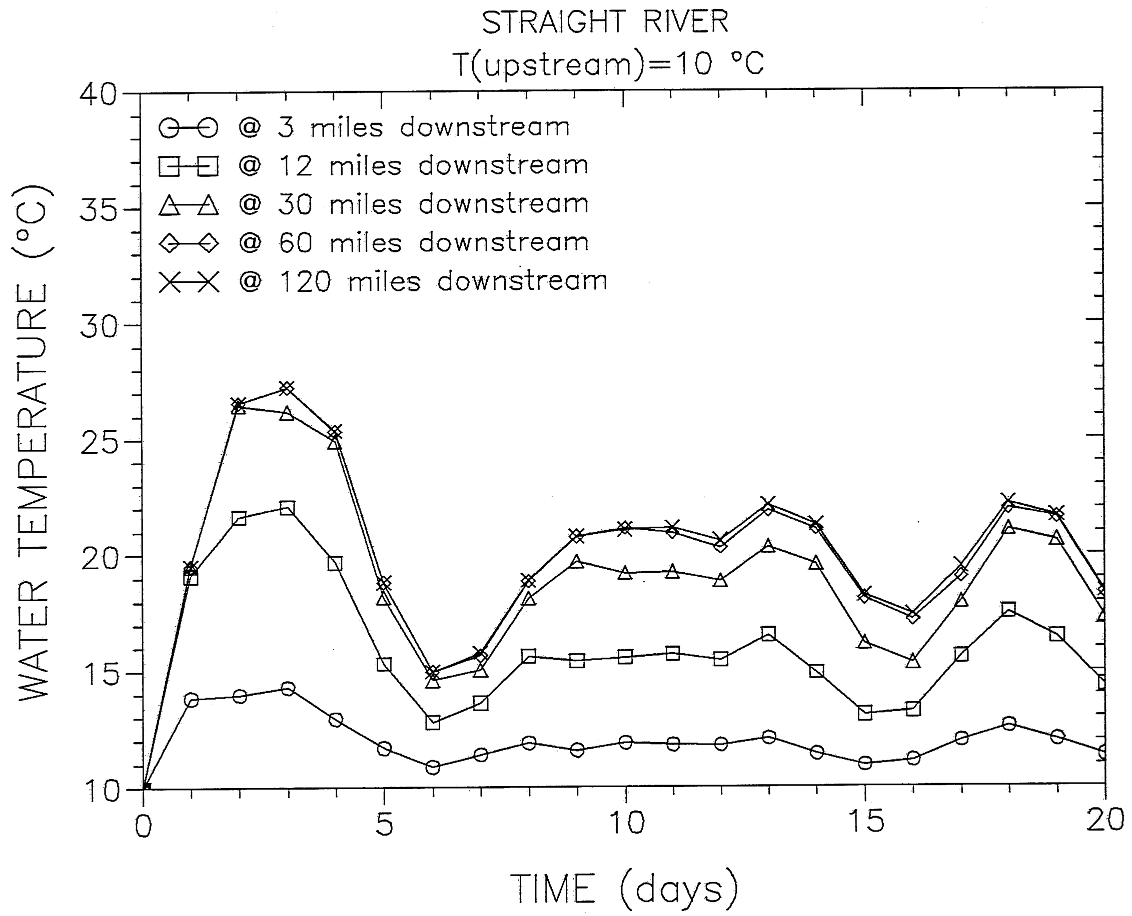


Figure 3.3. Illustration of freely flowing stream principle.

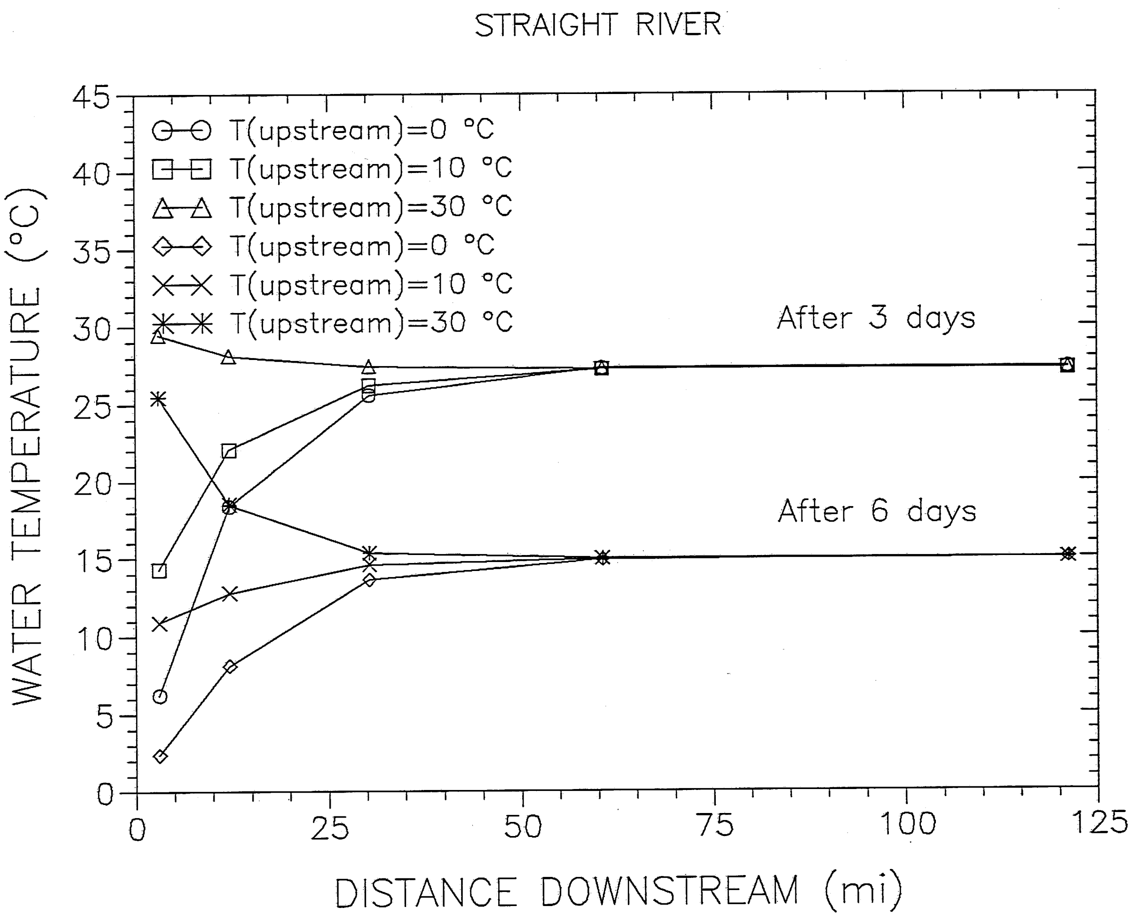


Figure 3.4. Illustration of freely flowing stream principle.

Equation 19b states that the time change of heat storage within a well–mixed water column is equal to the heat exchange between the water and the surrounding environment. The simplified model can be used in the freely flowing scenario and it will result in a significant saving in time (cost).

3.3. Data requirements

The data needed for the solution of equation (3.1b) are (1) geographic location of the stream (2) weather data and (3) stream data. Table 3.1 lists the data required in more detail.

Dispersion in the model can be handled in one of two ways: (1)specifying a dispersion coefficient based on stream dimensions and flow (Fischer et. al., 1979; McQuivey and Keefer, 1974) or (2)using numerical dispersion only, which was the method used in this study. The five streams modeled in this study were insensitive to the dispersion coefficient because of the relatively high velocity of flow and the low longitudinal temperature gradients.

Table 3.1. Data required by the MNSTREM model

Location	**Weather Data**	**Stream Data**
Latitude	Air Temperature	Total Length of River Reach
Altitude	Relative Humidity	Cross-sectional Area and Surface Width as a Function of Discharge
	Solar Radiation	Upstream Water Temperatures as a Boundary Condition
	Wind Velocity	Observed Water Temperature for Calibration
	Cloud Cover	Stream Flow Rate
	Air Pressure	Groundwater Inflow/Outflow
		Stream Bed Data: (Temperature Profile in the Sediment)

4. MODEL SENSITIVITY

4.1. Introduction

Stream water temperatures are mainly affected (driven) by the atmospheric conditions. Weather parameters such as air temperature, solar radiation, relative humidity, cloud cover, wind speed and barometric pressure play the main role in the heat exchange between the atmosphere and the stream water. Each of these weather parameters is accounted for in the model through empirical equations. It is expected that some of these parameters are more important than others, i.e., contribute more to the heat exchange process. Therefore, more attention should be given to the formulation of the empirical equations used to account for the heat exchange due to that parameter. This is one of the reasons why we are studying sensitivity analysis, another reason is the formulation of a simpler model to predict water temperature in streams (Stefan and Sinokrot, 1992), a model that would only consider one or two weather parameters instead of six. This, if achieved, could result in a quick and easy first approximation of the stream water temperature.

In other words, the objective of the sensitivity analysis is to determine the system response to changes in the system parameters. Sensitivity of the model to each of the aforementioned weather parameters is found by calculating the sensitivity coefficients. The average and/or standard deviation of each of the weather parameters are also used to compare the sensitivity of the model to each of the parameters.

4.2. Sensitivity coefficients

Sensitivity coefficients represent the change of the dependent variable (stream water temperature in this case) as a result of a unit change in each of the model parameters, one at a time, holding the rest of the parameters constant. Mathematically speaking, sensitivity coefficients are the partial derivatives of the dependent variable with respect to each of the parameters (Willis and Yeh, 1987). Sensitivity coefficients have been used extensively in groundwater research (Vermuri and Karplus, 1969; Neuman, 1980 a,b; Neuman and Carrera, 1985; Yeh, 1986; McKinney, 1990). Chavent et.al. (1975) and Dogru and Seinfeld (1981) used sensitivity coefficients in petroleum reservoir simulators. Sykes and Wilson (1984), Sykes et.al. (1985), Wilson and Metcalfe (1985), Townley and Wilson (1985) and Yeh (1986) analyzed various algorithms for computing sensitivity matrices and their computational requirements. Other researchers such as Schecher and Driscoll (1987) used the sensitivity coefficients in chemistry research, mainly to evaluate the uncertainty associated with Aluminum equilibrium calculations. Gulliver and Halverson (1989) and Thene and Gulliver (1990) used sensitivity coefficients in an analysis of uncertainty propagation in experimental measurements of air–water mass transfer. Wood and Gulliver (1990) used sensitivity coefficients to estimate the uncertainty of financial feasibility analyses for energy projects.

4.3. Methods for computing sensitivity coefficients

The Influence coefficient method, the Sensitivity equation method and the Variational method are the three most common methods for evaluating the sensitivity coefficients. Willis and Yeh (1987) presented the three methods. The first two methods will be used here. A comparison between the two methods will be also given.

4.3.1. Influence coefficient method

The influence coefficient method evaluates the sensitivity coefficients by perturbing each of the model parameters, one at a time. The sensitivity coefficient is presented as $\frac{\partial T}{\partial p}$. The finite difference method can be used to approximate this partial derivative.

The one-sided difference method is the simplest approach to approximate the partial derivative $(\frac{\partial T}{\partial p})$.

$$\frac{\partial T}{\partial p} \approx \frac{T(p_1,p_2,\ldots,p_i+\Delta p_i,\ldots,p_n)-T(p_1,p_2,\ldots,p_i,\ldots,p_n)}{\Delta p_i} \tag{4.1a}$$

$$(i = 1, 2, \ldots, N)$$

where T is the dependent variable (stream water temperature) and p_i is one of the model parameters (e.g. air temperature, solar radiation etc.).

The values of T(p) and $T(p+\Delta p)$ are obtained by solving equation 3.1 numerically. In order to obtain all the sensitivity coefficients, the model should be run (N+1) times, where N is the number of model parameters considered. One "reference run" is needed to find T(p), and an additional run is required for each of the N independent variables (model parameters) in order to calculate the sensitivity coefficients for these parameters.

Two sources of error control the accuracy of the calculated $\frac{\partial T}{\partial p}$: (1) the rounding error resulting from subtracting the two closely spaced values of T (T(p) and $T(p+\Delta p)$), and (2) the truncation error due to the approximation of the derivative by a finite difference.

The rounding error is inversely proportional to Δp. On the other hand, the truncation error approaches zero in the limit as $\Delta p \rightarrow 0$. So, the optimal value for Δp can be obtained by minimizing the total error resulting from the finite difference approximation of the partial derivative $(\frac{\partial T}{\partial p})$. Bard (1974) suggested that upper and lower limits be imposed on Δp. According to Bard, the value of Δp should fall between $10^{-5}x|p|$ and $10^{-2}x|p|$. Calculations should be performed in double precision for a smaller limit to be used.

A second method of approximating the partial derivative is the central difference scheme, which, if employed, will give a better estimate of $(\frac{\partial T}{\partial p})$:

$$\frac{\partial T}{\partial p} \approx \frac{T(p_1,p_2,\ldots,p_i+\Delta p_i,\ldots,p_n)-T(p_1,p_2,\ldots,p_i-\Delta p_i,\ldots,p_n)}{2\Delta p_i} \tag{4.1b}$$

$$(i = 1, 2, \ldots, N)$$

However, since the central difference scheme requires a 2xN model simulations compared to N+1 simulations for the one-sided difference scheme, the one-sided difference scheme may be preferred for economy of calculations. When using the one-sided difference scheme, double precision calculations and a small Δp will result in a more accurate approximation of the partial derivative $(\frac{\partial T}{\partial p})$.

4.3.2. Sensitivity equation method

The sensitivity coefficients are obtained by taking the partial derivatives with respect to each independent variable in the governing equations. Taking the partial derivative of the advection/dispersion equation (Eq. 4.1) results in

$$\frac{\partial\left(\frac{\partial T}{\partial p}\right)}{\partial t} = - U \frac{\partial\left(\frac{\partial T}{\partial p}\right)}{\partial x} + D_L \frac{\partial^2\left(\frac{\partial T}{\partial p}\right)}{\partial x^2} + \frac{\left(\frac{\partial S}{\partial p}\right)}{\rho c_p h} \tag{4.2}$$

The numerical value of $\frac{\partial T}{\partial p}$ is obtained from the numerical solution of equation 4.2. Equation 4.2 is identical to equation 3.1 after replacing $\frac{\partial T}{\partial p}$ by $\tilde{T}$ and $\frac{\partial S}{\partial p}$ by $\tilde{S}$. As a result, the original algorithm that was developed for the solution of the governing equation can be used to solve for the sensitivity coefficients. The original dependent variable T is still in equation 4.2 (in the $\tilde{S}$ term: refer to appendix-D) and this means that an initial simulation using the original model to solve the governing equation (Eq. 3.1) for the dependent variable T using the actual parameters is required. This means that in order to get all the sensitivity coefficients, the model should be run (N+1) times as in the influence coefficient method.

4.4. Application to model

The previously discussed methods were applied to a simpler form of equation 3.1. When considering a freely flowing stream (as discussed before in chapter 3) the stream water temperature is not a function of distance anymore. This means that $\frac{\partial T}{\partial x}$ is equal to zero. This will simplify the original equation (Eq. 3.1) to equation 3.19:

$$\frac{\partial T}{\partial t} = \frac{S}{\rho c_p h}$$

and equation 4.2 will take the following form

$$\frac{\partial\left(\frac{\partial T}{\partial p}\right)}{\partial\ t} = \frac{\left(\frac{\partial S}{\partial p}\right)}{\rho c_p h} \tag{4.3}$$

The sensitivity equation method requires calculating the partial derivatives of each of the source term components with respect to each of the independent variables. Appendix D gives the required partial derivatives for each component of the source term with respect to each weather parameter.

The model was applied to the Straight River covering the summer months of June, July and August. 25–year (1953–1977) average daily weather data from the Duluth (MN.) class–A weather station were used in the simulations. Figures 4.1(a, b, c, d and e) respectively show the daily mean values of air temperature, solar radiation, relative humidity, wind speed and cloud cover data used in this application.

In order to meaningfully compare the different sensitivities, the sensitivity coefficients should be combined with some parameter that represents the magnitude of each of the weather parameters. The standard deviation of each of the weather parameters is assumed to be a representative parameter for comparison. The sensitivity coefficients for each of the weather parameters (Fig. 4.2) were multiplied by the standard deviation. The sensitivity coefficients for the barometric pressure were found to be very small and assumed to be zero.

The model sensitivities calculated using the two different methods are listed in Table 4.1. The numbers shown in the table represent an average of the model sensitivities over the simulated period which is equivalent to the average change in stream water temperature in response to one standard deviation change in each of the weather parameters. The sensitivity coefficients calculated using the two methods compared good. Differences can be attributed to the assumption that all weather parameters used are considered uncorrelated or to the finite difference approximation of the partial derivatives (influence coefficient method). In the influence coefficient method, computed sensitivity coefficients are sensitive to the magnitude of the parameter perturbation, Δp, (Willis and Yeh, 1987). Accurate results can only be obtained by choosing the proper Δp which also varies from one parameter to another. Therefore, the sensitivity equation method is recommended for future calculations of the sensitivity coefficients. Figure 4.3 compares the model sensitivities calculated using the sensitivity equation method. The model is most sensitive to air temperature and solar radiation. Wind sensitivities have negative values. This means that the stream water temperature will decrease as a result of an increase in wind speed.

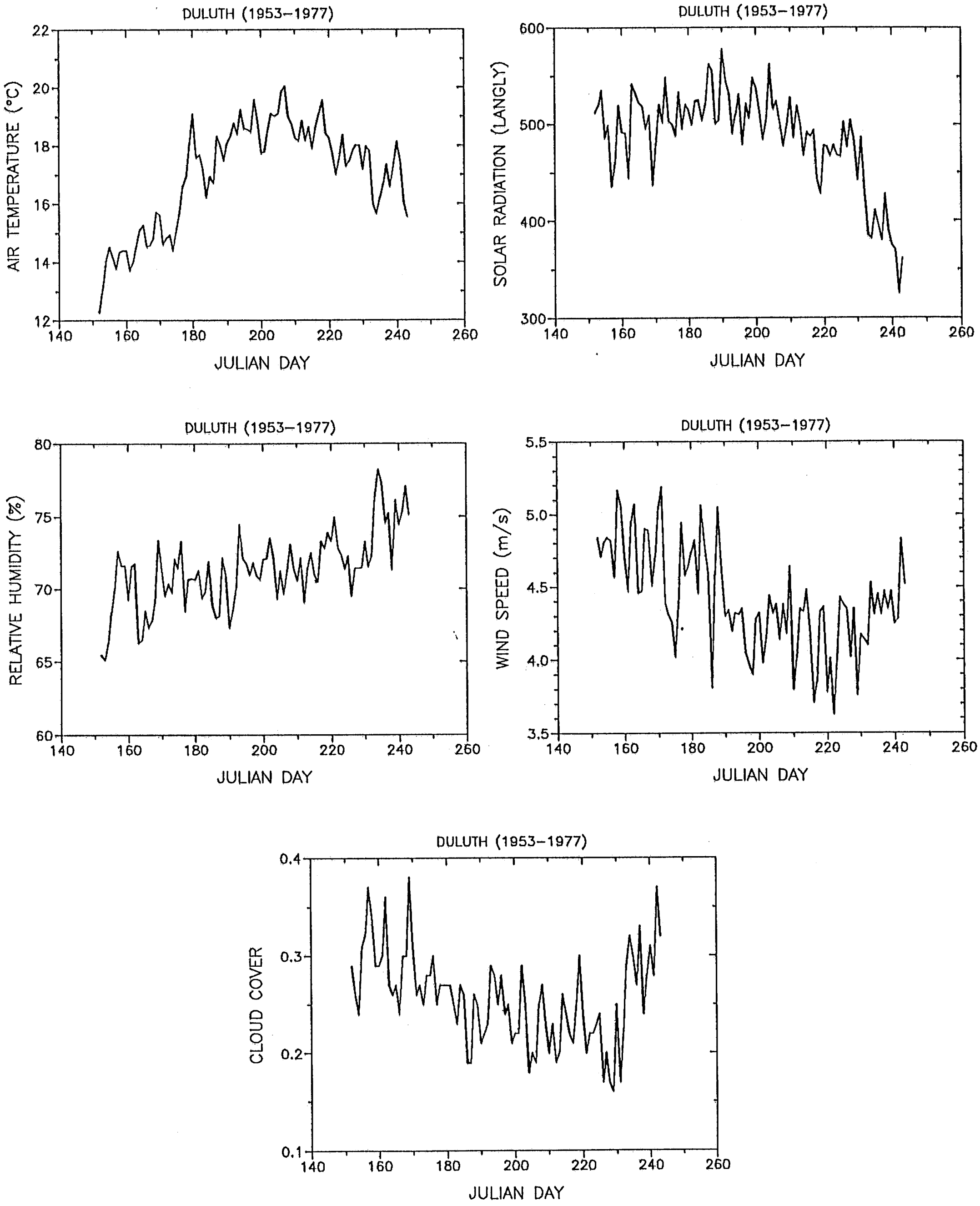


Figure 4.1. Weather data used to calculate model sensitivity.

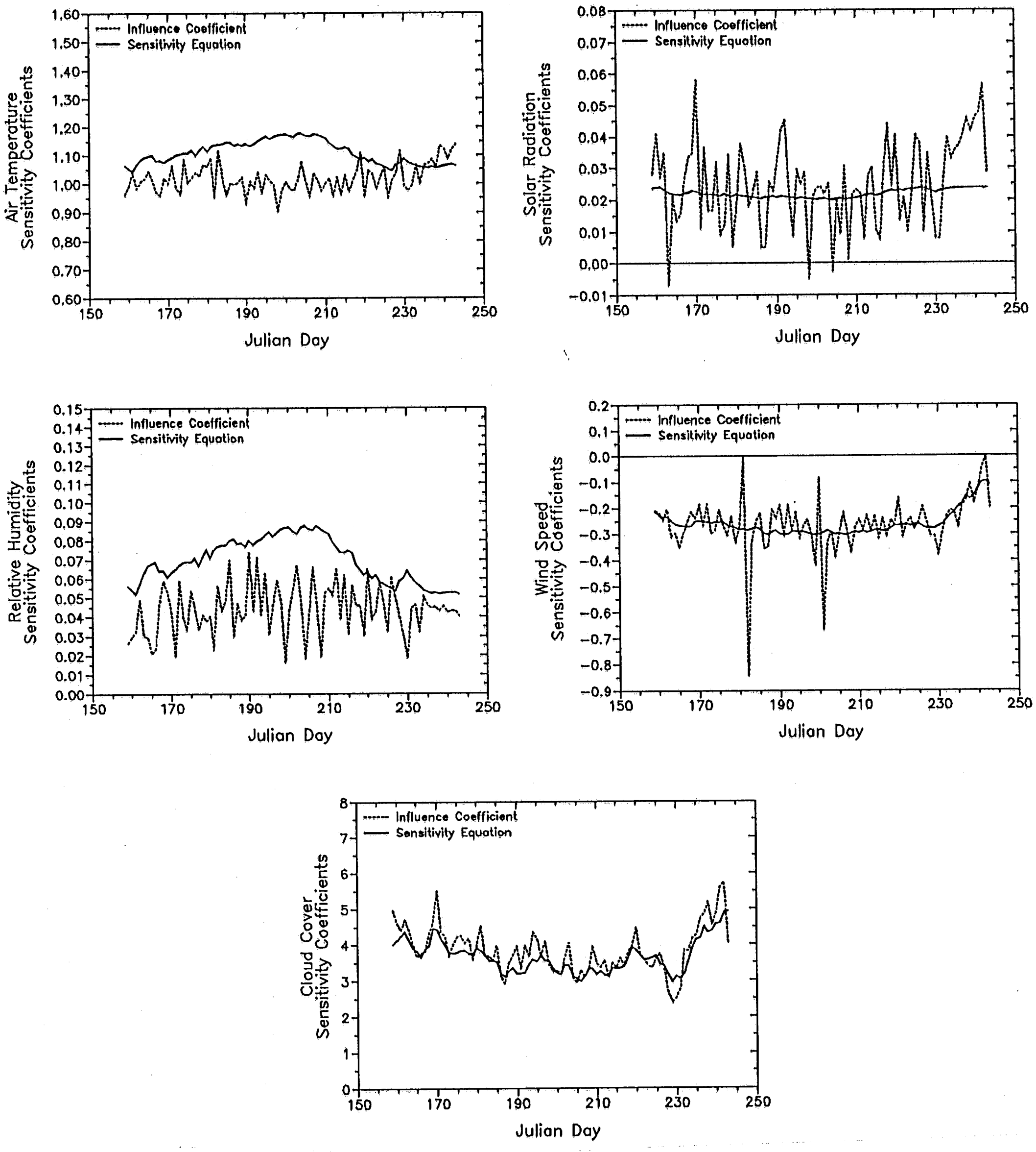


Figure 4.2. The change in stream water temperature as a result of a unit change in each of the weather parameters (sensitivity coefficients).

Table 4.1. Average model sensitivities* (°C) to different weather parameters using two differet methods

	Influence Coefficient Method	Sensitivity Equation Method
Air Temperature	3.53	3.84
Solar Radiation	3.33	2.89
Relative Humidity	0.43	0.69
Cloud Cover	0.70	0.66
Wind Speed	0.36	0.35

* Change in mean summer temperatures of the Straight River in response to one standard deviation change in the weather parameter

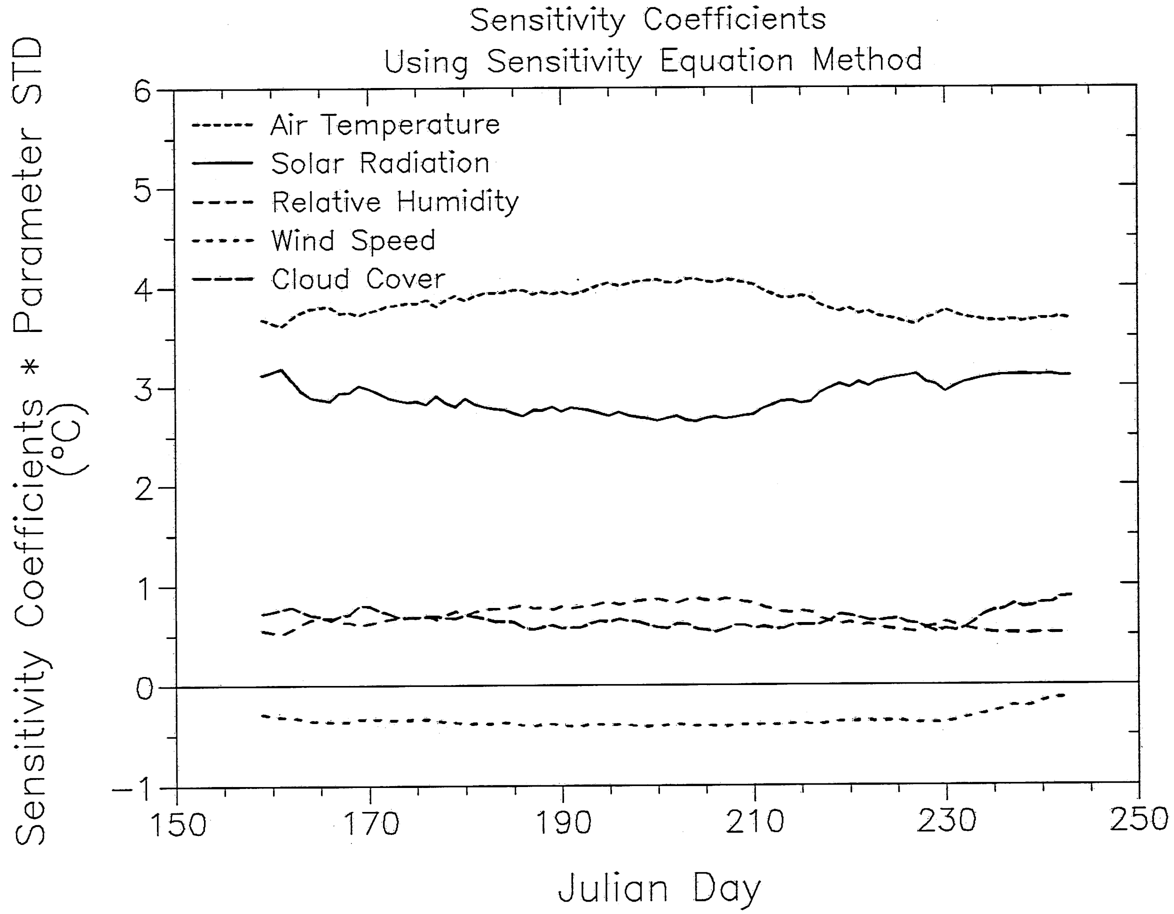


Figure 4.3. Model sensitivity to weather parameters.

4.5. Summary and conclusions

1) Accurate predictions of stream water temperatures require complete heat budget models.

(2) Simpler stream water temperature models which use fewer independent variables can be developed but care should be taken not to drop any significant parameter.

(3) Developing such simpler models in a good and safe way requires the study of the model sensitivity to all of the independent (weather) variables.

(4) Model sensitivities can be computed by the calculation of the sensitivity coefficients, a well documented approach in groundwater research.

(5) The sensitivity coefficients were calculated using two different methods: the influence coefficient method and the sensitivity equation method.

(6) The two methods used to calculate the sensitivity coefficients gave results on the same order of magnitude.

(7) The sensitivity coefficients computed using the influence coefficient method are sensitive to the magnitude of the parameter perturbation (Δp). Therefore, the sensitivity equation method is recommended for future calculations of the sensitivity coefficients.

(8) The sensitivity coefficients have to be combined with some parameter that represents the range of each of the independent variables (e.g. average or standard deviation) in order to meaningfully compare the different model sensitivities.

(9) The model is shown to be most sensitive to air temperature and shortwave (solar) radiation. This imply that any simplified model should include, at least, these two weather parameters in order to obtain good approximation of stream water temperatures.

(10) The barometric pressure, used to calculate convective heat transfer, can be assumed constant since the sensitivity analysis indicates that the model sensitivity to it is approximately zero.

5. MODEL CALIBRATION TO SPECIFIC STREAMS

5.1. Selected streams: Criteria and description

Reaches of the Straight River, Baptism River, Clearwater River, Zumbro River and the Mississippi River in Minnesota were selected for this study. Figure 1.1 shows the location of the selected stream reaches and Table 5.1 summarizes the stream characteristics in those reaches.

A statewide documentation of regional stream characteristics in Minnesota has not been found although state agencies and the literature (Waters 1977, MPCA 1988, EPA 1988) were consulted. It is therefore not possible to relate statistically the widths, depths, flow rates and bank vegetation of the selected streams to all streams of the state. However, the selected streams are representative of valuable fisheries resources, and occur in several different ecoregions (EPA, 1988). Streams in Minnesota can be considered representative of the north–central U.S.

It was necessary to have water temperature data and stream flow data to calibrate and validate the water temperature model for each selected stream reach. Following is a description of each of the selected stream reaches:

1. Straight River

The Straight River in north–central Minnesota is located in Becker and Hubbard counties (in the Northern Lakes and Forests Ecoregion and at the border of the North Central Hardwood Forests Ecoregion). It flows about 15 miles from its source in Becker County to its mouth in Hubbard County. A dam at Osage forms the Straight Lake and controls discharge of the river near its upstream end (Figure 5.1). The river has an average width of about 45(ft), an average maximum depth of 1–2(ft) and a slope of 4.76(ft/mi).

The Straight River watershed covers 95 square miles, it is heavily forested with mixed hardwoods and softwoods. The watershed is mostly used for agriculture or as forests.

Base discharge of the Straight River varies from about 30(cfs) downstream from Straight Lake to about 60(cfs) near its mouth. The flow rate in addition to water temperature were measured by the U.S.G.S. for the last two years to study the effects of groundwater withdrawals for irrigation on the quality of the Straight River. Table 5.1 lists some of the different U.S.G.S. gaging stations located on the river and the flow rate information available.

The Straight River is designated as a trout stream. It is generally cold and clear. According to the DNR fisheries surveys, some of the fish present in the river includes : Brown Trout, Sucker, Northern Pike and others.

Table 5.1. Morphometric and hydrologic characteristics of the selected streams.

USGS Gaging Station	Period of Record	Average Flowrate (cfs)	Min. Flow (cfs)	Max. Flow (cfs)	Drainage Area (mi^2)	Stream Length (mi)	Average Width (ft)	Average Depth (ft)	Slope (ft/mi)	Fish Present	Remarks
Straight River near Ossage	1987...		21.0	62.0						Brown Trout Rainbow Trout Northern Pike White Sucker Black Crappie	Soil: sand and gravel with some muck and rubble. Cover types: heavely forested with mixed hardwoods and soft woods. Watershed use: Mostly wild forested with a small amount used for pasture. Sinuosity=1.336
Straight River near Park Rapids @ Hwy 115	1987...		26.0	81.0							
Straight River near Park Rapids	1970-71 1973 1975-76 1987...	45.0	28.0	87.0	53.2	14.7	45.0	1.0	4.76		
Baptism River near Beaver Bay	1927...	169	5.0	10,000	140	26.5	64.5	2.0		Brown T. Rainbow T. Chinook Salm.	The stream bed is composed of predominately coarse material.
Clearwater River @Plummer	1939-79 1982...	177.0	zero	3,940	512	150.0	97.7	3.1	2.1	Brown T. Rainbow T. Northern Pike White S.	Sinuosity=2.8
Clearwater River @Red Lake Falls	1909-17 1939-79 1982...	318.0	zero	10,300	1370						
Zumbro River @Zumbro Falls	1930...	517	27.0	35,000	1,400	57.7	143.0	1.5	2.9	Sauger Walleye Black & White Crappie White Sucker	Watershed: Upland soils are silt loams. Most of the stream flows through a narrow, wooded corridor with adjacent row crops and pasture. Sinuosity=2.0
Mississippi River near Anoka	1931...	8,019	529	91,000	19,100		492.4	5.8		Northern Pike Walleye	

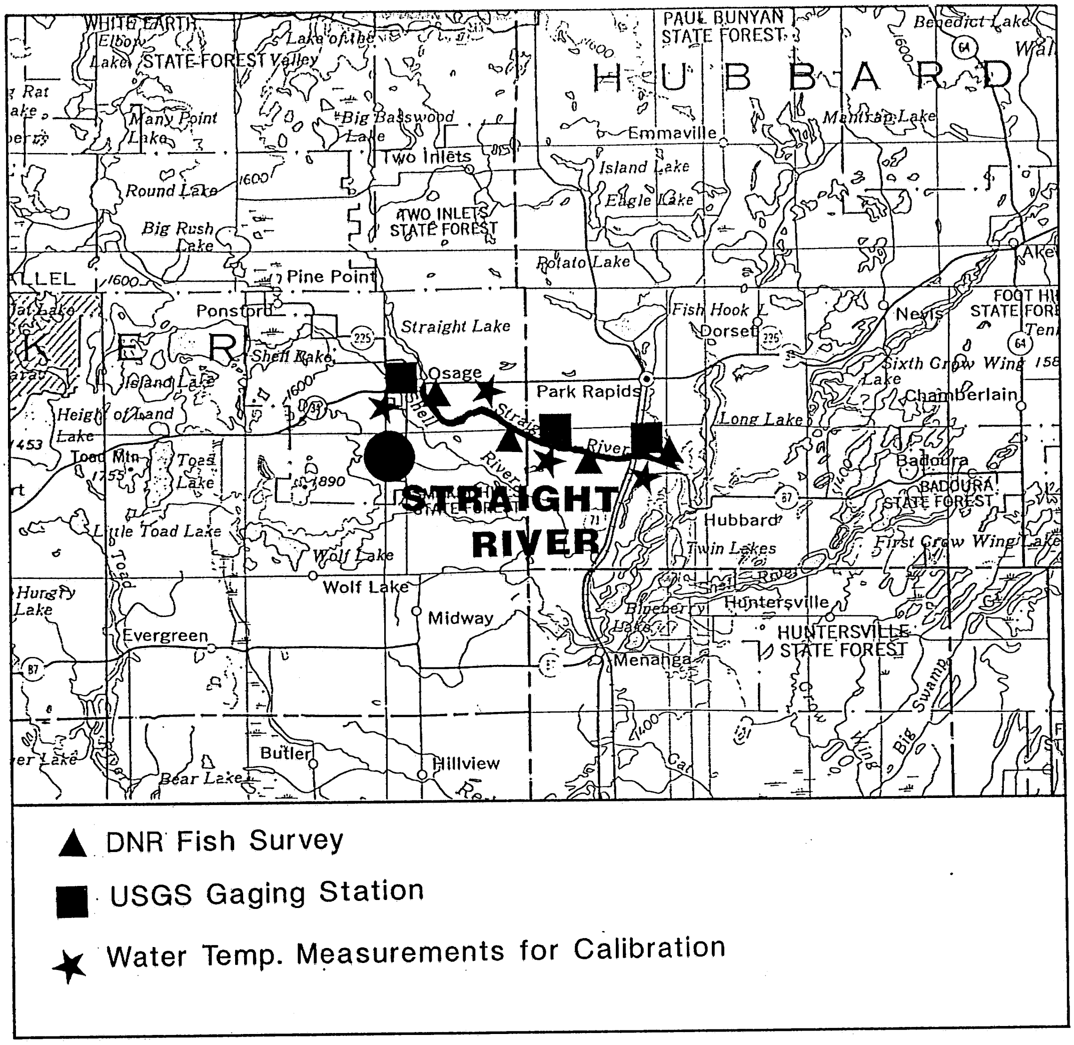


Figure 5.1. Map of the Straight River showing the modeled reach.

The photo shown in Fig. 5.2 shows some of the characteristics of the Straight River and its Watershed.

2. Baptism River

The Baptism River in north–eastern Minnesota is located in Lake County at the North Shore of Lake Superior (in the Northern Lakes and Forests Ecoregion). It is one of the largest rivers on the North Shore. It flows 26.5 miles from its source to its mouth at Lake Superior (Figure 5.3). The River has an average width of about 40(ft) at sector–I which is entirely within the Baptism State Park and it is 4,910 feet long. The stream bed is composed of predominantly coarse material. The river drops about 73 feet in a mile in sector–I.

The Baptism River watershed covers 140 square miles. As most of the streams on the North Shore near Duluth, the lack of water storage in the headwaters causes a seasonal fluctuation of the discharge over wide ranges, leading to virtual drying up in late summer. Table 5.1 lists the different U.S.G.S. gaging station(s) located on the river and some of the flow rate information available.

The Baptism River can be classified as a Trout stream (Cold water fishery). The fish present in the river (according to the DNR fisheries surveys) are : Rainbow Trout, Brown Trout and Brook Trout.

The photo shown in Fig. 5.4 shows some of the characteristics of the Baptism River and its watershed.

3. Clearwater River

The Clearwater River in north–central Minnesota is located in Beltrami, Clearwater and Red Lake Counties (at the borders of the Northern Lakes and Forests, the Northern Minnesota Wetlands and the North Central Hardwood Forests Ecoregions). It flows about 150 miles from its source to its discharge into the Red Lake River near Red Lake Falls, (Figure 5.5).

Two U.S.G.S. gaging stations exists on the river. One is at Plummer with a drainage area of about 512 square miles, and the other is at Red Lake Falls with a drainage area of about 1,370 square miles. Table 5.1 lists the different U.S.G.S. gaging stations located on the river and some of the flow rate information available.

The Clearwater River can be classified as a Trout stream (coldwater fishery). The fish present in the river (according to the DNR fisheries surveys) are : Rainbow Trout and Brown Trout.

The photo shown in Fig. 5.6 shows some of the characteristics of the Clearwater River and its watershed.

4. Zumbro River

The Zumbro River in south–eastern Minnesota is located in Wabasha County (in the Central Corn Belts Plains and the Driftless Area Ecoregions).

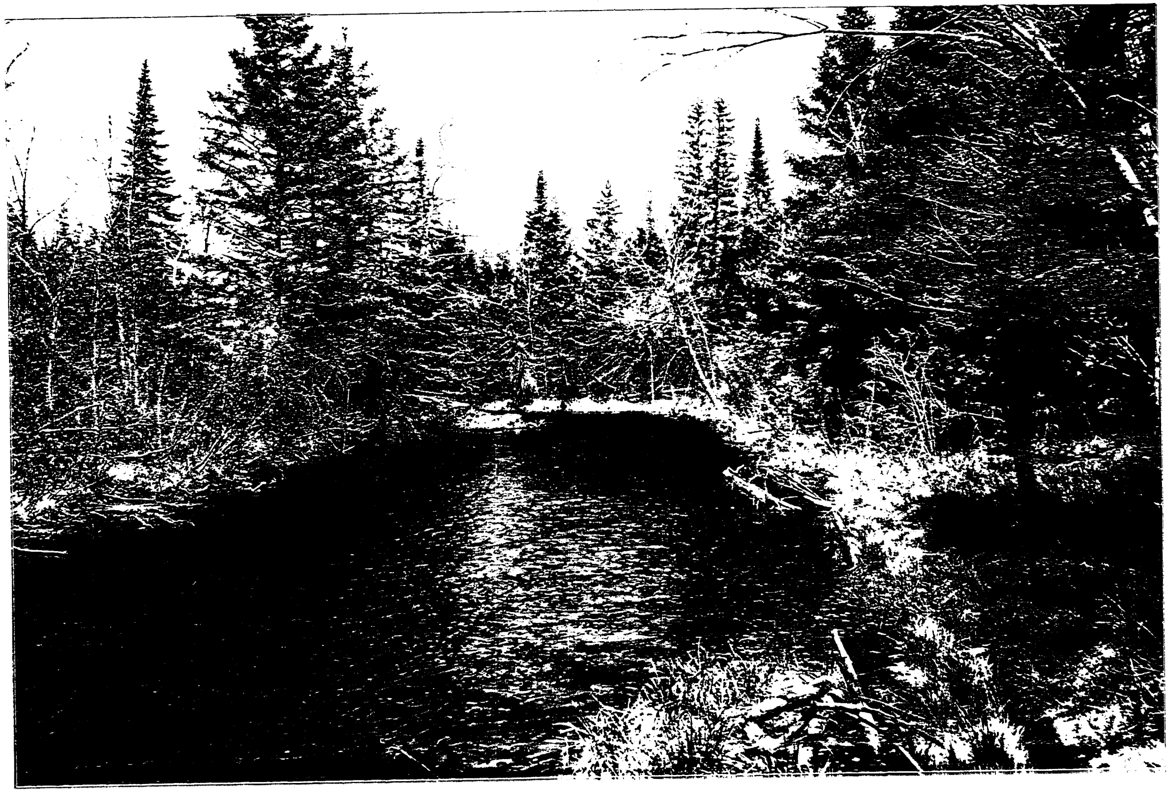


Figure 5.2. Straight River just upstream of station–1 (looking upstream).

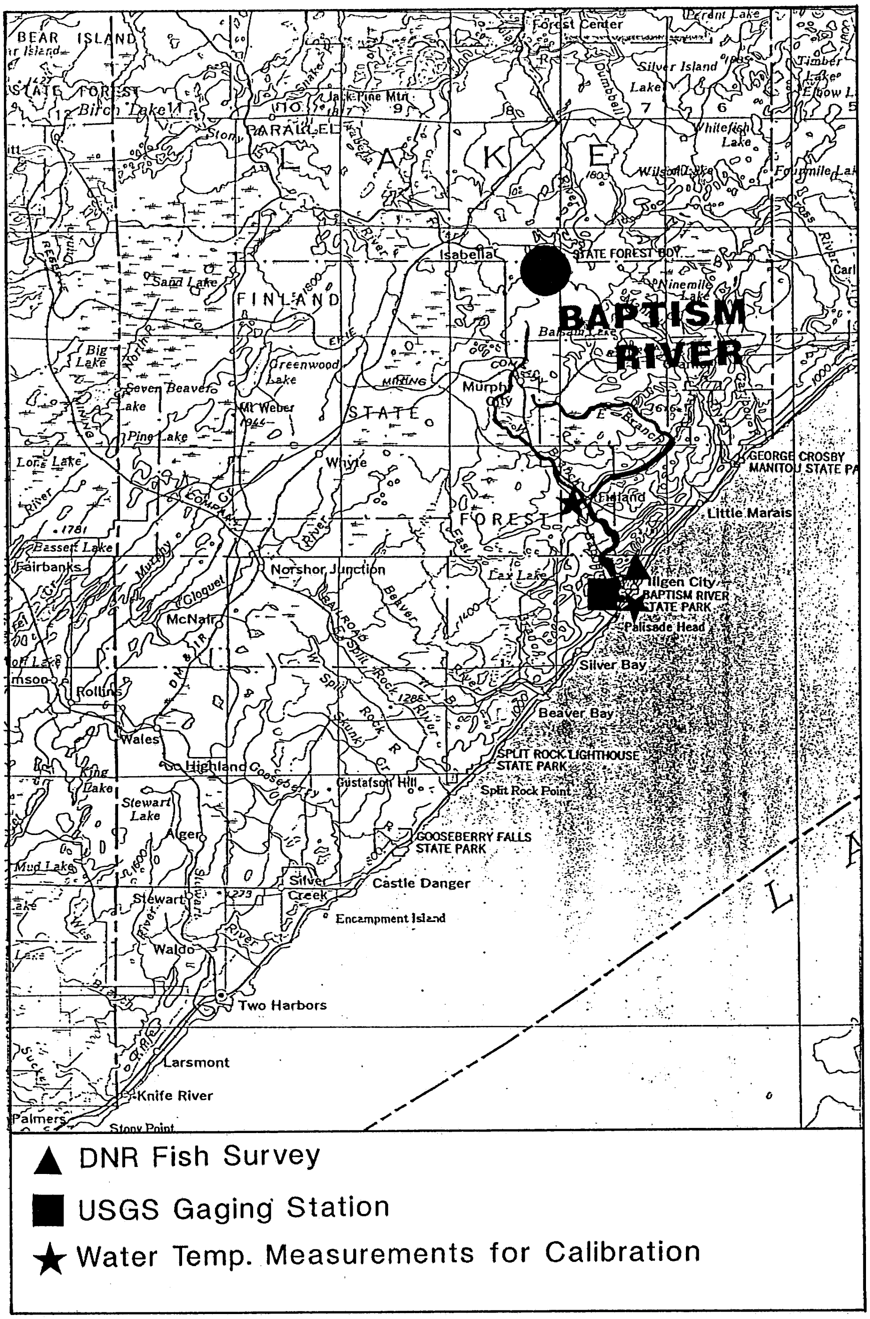


Figure 5.3. Map of the Baptism River showing the modeled reach.

Figure 5.4. Baptism River near Finland (MN.).

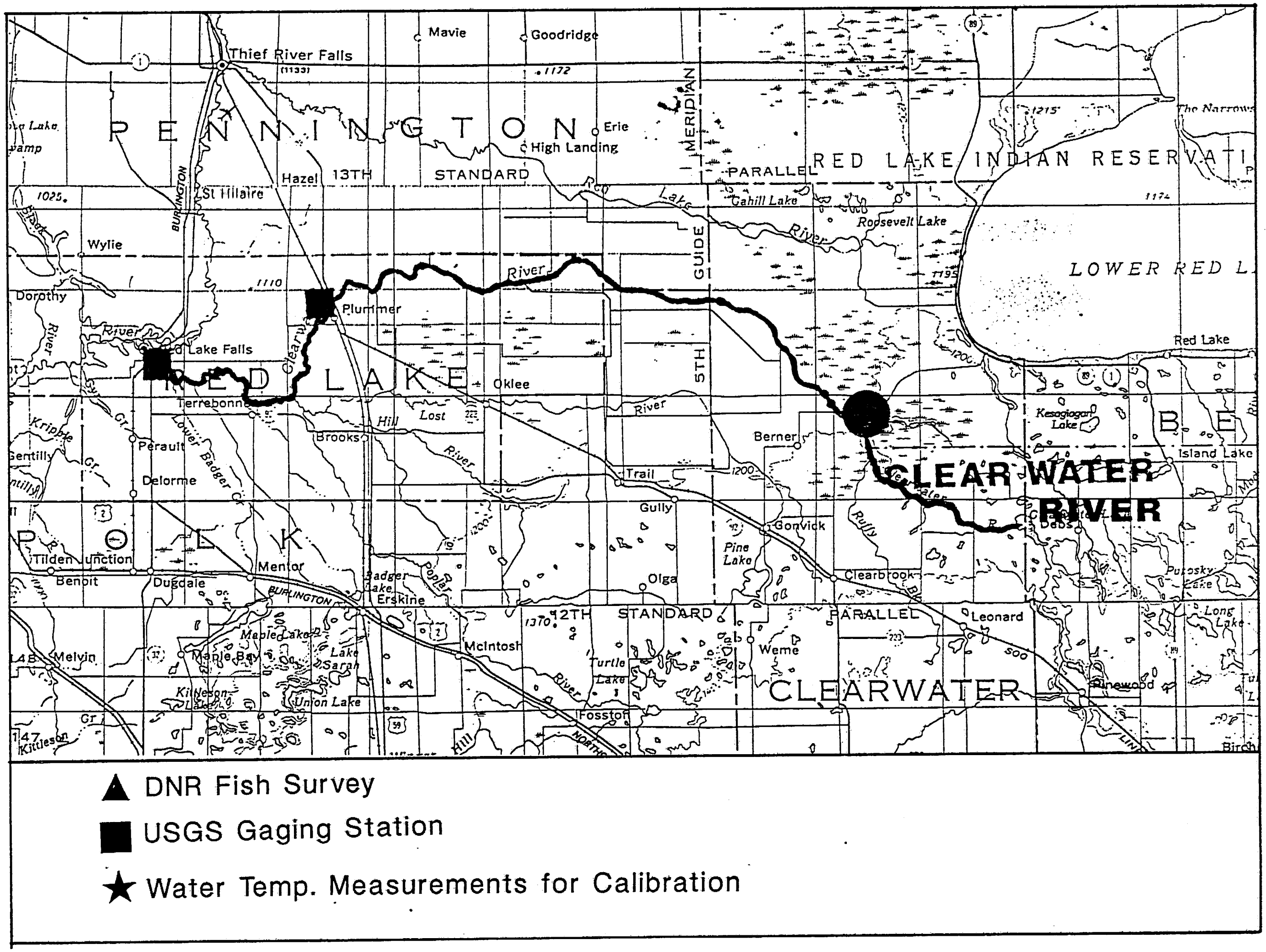


Figure 5.5. Map of the Clearwater River showing the modeled reach.

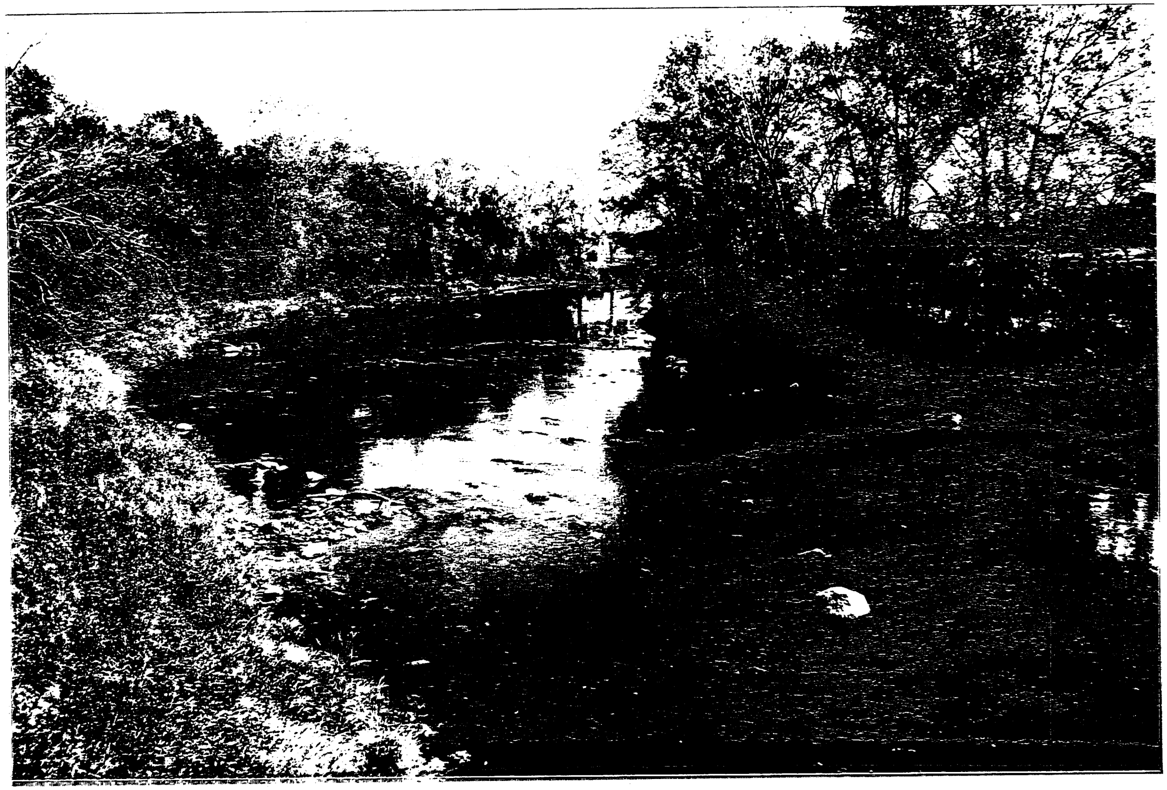


Figure 5.6. Clearwater River at Red Lake Falls (MN.): looking upstream.

It flows about 57.7 miles from Zumbro Lake to its mouth at the Mississippi River (Figure 5.7). The river in that reach has an average width of about 135(ft) and a slope of 2.9(ft/mi).

The Zumbro River watershed covers 1,400 square miles. The watershed upland soils are silt loams and the valley bottom soils are alluvial. The flat valley bottom is bordered by steep bluffs and is surrounded by rolling uplands. Bluffs are wooded, the valley bottom and uplands are intensively agricultural. Most of the stream flows through a narrow, wooded corridor with adjacent row crops and pasture. Table 5.1 lists the different U.S.G.S. gaging stations located on the river and some of the flow rate information available.

The Zumbro River can be classified as a cool water fishery stream. According to the DNR fisheries surveys, fish present in the river include : Walleye, Rainbow Trout, Sauger, Small Mouth Bass and Large Mouth Bass.

The photo shown in Fig. 5.8 shows some of the characteristics of the Zumbro River and its Watershed.

5. Mississippi River

The Mississippi River, in terms of volume of flow, is the largest river in North America and it is the seventh largest in the world. The Mississippi River basin is one and a quarter million square miles in size. It drains all or parts of thirty–one states and two Canadian provinces (Waters, 1977).

The Mississippi River reach selected for this study is located in central Minnesota north of the Twin Cities (Minneapolis / St. Paul) on the boarder between Sherburne and Wright counties (in the North Central Hardwood Forests Ecoregion). The reach is about 17 miles long starting from Monticello (MN.) and ending just upstream of the Crow River mouth (Fig. 5.9).

The Mississippi River basin is shaped by the glaciers and it is mostly a land of prairie and forest. The river bed mainly consists of fine materials (clay, silt and sand) due to the small slope of the river.

The Mississippi River can be classified as a warm water fishery stream. Some of the fish present in the studied river reach include: Northern Pike, Walleye, White Sucker, Yellow Perch, Black Crappie, Bass, Carp and Bluegill.

The photo shown in Fig. 5.10 shows some of the characteristics of the Mississippi River reach and its watershed.

5.2. Data collection

Data required by the model (Table 3.1) were assembled from different sources. Stream location (latitude and altitude) was obtained from the USGS (United States Geological Survey) contour maps. The weather data were

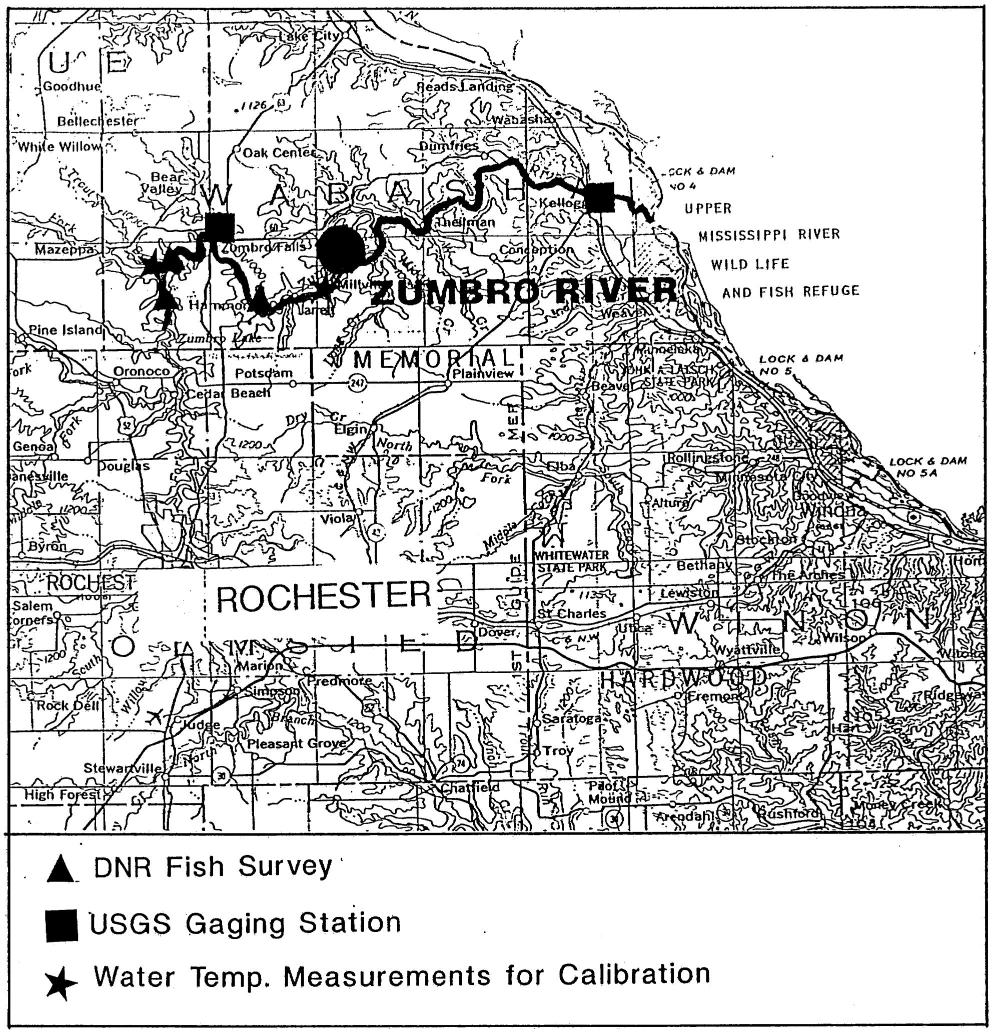


Figure 5.7. Map of the Zumbro River showing the modeled reach.

Figure 5.8. Zumbro River at Reads Park in Millville (MN.).

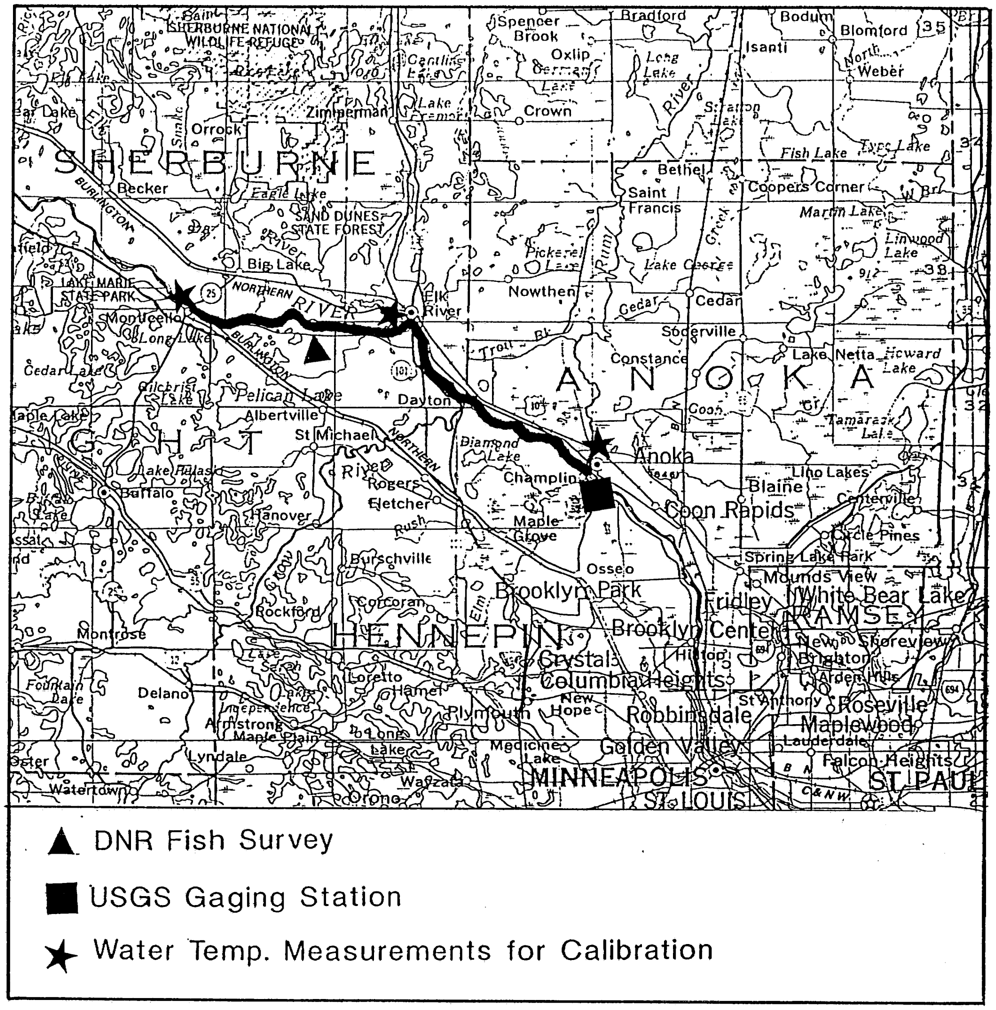


Figure 5.9. Map of the Mississippi River showing the modeled reach.

Figure 5.10. Mississippi River at Anoka (MN.).

obtained from the National Weather Service. Stream data were obtained by direct field measurements. Following is a description of the main field data collection efforts:

(a) Water temperature

Campbell Scientific CR10 data loggers were installed at two different sites on each of the four selected streams for periods of 2 to 4 weeks. Water temperature records for the Straight River were obtained from the USGS (Stark, 1989). Each of the data loggers was connected to five thermistors. Absolute accuracy (the difference between successive measurements by the same probe) was ±0.01°C. The thermistors were placed at five different locations across the stream's cross–section. Water temperatures were taken every 2 minutes. Every 20 minutes, the preceding 10 measurements were averaged and stored. This measurement scheme was adopted to reduce the "noise" inherent in single measurements while temporally resolving the fluctuations expected in the data. Periods for which the data were collected are shown in Table 5.2. Examples of the measured water temperatures are shown in Fig. 2.2.

For comparison with model simulation results, the recorded water temperatures were averaged over 1–hr and 24–hrs. Water temperatures measured upstream were used as upstream boundary condition in the model. Temperature measured downstream were used for comparison with the computed (predicted) water temperatures.

(b) Stream morphometry and hydrology

Several cross–sectional profiles in the stream reach were measured in the field. The model requires a functional relation between cross–sectional area A, surface width B and flow rate Q. Leopold and Maddock (1953), Richards (1982), EPA (1987) and Jarvis and Woldenberg (1984) suggested the following forms of these relationships

$$A = aQ^b \tag{5.1}$$

and

$$B = cQ^d \tag{5.2}$$

where a, b, c and d are constants depend on the shape of the stream's cross–section and can be determined by plotting the cross–sectional area and the surface width versus the stream flow rate on a log–log graph paper. The cross–sectional area and surface width can be calculated from the measured cross–sectional profiles, the flow rate is obtained from the USGS gaging station. The established relationships for the selected stream reaches are shown in Fig. 5.11(a, b and c). The coefficients a, b, c, and d are given in Appendix F.

Stream reach length was obtained from USGS quadrangle maps, stream flow rate record was obtained from USGS gaging records. Stream reaches had been selected to include a gaging station and no major tributary inflow.

Table 5.2. List of all measurements performed in this study

STREAM NAME	**TYPE OF MEASUREMENTS**	**PERIODS OF MEASUREMENTS**	**TOTAL NUMBER OF DAYS**
STRAIGHT RIVER	-WATER(4 SITES) -AIR(4 SITES) -CROSS-SECTION PROFILES	MONITERED BY THE USGS AND THE DNR (1987-....)	
BAPTISM RIVER	-WATER(2 SITES) -CROSS-SECTION PROFILES	SEPT. 4-25, 1990 JULY 10 - AUG. 3, 1991	42
CLEARWATER RIVER	-WATER(2 SITES) -CROSS-SECTION PROFILES	OCT. 6-27, 1990 SEPT. 5 - OCT. 6, 1991	51
ZUMBRO RIVER	-WATER(2 SITES) -CROSS-SECTION PROFILES	JULY 25 - AUG. 8, 1990 AUG. 9-21, 1990 OCT. 21 - NOV. 13, 1991	49
MISSISSIPPI RIVER	-WATER(3 SITES)	JUNE 20 - JULY 10, 1991	20
RUM RIVER	-WATER and SEDIMENT (1 SITE)	SEP. 6 - OCT. 8, 1991	32

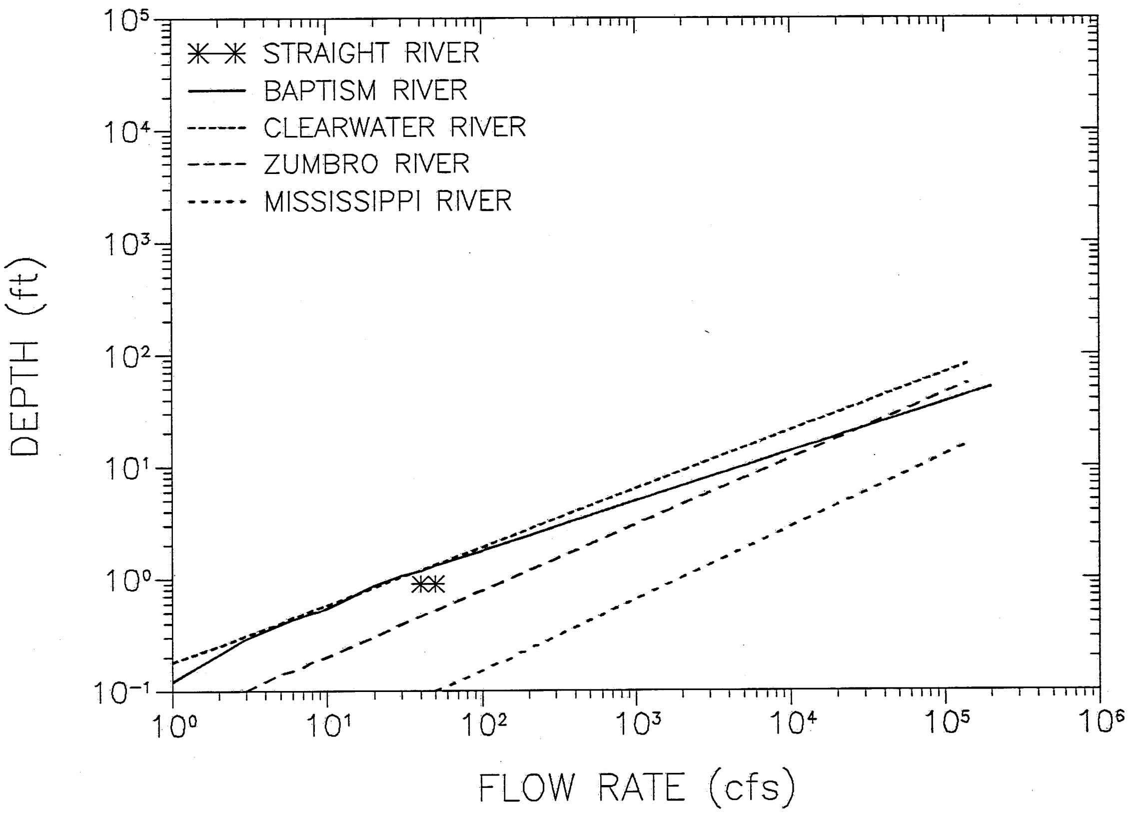


Figure 5.11a. Relationship between stream flow rate and stream average depth.

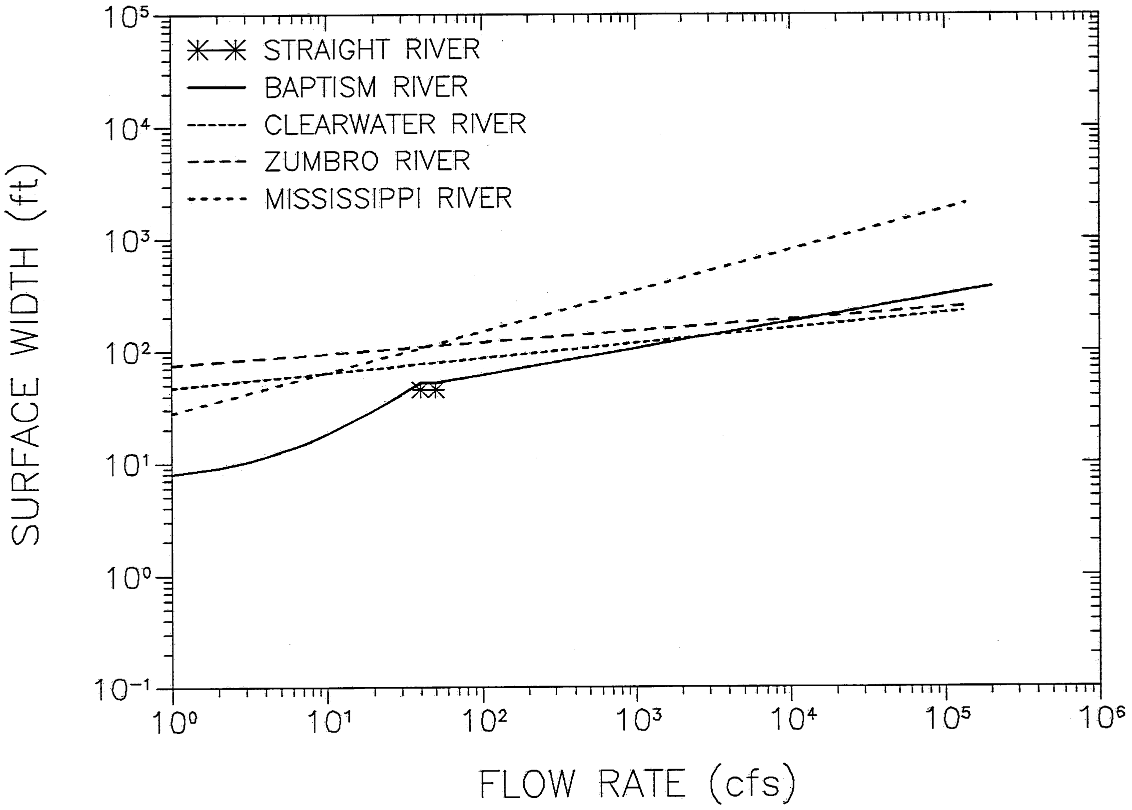


Figure 5.11b. Relationship between stream flow rate and stream surface width.

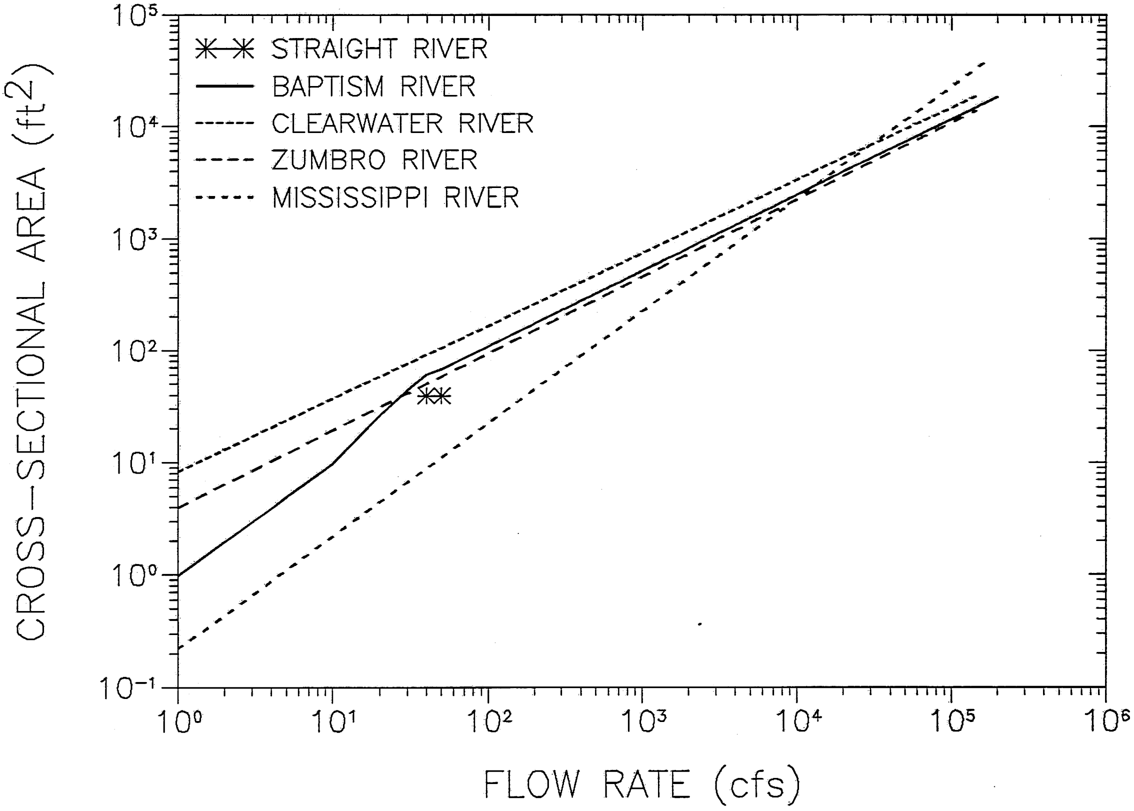


Figure 5.11c. Relationship between stream flow rate and stream cross–sectional area.

(c) Streambed heat transfer

Temperature profiles in the streambed and water temperature of the Rum River were measured for a period of 1–month using the same equipment and procedure discussed in the water temperature measurements. The measurement setup is shown in Fig. 5.12. The purpose of the measurements is to calibrate and validate the streambed heat transfer subroutine introduced in the model. Fig. 5.13 shows examples of such profiles. Fig. 5.14 shows the measured temperatures of the streambed at different depths as a function of time. The streambed heat transfer subroutine and its calibration and validation are discussed in detail in Appendix C.

5.3. Model calibration

The model was calibrated using measured water temperatures at two sites (stations) on each of the selected stream reaches. The measured water temperatures at the upstream site were used as an upstream boundary condition. The measured water temperatures at the downstream site were used as a comparison with the computed water temperatures. Downstream water temperatures were computed using daily flow rate at a USGS gaging station and hourly or daily weather data obtained from the National Weather Service class–A weather station. More accurate simulations could be achieved using weather data measured at the stream site. Usually this is not available.

Sun–shading and wind–sheltering are two important coefficients that should be considered when modeling stream water temperatures. Brown (1969), Rishel et.al. (1982) and Meisner (1990) illustrated the effect of sun–shading on stream water temperature.

Optimal values of sun–shading and wind–sheltering coefficients were established for each stream separately by model calibration. The water temperatures for each stream reach were computed (at the downstream site) using ranges of sun–shading and wind–sheltering coefficients from 0 to 100%. The standard error between measured and computed water temperatures was then found for each stream reach:

$$\mathrm{SEE} = \left[\sum \frac{(T_m - T_c)^2}{n-1}\right]^{0.5} \tag{5.3}$$

where SEE is the standard error of estimate, T_m is the measured water temperature, T_c is the computed water temperature and n is the number of data pairs compared.

The standard error of estimate was plotted as a function of the sun–shading and wind–sheltering coefficients for each stream reach (Fig. 5.15 and Fig. 5.16). The figures show that model sensitivity to sun–shading is greater than to wind–sheltering. This may suggest that radiation balance is more important than evaporative cooling or convective heating or cooling, as

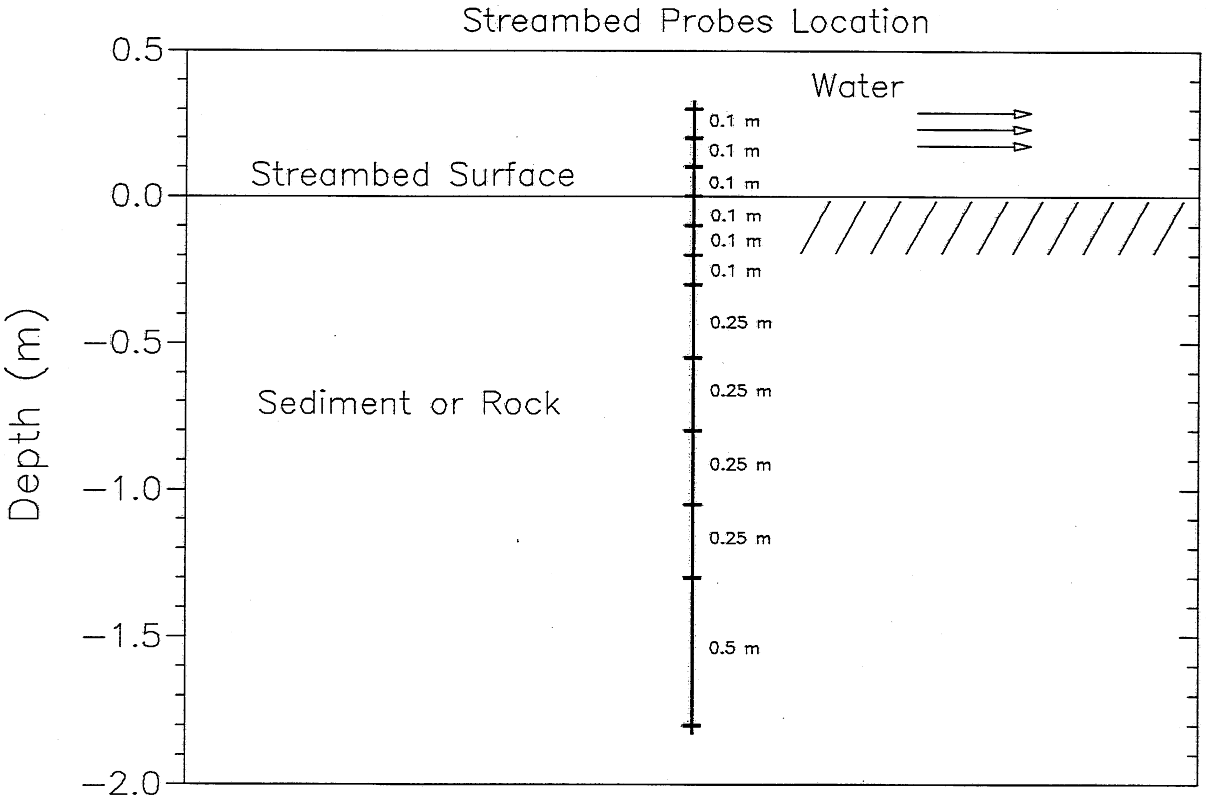


Figure 5.12. Location of streambed temperature probes.

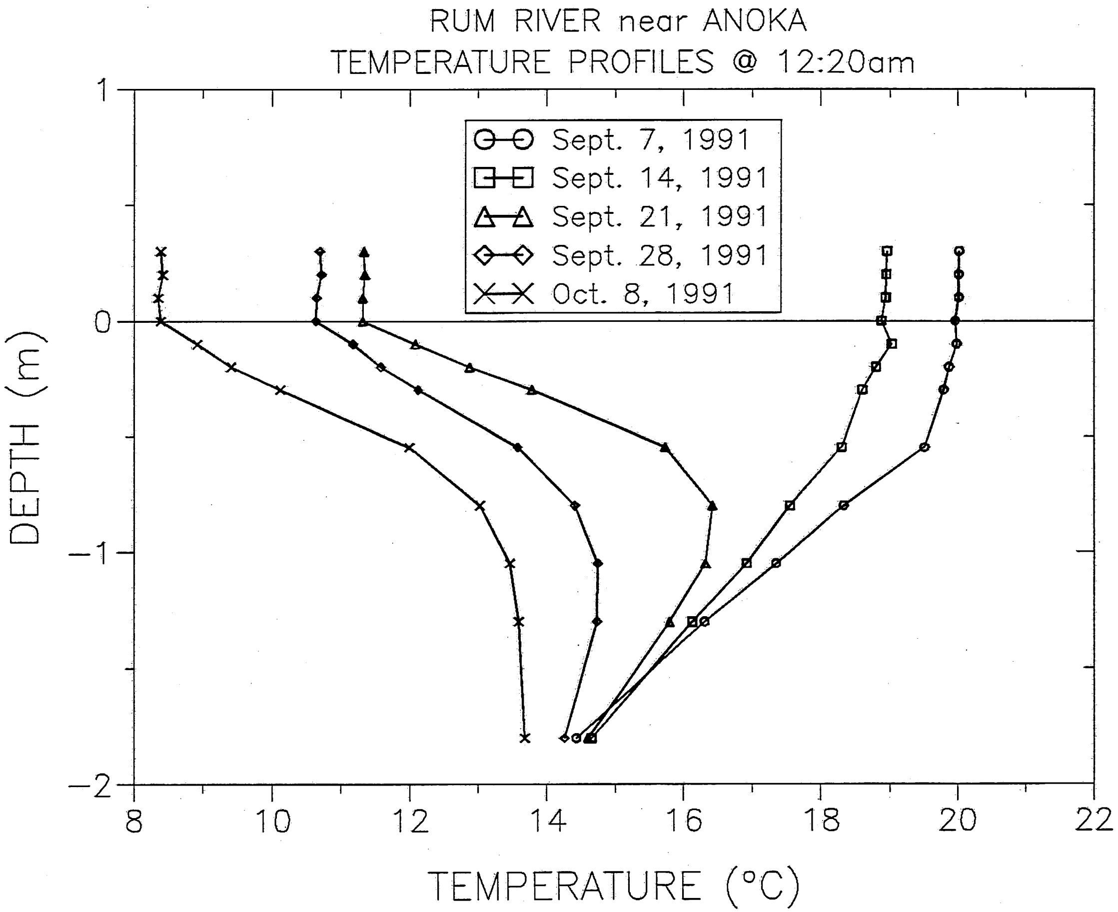


Figure 5.13. Examples of measured streambed temperature profiles at the Rum River near Anoka (MN.).

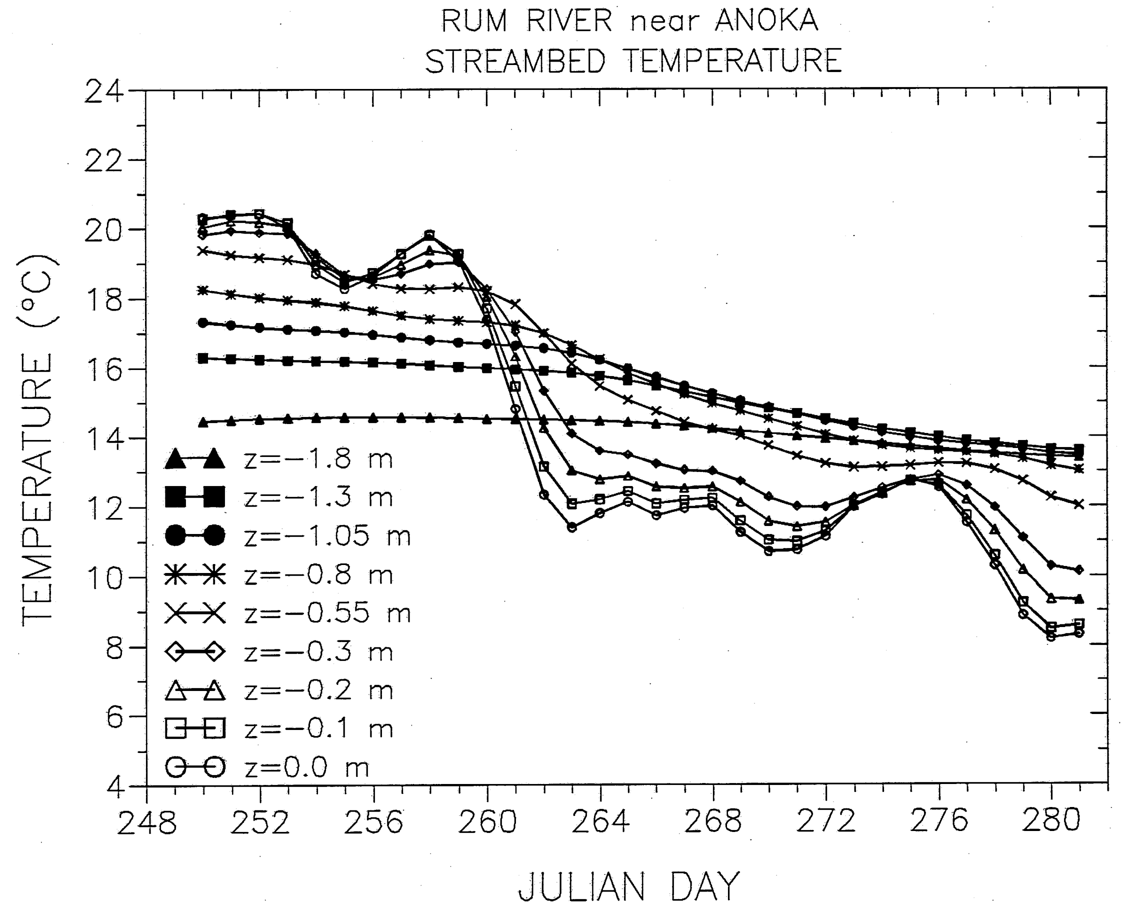
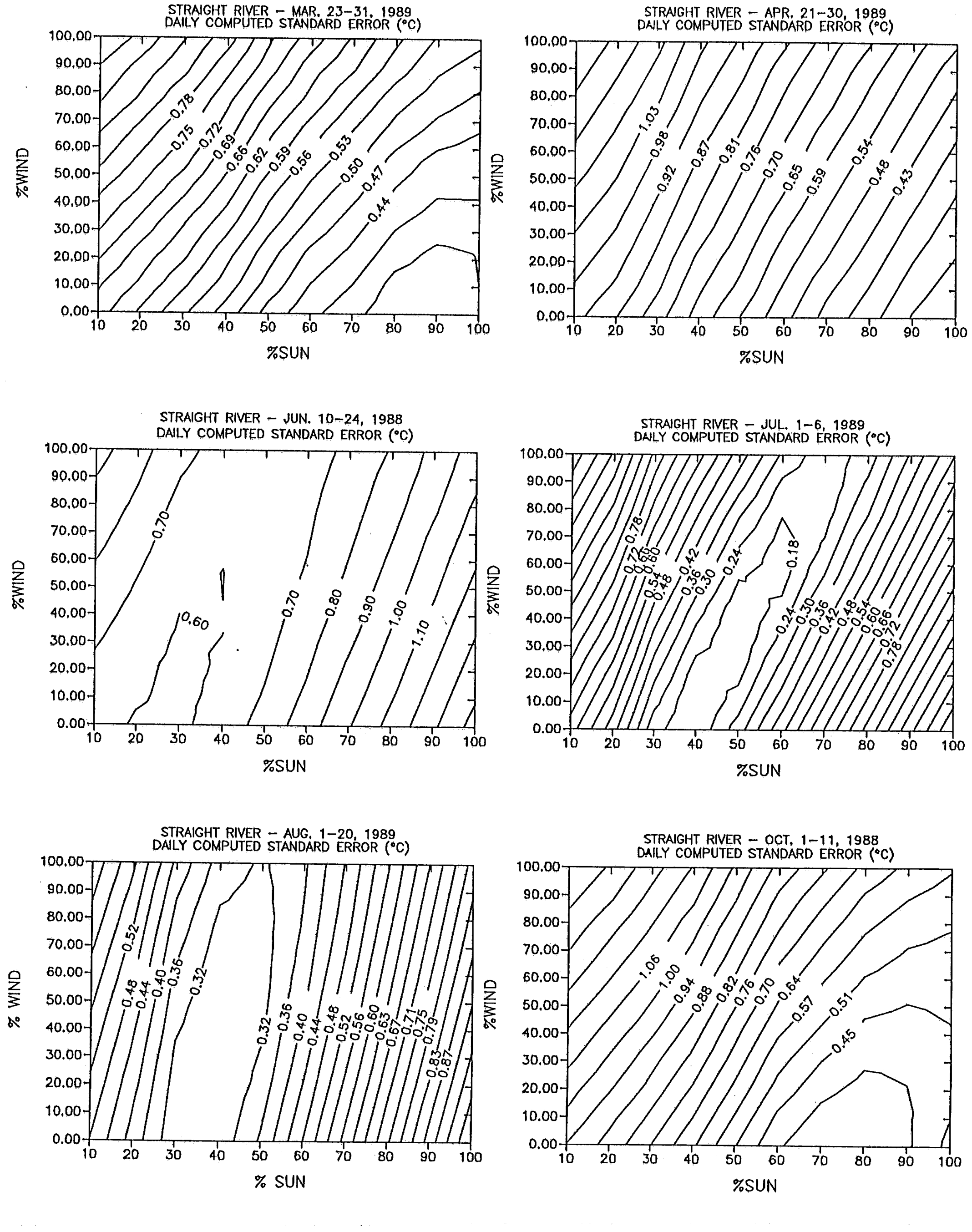


Figure 5.14. Measured streambed temperatures at the Rum River near Anoka (MN.).



STRAIGHT RIVER – MAR. 23-31, 1989
DAILY COMPUTED STANDARD ERROR (°C)

STRAIGHT RIVER – APR. 21-30, 1989
DAILY COMPUTED STANDARD ERROR (°C)

STRAIGHT RIVER – JUN. 10-24, 1988
DAILY COMPUTED STANDARD ERROR (°C)

STRAIGHT RIVER – JUL. 1-6, 1989
DAILY COMPUTED STANDARD ERROR (°C)

STRAIGHT RIVER – AUG. 1-20, 1989
DAILY COMPUTED STANDARD ERROR (°C)

STRAIGHT RIVER – OCT. 1-11, 1988
DAILY COMPUTED STANDARD ERROR (°C)

Figure 5.15. Sensitivity of the Straight River water temperature simulation to shading (from solar radiation) and to sheltering (from wind).

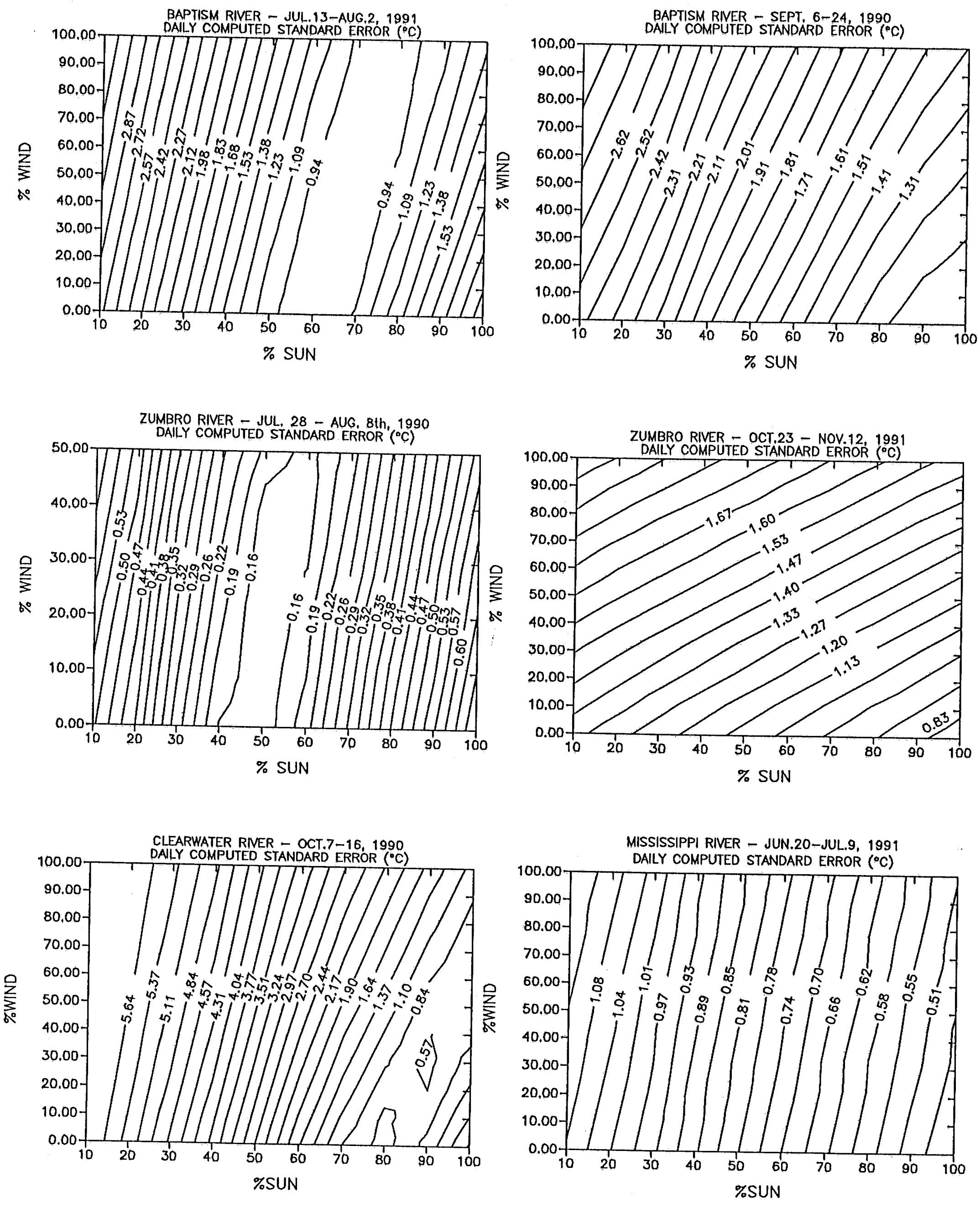


Figure 5.16. Sensitivity of the stream water temperature simulation to shading (from solar radiation) and to sheltering (from wind).

already pointed out by Brown (1969). Trees on stream banks and topography of the stream valley are the main factors governing the shading and sheltering processes.

Optimal values for the sun–shading and wind–sheltering coefficients for each stream reach were selected from Fig. 5.15 and Fig. 5.16.

Figure 5.17(a, b, c, d and e) and 5.18(a, b, c, d and e) give examples of hourly and daily simulation results for the five selected streams using the optimal values for the sun–shading and wind–sheltering coefficients. The figures also show hourly and daily measured water temperatures for comparison.

Figure 5.17(a, b, c, d and e) shows that the model simulates the diurnal amplitudes of the water temperatures with a good accuracy. These amplitudes are due to the dynamic changes in air temperature and solar radiation as discussed earlier in chapter 2. Figure 5.18(a, b, c, d and e) shows no diurnal amplitudes because daily average weather was used in the simulations. Nevertheless, Fig. 5.18 shows that the model simulations compare well with the measured water temperatures. The standard error of estimate for both hourly and daily simulations is on the order of 1 °C in all cases modeled. One reason for simulations error is the use of weather data from weather stations not actually at the stream site. Table 5.3 lists the average flow rate, depth and surface width for all selected streams for all periods simulated. The listing demonstrates that the model can be applied to a very wide range of flows (36 to 12406 cfs). Table 5.3 also lists the standard error of estimate and the optimal sun–shading and wind–sheltering coefficients for all the simulation periods.

The sun–shading coefficient is a function of bank vegetation, stream valley topography and stream width. Leaf cover on trees is a function of time (season) and it will strongly influence the sun–shading coefficient. The percentage exposure of the stream surface to sun is greater in early spring and fall before leaves grow on trees or after leaves fall from trees. Therefore, different shading percentages were found through separate calibrations with spring, summer and fall data (Table 5.3).

The change from winter to summer shading begins around the third week of April in the Minneapolis/St. Paul area and is completed in about three weeks. The summer to fall change of shading starts around the third week of September and is assumed to be completed in about three weeks too. To account for the effects of latitude an adjustment to these dates was made by adding or subtracting one week for every 100 miles north or south from the Minneapolis/St. Paul area (Fig. 5.19). This was recommended by the Horticulture Department of the University of Minnesota, St. Paul. The x–symbols in Fig. 5.19 represent percentages of sunshine obtained by model calibration with actual measured water temperatures.

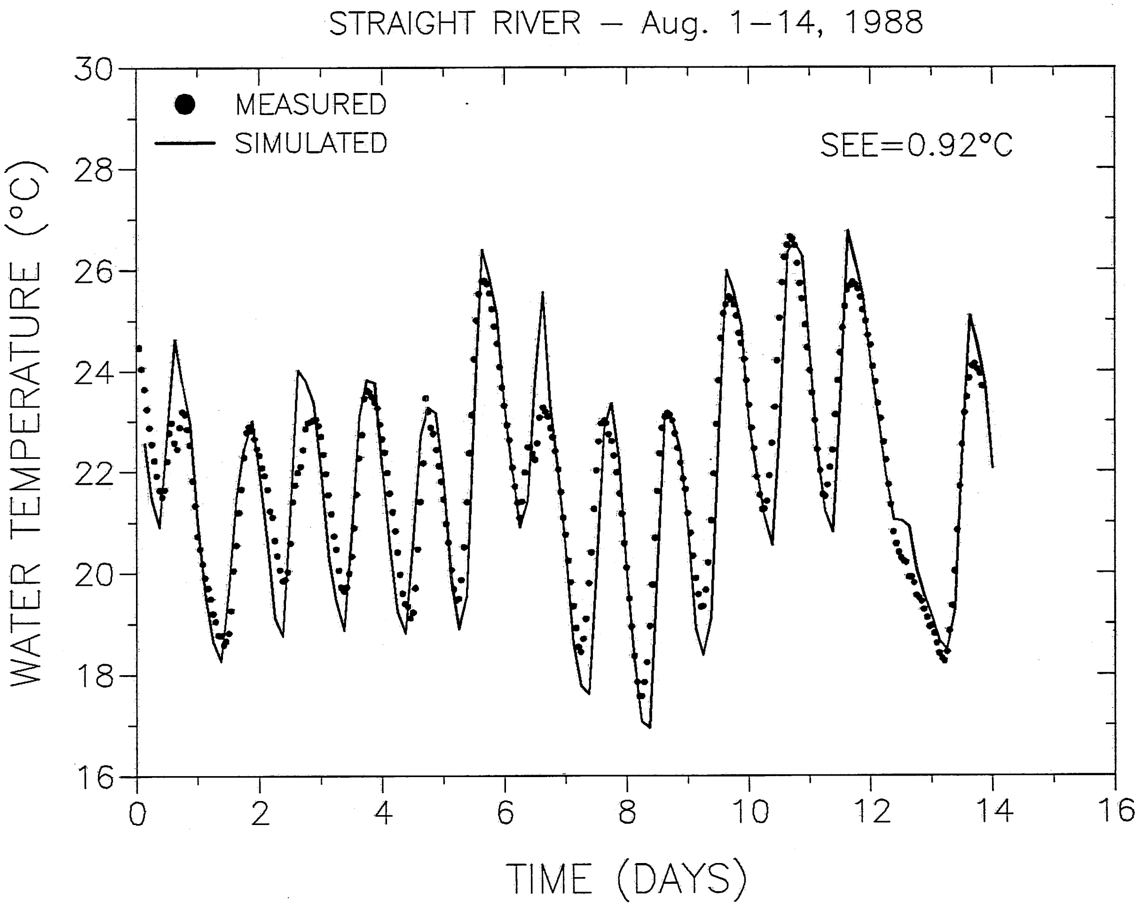


Figure 5.17a. Comparison between hourly measured and computed stream water temperatures for the Straight River.

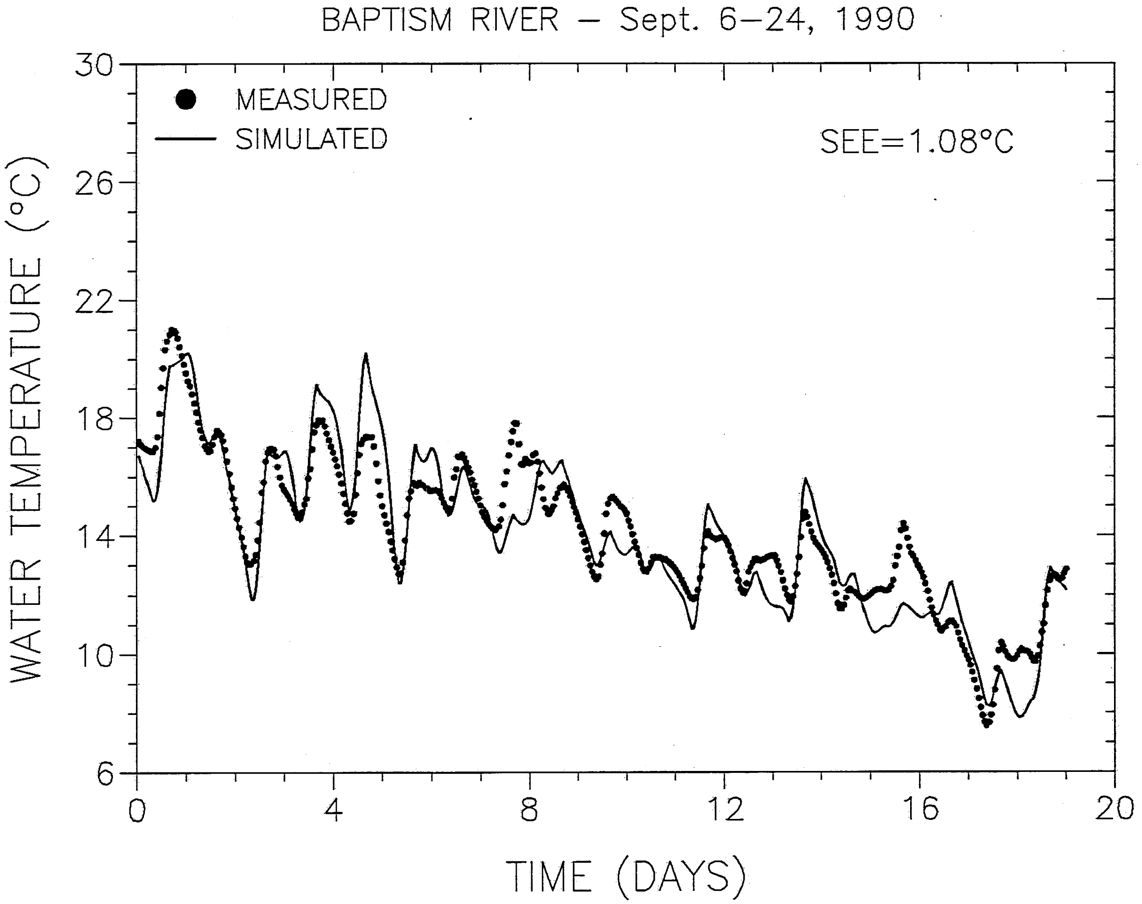


Figure 5.17b. Comparison between hourly measured and computed stream water temperatures for the Baptism River.

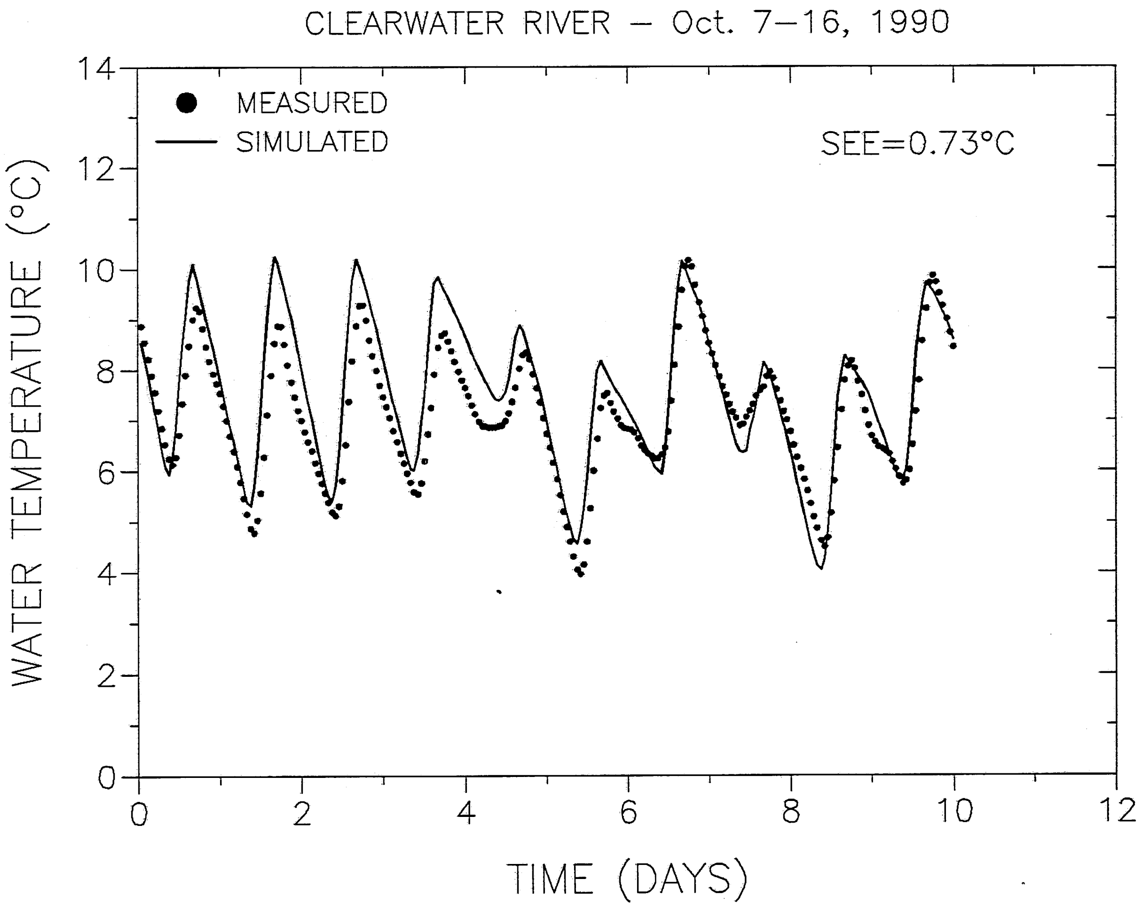


Figure 5.17c. Comparison between hourly measured and computed stream water temperatures for the Clearwater River.

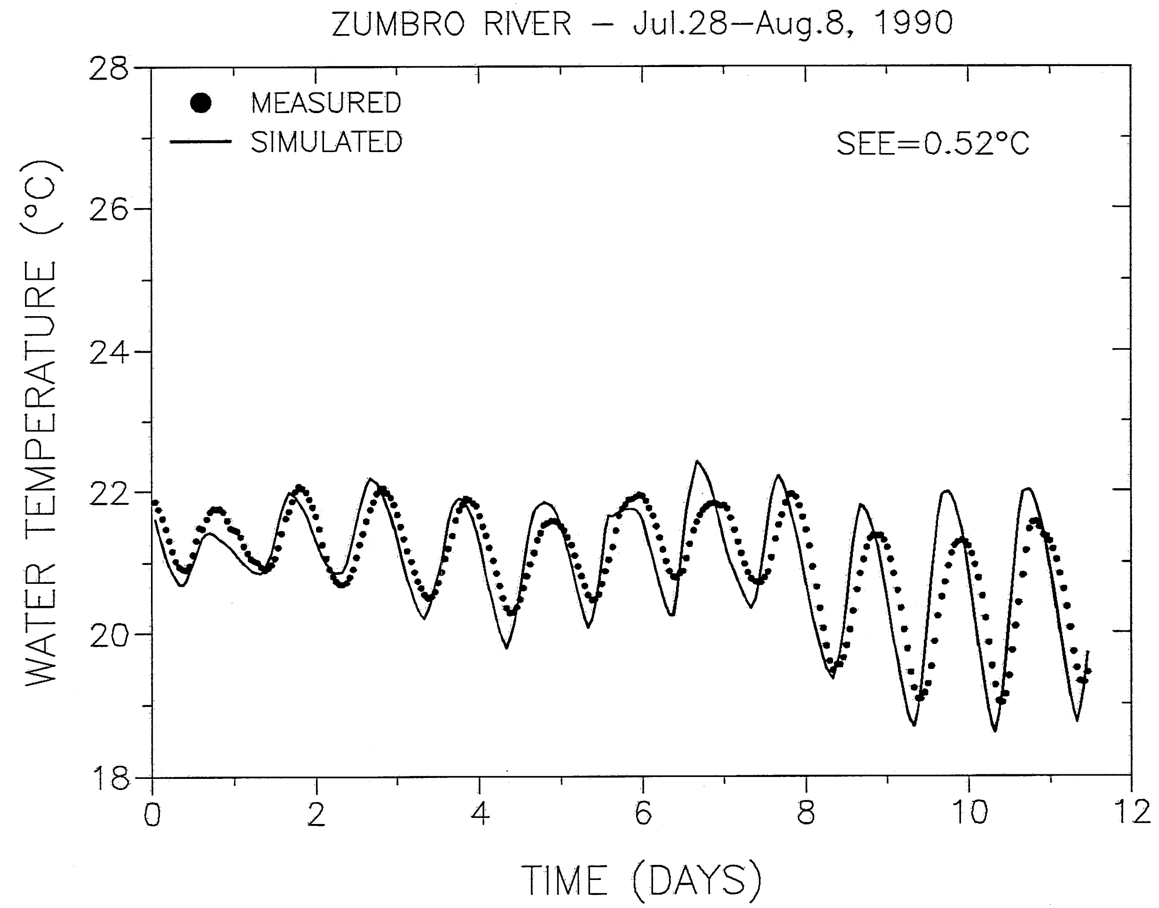


Figure 5.17d. Comparison between hourly measured and computed stream water temperatures for the Zumbro River.

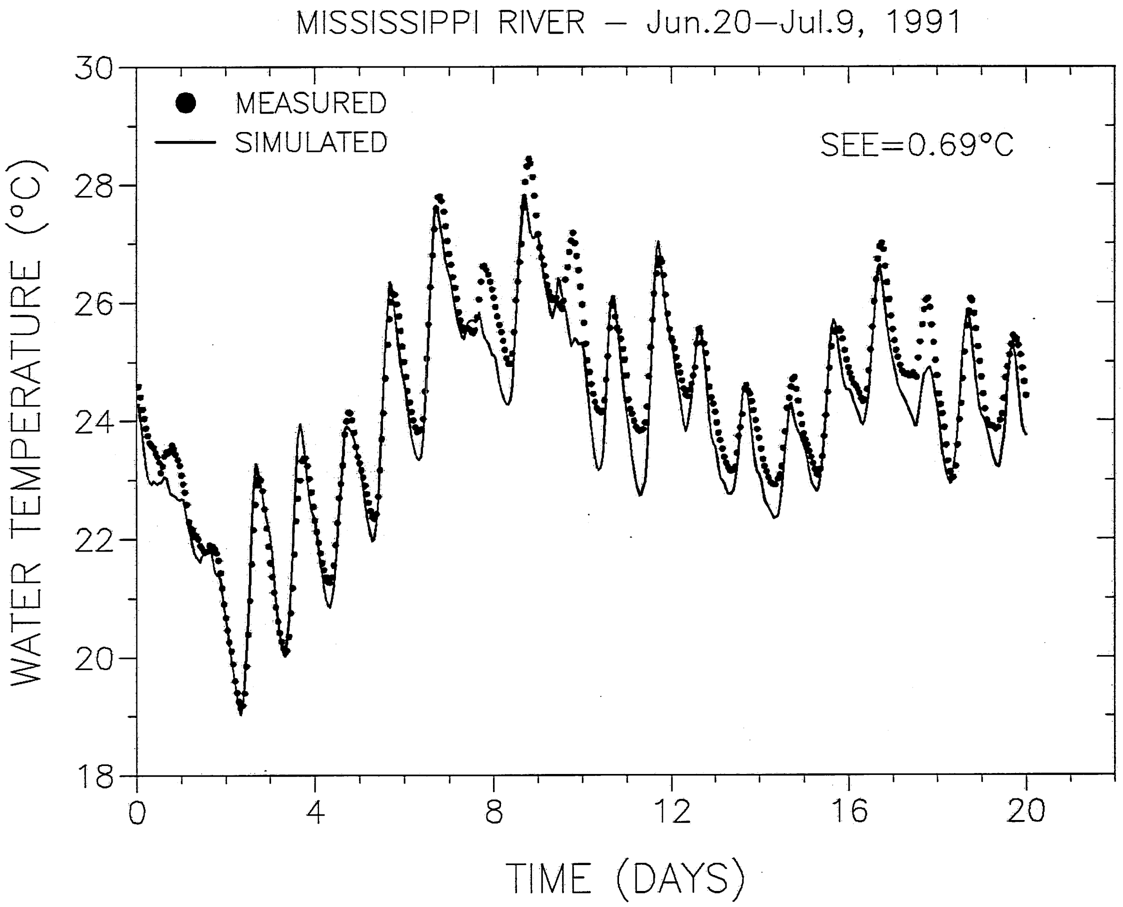


Figure 5.17e. Comparison between hourly measured and computed stream water temperatures for the Mississippi River.

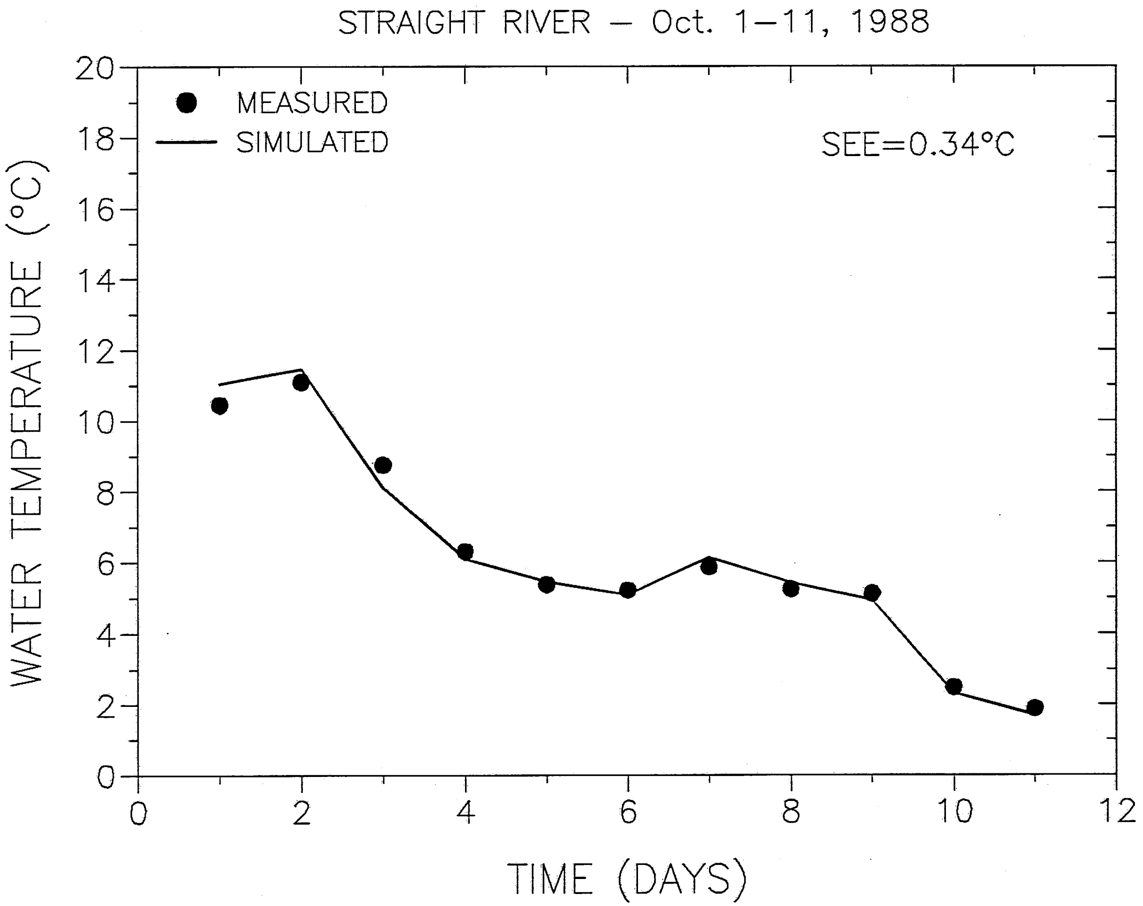


Figure 5.18a. Comparison between daily measured and computed stream water temperatures for the Straight River.

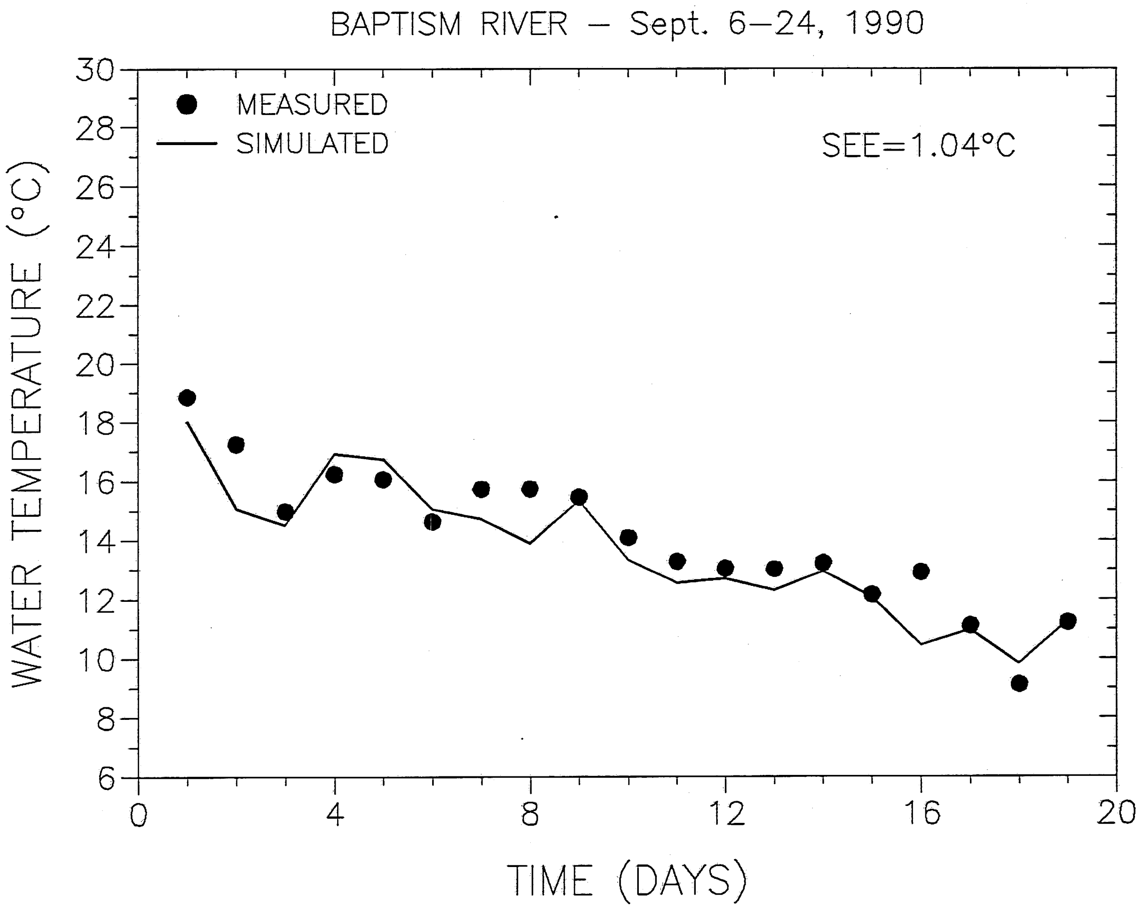


Figure 5.18b. Comparison between daily measured and computed stream water temperatures for the Baptism River.

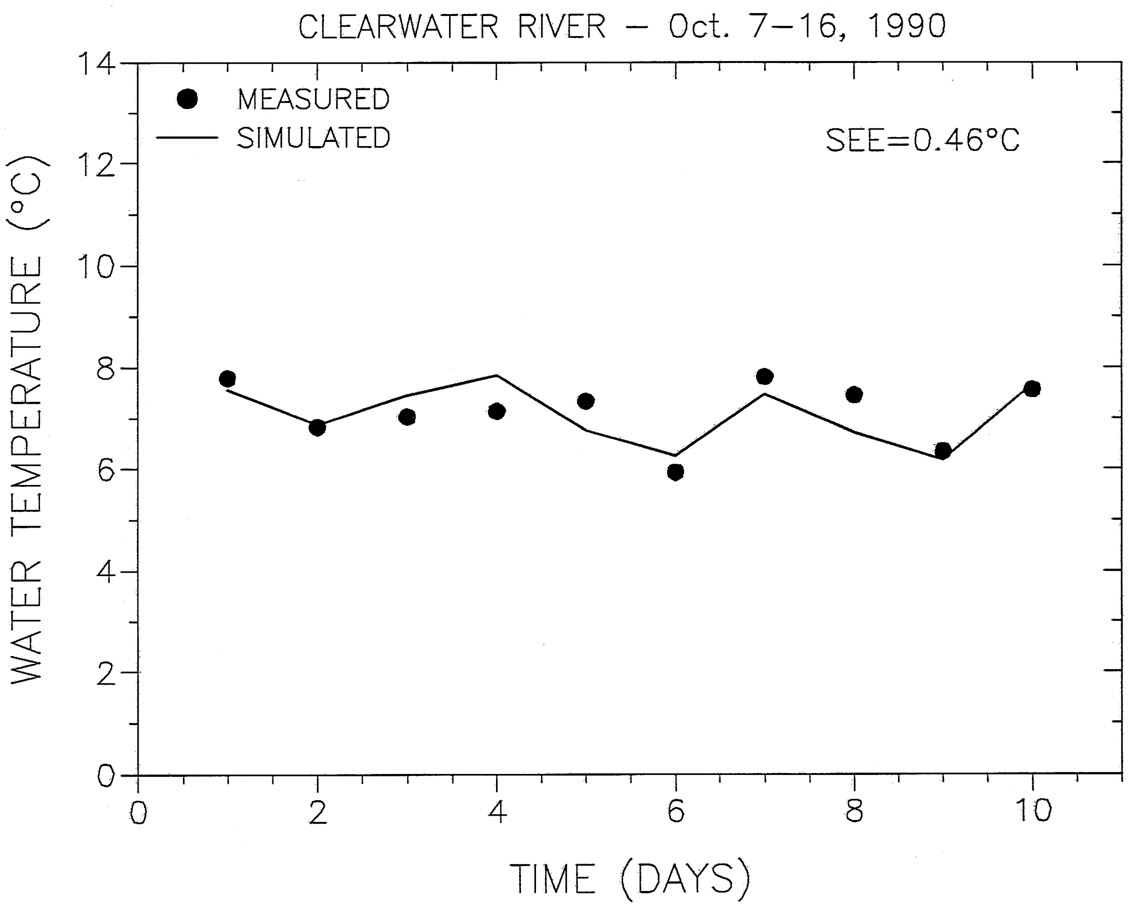


Figure 5.18c. Comparison between daily measured and computed stream water temperatures for the Clearwater River.

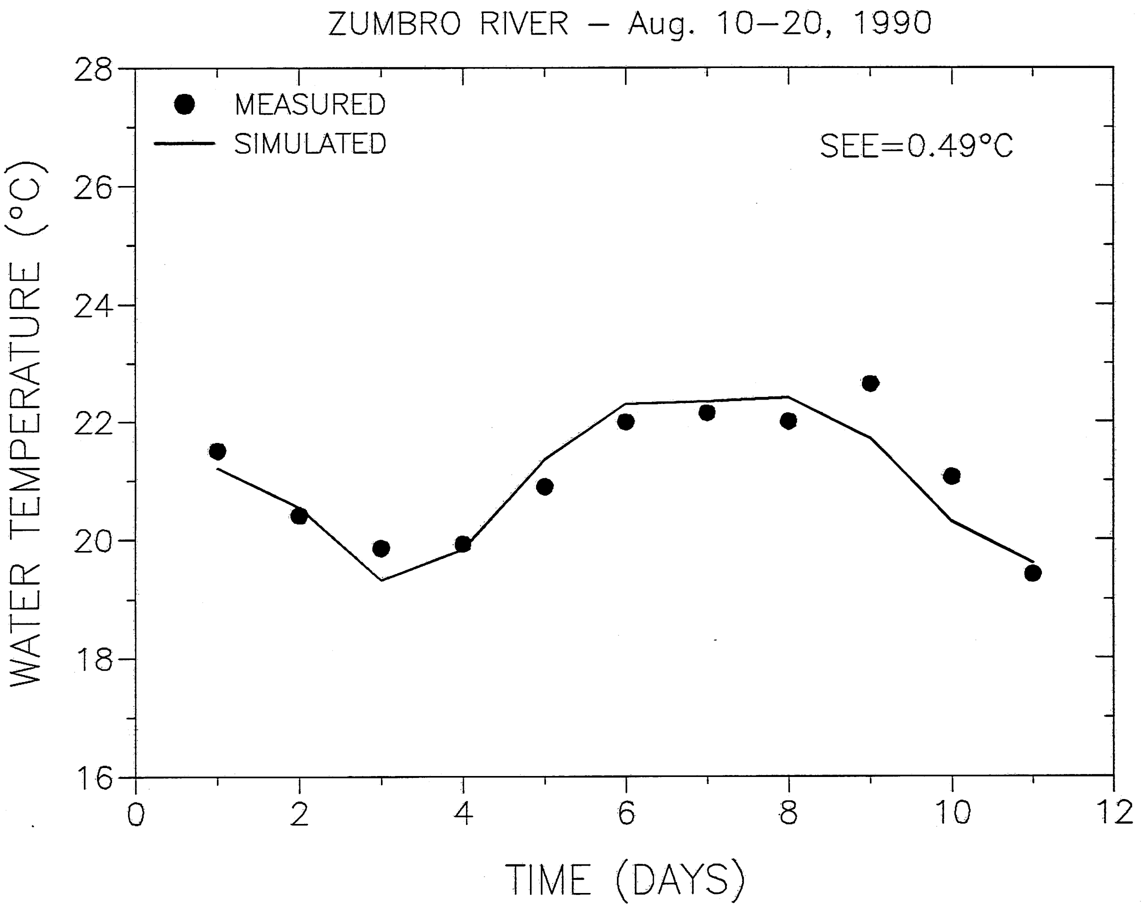


Figure 5.18d. Comparison between daily measured and computed stream water temperatures for the Zumbro River.

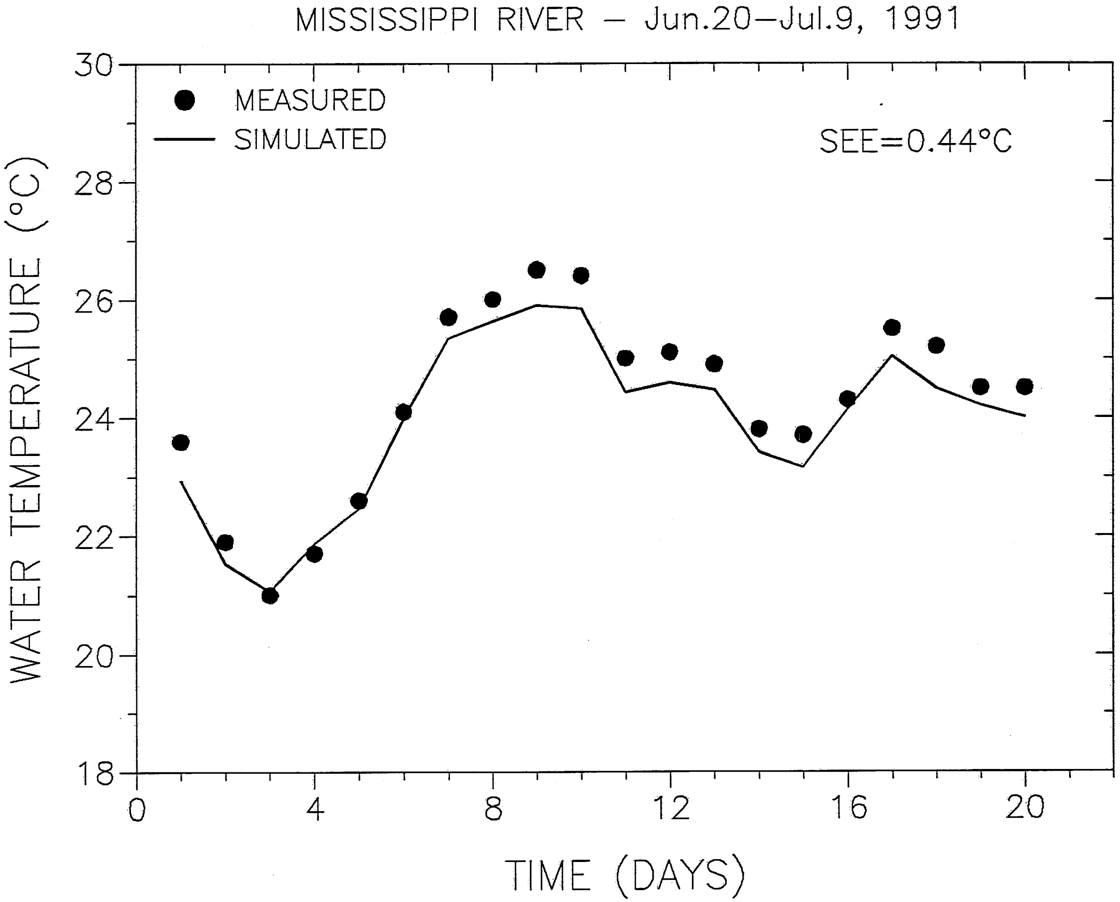


Figure 5.18e. Comparison between daily measured and computed stream water temperatures for the Mississippi River.

Table 5.3. Summary of MNSTREM model Simulations

Stream	Period of Simulation	Avg. Q(cfs)	Avg. d(ft)	Avg. W(ft)	%Sun	%Wind	SEE* (°C)
Straight R.	Mar.23-31, 1989	54	0.9	45.0	90	10	0.38
	Apr.21-30, 1989	68	1.0	45.0	100	10	0.28
	Jun.10-24, 1988	47	0.9	45.0	30	30	0.60
	Jul.1-6, 1989	47	0.9	45.0	40	20	0.18
	Aug.1-20, 1989	37	0.9	45.0	40	30	0.32
	Oct.1-11, 1988	36	0.9	45.0	80	10	0.39
Baptism R.	Jul.13-Aug.2, 1991	148	2.1	67.1	60	10	0.79
	Sept.6-24, 1990	36	1.1	47.5	90	10	1.04
Clearwater R.	Oct.7-16, 1990	33	1.2	77.0	80	10	0.57
Zumbro R.	Jul.28-Aug.8, 1990	2283	4.1	148.2	50	10	0.16
	Aug.10-20, 1990	704	1.8	143.6	50	10	0.45
	Oct.23-Nov.12,1991	685	1.7	143.5	100	10	0.83
Mississippi R.	Jun.-Jul.9, 1991	12406	3.3	858.0	100	30	0.47

* SEE: Standard Error of Estimate

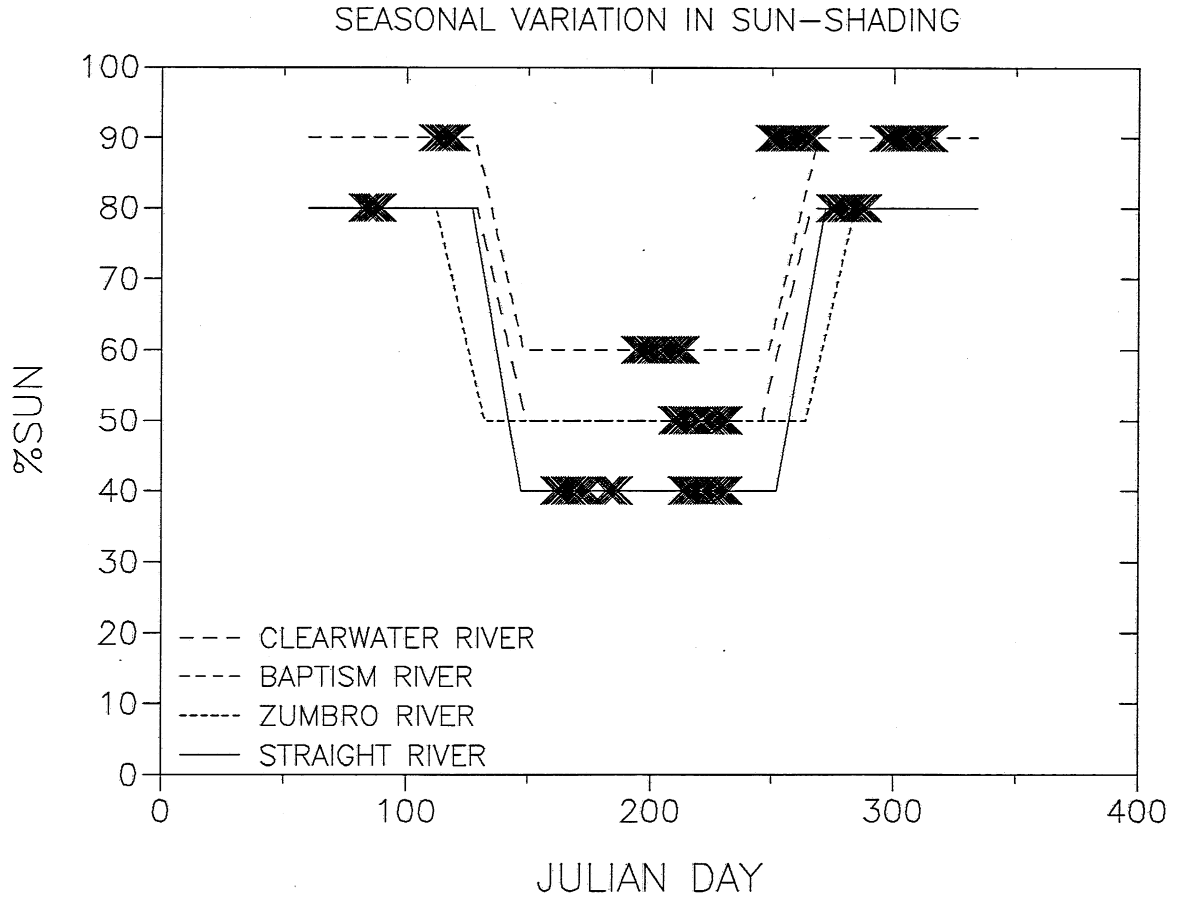


Figure 5.19. Seasonal variation in sun-shading of the selected streams.

In the case where no measurements of water temperatures are available, the sun-shading coefficient could be estimated by other means. Meisner (1990) estimated the shading on two Canadian streams located in southern Ontario by visual inspection. Aerial photographs could be another alternative.

5.4. Heat fluxes

The heat exchange between the stream water and its surrounding environment (mainly atmosphere and streambed) can be divided into five different components (as discussed earlier): streambed heat transfer, shortwave radiation, longwave radiation, evaporative heat flux and convective heat flux.

In order to quantify these different components, they were plotted on the same graph for two of the selected streams: the Clearwater River and the Mississippi River (Fig. 5.20a and 5.20b). Figure 5.20a shows that the shortwave radiation (solar radiation) is the dominant component of the heat exchange process. The streambed heat flux showed to be as important as the other heat exchange components in this case (shallow stream). The streambed acted as an energy sink during the midday hours and as an energy source later in the day. Fig. 5.20b also showed that the shortwave radiation is the dominant component of the heat exchange process. On the other hand, it showed that the streambed heat flux in addition to the evaporative and convective heat fluxes are not as important in this case because of the large volume of water involved. Streambed heat flux depends on the temperature gradient in the streambed and on the thermal conductivity of the streambed material. Streambeds composed of rocks will have more streambed heat flux compared to those composed of mud or peat.

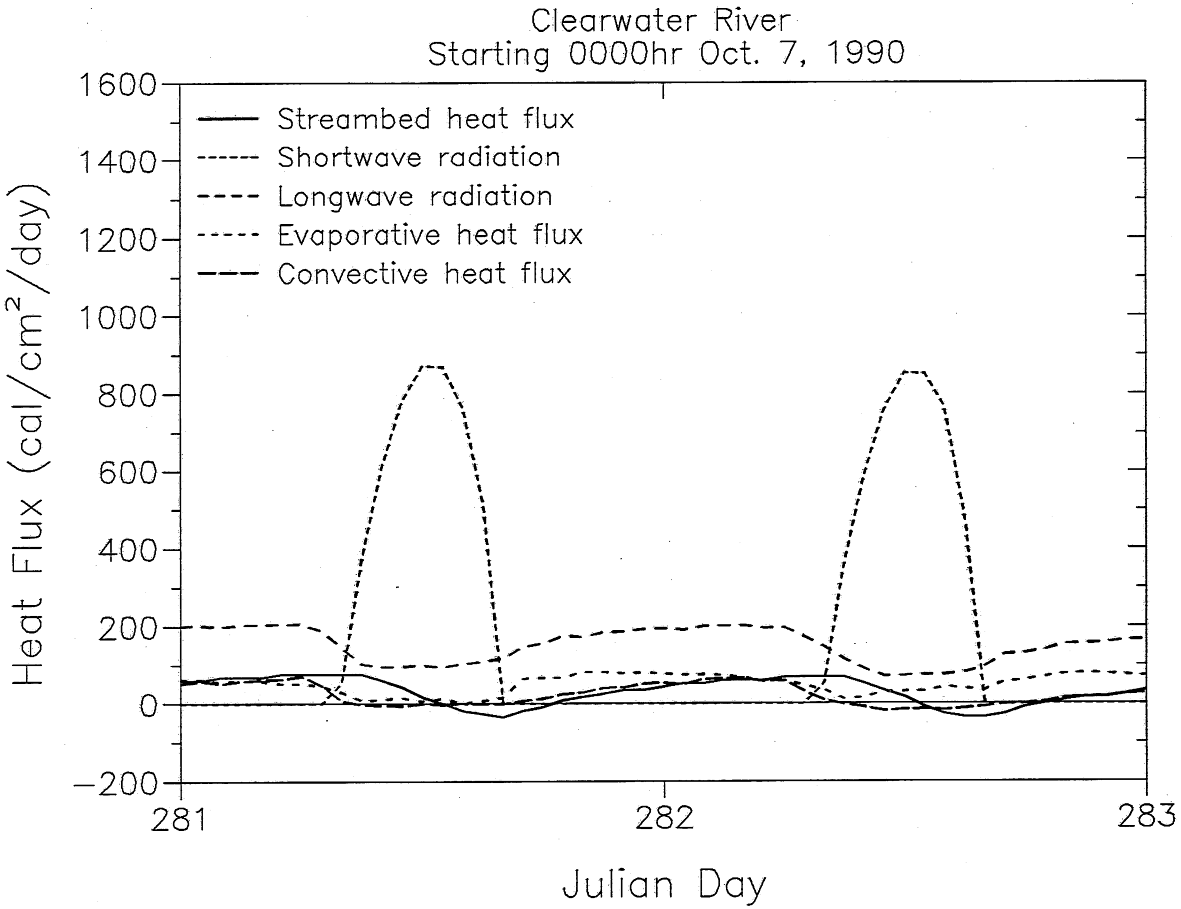


Figure 5.20a. Comparison between different heat flux components for the Clearwater River.

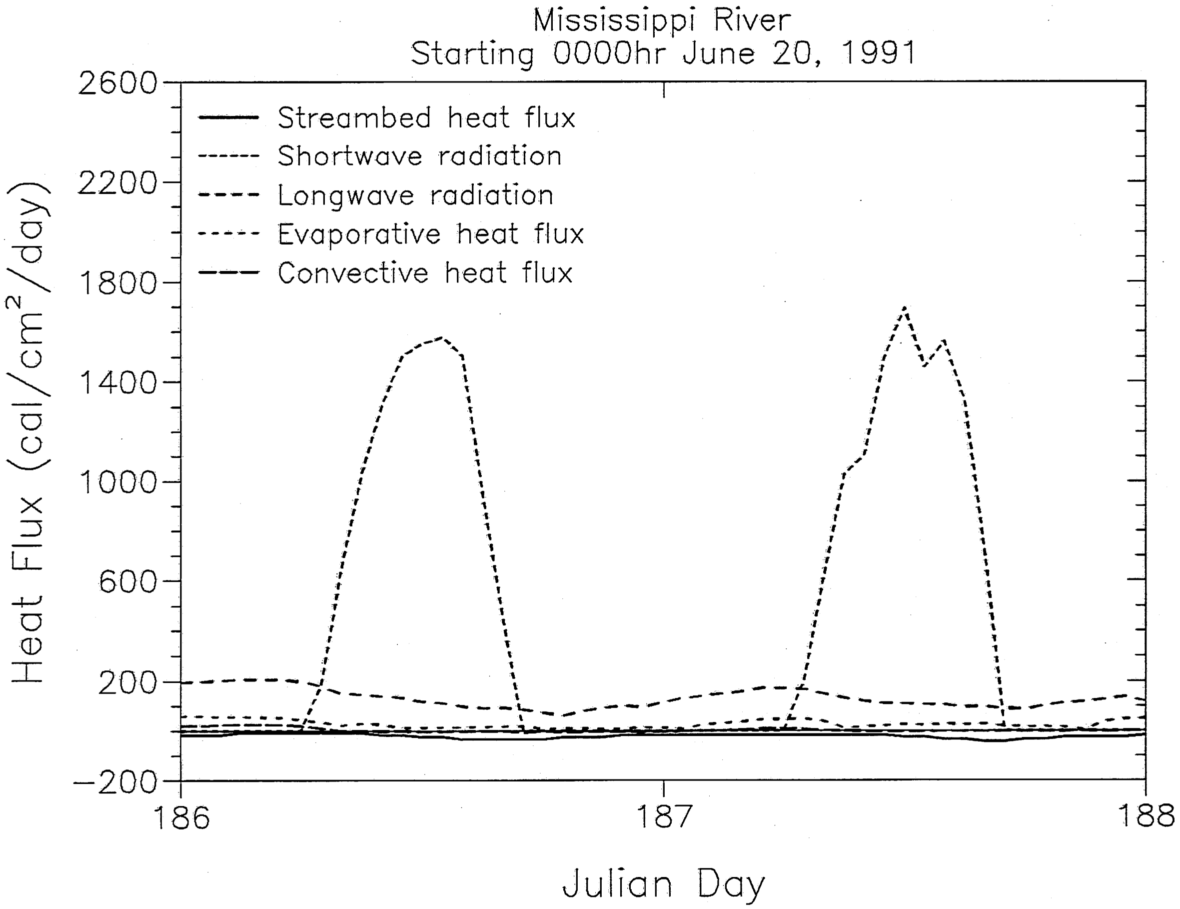


Figure 5.20b. Comparison between different heat flux components for the Mississippi River.

6. MODEL APPLICATION: GLOBAL CLIMATE CHANGE IMPACTS ON STREAM WATER TEMPERATURE

6.1. Introduction

A 1979 report on carbon dioxide and climate by the U.S. National Academy of Sciences concluded that a doubling of ambient CO_2 concentrations could increase global mean air temperatures by 1.5 to 4.5 °C in approximately the next half century. This "greenhouse effect" projection has been reinforced by the development of several General Circulation Models (GCM) of ocean/atmosphere heat budgets and other analyses producing similar temperature change estimates (Bolin and Doos 1986). Recognition that such changes are occurring many times faster than the background rate and might have severe and unexpected consequences (Harrington 1987, Schneider 1989, NAS 1988, Houghton, et.al., 1989) has led to anxious requests for information on causes, effects and mitigation or accommodation possibilities.

To explore how stream water temperatures might be affected by climate change, an analysis of 5 selected, representative streams in Minnesota was conducted. A deterministic, physics–based mathematical model was used to simulate stream water temperatures for various climate change scenarios. The output of this model is in the form of daily average water temperatures and covers the period 1953 to 1979. Results will be presented here. As discussed earlier in chapter 5, the percentage exposure of the stream surface to sun is greater in early spring and in fall before leaves grow on trees or after leaves fall from trees. Therefore lower shading percentages were applied during the spring and fall. Table 6.1 summarizes the optimal percentages of sun and wind found by calibration (Fig. 5.20) for the selected streams in seasons with and without leaf–cover of trees.

6.2. Application to past climate

The stream temperature model requires mean daily values of the following meteorological variables as input: air temperature, relative humidity, wind speed, solar radiation and cloud cover percentage. Extensive daily weather data files were assembled for three principal weather stations (Minneapolis/St. Paul, MN, Duluth, MN, and Fargo, ND) for the period from 1953 to 1979. The weather data were obtained from the National Center for Atmospheric Research (NCAR), the Midwestern Climate Center in Champaign, IL, and from the files of the Soil Science Department (Professor D.G. Baker) at the University of Minnesota, St. Paul.

Figure 6.1(a, b, c and d) illustrates the long term averages and standard deviations of the measured daily weather parameters at the principal weather stations under past conditions (actual measurements).

Table 6.1. Percentages of sun and wind for optimal water temperature prediction in the selected streams.

	WINTER		SUMMER	
	%SUN	%WIND	%SUN	%WIND
STRAIGHT RIVER	80	20	40	20
BAPTISM RIVER	90	10	60	10
CLEARWATER RIVER	80	10	50	10
ZUMBRO RIVER	80	10	50	10
MISSISSIPPI RIVER	100	50	100	50

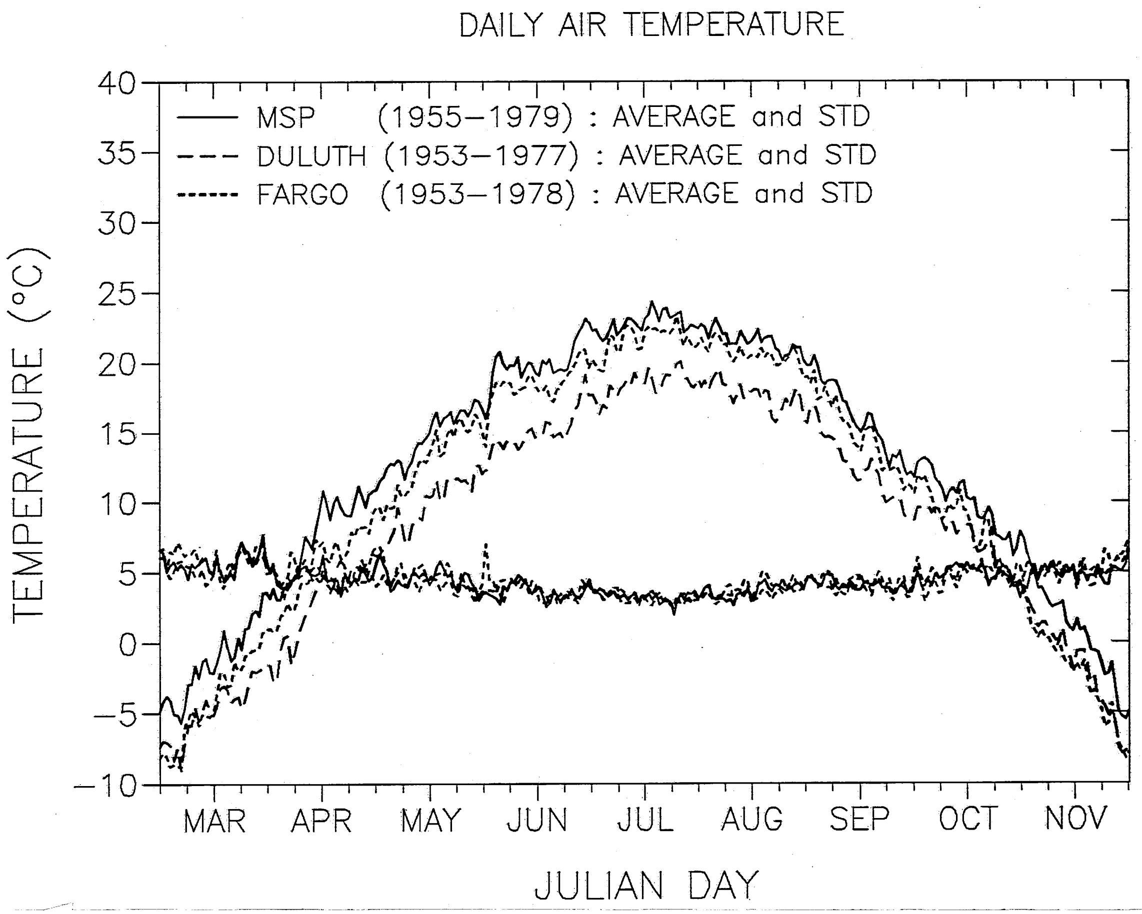


Figure 6.1a. 25–year average and standard deviation of measured air temperature for three weather stations.

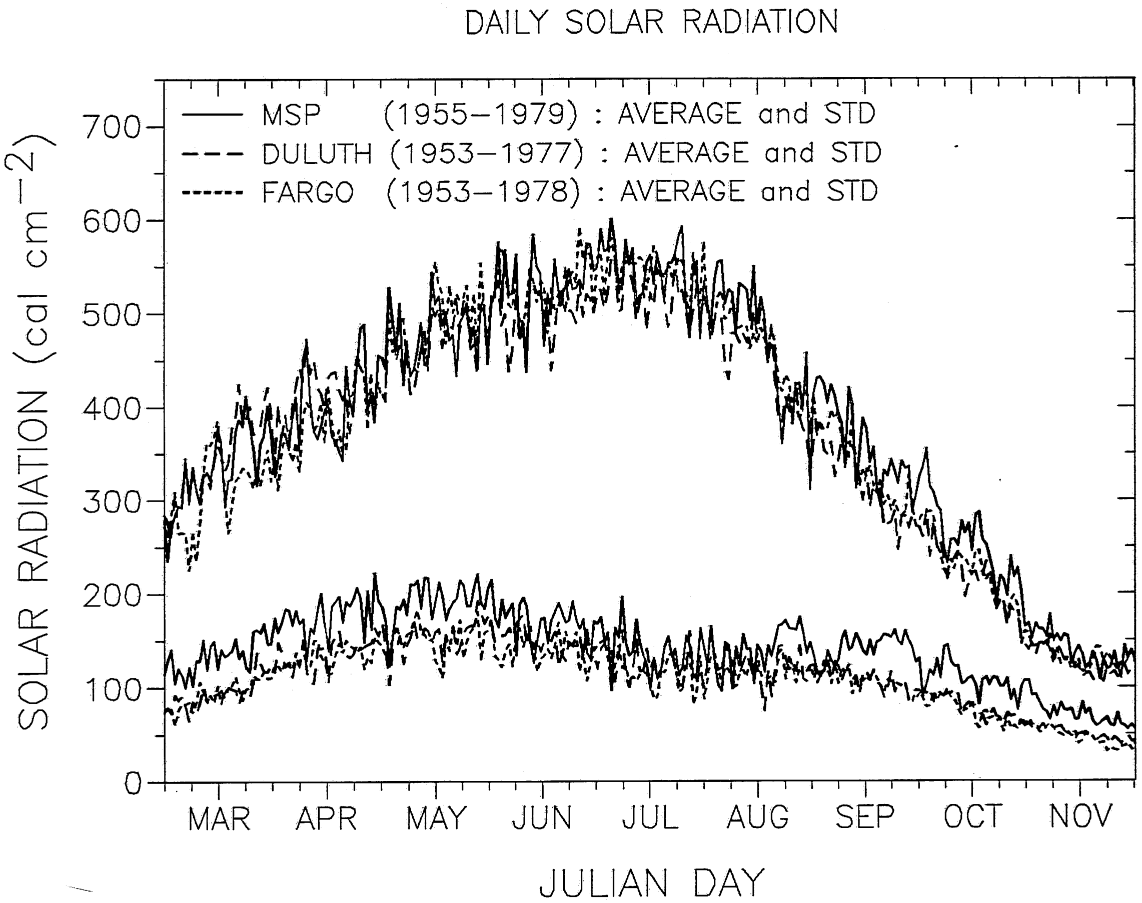


Figure 6.1b. 25–year average and standard deviation of measured solar radiation for three weather stations.

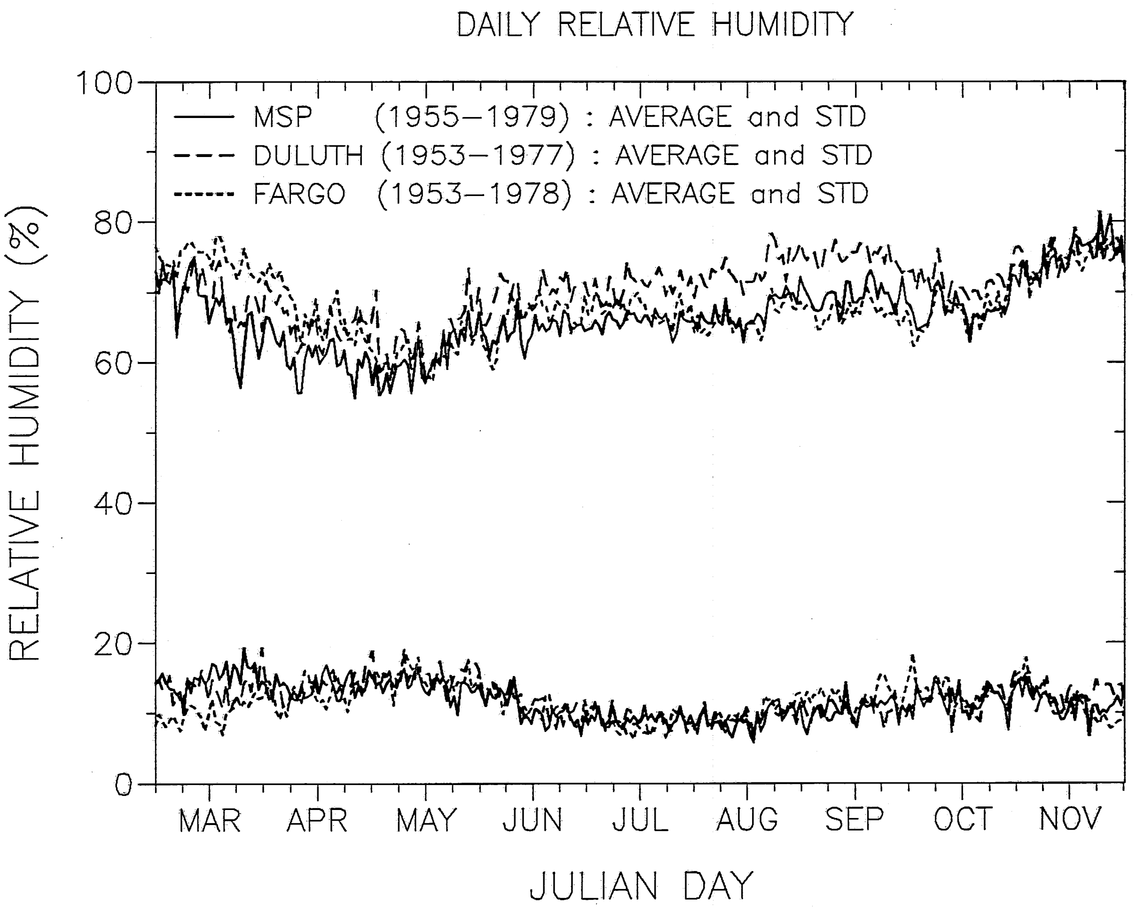


Figure 6.1c. 25–year average and standard deviation of measured relative humidity for three weather stations.

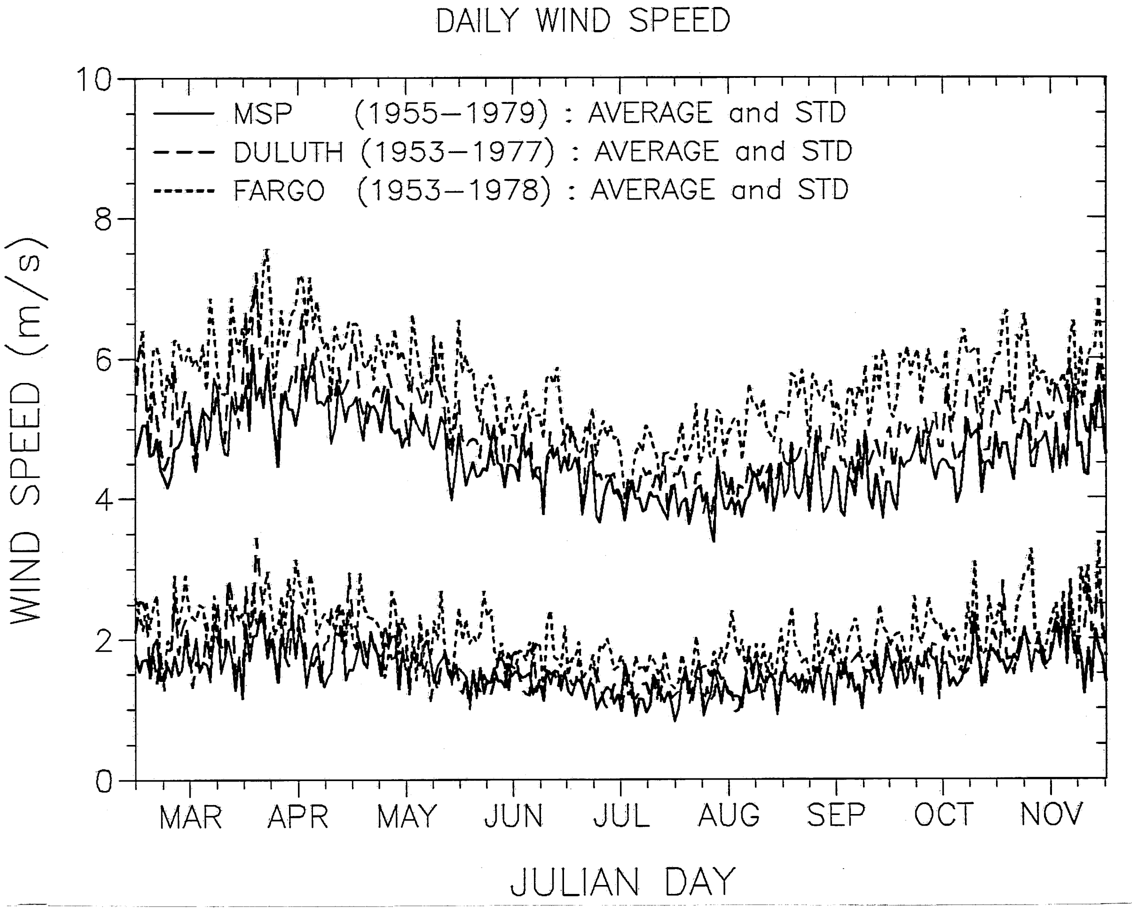


Figure 6.1d. 25–year average and standard deviation of measured wind speed for three weather stations.

6.3. Application to future climate scenarios

The climate scenarios used in this study are for doubling of CO_2 in the atmosphere. These climate scenarios are obtained from simulations with Global Circulation Models (GCM's). The climate scenarios represent equilibrium conditions i.e. they estimate the full effects of a doubling of carbon dioxide on climate (Hansen et.al., 1983) The GCM outputs were from the (1) GISS (Goddard Institute for Space Studies, Columbia University) (2) GFDL (Geophysical Fluid Dynamics Laboratory, Princeton University) (3) UKMO (United Kingdom Meteorology Office) and (4) OSU (Oregon State University) models. The GCM outputs consist of weather parameter values for $1xCO_2$ and $2xCO_2$ in the atmosphere. Ratios or differences of mean monthly weather parameter values from simulation runs with $2xCO_2$ and $1xCO_2$ in the atmosphere were provided by the National Center for Atmospheric Research in Boulder, Colorado. Table 6.2 summarizes the changes in mean annual weather parameters predicted by the the GISS, GFDL, UKMO and OSU global circulation models for a doubling of atmospheric CO_2.

The climate scenarios model output was applied to the historic daily data. Multiplying or adding to the past measured daily average weather parameters the mean monthly ratios or differences obtained by simulations with $2xCO_2$ and $1xCO_2$ concentrations in the atmosphere produced the daily weather data anticipated after climate change.

6.4. Stream temperature model results

Daily stream water temperatures from March 1 through November 30 were simulated for a 25–year period with past climate records and future climate scenarios as input. Daily stream flow rates obtained from the USGS stream flow records were used in the simulations. Figure 6.2 gives an example of the water temperature time series generated for the Zumbro River. Long term averages and standard deviations of the daily water temperatures were calculated from the time series. Figure 6.3 shows the simulated long–term weekly average water temperatures for the Zumbro River under weather conditions which existed from 1955 to 1979 (25 years). In addition, the 95 percentile confidence value (weekly average ± 1.96 standard deviation) is also shown. Figures 6.4a and 6.4b compare the weekly averaged water temperatures and standard deviations for the five selected streams under past weather conditions. The Mississippi River exhibited the warmest water temperatures over the summer months. On the other hand, the Straight River had the coldest water temperatures for the same period. The differences in water temperatures between the five streams is directly related to stream shading and to a lesser degree to the location (latitude) of the stream. The Straight River is the most shaded of the five streams, and the Mississippi River is the least shaded. Standard deviations of stream water temperatures were almost equal for all five streams and ranged between 2 and 4 °C. Figures 6.5(a,b,c,d and e) show a comparison between past and future weekly averaged stream water temperatures under different climate scenarios. Inevitable increase in stream water temperatures in the five streams can be seen. The water temperatures found using the UKMO scenario are noteworthy because they are consistently and notably higher than

Table 6.2. Changes in mean annual weather parameters predicted by the GISS, GFDL, UKMO and OSU global circulation models for a doubling of atmospheric CO_2

Air Temperature :

[°C]	PAST		CHANGE [°C]			
	AVG.	STD	GISS	GFDL	UKMO	OSU
Minneapolis / St. Paul	12.38	4.37	4.38	4.90	8.37	3.42
Fargo	10.56	4.61	4.62	4.41	8.37	3.42
Duluth	8.50	4.22	3.78	4.90	8.37	3.39

Solar Radiation :

[$cal.cm^{-2}$]	PAST		CHANGE [%]			
	AVG.	STD	GISS	GFDL	UKMO	OSU
Minneapolis / St. Paul	389.4	141.8	+2	+10	+16	+1
Fargo	377.8	109.0	+0	+1	+16	+1
Duluth	372.4	113.2	+0	+10	+16	+2

Wind Speed :

[m/s]	PAST		CHANGE [%]			
	AVG.	STD	GISS	GFDL	UKMO	OSU
Minneapolis / St. Paul	4.59	1.55	+43	+5	-6	+7
Fargo	5.64	2.04	+3	+40	-6	+7
Duluth	4.96	1.68	-20	+5	-6	+10

Relative Humidity :

[%]	PAST		CHANGE [%]			
	AVG.	STD	GISS	GFDL	UKMO	OSU
Minneapolis / St. Paul	66.49	11.66	+0	+1	+4	-6
Fargo	68.08	11.54	+2	+7	+4	-6
Duluth	70.42	11.99	+5	+1	+4	-6

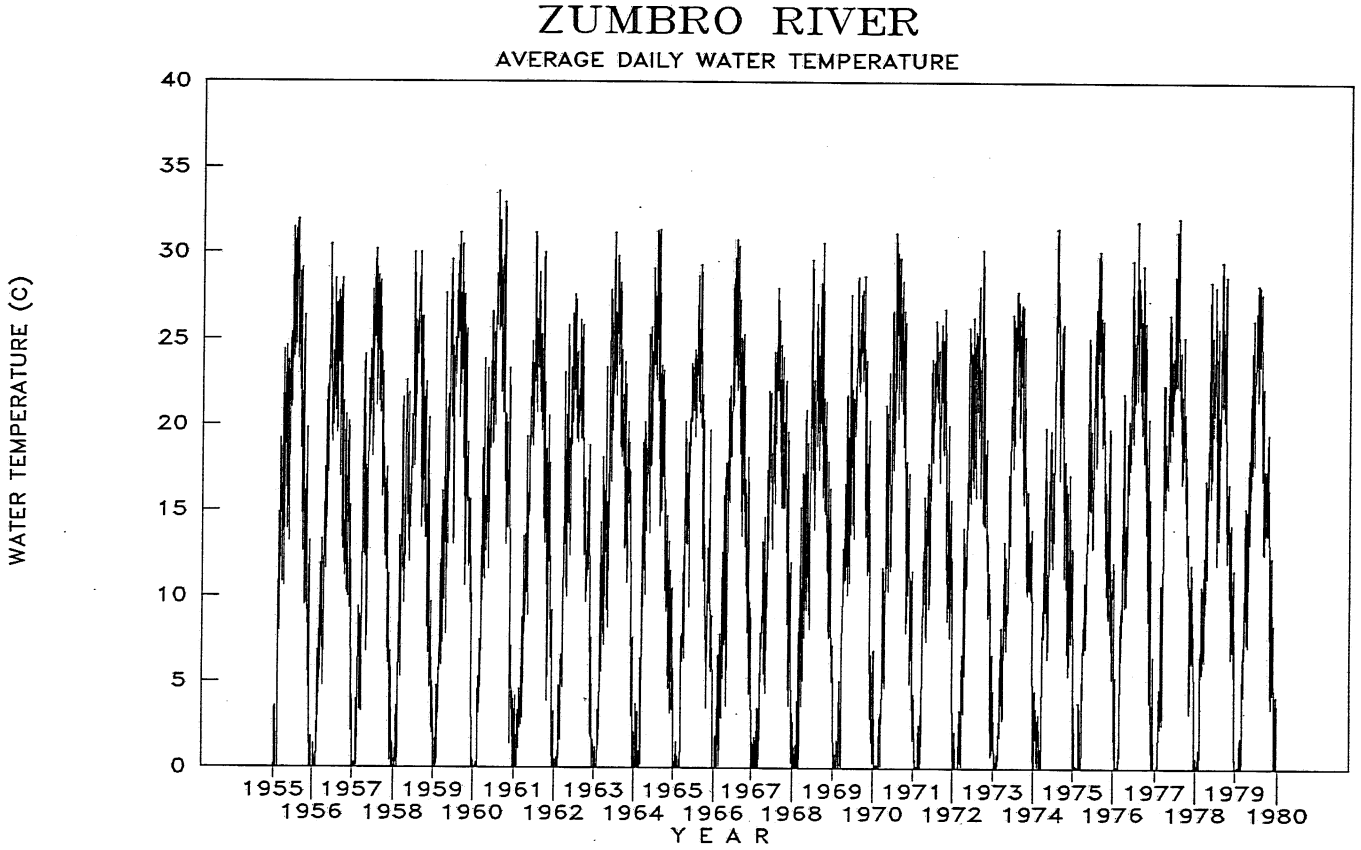


Figure 6.2. Daily water temperature time series simulated for the Zumbro River.

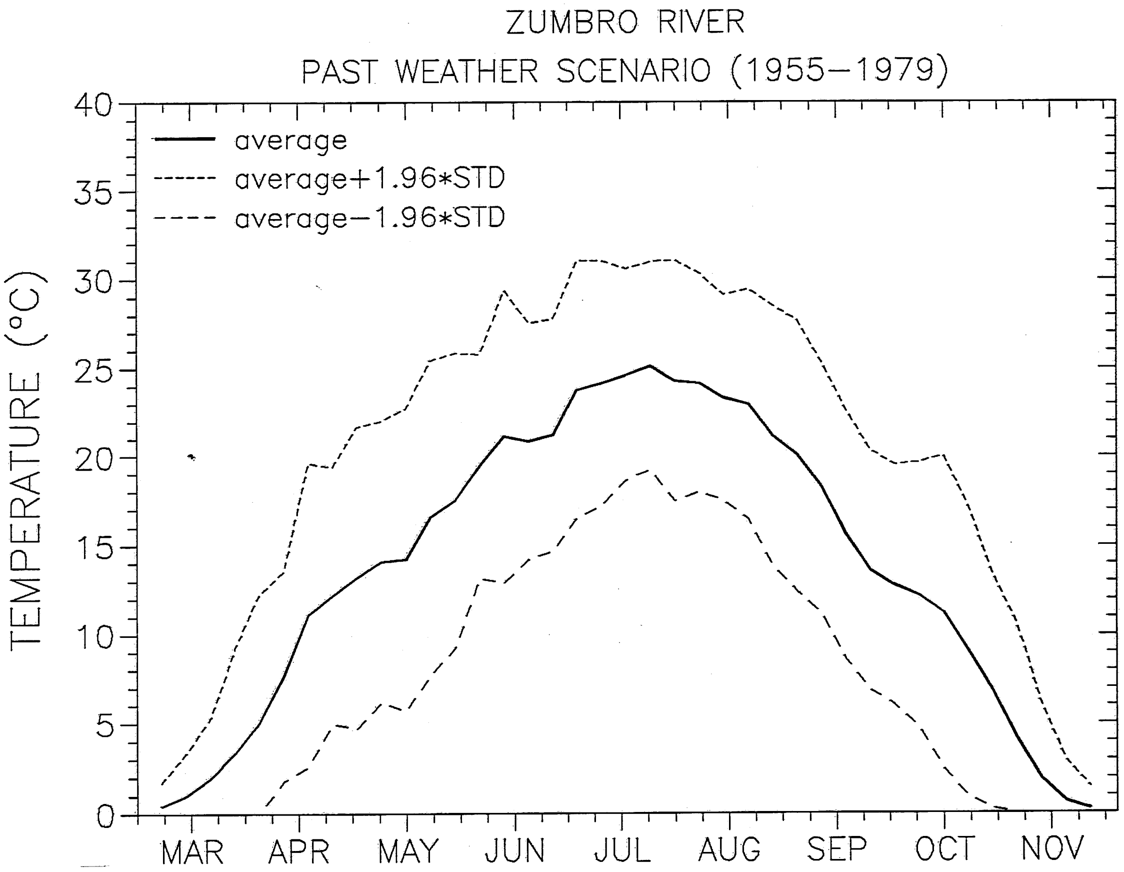


Figure 6.3. Simulated 25–year average and ±95 percentile water temperatures for the Zumbro River using the past (measured) weather data as input.

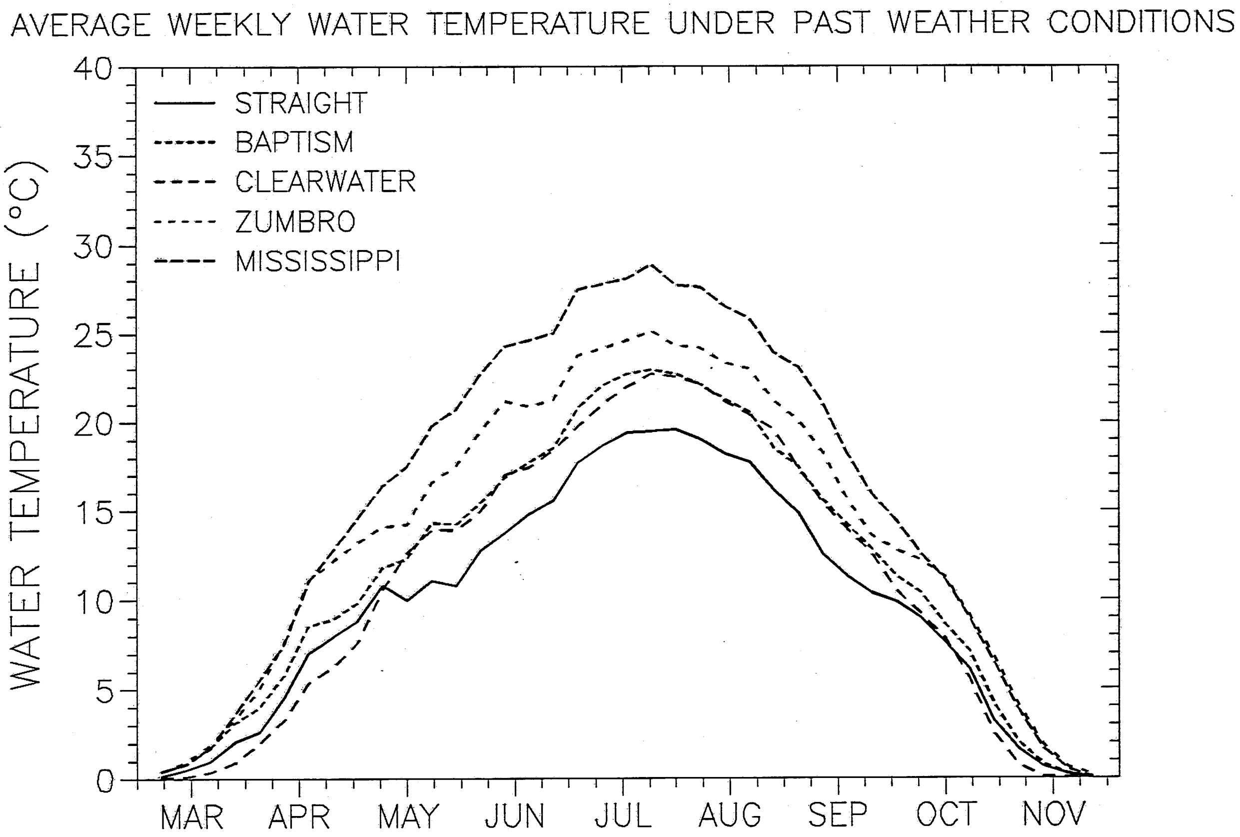


Figure 6.4a. 25–year averages of the simulated water temperatures for the selected streams.

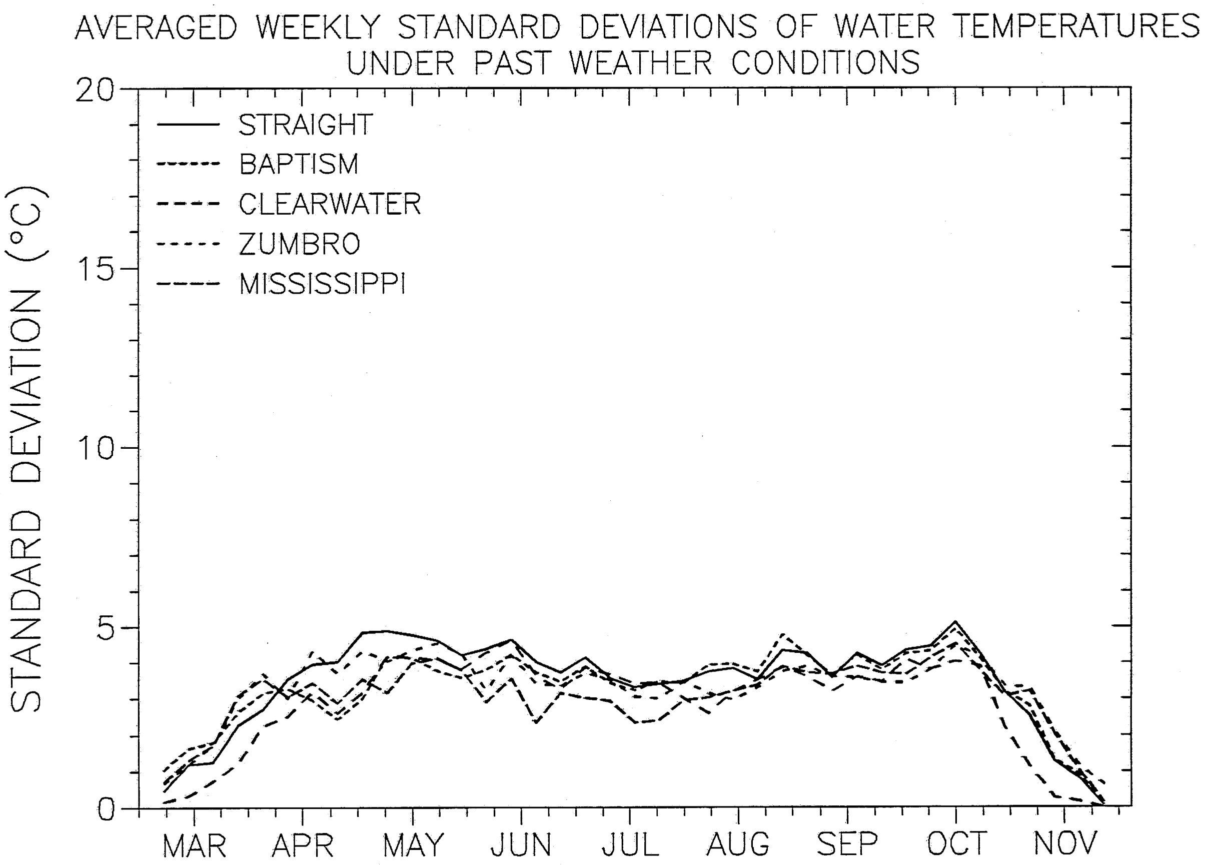


Figure 6.4b. 25–year standard deviations of the simulated water temperatures for the selected streams.

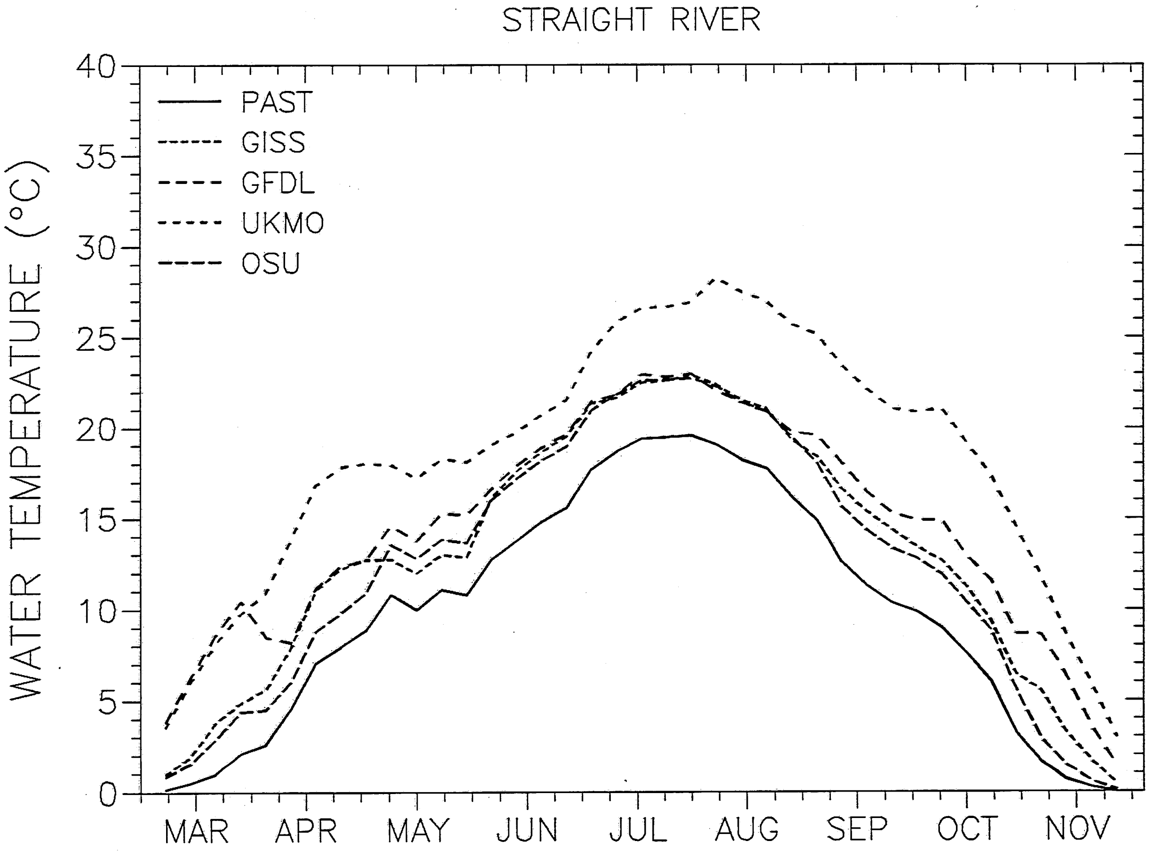


Figure 6.5a. Simulated 25–year average water temperatures for the Straight River under past, GISS, GFDL, UKMO and OSU weather.

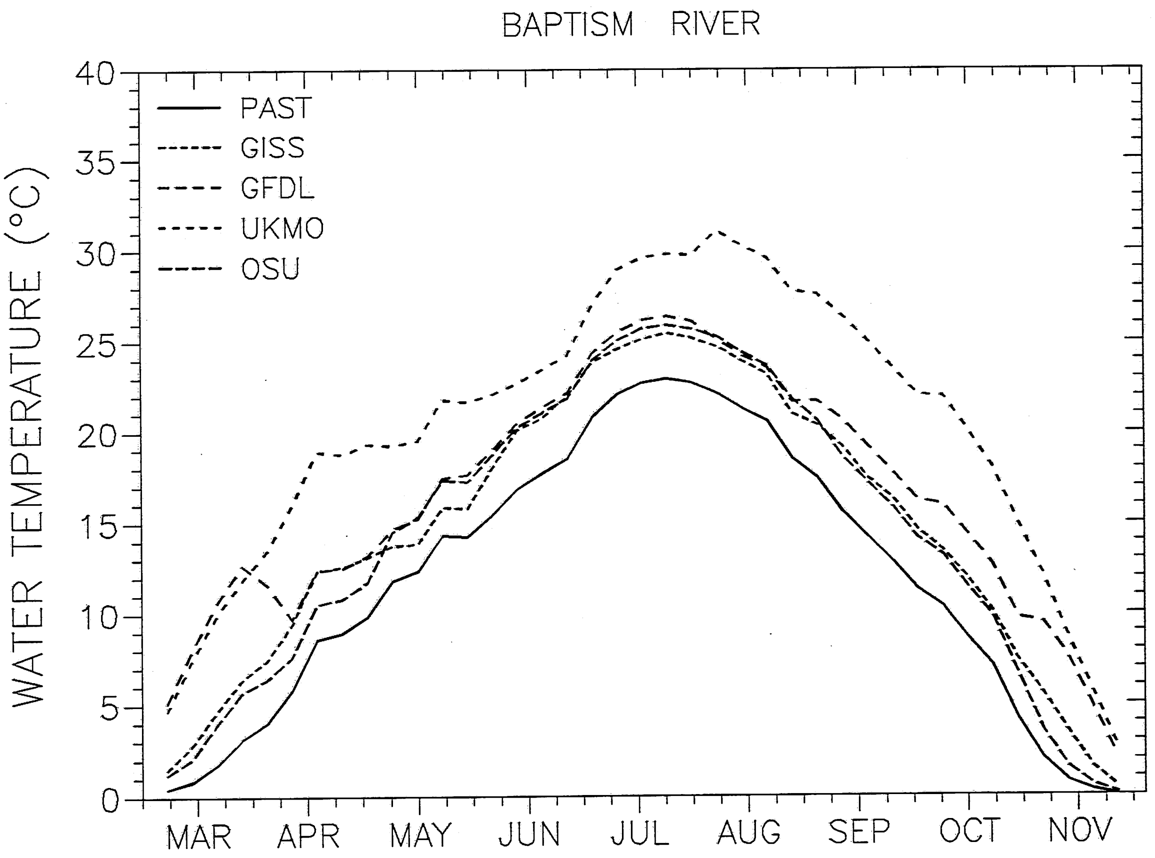


Figure 6.5b. Simulated 25–year average water temperatures for the Baptism River under past, GISS, GFDL, UKMO and OSU weather.

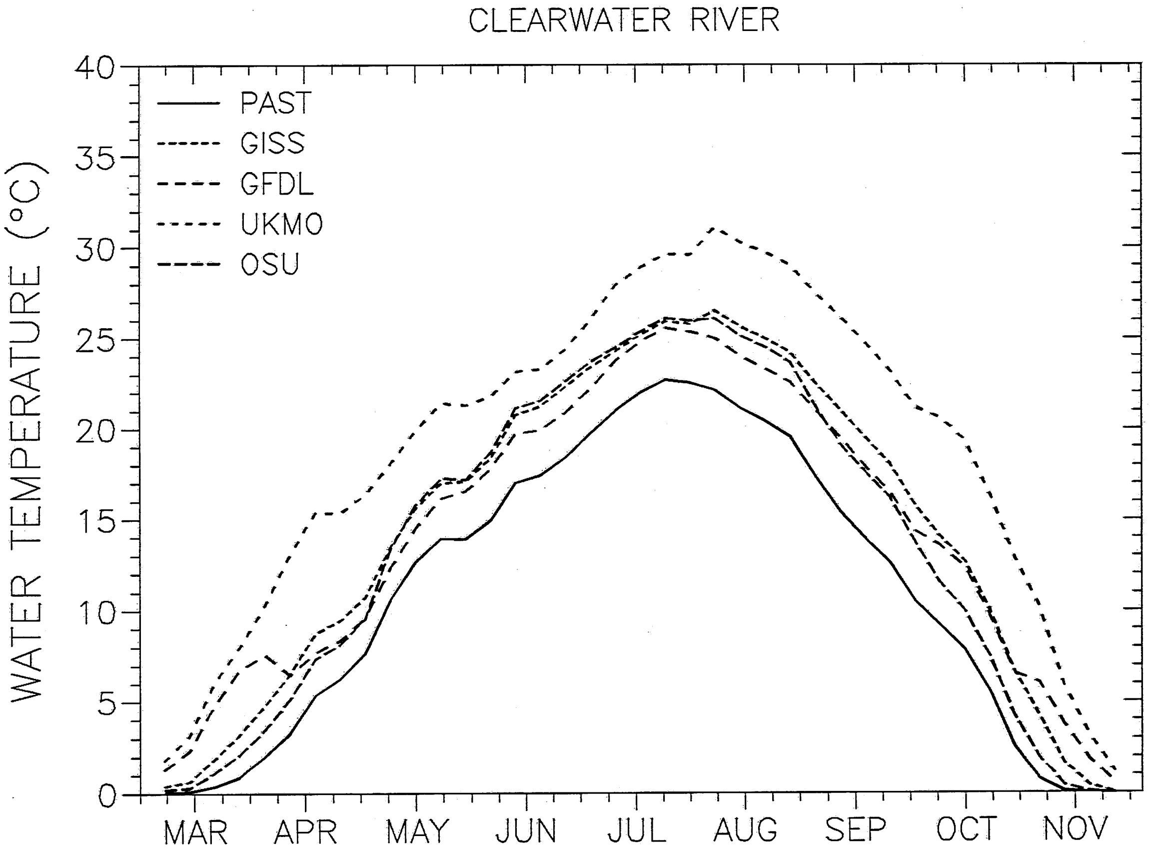


Figure 6.5c. Simulated 25–year average water temperatures for the Clearwater River under past, GISS, GFDL, UKMO and OSU weather.

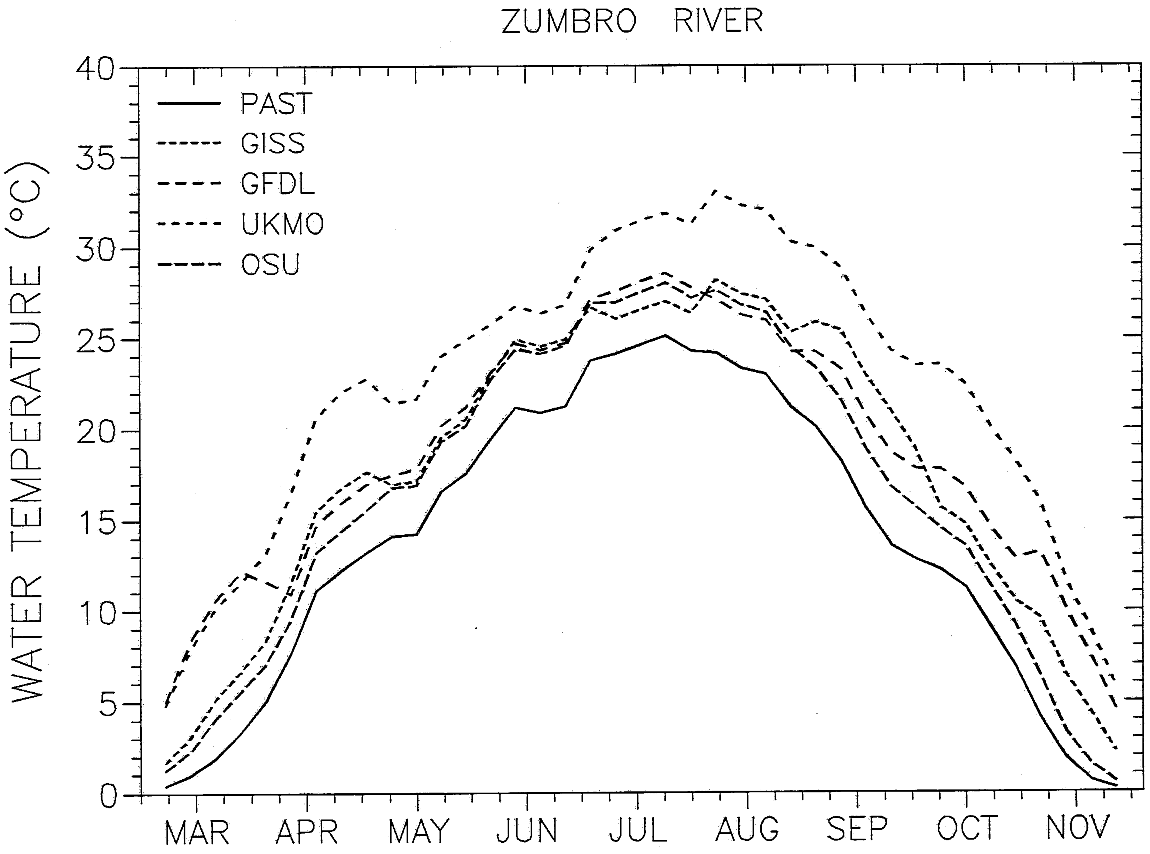


Figure 6.5d. Simulated 25-year average water temperatures for the Zumbro River under past, GISS, GFDL, UKMO and OSU weather.

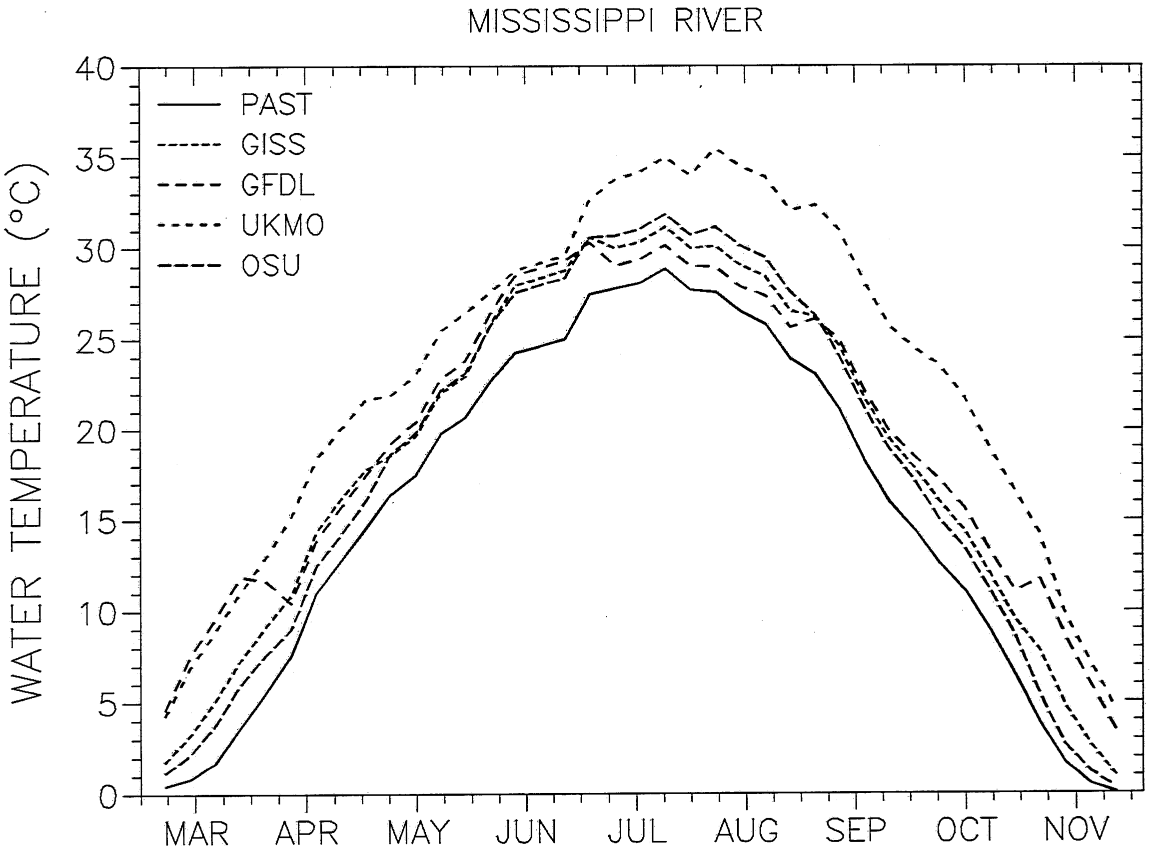


Figure 6.5e. Simulated 25–year average water temperatures for the Mississippi River under past, GISS, GFDL, UKMO and OSU weather.

the water temperatures found using the other three climate change models. Water temperatures simulated by the other three models depicted similar patterns for each of the streams.

A summary of the averages of computed stream water temperatures over the 25–year simulation period (March 1 through November 30 of each year) under different climate scenarios is given in Table 6.3. A similar summary for seasonal weekly maximum temperatures is given in Table 6.4. The results in these two tables indicate that an increase of water temperature is inevitable if the $2xCO_2$ climate scenario materializes, even if stream flow rates and shading remain unchanged. Tables 6.5(a,b,c,d and e) give mean water temperature rises due to climate change for individual streams. The values shown are the differences between the long term average water temperatures for the simulated period under future climate scenarios minus the value under past weather conditions. In addition to annual averages, the increments which correspond to the warming season (Mar.–Jul.) and the cooling season (Aug.–Nov.) are given separately. Interestingly the cooling season often has the larger water temperature increment, probably because cooling in fall is delayed more than heating is advanced in spring. The water temperature rise is typically on the order of 2.5 to 4.5 °C, with an average near 3.5 °C for three of the climate models (GISS, GFDL and OSU). The UKMO model predicts consistently much higher increments (7.3 to 8.4 °C).

The increases in water temperatures shown in Tables 6.3, 6.4 and 6.5 will have an impact on aquatic life in these and similar streams. This impact will vary from favorable to unfavorable depending on the type of aquatic life present. A more detailed analysis of the impact of climate change on fish in these streams is presented in chapter 7.

6.5. Positive feedback from vegetation in the watershed

Climate change may alter hydrologic and ecological characteristics of streams, e.g. stream flow and bank vegetation. What would happen if global warming caused all the trees along stream banks to vanish? Or what would happen if the stream flow rate were significantly reduced by changes in precipitation and/or ground cover in the watershed? Answers to these two particularly important questions were explored. Figures 6.6a and 6.6b give simulated weekly average water temperatures of the Straight River under past weather conditions and for the $2xCO_2$ GISS scenario. Simulation with and without bank vegetation, i.e. with and without shading of the stream are shown in Fig. 6.6a. The simulations results indicate that loss of existing shade trees would lead to a very significant increase in water temperature. An additional 6° C water temperature rise is projected for the Straight River if the shade trees are lost. The influence of riparian trees on stream temperatures was previously pointed out by Brown (1969) and Rishel et.al. (1982). Since trees take a long time to grow, planting trees adopted to warmer climate along stream banks may be a worthwhile measure to protect cold stream habitats from warming if climate change is anticipated.

Table 6.3. Simulated 25-year average of daily water temperatures from March 1 to November 30.

	PAST	GISS	GFDL	UKMO	OSU
STRAIGHT RIVER	9.9	13.0	14.4	18.2	12.4
BAPTISM RIVER	11.9	14.6	16.4	20.2	14.4
CLEARWATER RIVER	11.1	14.5	14.2	18.9	13.7
ZUMBRO RIVER	13.9	17.6	18.6	22.3	16.4
MISSISSIPPI RIVER	15.6	18.6	19.4	22.9	18.0
All	12.5	15.6	16.6	20.5	15.0

Table 6.4. Maximum of Computed Weekly Average Water Temperatures.

	PAST	GISS	GFDL	UKMO	OSU
STRAIGHT RIVER	19.6	22.9	23.0	28.2	22.7
BAPTISM RIVER	22.9	25.4	26.4	31.0	25.9
CLEARWATER RIVER	22.7	26.5	25.6	31.1	26.1
ZUMBRO RIVER	25.1	28.2	28.5	33.0	28.0
MISSISSIPPI RIVER	28.9	31.2	30.3	35.4	31.8
ALL	23.8	26.8	26.8	31.7	26.9

Table 6.5. Average increase in water temperature due to changes in the weather predicted by the GISS, GFDL, UKMO and OSU global circulation models of doubling of atmospheric CO_2.

		GISS	GFDL	UKMO	OSU
STRAIGHT R.	AVG.	3.1	4.5	8.3	2.5
	AVG. (WARMING)	3.0	4.4	7.2	2.5
	AVG. (COOLING)	3.2	4.6	9.6	2.4

		GISS	GFDL	UKMO	OSU
BAPTISM R.	AVG.	2.7	4.5	8.3	2.5
	AVG. (WARMING)	2.7	4.4	7.5	2.6
	AVG. (COOLING)	2.8	4.7	9.4	2.4

		GISS	GFDL	UKMO	OSU
CLEARWATER R.	AVG.	3.4	3.1	7.8	2.6
	AVG. (WARMING)	2.9	2.8	6.9	2.6
	AVG. (COOLING)	4.0	3.5	9.0	2.6

		GISS	GFDL	UKMO	OSU
ZUMBRO R.	AVG.	3.8	4.7	8.4	2.5
	AVG. (WARMING)	3.1	4.4	7.2	2.5
	AVG. (COOLING)	4.7	5.1	9.9	2.6

		GISS	GFDL	UKMO	OSU
MISSISSIPPI R.	AVG.	2.9	3.8	7.3	2.4
	AVG. (WARMING)	2.9	3.7	6.0	2.4
	AVG. (COOLING)	3.0	3.9	9.0	2.4

		GISS	GFDL	UKMO	OSU
ALL	AVG.	3.2	4.1	8.0	2.5
	AVG. (WARMING)	2.9	3.9	7.0	2.5
	AVG. (COOLING)	3.5	4.4	9.4	2.5

Figure 6.6b shows the effect of a reduction of stream flow on water temperatures. The reduction is by 50%. No significant change in water temperature is projected by the simulation. This is due to the fact that a freely flowing stream scenario is used.

6.6. Extrapolation to other streams / Water temperature and climate correlation

The use of a full heat budget/transport equation to estimate stream water temperatures as used herein is timeconsuming. The search for simpler relationships between climate parameters and water temperatures, even though less accurate, is therefore legitimate. As an example, linear relationships between air and water temperatures have been proposed to forecast or estimate water temperatures (e.g. Song et.al., 1973). These relationships are attractive because they use only one weather parameter, air temperature. This is an advantage over heat budget models (e.g. MNSTREM) which require additional weather parameters such as wind speed, solar radiation, cloud cover and relative humidity. Complete heat budget models, however, predict stream water temperatures more accurately. This accuracy is considered to be important in studies of global climate change impacts on fish (e.g. Stefan et.al., 1991) because climate change will influence not only air temperature but also other weather parameters. Relationships between air and water temperatures established empirically with data from the past may therefore not hold under changed climate conditions. To examine this question, it was considered of interest to relate the simulated water temperature results to some selected weather and stream parameters. It was hoped that this would allow to tie together the results from all five streams studied including past and future climate conditions. It might also permit interpolation and some extrapolation to other streams of the region, not specifically studied herein.

As a first step, increases in air temperature forecast by the GCM's were plotted against simulated resulting water temperature increases (Fig. 6.7). There is a correlation between the two parameters, but also significant scatter. The relationship is non–linear and deviations from linearity are due to the influence of weather parameters other than air temperature such as wind speed, solar radiation, cloud cover and relative humidity, in addition to stream shading.

To improve the relationship between air and stream water temperatures, applied solar radiation (ASR) on the stream surface was added as a second independent variable. This parameter value can be found by multiplying the incident solar radiation measured at a weather station by the shading factor. Figure 6.8 shows the June, July and August mean monthly water temperatures as a function of the June, July and August mean monthly air temperatures and the ASR. The significance of solar radiation and shading is seen explicitly in this plot. The symbols are values from all five streams. The graph suggests that interpolation to other streams is meaningful.

A linearized relationship between equilibrium water temperature as the dependent variable and dew point and net solar radiation as the independent variables was proposed by Brady et.al. (1969). Dew point accounts for

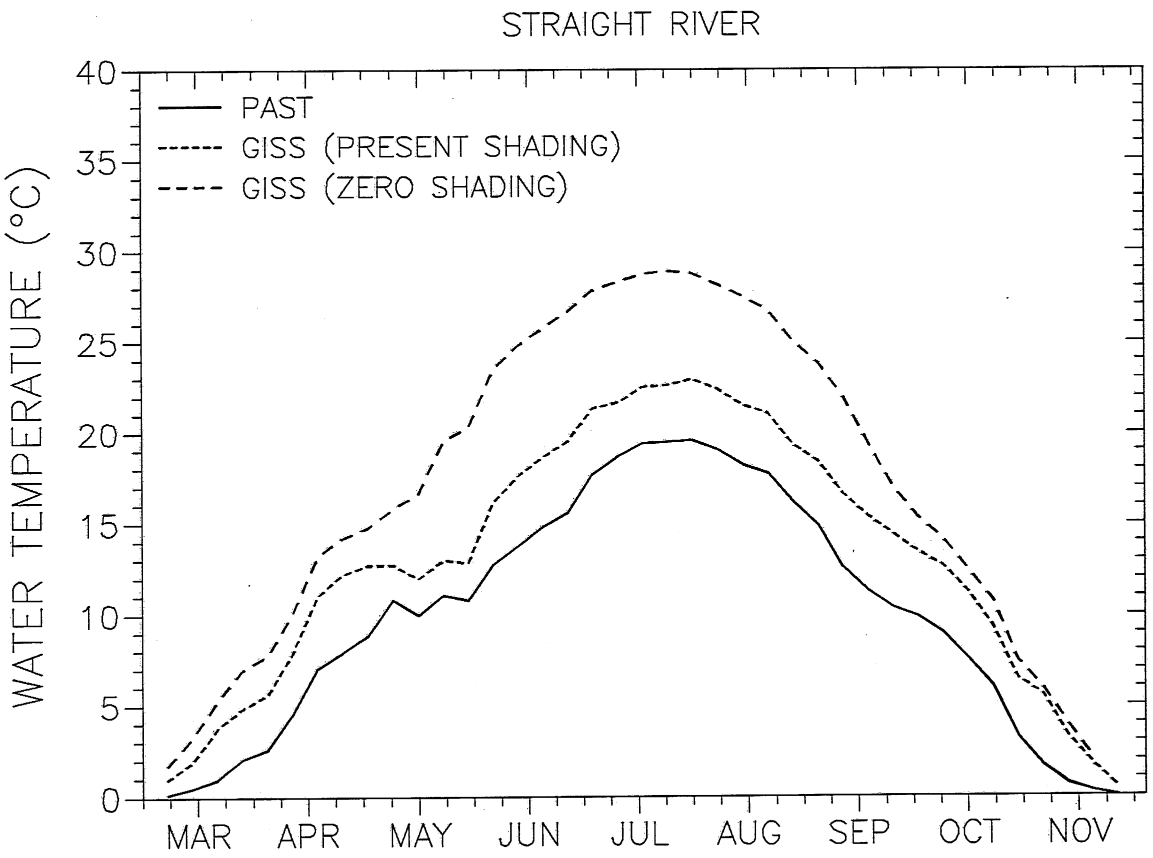


Figure 6.6a. **Sensitivity of stream temperature to shading.**

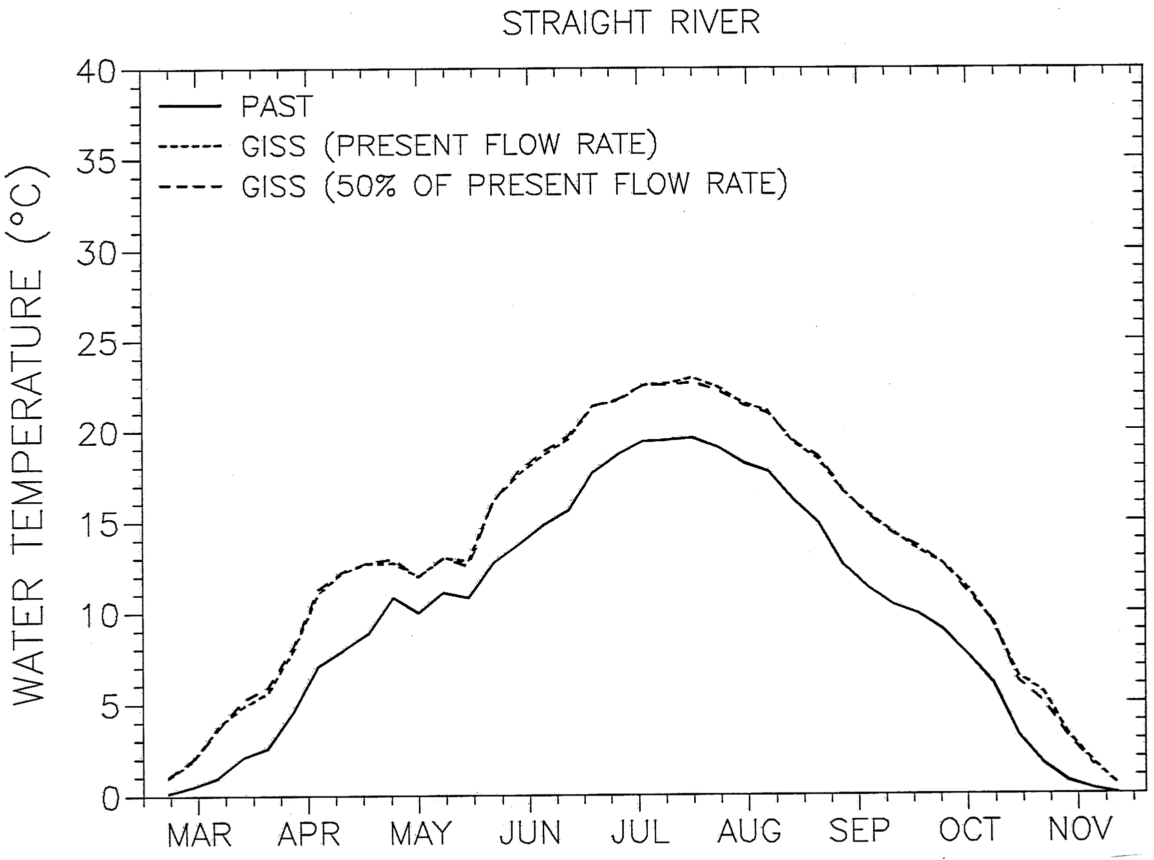


Figure 6.6b. Sensitivity of stream temperature to flow rate.

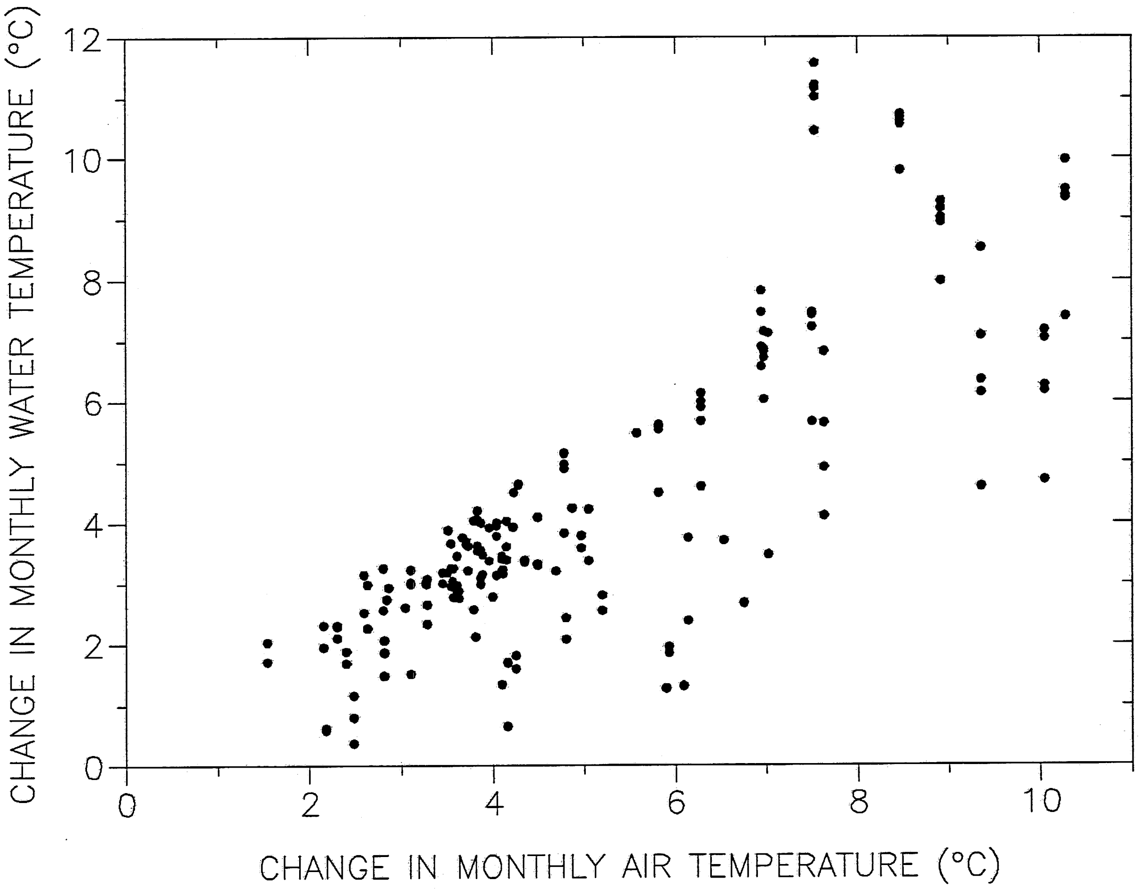


Figure 6.7. Correlation between increases of air and water temperatures due to climate change.

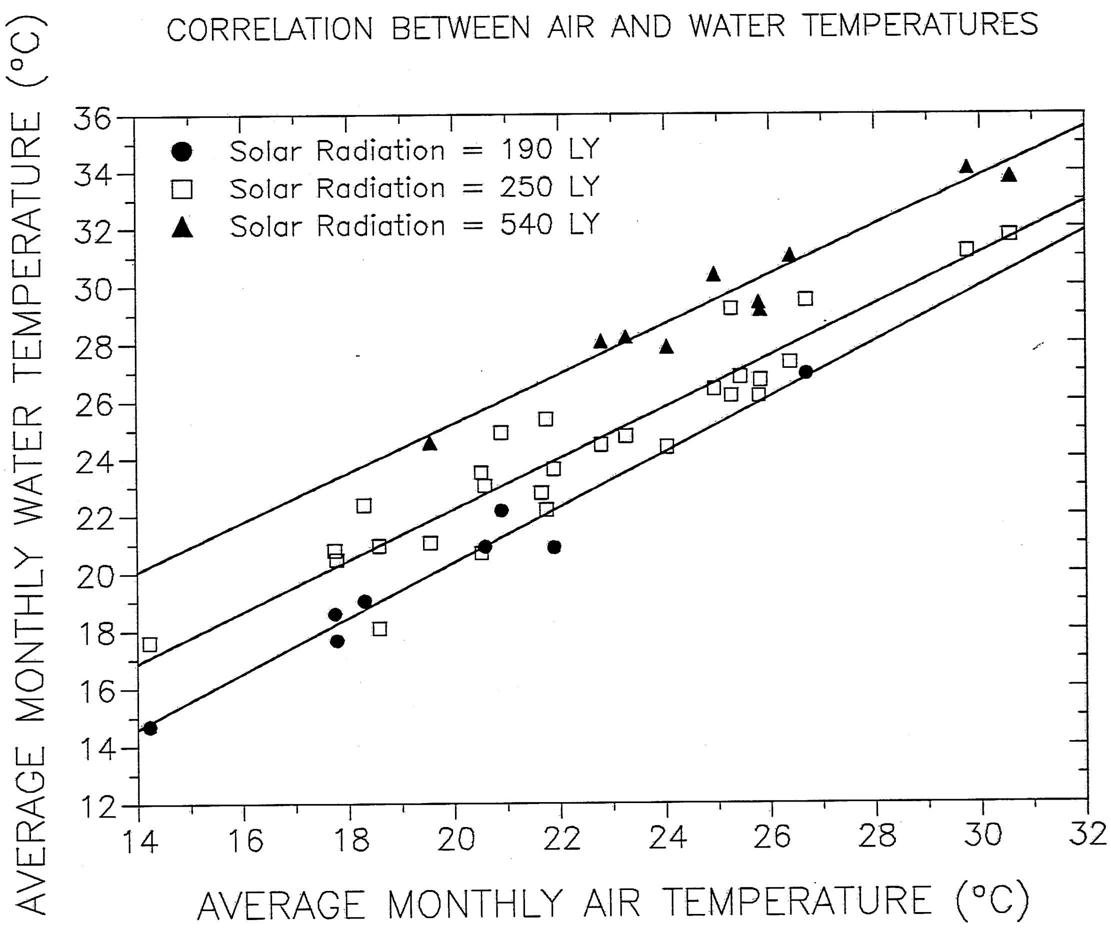


Figure 6.8. Correlation between water temperature, air temperature and solar radiation.

atmospheric moisture content which affects evaporative cooling at a water surface. Following this concept, air temperature in Fig. 6.8 was replaced by dew point temperature to produce Fig. 6.9. The results are similar to the one of Fig. 6.8 without improvement. The scatter seen in the plot can be explained by the fact that daily water temperatures are not equilibrium temperatures. Equilibrium water temperature is the water temperature at which the rate of net surface water heat transfer is zero (Gu and Stefan, 1985). Stream water temperatures reach equilibrium in time over a period of hours, days or weeks depending on water depth. In a freely flowing river of moderate depth, mean monthly water temperatures can be expected to be close to equilibrium temperatures, especially in mid–summer.

Brady et.al. (1969) indicated that an approximate value of the equilibrium water temperature T_e is equal to the dew point temperature T_d plus net solar radiation H_{sn} divided by the bulk coefficient of surface heat transfer K.

$$T_e = T_d + \frac{H_{sn}}{K} \tag{6.1}$$

Equation (6.1) agrees with the format of the data plot in Fig. 6.9 and also Fig. 6.8 if T_e is approximated as T_w (water temperature) and dew point temperature T_d is replaced by air temperature T_a.

6.7. Conclusions

(1) Average summer time increases in stream water temperatures on the order of 2.4 to 4.7 °C as a result of global climate change due to doubling of atmospheric CO_2 were predicted.

(2) Shading of streams was found to be most important for stream temperatures. Detailed measurements of stream water temperature used to estimate the seasonally variable shading and wind sheltering.

(3) A loss in stream bank vegetation (shading) will lead to a significant additional increase of water temperature in small streams. The increase may be as much as 6° C in summer.

(4) Complete heat budget models can accurately predict the the global climate change impacts on stream water temperatures.

(5) Experimenting with different weather and hydrologic scenarios that could result from climate change, e.g. the two discussed in section 6, is feasible with numerical models similar to the one used in this study.

(6) Approximate stream water temperature estimates can be made with relationships between water temperature, air temperature and "applied solar radiation".

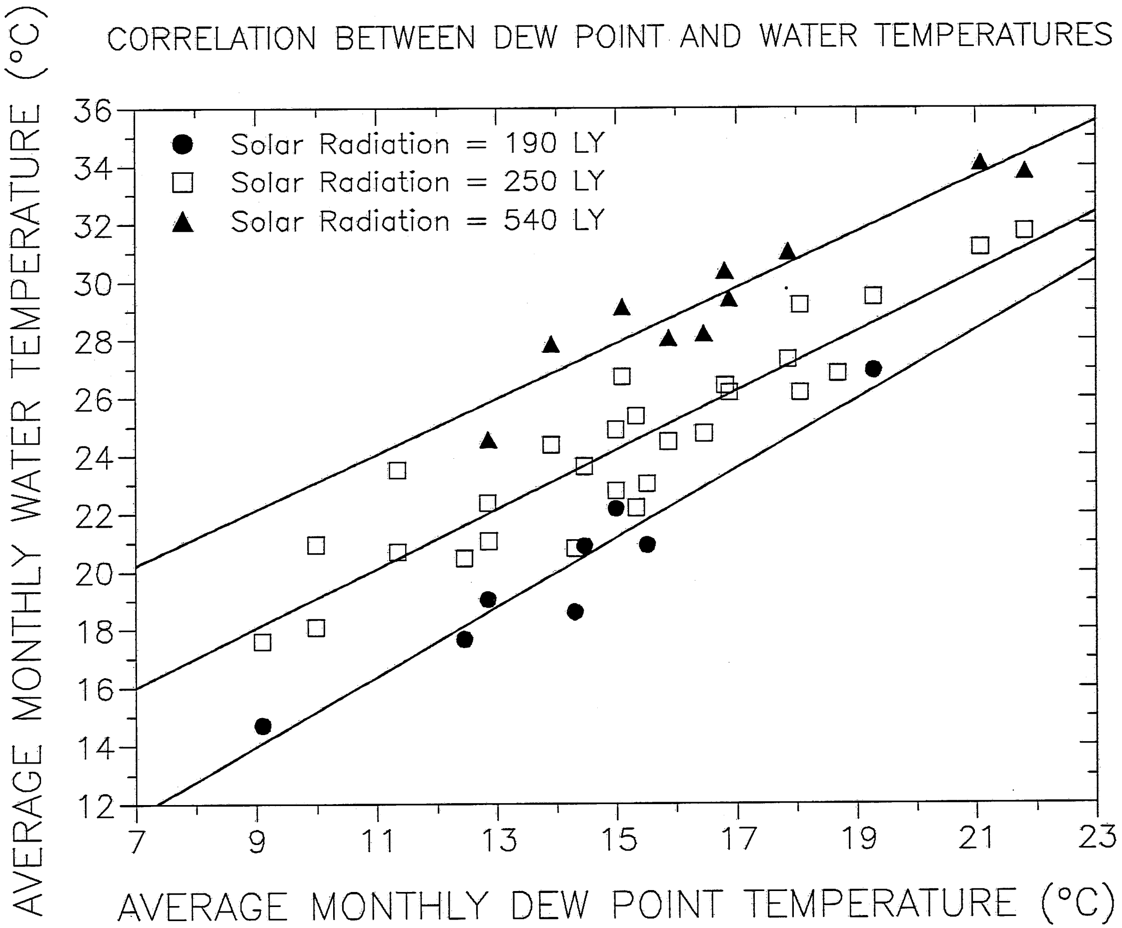


Figure 6.9. Correlation between water temperature, dew point temperature and solar radiation.

7. GLOBAL CLIMATE CHANGE EFFECTS ON FISH

7.1. Introduction

Outputs from the water quality modeling are interfaced with temperature sensitivity data for North American freshwater fishes. Habitat space for fish species is normally constrained by extreme temperatures. The EPA Duluth Environmental Research Laboratory has conducted lab tests and compiled data from many sources on fish sensitivities that are directly related to climate–modified environmental conditions. Empirical models relating distributions of 30 fish species to surface water temperatures are available. The importance of other factors interacting with climate change to influence species distributions will also be discussed.

Climate change impacts are measured in terms of habitat space available for survival and for growth throughout the ice–free season. All analyses and simulations are therefore made for the period from March 1 to November 30. Temperature and dissolved oxygen are considered as the two most significant water quality parameters influenced by climate change and controlling survival and growth of adult or juvenile fish. The deterioration of fish habitat for certain species of fishes and the improvement for others are assessed in terms of temperature only. The results indicate which fishes can be present in five different stream habitats before and after climate change, as well as effects on potential production and yield. Not included in this study are changes due to secondary effects of climate change such as loss of food supply, invasion of predators and changes in flow regimes.

7.2. Fish thermal requirements

Concepts

Analysis of climate change impacts is based on a temperature classification scheme that recognizes three limits of thermal requirements for growth and survival and three patterns of gonadal development for temperate stenotherm (coldwater), temperate mesotherm (coolwater), and temperate eurytherm (warmwater) fishes (Hokanson, 1990). Loss of habitat for cold and coolwater fishes may be a significant impact of climate change in the United States and may have its greatest impact at higher latitudes and altitudes. The empirical model relating fish distribution to water temperature is developed from stream data (Hokanson et al. ,1991).

Surface water temperatures within the United States limit the distributions of cold and coolwater stream fishes. Changes in the distribution of thermal guilds with rising surface water temperatures is the most likely serious consequence of global warming. Increases in surface water temperature would be expected to cause guild succession from coldwater, to coolwater, to warmwater forms. Warmwater fishes could tolerate modest increases in surface water temperatures.

Fish Extinction Versus Invasion

In the analysis herein, only the upper temperature limit as it occurs in summer is used to estimate the geographic distribution of fishes in relation to surface water temperatures. There is also a lower temperature limit which occurs in winter that can be limiting for a fish species or guild of fishes. Warmwater fishes are especially sensitive to low winter temperatures, and evidence is mounting that fishes in other guilds may also be vulnerable (e.g. Johnson and Evans, 1990). Global climate change is predicted to raise most water temperatures in streams. Therefore additional stress for fishes now present in a stream will likely occur in summer, but not in winter. For fishes known to inhabit a particular stream, it is therefore meaningful to explicitly examine the upper temperature limits in the summer to determine if extinction due to elevated temperatures is likely. On the other hand, fishes currently excluded in a stream reach may or may not invade if thermal conditions become acceptable. To determine if colonization is possible both summer and winter limits need to be examined.

The lower temperature bound to be examined for winter is not necessarily a minimum tolerated temperature value since many species of fish survive at 0°C, but instead may be a combination of low temperature plus the duration of that temperature. For potential invader species winter conditions need to be examined. Invasion is much more difficult to project than elimination. Whether an invading species will succeed does not depend on water temperature alone. Winter survival of warmwater fish depends upon body size, fat stores, and starvation time and duration. Where accessibility and connections of waterbodies are poor or insufficient, natural invasion may be so poor that stocking is necessary to establish warmwater fish species if that is desirable. Therefore, only colonization potential which is a function of temperature will be assessed in this study.

7.3. Water temperature requirements of fishes

Fish presence summer temperature limits

Analysis of data contained in the GCC/IMS included a temperature limit for fish presence or geographic distribution. The highest summer 95 percentile value (a weekly mean) for each species of thermal regime obtained from the FTDMS database was selected as the maximum temperature value at which a fish species or guild would be present in a water body. This seemed appropriate (instead of the 100 percentile) in light of the wide geographic data distribution and the range of time–scales over which measurements had been made. Possible sources of error such as measurement errors, fish presence due to refugia, and lack of temporal correspondence of fish and temperature records were considered. The values obtained in this way also compare favorably with laboratory test results involving exposures of several days (e.g. FTDMS 95 percentile values are mostly 1° to 3°C lower than acute mortality temperatures (UUILT), but comparable to upper zero net growth (UZNG) temperatures (USEPA, 1976). Herein the presence or absence of a fish species or guild will also be indicated by terms such as "survival" or "non–survival," although a direct relationship to mortality is not implied. The 95 percentile FTDMS value will be used exclusively as the limit between presence (survival) or absence (non–survival). Table 7.1 gives the FTDMS distribution limit (maximum 95 percentile) temperatures for a number of fish species subdivided into guilds. Further information on the FTDMS database can be obtained from Hokanson et al. (1990a).

Because water temperatures corresponding to the southern boundary of the range of warmwater fishes (i.e. south of the U.S.) are not included in the database, the FTDMS 95th percentile values are known to be too low to reflect the upper thermal tolerance limits for these species. These values are not important for the present analysis because surface water temperatures will not get this hot in the northcentral region of the U.S., particularly Minnesota, even under climate change conditions. A regression relationship between upper incipient lethal temperature and 95th percentile vales for cool and coldwater fishes has been determined to provide the best estimate of FTDMS values for warmwater fish (guild mean = 33.1°C). Figure 6 in Hokanson et al. (1991) provides an estimate of 35.3°C based on a 95 percent stream temperature and UZNG relationship.

Fish growth thermal criteria

In addition to using the ability to survive as a gross measure of climate change effect, a measure of growth potential was sought as a sublethal effect indicator. The arbitrarily chosen measure was the temperature range between that at which 50% of maximum growth occurred and the EPA (1976) maximum temperature for prolonged duration of exposure (see Stefan et. al., 1991 for details of derivation). This "good growth" temperature range could be calculated from growth rate experiments for several species in each guild, the values of which were averaged to obtain guild good growth values. Since the amount of time spent within this range could be expected to contribute heavily to production of a fish population, a comparison of this time before and after climate change should be a useful measure of relative effects on growth potential. The lower and upper good growth values used in this analysis are shown in Table 7.1.

7.4. Climate change impact analysis

Application of Fish Temperature Criteria

Fish distribution (survival) and growth temperature criteria were applied to simulated daily water temperatures for the five streams shown in Fig. 1.1 and listed in Table 5.1. An example of a simulated time series of stream water temperatures during a season and a set of survival and growth temperature criteria for one species of fish is shown in Fig. 7.1. Four particular dates are defined by the intersects. GSB and GSE mark the beginning and end of the good growth season, SCB and SCE the beginning and end of non–survivable temperatures, respectively. These parameters were determined for each of the fish species in Table 7.1 and the three guilds (cold, cool and warm). Also determined were other parameters called SCL. SCL = length of time that 95 percentile FTDMS fish temperature distribution limits (herein also called survival limits) are exceeded (days);

Table 7.1. Thermal criteria for fish.

Cold-Water Species	Lower 50% Growth Limits	Upper Growth Criteria[c]	Current FTDMS max 95th percentile	Optimum Temp.
Pink Salmon		20.3	22.3	18.3
Sockeye Salmon	9.2[b]	18	23.1	17.4
Chinook Salmon	11.8[a]	21.2[e]	23.7	18.7[f]
Chum Salmon		16.5	22.2	12.7
Coho Salmon	10.0[b]	19.9	23.1	17
Brown Trout	7.8[a]	18.5	26.6	13.3[f]
Rainbow Trout	9.2[a]	19.5	23.9	16.1[f]
Brook Trout	6.4[a]	17.3	22.1	13.0[f]
Lake Trout		15.5		11.5[d]
Mountain Whitefish			23.5	
Guild Means	9.0 (6.4-11.8)	18.5 (15.5-21.2)	23.4 (22.1-26.6)	15.3 (11.5-18.7)

Cool-Water Species	Lower 50% Growth Limits	Upper Growth Criteria[c]	Current FTDMS max 95th percentile	Optimum Temp
Northern Pike	13.2[a]	28.8[e]	31.1	25.7[f]
Muskellunge				24[d]
White Sucker	16.0[a]	27.8	28.0	25.4[f]
Black Crappie			32.2	
White Crappie			32.3	
Yellow Perch	17.7[a]	28.1	28.9	25.4[f]
Sauger			31.2	
Walleye	18.2[a]	28.2	29.0	25.2[f]
Guild means	16.3 (13.2-18.2)	28.2 (27.8-28.8)	30.4 (28.0-32.3)	25.1 (24-25.7)

(Contd). Thermal Criteria for Fish

Warm-Water Species	Lower 50% Growth Limits	Upper Growth Criteria[c]	Current FTDMS max. 95th percentile	Optimum Temp
Gizzard Shad		32.3[d]	33.6	28.9[d]
Carp		32.8	32.2	30
Golden Shiner			30.6	
Channel Catfish	22.5[b]	32.8	31.7	30
Brown Bullhead	17.7[a]	31.4[e]	30.2	27.1[f]
White Bass	18.1[a]	29.9[e]	32.3	27.0[f]
Largemouth bass	20.1[a]	34.7	31.1	32[f]
Smallmouth bass	20.2[a]	32.0[e]	28.7	27.7[f]
Rock Bass		32.2[d]	31.0	29[d]
Green Sunfish		32.6[e]	31.2	30
Bluegill	19.8[a]	31.7	31.8	28.7[f]
Freshwater Drum		32.5[d]	32.2	31.3[d]
Guild means	19.7 (17.7-22.5)	32.3 (31.4-34.7)	31.4 (28.7-33.6)	29.2 (27-32)

[a] Lower limit value interpolated from species growth curve.

[b] Lower limit value calculated from species $\frac{OptT+LZNG}{2}$

[c] $\frac{OptT+UZNG}{2}$ or $OptT+\frac{UUILT-OptT}{3}$

Formulas from NAS, NAE 'Blue Book' (1974) and/or U.S. EPA 'Red Book' (1976).

[d] Final Temperature Preferendum used for Optimum Temperature.

[e] UUILT calculated from regression of UILTxUUILT.

[f] Maximum temperature as derived from growth equation.

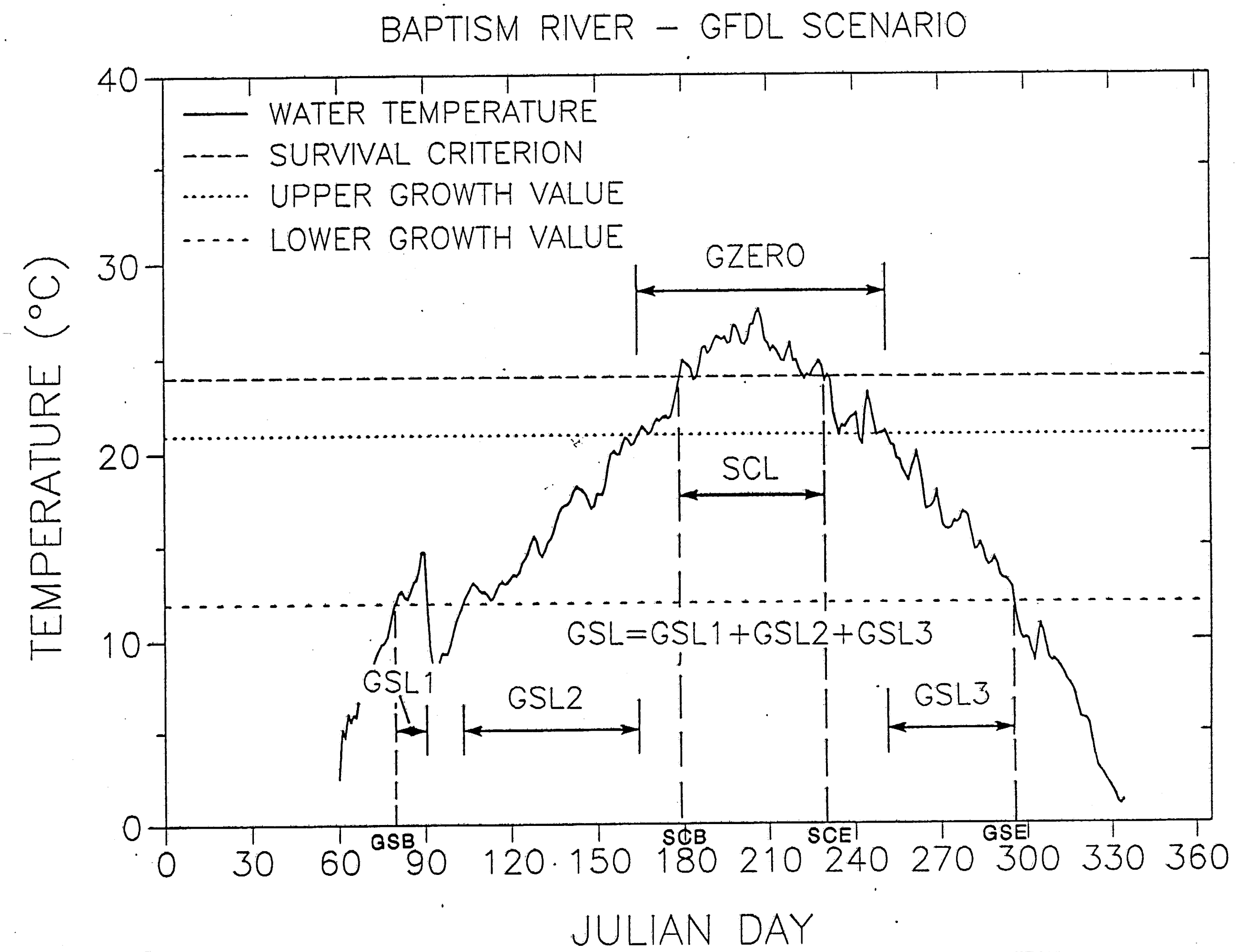


Figure 7.1. Example graph for fish survival and growth parameters. For acronyms see appendix A.

GSL = length of good growth season (days), i.e. length of time that water temperature is within the range of good growth limits as defined in Stefan et. al. (1991); GZER = length of time that water temperature exceeds the upper good growth limit (days) as defined in Stefan et. al. (1991). During the period designated by GZER, growth is much reduced. GZER is therefore a period of low growth and/or stress including uninhabitable temperatures (SCL).

During the period designated by GZER, population biomass gain tends to be reduced below that of good growth due to direct thermal stress on individuals and subsequent deaths (Hokanson, 1990b), as well as due to bioenergetically induced increased energy demands for survival with weight loss of individuals and indirect enhanced vulnerability to disease, the combination of which is the loss of population biomass as the more thermally intolerant individuals are eliminated (McCormick et al., 1972). As a consequence, when trying to evaluate the relative suitability of one set of environmental conditions to another, in terms of production potential, it is necessary not only to compare the GLS's of the two but also to incorporate the effects of exposure to temperatures in exceedance of the good growth range. To achieve this, a ratio (R) was developed which divides the GSL by the GZER. A value R=1 indicates that the good growth period and the stress period are of equal length. A very large value of R indicates a long growth period relative to the stress period, and $R \approx 0$ indicates that the good growth period is totally overshadowed by the length of the stress period. The comparisons between expected growth potential of fish after global climate change (GCC) in particular habitats to that before GCC can now be achieved by comparing R ratios between the two times, i.e. R before may = 3.2 while R for the same habitat after GISS warming may = 0.5; 3.2 − 0.5 = 2.7 or post GISS warming would be expected to have an 84% reduction in relative growth potential.

This consideration is not necessary for temperatures below 50 percent maximum growth because growth without the same degree of hazard still occurs in that temperature range until feeding is halted by cool torpor.

In Table 7.2, the three parameters considered most significant are given for fish guilds in all five streams and for five climate conditions. To relate future to past climate conditions, differences between future and past values of SCL, GSL, and R are presented. Under existing conditions the good growth season length varies with fish guild and stream temperature as expected. In cold streams such as the Straight river the GSL values are 120, 60 and 8 days for cold–, cool– and warmwater fishes, respectively. In the warmer Mississippi River, the values are 73, 130 and 118, respectively. The most favorable R ratios are at present for coolwater fishes in the cooler smaller streams, and for warmwater fishes in the warmer Mississippi River. Results in Table 7.2 also indicate that the length of the good growth season is shortened for coldwater fish and lengthened for coolwater and warmwater fishes as the climate changes. (The $2xCO_2$ GFDL scenario gives results which diverge from this statement.)

Table 7.2. Summary of simulated main fish survival and growth parameters of three fish guilds in five streams under five climate scenarios. Based on 25–year simulated daily average temperatures.

	FISH THERMAL GUILD	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
		SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
STRAIGHT R.	COLD	0	121	3.2	4	-4	-1.7	2	7	-1.8	74	-36	-2.6	2	-2	-1.5
	COOL	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
	WARM	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
BAPTISM R.	COLD	3	113	1.8	47	-13	-0.8	51	10	-0.7	94	-63	-1.5	51	-17	-0.8
	COOL	0	91	92.0	0	24	24.0	0	49	49.0	13	55	-89.2	0	38	38.0
	WARM	0	54	55.0	0	36	36.0	0	47	47.0	2	100	100.0	0	37	37.0
CLEARWATER R.	COLD	0	90	1.3	59	-8	-0.6	42	-11	-0.5	97	-33	-0.9	59	-18	-0.6
	COOL	0	92	93.0	0	43	43.0	0	31	31.0	9	33	-90.6	0	39	39.0
	WARM	0	55	56.0	0	48	48.0	0	37	37.0	2	96	96.0	0	40	40.0
ZUMBRO R.	COLD	44	96	1.0	58	-19	-0.4	53	14	-0.2	98	-44	-0.7	47	-14	-0.3
	COOL	0	119	120.0	0	49	-63.7	0	44	-106.3	54	15	-118.2	0	20	-92.0
	WARM	0	92	93.0	0	37	37.0	0	34	34.0	35	89	-77.8	0	19	19.0
MISSISSIPPI R.	COLD	88	73	0.6	17	-1	-0.1	24	14	0.0	57	-25	-0.3	17	-15	-0.2
	COOL	0	130	11.9	17	-31	-10.5	7	-29	-10.3	76	-29	-10.9	36	-33	-10.3
	WARM	0	118	119.0	2	13	13.0	2	16	16.0	69	6	-116.9	10	14	14.0

R–values become worse for coldwater fishes in all streams, worse for coolwater fishes in the Mississippi and under the extreme climate scenario (UKMO).

An analysis by fish guilds gives only a very rough idea of fish habitat. Therefore, a breakdown of the parameters by fish species is given in Tables 7.3a through 7.3e. Variations within guilds are apparent, e.g. between Northern Pike and Yellow Perch in Table 7.3e. A complete simulation output for streams is given in Stefan et. al. (1991).

An interpretation of the numbers in Tables 7.2 and 7.3 was made in Tables 7.4 and 7.5 by indicating (in shading) uninhabitable conditions and by listing the length of the good growth season (GSL) in days. Uninhabitable conditions are considered to exist when the upper 95% FTDMS limit is exceeded by more than seven days (SCL larger than 7 days).

Table 7.4 gives an overview of the habitat conditions for the five streams, three fish guilds and past, future and extreme future climate conditions. "Extreme future" habitat conditions are based on the most extreme SCL or GSL–value usually associated with the UKMO climate scenario. Future habitat values are those excluding the extreme parameter value and are the average of the GISS, GFDL and OSU model results. The numerical values in Tables 7.4 and 7.5 give the length of the good growth season GSL. Uninhabitable conditions are identified by shaded boxes. The streams are arranged, more or less, from coldest to warmest. The habitat classification given in Table 7.4 for guilds is broken down by individual species in Table 7.5. In Table 7.5 as previously in Table 7.3 all fish species in the database are listed. This is not meant to imply that all species listed are present in every stream. Those which have been observed are listed by the frequency observations (e.g. 5/22) in the first column under the heading OBS. For the Mississippi River fish species reported are shown by an asterisk because the frequency of observations is not known.

It needs to be clarified or recalled here that the parameters SCL, GSL and R as defined earlier in this section are not of equal significance. SCL is a parameter directly related to the FTDMS data base which is presumably broad enough to integrate all phenomena important to fish presence in a stream such as reproduction, food supply, winter survival and upper lethal temperatures. FTDMS also covers a broad segment of the geographic range in which a species is present.

GSL values, on the other hand, are derived from growth rate curves for individual species. This is a data source totally different from the FTDMS data base. GSL designates the length of the period when growth rates are good (better than 50% of the maximum), but there is growth even where GSL approaches 0 albeit poor or restricted growth. GSL is used as a relative measure of the change in the growth potential of the species or guilds of fishes within a waterbody with climate change.

For future climate scenarios, the percentage of shading is varied because stream temperatures are sensitive to this parameter as will be discussed earlier.

Table 7.3a. Survival and growth parameters of 32 fish species under five climate scenarios for the Straight River.

	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
FISH	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
Brook Trout	0	140	2.7	28	-23	-1.4	27	4	-1.2	87	-68	-2.3	24	-25	-1.3
Brown Trout	0	138	3.7	0	-19	-2.2	0	-1	-2.1	30	-47	-3.1	0	-13	-1.9
Coho Salmon	0	136	22.8	6	-1	-20.4	7	8	-20.5	75	-33	-22.0	5	-18	-20.8
Rainbow Trout	0	147	14.8	1	-10	-12.5	1	1	-12.6	71	-40	-14.0	1	-21	-12.7
Lake Herring	0	121	3.2	4	-4	-1.7	2	7	-1.8	74	-36	-2.6	2	-2	-1.5
Chinook Salmon	0	105	106.0	2	15	-103.5	2	33	-103.2	73	11	-104.8	1	6	-103.6
Chum Salmon	0	100	1.7	23	-3	-0.7	25	10	-0.7	84	-57	-1.5	24	-3	-0.7
Mountain Whitefish	0	121	3.2	3	-4	-1.7	2	7	-1.8	74	-36	-2.6	2	-2	-1.5
Pink Salmon	0	156	52.3	23	-14	-49.7	24	3	-49.5	81	-37	-51.3	20	-18	-49.7
Lake Trout	0	93	1.4	4	-2	-0.5	2	1	-0.6	74	-55	-1.2	2	-3	-0.5
Sockeye Salmon	0	111	2.4	6	2	-1.0	7	13	-1.0	75	-41	-2.0	5	-5	-1.1
Guild (Cold)	0	121	3.2	4	-4	-1.7	2	7	-1.8	74	-36	-2.6	2	-2	-1.5
Northern Pike	0	93	94.0	0	43	43.0	0	68	68.0	0	110	-26.0	0	42	42.0
Sauger	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
White Sucker	0	62	63.0	0	41	41.0	0	48	48.0	5	121	-48.8	0	36	36.0
Yellow Perch	0	51	52.0	0	35	35.0	0	43	43.0	1	116	-18.4	0	32	32.0
Walleye	0	40	41.0	0	42	42.0	0	48	48.0	1	116	-1.7	0	38	38.0
Muskellunge	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
Black Crappie	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
White Crappie	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
Guild (Cool)	0	60	61.0	0	39	39.0	0	47	47.0	0	130	-13.2	0	35	35.0
Smallmouth Bass	0	2	3.0	0	52	52.0	0	55	55.0	2	114	114.0	0	51	51.0
Brown Bullhead	0	51	52.0	0	35	35.0	0	43	43.0	0	120	120.0	0	32	32.0
Carp	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Freshwater Drum	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Gizzard Shad	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Golden Shiner	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Green Sunfish	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
White Bass	0	45	46.0	0	38	38.0	0	45	45.0	0	115	115.0	0	35	35.0
Lake Sturgeon	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Rock Bass	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0
Channel Catfish	0	0	1.0	0	16	16.0	0	20	20.0	0	80	80.0	0	14	14.0
Largemouth Bass	0	2	3.0	0	53	53.0	0	58	58.0	0	115	115.0	0	52	52.0
Bluegill	0	6	7.0	0	51	51.0	0	55	55.0	0	118	118.0	0	52	52.0
Guild (Warm)	0	8	9.0	0	49	49.0	0	55	55.0	0	117	117.0	0	52	52.0

Table 7.3b. Survival and growth parameters of 32 fish species under five climate scenarios for the Baptism River.

	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
FISH	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
Brook Trout	25	114	1.4	32	-1	-0.3	36	12	-0.4	99	-55	-1.1	34	-17	-0.6
Brown Trout	0	127	2.0	0	-19	-0.9	7	10	-0.7	71	-70	-1.7	2	-27	-1.0
Coho Salmon	7	107	2.0	48	1	-0.8	49	12	-0.8	94	-27	-1.5	47	-4	-0.8
Rainbow Trout	1	114	2.1	41	-11	-1.0	49	13	-0.9	91	-38	-1.6	49	-13	-1.0
Lake Herring	3	113	1.8	47	-13	-0.8	51	10	-0.7	94	-63	-1.5	51	-17	-0.8
Chinook Salmon	2	105	2.7	45	12	-0.9	52	23	-1.0	93	-26	-2.1	49	-13	-1.4
Chum Salmon	24	86	1.0	33	2	-0.2	36	9	-0.3	97	-44	-0.8	34	-18	-0.5
Mountain Whitefish	3	113	1.8	46	-13	-0.8	51	10	-0.7	94	-63	-1.5	50	-17	-0.8
Pink Salmon	21	122	2.3	35	-5	-0.9	37	14	-0.9	98	-33	-1.7	35	-12	-1.0
Lake Trout	3	76	0.8	47	-6	-0.3	51	9	-0.2	94	-37	-0.6	51	-13	-0.3
Sockeye Salmon	7	97	1.3	48	-2	-0.4	49	18	-0.3	94	-52	-1.1	47	-5	-0.4
Guild (Cold)	3	113	1.8	47	-13	-0.8	51	10	-0.7	94	-63	-1.5	51	-17	-0.8
Northern Pike	0	129	130.0	0	31	31.0	0	49	49.0	2	44	-126.2	0	28	28.0
Sauger	0	91	92.0	0	24	24.0	0	49	49.0	2	55	-89.2	0	38	38.0
White Sucker	0	95	96.0	0	26	26.0	0	47	47.0	53	50	-93.3	0	35	35.0
Yellow Perch	0	76	77.0	0	29	29.0	0	45	45.0	44	66	-74.3	0	30	30.0
Walleye	0	69	70.0	0	33	33.0	0	43	43.0	43	73	-67.2	0	32	32.0
Muskellunge	0	91	92.0	0	24	24.0	0	49	49.0	13	55	-89.2	0	38	38.0
Black Crappie	0	91	92.0	0	24	24.0	0	49	49.0	0	55	-89.2	0	38	38.0
White Crappie	0	91	92.0	0	24	24.0	0	49	49.0	0	55	-89.2	0	38	38.0
Guild (Cool)	0	91	92.0	0	24	24.0	0	49	49.0	13	55	-89.2	0	38	38.0
Smallmouth Bass	0	54	55.0	0	29	29.0	0	42	42.0	46	97	97.0	0	33	33.0
Brown Bullhead	0	76	77.0	0	29	29.0	0	45	45.0	19	116	-12.7	0	30	30.0
Carp	0	54	55.0	0	36	36.0	0	47	47.0	0	100	100.0	0	37	37.0
Freshwater Drum	0	54	55.0	0	36	36.0	0	47	47.0	0	100	100.0	0	37	37.0
Gizzard Shad	0	54	55.0	0	36	36.0	0	47	47.0	0	100	100.0	0	37	37.0
Golden Shiner	0	54	55.0	0	36	36.0	0	47	47.0	10	100	100.0	0	37	37.0
Green Sunfish	0	54	55.0	0	36	36.0	0	47	47.0	2	100	100.0	0	37	37.0
White Bass	0	71	72.0	0	32	32.0	0	42	42.0	0	97	-65.5	0	30	30.0
Lake Sturgeon	0	54	55.0	0	36	36.0	0	47	47.0	2	100	100.0	0	37	37.0
Rock Bass	0	54	55.0	0	36	36.0	0	47	47.0	2	100	100.0	0	37	37.0
Channel Catfish	0	14	15.0	0	42	42.0	0	44	44.0	1	103	103.0	0	41	41.0
Largemouth Bass	0	54	55.0	0	30	30.0	0	42	42.0	2	97	97.0	0	34	34.0
Bluegill	0	54	55.0	0	34	34.0	0	47	47.0	1	99	22.0	0	36	36.0
Guild (Warm)	0	54	55.0	0	36	36.0	0	47	47.0	2	100	100.0	0	37	37.0

Table 7.3c. Survival and growth parameters of 32 fish species under five climate scenarios for the Clearwater River.

	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
FISH	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
Brook Trout	20	97	1.2	53	-12	-0.5	40	12	-0.2	95	-28	-0.8	50	-20	-0.5
Brown Trout	0	101	1.5	3	-16	-0.7	0	-5	-0.5	65	-36	-1.1	2	-14	-0.6
Coho Salmon	2	101	1.9	60	-21	-1.1	45	-10	-0.8	102	-33	-1.4	61	-28	-1.1
Rainbow Trout	0	99	1.7	53	-14	-0.9	37	-14	-0.8	92	-31	-1.2	52	-23	-0.9
Lake Herring	0	90	1.3	59	-8	-0.6	42	-11	-0.5	97	-33	-0.9	59	-18	-0.6
Chinook Salmon	0	106	3.1	57	-20	-2.1	40	-9	-1.7	92	-26	-2.5	54	-34	-2.2
Chum Salmon	18	68	0.8	54	-10	-0.4	42	-9	-0.3	97	-23	-0.5	51	-24	-0.5
Mountain Whitefish	0	90	1.3	59	-8	-0.6	41	-11	-0.5	94	-33	-0.9	57	-18	-0.6
Pink Salmon	14	112	2.5	58	-16	-1.5	43	-10	-1.2	100	-39	-2.0	55	-28	-1.6
Lake Trout	0	61	0.6	59	-11	-0.2	42	-15	-0.2	97	-27	-0.4	59	-23	-0.3
Sockeye Salmon	2	88	1.3	60	-11	-0.6	45	-14	-0.6	102	-32	-1.0	61	-20	-0.6
Guild (Cold)	0	90	1.3	59	-8	-0.6	42	-11	-0.5	97	-33	-0.9	59	-18	-0.6
Northern Pike	0	130	131.0	0	26	26.0	0	23	23.0	3	28	-127.5	0	20	20.0
Sauger	0	92	93.0	0	43	43.0	0	31	31.0	3	33	-90.6	0	39	39.0
White Sucker	0	94	95.0	0	44	44.0	0	34	34.0	55	28	-92.8	0	38	38.0
Yellow Perch	0	71	72.0	0	42	42.0	0	36	36.0	40	40	-70.0	0	36	36.0
Walleye	0	69	70.0	0	42	42.0	0	34	34.0	40	44	-67.8	0	33	33.0
Muskellunge	0	92	93.0	0	43	43.0	0	31	31.0	9	33	-90.6	0	39	39.0
Black Crappie	0	92	93.0	0	43	43.0	0	31	31.0	0	33	-90.6	0	39	39.0
White Crappie	0	92	93.0	0	43	43.0	0	31	31.0	0	33	-90.6	0	39	39.0
Guild (Cool)	0	92	93.0	0	43	43.0	0	31	31.0	9	33	-90.6	0	39	39.0
Smallmouth Bass	0	47	48.0	0	51	51.0	0	31	31.0	46	100	100.0	0	44	44.0
Brown Bullhead	0	71	72.0	0	42	42.0	0	36	36.0	15	92	-17.3	0	36	36.0
Carp	0	55	56.0	0	48	48.0	0	37	37.0	0	96	96.0	0	40	40.0
Freshwater Drum	0	55	56.0	0	48	48.0	0	37	37.0	0	96	96.0	0	40	40.0
Gizzard Shad	0	55	56.0	0	48	48.0	0	37	37.0	0	96	96.0	0	40	40.0
Golden Shiner	0	55	56.0	0	48	48.0	0	37	37.0	8	96	96.0	0	40	40.0
Green Sunfish	0	55	56.0	0	48	48.0	0	37	37.0	3	96	96.0	0	40	40.0
White Bass	0	69	70.0	0	43	43.0	0	35	35.0	0	77	-62.3	0	33	33.0
Lake Sturgeon	0	55	56.0	0	48	48.0	0	37	37.0	2	96	96.0	0	40	40.0
Rock Bass	0	55	56.0	0	48	48.0	0	37	37.0	4	96	96.0	0	40	40.0
Channel Catfish	0	11	12.0	0	59	59.0	0	41	41.0	0	100	100.0	0	57	57.0
Largemouth Bass	0	47	48.0	0	51	51.0	0	33	33.0	3	100	100.0	0	44	44.0
Bluegill	0	55	56.0	0	46	46.0	0	33	33.0	0	95	95.0	0	39	39.0
Guild (Warm)	0	55	56.0	0	48	48.0	0	37	37.0	2	96	96.0	0	40	40.0

Table 7.3d. Survival and growth parameters of 32 fish species under five climate scenarios for the Zumbro River.

	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
FISH	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
Brook Trout	57	100	0.9	53	-16	-0.3	45	4	-0.2	107	-47	-0.6	41	-10	-0.2
Brown Trout	0	99	1.0	40	-14	-0.4	42	19	-0.1	90	-42	-0.7	45	-13	-0.3
Coho Salmon	48	97	1.1	55	-13	-0.4	49	14	-0.2	95	-45	-0.8	44	-10	-0.3
Rainbow Trout	31	100	1.1	70	-19	-0.5	60	16	-0.2	101	-45	-0.8	51	-8	-0.3
Lake Herring	44	96	1.0	58	-19	-0.4	53	14	-0.2	98	-44	-0.7	47	-14	-0.3
Chinook Salmon	40	107	1.6	61	-23	-0.9	55	4	-0.6	97	-55	-1.3	49	-14	-0.7
Chum Salmon	57	76	0.6	52	-29	-0.3	44	-4	-0.2	107	-34	-0.4	41	-8	-0.1
Mountain Whitefish	43	96	1.0	59	-19	-0.4	54	14	-0.2	98	-44	-0.7	47	-14	-0.3
Pink Salmon	57	104	1.2	52	-13	-0.5	44	22	-0.1	106	-45	-0.9	39	-5	-0.3
Lake Trout	44	72	0.6	58	-33	-0.4	53	-12	-0.3	98	-33	-0.4	47	-22	-0.3
Sockeye Salmon	48	92	0.9	55	-19	-0.4	49	12	-0.2	95	-43	-0.7	44	-15	-0.3
Guild (Cold)	44	96	1.0	58	-19	-0.4	53	14	-0.2	98	-44	-0.7	47	-14	-0.3
Northern Pike	0	152	153.0	0	40	40.0	0	47	-103.0	38	-5	-151.0	0	31	31.0
Sauger	0	119	120.0	0	49	-63.7	0	44	-106.3	37	15	-118.2	0	20	-92.0
White Sucker	0	119	120.0	3	48	-99.0	14	45	-110.3	77	14	-118.3	7	18	-107.5
Yellow Perch	0	106	107.0	0	35	-71.5	3	25	-97.6	73	23	-105.3	0	18	-86.2
Walleye	0	101	102.0	0	37	-55.7	0	26	-91.3	73	23	-100.4	0	22	-77.2
Muskellunge	0	119	120.0	0	49	-63.7	0	44	-106.3	54	15	-118.2	0	20	-92.0
Black Crappie	0	119	120.0	0	49	-63.7	0	44	-106.3	14	15	-118.2	0	20	-92.0
White Crappie	0	119	120.0	0	49	-63.7	0	44	-106.3	11	15	-118.2	0	20	-92.0
Guild (Cool)	0	119	120.0	0	49	-63.7	0	44	-106.3	54	15	-118.2	0	20	-92.0
Smallmouth Bass	0	90	91.0	1	35	35.0	3	34	34.0	74	80	-83.2	0	18	18.0
Brown Bullhead	0	106	107.0	0	38	38.0	0	38	38.0	58	65	-102.2	0	23	23.0
Carp	0	92	93.0	0	37	37.0	0	34	34.0	14	96	-55.2	0	19	19.0
Freshwater Drum	0	92	93.0	0	37	37.0	0	34	34.0	14	92	-72.4	0	19	19.0
Gizzard Shad	0	92	93.0	0	37	37.0	0	34	34.0	1	89	-77.8	0	19	19.0
Golden Shiner	0	92	93.0	0	37	37.0	0	34	34.0	49	89	-77.8	0	19	19.0
Green Sunfish	0	92	93.0	0	37	37.0	0	34	34.0	37	94	-66.3	0	19	19.0
White Bass	0	101	102.0	0	39	39.0	0	38	38.0	14	39	-99.7	0	26	26.0
Lake Sturgeon	0	92	93.0	0	37	37.0	0	34	34.0	35	89	-77.8	0	19	19.0
Rock Bass	0	92	93.0	0	37	37.0	0	34	34.0	41	87	-80.1	0	19	19.0
Channel Catfish	0	55	56.0	0	52	52.0	0	46	46.0	29	96	-25.6	0	39	39.0
Largemouth Bass	0	91	92.0	0	35	35.0	0	34	34.0	38	100	100.0	0	19	19.0
Bluegill	0	92	93.0	0	34	34.0	0	34	34.0	26	72	-87.3	0	18	18.0
Guild (Warm)	0	92	93.0	0	37	37.0	0	34	34.0	35	89	-77.8	0	19	19.0

Table 7.3e. Survival and growth parameters of 32 fish species under five climate scenarios for the Mississippi River.

	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
FISH	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
Brook Trout	96	77	0.6	18	-10	-0.2	28	15	0.0	59	-19	-0.3	22	-3	-0.1
Brown Trout	45	76	0.6	40	1	-0.1	36	19	0.0	69	-19	-0.3	45	-6	-0.1
Coho Salmon	90	76	0.7	17	-5	-0.2	23	18	0.0	57	-24	-0.4	16	-8	-0.2
Rainbow Trout	80	75	0.6	21	7	0.0	26	25	0.1	62	-20	-0.3	20	-8	-0.1
Lake Herring	88	73	0.6	17	-1	-0.1	24	14	0.0	57	-25	-0.3	17	-15	-0.2
Chinook Salmon	85	73	0.7	18	-3	-0.1	22	8	-0.1	58	-25	-0.4	15	-8	-0.2
Chum Salmon	96	56	0.4	18	-4	-0.1	26	17	0.0	56	-19	-0.2	20	-15	-0.1
Mountain Whitefish	88	73	0.6	17	-1	-0.1	23	14	0.0	56	-25	-0.3	16	-15	-0.2
Pink Salmon	96	83	0.8	16	4	-0.1	23	23	0.0	54	-22	-0.5	18	-12	-0.2
Lake Trout	88	51	0.4	17	-8	-0.1	24	10	-0.1	57	-19	-0.2	17	-16	-0.2
Sockeye Salmon	90	67	0.5	17	-3	-0.1	23	14	0.0	57	-21	-0.3	16	-14	-0.1
Guild (Cold)	88	73	0.6	17	-1	-0.1	24	14	0.0	57	-25	-0.3	17	-15	-0.2
Northern Pike	0	158	19.9	9	-20	-17.3	3	-8	-16.5	72	-40	-18.7	14	-32	-17.7
Sauger	0	130	11.9	7	-31	-10.5	2	-29	-10.3	72	-29	-10.9	12	-33	-10.3
White Sucker	12	121	5.5	63	-28	-4.3	54	-24	-4.1	94	-22	-4.6	56	-35	-4.3
Yellow Perch	6	115	8.9	45	-28	-7.6	35	-22	-7.5	90	-27	-8.1	51	-30	-7.6
Walleye	2	115	10.5	48	-35	-9.3	32	-26	-9.1	90	-25	-9.6	54	-32	-9.1
Muskellunge	0	130	11.9	17	-31	-10.5	7	-29	-10.3	76	-29	-10.9	36	-33	-10.3
Black Crappie	0	130	11.9	0	-31	-10.5	0	-29	-10.3	63	-29	-10.9	0	-33	-10.3
White Crappie	0	130	11.9	0	-31	-10.5	0	-29	-10.3	59	-29	-10.9	0	-33	-10.3
Guild (Cool)	0	130	11.9	17	-31	-10.5	7	-29	-10.3	76	-29	-10.9	36	-33	-10.3
Smallmouth Bass	7	111	112.0	47	19	19.0	42	20	-46.0	91	3	-110.2	50	15	-69.7
Brown Bullhead	0	127	128.0	20	27	-76.3	10	29	-75.7	77	-3	-126.2	43	11	-115.4
Carp	0	118	119.0	0	13	13.0	0	16	16.0	63	11	-116.6	0	14	14.0
Freshwater Drum	0	118	119.0	0	13	13.0	0	16	16.0	63	9	-116.7	0	14	14.0
Gizzard Shad	0	118	119.0	0	13	13.0	0	16	16.0	43	6	-116.9	0	14	14.0
Golden Shiner	0	118	119.0	13	13	13.0	3	16	16.0	73	6	-116.9	33	14	14.0
Green Sunfish	0	118	119.0	7	13	13.0	2	16	16.0	72	10	-116.7	12	14	14.0
White Bass	0	126	127.0	0	-11	-123.6	0	15	-116.9	63	-11	-125.5	0	-31	-125.1
Lake Sturgeon	0	118	119.0	2	13	13.0	2	16	16.0	69	6	-116.9	10	14	14.0
Rock Bass	0	118	119.0	9	13	13.0	3	16	16.0	72	1	-117.1	17	14	14.0
Channel Catfish	0	92	93.0	0	20	20.0	2	26	26.0	68	4	-91.2	7	20	20.0
Largemouth Bass	0	111	112.0	9	19	19.0	3	21	21.0	72	52	-102.4	14	18	18.0
Bluegill	0	116	117.0	0	14	14.0	2	16	-72.7	67	-2	-115.3	7	8	-101.4
Guild (Warm)	0	118	119.0	2	13	13.0	2	16	16.0	69	6	-116.9	10	14	14.0

Table 7.4. Summary of survival and good growth periods (days) of three fish guilds in five streams under past, probable future and extreme future climate.

STREAM	GUILD	GSL (days)		
		PAST[a]	FUTURE[b]	EXT. FUT.[c]
STRAIGHT R.	COLD	121	121	▨
	COOL	60	100	190
	WARM	8	60	125
BAPTISM R.	COLD	113	▨	▨
	COOL	91	128	▨
	WARM	54	94	154
CLEARWATER R.	COLD	90	▨	▨
	COOL	92	130	▨
	WARM	55	97	151
ZUMBRO R.	COLD	▨	▨	▨
	COOL	119	157	▨
	WARM	92	122	181
MISSISSIPPI R.	COLD	▨	▨	▨
	COOL	130	▨	▨
	WARM	118	132	124

Shaded boxes indicate uninhabitable conditions.

a- Based on simulation with historical weather (1953-1979).
b- Based on arithmetic average simulation of three GCC models.
c- Based on highest simulated response of climate change model (UKMO climate scenario).

Table 7.5. Fish observations, survival and good growth periods (days) of 32 fish species derived from long–term, daily average water temperatures simulated for past and future climate conditions with current shading and no future shading.

Straight River :	GSL (days)	60%(PRESENT) SHADING			20% SHADING		0% SHADING	
FISH	OBS	PAST[a]	FUT.[b]	EXT FUT[c]	FUT.	EXT FUT	FUT.	EXT FUT
Brook Trout		140	▨	▨	▨	▨	▨	▨
Brown Trout	22/22	138	127	▨	▨	▨	▨	▨
Coho Salmon		136	132	▨	▨	▨	▨	▨
Rainbow Trout	5/22	147	137	▨	▨	▨	▨	▨
Lake Herring		121	121	▨	▨	▨	▨	▨
Chinook Salmon		100	123	▨	▨	▨	▨	▨
Chum Salmon		100	▨	▨	▨	▨	▨	▨
Mountain Whitefish		121	121	▨	▨	▨	▨	▨
Pink Salmon		156	▨	▨	▨	▨	▨	▨
Lake Trout		93	92	▨	▨	▨	▨	▨
Sockeye Salmon		111	114	▨	▨	▨	▨	▨
Guild (Cold)		121	121	▨	▨	▨	▨	▨
Northern Pike	8/32	93	144	203	175	▨	165	▨
Sauger		60	100	190	137	▨	118	▨
White Sucker	13/39	62	104	183	139	▨	▨	▨
Yellow Perch	3/22	51	88	167	123	▨	▨	▨
Walleye	1/22	40	83	156	117	▨	▨	▨
Muskellunge		60	100	190	137	▨	118	▨
Black Crappie	2/7	60	100	190	137	137	118	▨
White Crappie		60	100	190	137	137	118	▨
Guild (Cool)		60	100	190	137	▨	118	▨
Smallmouth Bass		2	55	116	99	158	115	123
Brown Bullhead		51	88	171	124	180	130	150
Carp		8	60	125	103	173	118	151
Freshwater Drum		8	60	125	103	172	118	142
Gizzard Shad		8	60	125	103	172	118	137
Golden Shiner	1/22	8	60	125	103	172	118	137
Green Sunfish	1/22	8	60	125	103	172	118	147
White Bass		45	84	125	119	148	128	132
Lake Sturgeon		8	60	125	103	172	118	137
Rock Bass	2/22	8	60	125	103	172	118	137
Channel Catfish		0	17	80	81	131	98	118
Largemouth Bass	5/22	2	56	117	101	170	116	170
Bluegill	1/22	6	59	124	102	162	117	128
Guild (Warm)		8	60	125	103	172	118	137

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 5/22 means fish species observed in 5 of 22 surveys.
a, b and c - See footnotes on table 6.

Cont. (Table 7.5.)

Baptism River : GSL (days)		40%(PRESENT) SHADING			20% SHADING		0% SHADING	
FISH	OBS.	PAST	FUT.	EXT. FUT.	FUT.	EXT. FUT.	FUT.	EXT. FUT.
Brook Trout	1/7	▨	▨	▨	▨	▨	▨	▨
Brown Trout	2/7	127	115	▨	▨	▨	▨	▨
Coho Salmon		107	▨	▨	▨	▨	▨	▨
Rainbow Trout	7/10	114	▨	▨	▨	▨	▨	▨
Lake Herring		113	▨	▨	▨	▨	▨	▨
Chinook Salmon	5/7	105	▨	▨	▨	▨	▨	▨
Chum Salmon		▨	▨	▨	▨	▨	▨	▨
Mountain Whitefish		113	▨	▨	▨	▨	▨	▨
Pink Salmon		▨	▨	▨	▨	▨	▨	▨
Lake Trout		76	▨	▨	▨	▨	▨	▨
Sockeye Salmon		97	▨	▨	▨	▨	▨	▨
Guild (Cold)		113	▨	▨	▨	▨	▨	▨
Northern Pike		129	165	173	179	▨	144	▨
Sauger		91	128	146	133	▨	95	▨
White Sucker	2/7	95	131	▨	▨	▨	▨	▨
Yellow Perch	3/7	76	111	▨	121	▨	▨	▨
Walleye		69	105	▨	118	▨	▨	▨
Muskellunge		91	128	▨	133	▨	95	▨
Black Crappie		91	128	146	133	▨	95	▨
White Crappie		91	128	146	133	▨	95	▨
Guild (Cool)		91	128	▨	133	▨	95	▨
Smallmouth Bass		54	89	151	106	149	120	122
Brown Bullhead		76	111	192	130	162	132	139
Carp		54	94	154	112	176	122	140
Freshwater Drum		54	94	154	112	172	122	135
Gizzard Shad		54	94	154	112	167	122	135
Golden Shiner		54	94	154	112	167	122	135
Green Sunfish		54	94	154	112	174	122	138
White Bass		71	106	168	127	143	119	123
Lake Sturgeon		54	94	154	112	167	122	135
Rock Bass		54	94	154	112	162	122	135
Channel Catfish		14	56	117	90	137	102	102
Largemouth Bass		54	89	151	108	174	121	169
Bluegill		54	93	153	111	153	122	130
Guild (Warm)		54	94	154	112	167	122	135

Cont. (Table 7.5.)

Clearwater River : GSL (days)		50%(PRESENT) SHADING			20% SHADING		0% SHADING	
FISH	OBS.	PAST	FUT.	EXT. FUT.	FUT.	EXT. FUT.	FUT.	EXT. FUT.
Brook Trout		▨	▨	▨	▨	▨	▨	▨
Brown Trout	11/13	101	89	▨	▨	▨	▨	▨
Coho Salmon		101	▨	▨	▨	▨	▨	▨
Rainbow Trout	11/13	99	▨	▨	▨	▨	▨	▨
Lake Herring		90	▨	▨	▨	▨	▨	▨
Chinook Salmon		106	▨	▨	▨	▨	▨	▨
Chum Salmon		▨	▨	▨	▨	▨	▨	▨
Mountain Whitefish		90	▨	▨	▨	▨	▨	▨
Pink Salmon		▨	▨	▨	▨	▨	▨	▨
Lake Trout		61	▨	▨	▨	▨	▨	▨
Sockeye Salmon		88	▨	▨	▨	▨	▨	▨
Guild (Cold)		90	▨	▨	▨	▨	▨	▨
Northern Pike	5/18	130	153	158	130	▨	▨	▨
Sauger		92	130	125	97	▨	▨	▨
White Sucker	8/18	94	133	▨	▨	▨	▨	▨
Yellow Perch	2/13	71	109	▨	▨	▨	▨	▨
Walleye	3/18	69	105	▨	▨	▨	▨	▨
Muskellunge		92	130	▨	97	▨	▨	▨
Black Crappie		92	130	125	97	▨	83	▨
White Crappie		92	130	125	97	▨	83	▨
Guild (Cool)		92	130	▨	97	▨	▨	▨
Smallmouth Bass		47	89	147	114	104	124	104
Brown Bullhead	1/13	71	109	163	130	115	128	114
Carp	1/13	55	97	151	118	121	130	114
Freshwater Drum	2/13	55	97	151	118	115	129	109
Gizzard Shad		55	97	151	118	110	128	108
Golden Shiner		55	97	151	118	110	128	108
Green Sunfish	1/13	55	97	151	118	117	129	110
White Bass		69	106	146	123	97	95	100
Lake Sturgeon		55	97	151	118	110	128	108
Rock Bass	6/18	55	97	151	118	109	127	107
Channel Catfish	2/13	11	63	111	99	100	114	94
Largemouth Bass		47	90	147	114	152	129	139
Bluegill	1/13	55	94	150	117	99	121	101
Guild (Warm)		55	97	151	118	110	128	108

Cont. (Table 7.5.)

Zumbro River : GSL (days)		50%(PRESENT) SHADING			20% SHADING		0% SHADING	
FISH	OBS.	PAST	FUT.	EXT. FUT.	FUT.	EXT. FUT.	FUT.	EXT. FUT.
Brook Trout								
Brown Trout	1/50	99						
Coho Salmon								
Rainbow Trout	4/50							
Lake Herring								
Chinook Salmon								
Chum Salmon								
Mountain Whitefish								
Pink Salmon								
Lake Trout								
Sockeye Salmon								
Guild (Cold)								
Northern Pike	6/50	152	191					
Sauger	17/50	119	157					
White Sucker	16/67	119	157					
Yellow Perch	4/50	106	132					
Walleye	14/54	101	129					
Muskellunge		119	157					
Black Crappie	15/50	119	157		111			
White Crappie	10/50	119	157		111			
Guild (Cool)		119	157					
Smallmouth Bass	35/54	90	119	170	142	126	115	111
Brown Bullhead		106	139	171	164	132	122	114
Carp	11/50	92	122	188	150	137	138	125
Freshwater Drum	5/50	92	122	184	150	135	131	124
Gizzard Shad	2/50	92	122	181	150	133	126	122
Golden Shiner		92	122	181	150	133	126	122
Green Sunfish	5/50	92	122	186	150	136	133	124
White Bass	16/63	101	135	140	122	120	92	92
Lake Sturgeon		92	122	181	150	133	126	122
Rock Bass		92	122	179	150	132	123	122
Channel Catfish	16/63	55	101	151	126	123	114	111
Largemouth Bass	25/50	91	120	191	145	168	156	139
Bluegill	14/50	92	121	164	146	129	111	109
Guild (Warm)		92	122	181	150	133	126	122

Cont. (Table 7.5.)

Mississippi River : GSL (days)   0%(PRESENT) SHADING

FISH	OBS.	PAST	FUTURE	EXT. FUT.
Brook Trout		▨	▨	▨
Brown Trout		▨	▨	▨
Coho Salmon		▨	▨	▨
Rainbow Trout		▨	▨	▨
Lake Herring		▨	▨	▨
Chinook Salmon		▨	▨	▨
Chum Salmon		▨	▨	▨
Mountain Whitefish		▨	▨	▨
Pink Salmon		▨	▨	▨
Lake Trout		▨	▨	▨
Sockeye Salmon		▨	▨	▨
Guild (Cold)		▨	▨	▨
Northern Pike	*	158	▨	▨
Sauger		130	▨	▨
White Sucker	*	▨	▨	▨
Yellow Perch	*	115	▨	▨
Walleye	*	115	▨	▨
Muskellunge		130	▨	▨
Black Crappie	*	130	99	▨
White Crappie		130	99	▨
Guild (Cool)		130	▨	▨
Smallmouth Bass	*	111	129	114
Brown Bullhead		127	149	124
Carp	*	118	132	129
Freshwater Drum		118	132	127
Gizzard Shad		118	132	124
Golden Shiner		118	132	124
Green Sunfish		118	132	128
White Bass		126	117	115
Lake Sturgeon		118	132	124
Rock Bass	*	118	132	119
Channel Catfish		92	114	96
Largemouth Bass	*	111	130	163
Bluegill	*	116	129	114
Guild (Warm)		118	132	124

* designates species collected from river reach modelled.

Tables 7.4 and 7.5 indicate that:

(1) With global climate change, coldwater fish will be all but eliminated from free flowing streams, except those in the north which have and can maintain strong shading (40% or better).

(2) Coolwater fish will be eliminated from the Mississippi River, in its central reach (Anoka, MN), but will find improved growth potential in colder streams with more shading. The extreme climate scenario predicts that even coolwater fish will be eliminated from all but the most shaded stream.

(3) Warmwater fish will have slightly improved growth conditions in the Mississippi River, and more improved growth in the smaller streams under future conditions.

7.5. Time scales and variability

Seven–day water temperature averages

A most important consideration for the fish habitat interpretation is the time scale at which the water temperatures are simulated or measured. Figure 7.1 and Tables 7.2 to 7.5 are for daily water temperatures simulated with daily average weather parameters as model input.

It is well–known that stream water temperatures have diurnal fluctuations which can amount to several °C within a day and are related to stream depth (Song et al., 1973). In this study such short–term variations at the time scale of hours have been ignored because it is assumed that fish can, within limits, "integrate" temperature effects over such short periods (i.e. they can resist short–term temperature peaks if the average temperature is not excessive). In fact fish can "integrate" temperature effects over periods of more then one day, and up to 4 to 7 days (Hokanson, Biesinger, Goodno, 1991). To determine how such long–term integration would affect the fish interpretations, computations of fish parameters have been repeated for the coldest (Straight) and the warmest (Mississippi) river with 7–day sliding average values instead of daily water temperature values. The result of these simulations is that the values for SCL, GSL and GZER change only by small amounts when seven–day sliding averages of water temperatures are used instead of daily values. The maximum differences for SCL, GSL and GZER were seven days, ten days and eleven days, respectively. The average differences were on the order of two days for SCL and GSL and one day for GZER. No consistent pattern was found. The reason for the relatively moderate changes is the probable reason that the water temperature time series is a 25–year average and therefore already a relatively smooth curve as shown for an example in Fig. 7.2. Averaging over seven days, in addition, only smoothes the curve some more.

Variability from year to year

Another aspect of time variable stream temperatures is the variation from year to year. A twenty–five year average is a reliable indicator of mean conditions in the past and the future but individual years can produce stream temperatures much different from the mean as illustrated in Fig. 6.3. Fish temperature criteria were therefore also applied to exceptionally high and low stream temperatures. These were obtained by adding or subtracting σ (σ = the standard deviation of stream temperatures calculated as a 25–year daily average) to the previously used 25–year mean stream temperatures.

These extreme temperatures have a probability of occurrence on the order of once in six years which is a sufficient frequency to have a lasting impact on fish species distributions. The fish habitat variables SCL, GSL and R for these high (ave. + std. dev.) and low (ave.– std. dev.) stream temperatures are shown in Tables 7.6a and 7.6b for guilds. Values of the fish parameters are markedly different from those in Tables 7.2 and 7.3. The values are measures of the growth potential in extreme years and indicate that growth conditions in extreme years are markedly different from average years. If these extreme temperatures were retained to indicate the presence or absence of a species or guild through survival and growth potential values, one would obtain the fish presence summaries in Tables 7.7a to 7.7e. Fish species actually observed in these streams have been marked in Table 7.7 by frequency of observation, e.g. 5/21, or by a star. A star means that a least one fish of the indicated species was present during three or less surveys.

One interpretation of the results in Table 7.7 is that infrequent (1 in 6 years) high water temperatures eliminate a number of species which would survive in average years (e.g. in the Baptism River and the Clearwater River, Table 7.7b and 7.7c). On the other hand exceptionally warm years enhance growth potential of coolwater and warmwater fish in cold streams by 50 percent and more. Conversely, exceptionally cool years virtually eliminate good summer growth potential of warmwater fishes in cool streams such as the Straight River (Table 7.7a) and the Clearwater River (Table 7.7c). While these effects can be qualitatively anticipated, the data in Tables 7.7a to 7.7e provide a quantitative estimate of these effects. This analysis is for summer conditions. Winter effects are not included.

7.6. Sensitivity to shading and flow

Changes in *bank vegetation* in response to climate change may have a drastic effect on stream temperatures and fish through reduction of shading. Simulations and analysis were therefore conducted for reduced shading by trees and reduced stream flow. The results of the no–shading or shading reduction analysis are added in Tables 7.5a to 7.5d. "No shading" means that 100 percent of the solar radiation is applied.

Table 7.6a. Summary of main fish survival and growth parameters of three fish guilds in five streams under five climate scenarios. Based on 25–year daily extreme (average + one standard deviation) simulated water temperatures.

T(AVG+STD)

	FISH THERMAL GUILD	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
		SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
STRAIGHT R.	COLD	4	113	1.3	59	-11	-0.4	68	-21	-0.7	143	-61	-1.0	60	-17	-0.4
	COOL	0	103	104.0	0	69	69.0	0	82	82.0	28	46	-101.8	0	55	55.0
	WARM	0	65	66.0	0	40	40.0	0	65	65.0	12	134	34.0	0	35	35.0
BAPTISM R.	COLD	59	91	0.9	36	-4	-0.3	44	2	-0.3	109	-41	-0.7	34	-21	-0.4
	COOL	0	138	139.0	0	1	-134.6	2	7	-135.5	71	0	-137.4	1	-11	-135.7
	WARM	0	95	96.0	0	30	30.0	0	56	56.0	58	56	-93.1	0	39	39.0
CLEARWATER R.	COLD	55	84	0.8	45	-24	-0.4	39	2	-0.2	108	-38	-0.6	42	-31	-0.4
	COOL	0	133	134.0	0	-9	-131.3	0	10	-126.0	67	-16	-132.7	0	-22	-131.6
	WARM	0	95	96.0	0	49	49.0	0	33	33.0	59	46	-93.2	0	41	41.0
ZUMBRO R.	COLD	94	80	0.6	39	-32	-0.3	36	-16	-0.3	104	-38	-0.4	24	-25	-0.3
	COOL	0	158	22.7	26	-56	-21.6	35	-22	-21.0	93	-61	-22.0	33	-38	-21.0
	WARM	0	123	124.0	9	53	-35.5	14	61	-62.3	79	16	-122.1	5	28	-48.0
MISSISSIPPI R.	COLD	117	61	0.4	17	-15	-0.1	19	12	0.0	70	-12	-0.2	15	-2	0.0
	COOL	32	106	1.8	51	-10	-0.8	50	1	-0.7	84	-31	-1.3	51	-18	-0.9
	WARM	3	138	139.0	63	-16	-136.3	58	17	-131.6	101	-25	-137.8	63	-37	-137.3

Table 7.6b. Summary of main fish survival and growth parameters of three fish guilds in five streams under five climate scenarios. Based on 25–year daily extreme (average – one standard deviation) simulated water temperatures.

T(AVG-STD)

	FISH THERMAL GUILD	PAST			GISS-PAST			GFDL-PAST			UKMO-PAST			OSU-PAST		
		SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R	SCL	GSL	R
STRAIGHT R.	COLD	0	94	95.0	0	12	-90.5	0	36	-90.1	30	29	-93.5	0	13	-91.0
	COOL	0	10	11.0	0	43	43.0	0	47	47.0	0	97	97.0	0	44	44.0
	WARM	0	0	1.0	0	6	6.0	0	12	12.0	0	71	71.0	0	6	6.0
BAPTISM R.	COLD	0	103	3.9	1	13	2.1	4	24	2.1	55	4	1.0	2	-6	1.7
	COOL	0	53	54.0	0	23	77.0	0	36	90.0	0	93	73.5	0	30	84.0
	WARM	0	8	9.0	0	36	45.0	0	45	54.0	0	87	96.0	0	45	54.0
CLEARWATER R.	COLD	0	105	4.1	1	11	-2.0	0	-5	-2.3	59	0	-3.1	5	-26	-3.0
	COOL	0	49	50.0	0	27	27.0	0	32	32.0	0	85	-23.0	0	35	35.0
	WARM	0	6	7.0	0	38	38.0	0	37	37.0	0	88	88.0	0	49	49.0
ZUMBRO R.	COLD	0	99	1.7	31	-18	-1.0	37	-3	-0.8	81	-30	-1.2	36	-13	-0.8
	COOL	0	90	91.0	0	32	32.0	0	28	28.0	2	65	-85.4	0	16	16.0
	WARM	0	51	52.0	0	51	51.0	0	42	42.0	0	79	79.0	0	35	35.0
MISSISSIPPI R.	COLD	46	76	0.8	35	3	-0.1	35	2	-0.1	66	-11	-0.4	38	-9	-0.2
	COOL	0	111	112.0	0	10	-98.4	0	20	-85.6	43	6	-110.1	1	-2	-106.5
	WARM	0	86	87.0	0	19	19.0	0	22	22.0	27	46	-73.7	0	20	20.0

Table 7.7. Fish observation, survival and growth periods (GSL–days) of 32 fish species derived from simulated extreme low, average and extreme high stream temperatures.

Straight River :

		GSL (days)		
FISH	OBSERVED	(LOW TEMP.)^{a}	(AVG. TEMP.)^{b}	(HIGH TEMP.)^{c}
Brook Trout		121	140	▨
Brown Trout	22/22	106	138	116
Coho Salmon		83	136	131
Rainbow Trout	5/22	91	147	130
Lake Herring		94	121	113
Chinook Salmon		63	105	127
Chum Salmon		88	100	▨
Mountain Whitefish		94	121	113
Pink Salmon		94	156	▨
Lake Trout		71	93	81
Sockeye Salmon		91	111	107
Guild (Cold)		94	121	113
Northern Pike	8/32	53	93	165
Sauger		10	60	103
White Sucker	13/39	16	62	107
Yellow Perch	3/22	0	51	91
Walleye	1/22	0	40	90
Muskellunge		10	60	103
Black Crappie	2/7	10	60	103
White Crappie		10	60	103
Guild (Cool)		10	60	103
Smallmouth Bass		0	2	64
Brown Bullhead		0	51	91
Carp		0	8	65
Freshwater Drum		0	8	65
Gizzard Shad		0	8	65
Golden Shiner	1/22	0	8	65
Green Sunfish	1/22	0	8	65
White Bass		0	45	90
Lake Sturgeon		0	8	65
Rock Bass	2/22	0	8	65
Channel Catfish		0	0	27
Largemouth Bass	5/22	0	2	64
Bluegill	1/22	0	6	65
Guild (Warm)		0	8	65

Shaded boxes indicate uninhabitable conditions.

a : 25-year average of water temperatures minus standard deviation.

b : 25-year average of water temperatures.

c : 25-year average of water temperatures plus standard deviation.

Cont. (Table 7.7.)

Baptism River :

		GSL (days)		
FISH	OBSERVED	(LOW TEMP.)[a]	(AVG. TEMP.)[b]	(HIGH TEMP.)[c]
Brook Trout	1/7	126	▨	▨
Brown Trout	2/7	118	127	98
Coho Salmon		120	107	▨
Rainbow Trout	7/10	117	114	▨
Lake Herring		103	113	▨
Chinook Salmon	5/7	100	105	▨
Chum Salmon		76	▨	▨
Mountain Whitefish		103	113	▨
Pink Salmon		127	▨	▨
Lake Trout		74	76	▨
Sockeye Salmon		96	97	▨
Guild (Cold)		103	113	▨
Northern Pike		80	129	169
Sauger		53	91	138
White Sucker	2/7	54	95	142
Yellow Perch	3/7	35	76	119
Walleye		31	69	109
Muskellunge		53	91	138
Black Crappie		53	91	138
White Crappie		53	91	138
Guild (Cool)		53	91	138
Smallmouth Bass		2	54	92
Brown Bullhead		35	76	119
Carp		8	54	95
Freshwater Drum		8	54	95
Gizzard Shad		8	54	95
Golden Shiner		8	54	95
Green Sunfish		8	54	95
White Bass		31	71	113
Lake Sturgeon		8	54	95
Rock Bass		8	54	95
Channel Catfish		0	14	67
Largemouth Bass		2	54	93
Bluegill		4	54	95
Guild (Warm)		0	54	95

Shaded boxes indicate uninhabitable conditions.

a : 25-year average of water temperatures minus standard deviation.

b : 25-year average of water temperatures.

c : 25-year average of water temperatures plus standard deviation.

Cont. (Table 7.7.)

Clearwater River : GSL (days)

FISH	OBSERVED	(LOW TEMP.)[a]	(AVG. TEMP.)[b]	(HIGH TEMP.)[c]
Brook Trout		108	▨	▨
Brown Trout	11/13	114	101	93
Coho Salmon		113	101	▨
Rainbow Trout	11/13	121	99	▨
Lake Herring		105	90	▨
Chinook Salmon		99	106	▨
Chum Salmon		85	▨	▨
Mountain Whitefish		105	90	▨
Pink Salmon		130	▨	▨
Lake Trout		69	61	▨
Sockeye Salmon		99	88	▨
Guild (Cold)		105	90	▨
Northern Pike	5/18	82	130	158
Sauger		49	92	133
White Sucker	8/18	54	94	137
Yellow Perch	2/13	36	71	113
Walleye	3/18	30	69	102
Muskellunge		49	92	133
Black Crappie		49	92	133
White Crappie		49	92	133
Guild (Cool)		49	92	133
Smallmouth Bass		0	47	92
Brown Bullhead	1/13	36	71	113
Carp	1/13	6	55	95
Freshwater Drum	2/13	6	55	95
Gizzard Shad		6	55	95
Golden Shiner		6	55	95
Green Sunfish	1/13	6	55	95
White Bass		31	69	107
Lake Sturgeon		6	55	95
Rock Bass	6/18	6	55	95
Channel Catfish	2/13	0	11	64
Largemouth Bass		1	47	93
Bluegill	1/13	5	55	94
Guild (Warm)		6	55	95

Shaded boxes indicate uninhabitable conditions.
a : 25-year average of water temperatures minus standard deviation.
b : 25-year average of water temperatures.
c : 25-year average of water temperatures plus standard deviation.

Cont. (Table 7.7.)

Zumbro River :

		GSL (days)		
FISH	OBSERVED	(LOW TEMP.)[a]	(AVG. TEMP.)[b]	(HIGH TEMP.)[c]
Brook Trout		112	▨	▨
Brown Trout	1/50	114	99	▨
Coho Salmon		90	▨	▨
Rainbow Trout	4/50	102	▨	▨
Lake Herring		99	▨	▨
Chinook Salmon		102	▨	▨
Chum Salmon		68	▨	▨
Mountain Whitefish		99	▨	▨
Pink Salmon		120	▨	▨
Lake Trout		63	▨	▨
Sockeye Salmon		93	▨	▨
Guild (Cold)		99	▨	▨
Northern Pike	6/50	107	152	193
Sauger	17/50	90	119	158
White Sucker	16/67	92	119	▨
Yellow Perch	4/50	65	106	133
Walleye	14/54	58	101	128
Muskellunge		90	119	158
Black Crappie	15/50	90	119	158
White Crappie	10/50	90	119	158
Guild (Cool)		90	119	158
Smallmouth Bass	35/54	41	90	117
Brown Bullhead		65	106	141
Carp	11/50	51	92	123
Freshwater Drum	5/50	51	92	123
Gizzard Shad	2/50	51	92	123
Golden Shiner		51	92	123
Green Sunfish	5/50	51	92	123
White Bass	16/63	60	101	134
Lake Sturgeon		51	92	123
Rock Bass		51	92	123
Channel Catfish	16/63	2	55	98
Largemouth Bass	25/50	45	91	118
Bluegill	14/50	50	92	122
Guild (Warm)		51	92	123

Shaded boxes indicate uninhabitable conditions.
a : 25-year average of water temperatures minus standard deviation.
b : 25-year average of water temperatures.
c : 25-year average of water temperatures plus standard deviation.

Cont. (Table 7.7.)

Mississippi River :

FISH	OBSERVED	GSL (days) (LOW TEMP.)[a]	(AVG. TEMP.)[b]	(HIGH TEMP.)[c]
Brook Trout		▨	▨	▨
Brown Trout		79	▨	▨
Coho Salmon		▨	▨	▨
Rainbow Trout		▨	▨	▨
Lake Herring		▨	▨	▨
Chinook Salmon		▨	▨	▨
Chum Salmon		▨	▨	▨
Mountain Whitefish		▨	▨	▨
Pink Salmon		▨	▨	▨
Lake Trout		▨	▨	▨
Sockeye Salmon		▨	▨	▨
Guild (Cold)		▨	▨	▨
Northern Pike	*	135	158	136
Sauger		111	130	106
White Sucker	*	112	▨	▨
Yellow Perch	*	101	115	▨
Walleye	*	98	115	▨
Muskellunge		111	130	▨
Black Crappie	*	111	130	106
White Crappie		111	130	106
Guild (Cool)		111	130	▨
Smallmouth Bass	*	82	111	▨
Brown Bullhead		101	127	▨
Carp	*	86	118	138
Freshwater Drum		86	118	138
Gizzard Shad		86	118	138
Golden Shiner		86	118	▨
Green Sunfish		86	118	138
White Bass		98	126	110
Lake Sturgeon		86	118	138
Rock Bass	*	86	118	▨
Channel Catfish		56	118	123
Largemouth Bass	*	82	111	135
Bluegill	*	85	116	135
Guild (Warm)		86	118	138

* designates species collected from river reach modelled

a : 25-year average of water temperatures minus standard deviation.

b : 25-year average of water temperatures.

c : 25-year average of water temperatures plus standard deviation.

The results in Table 7.5 indicate that if trees along the banks of Minnesota streams are eliminated in conjunction with climate change, cold and coolwater fish will be very adversely affected:

(1) Coldwater fish will be eliminated in free flowing streams. They will find adequate water temperatures only near sources of groundwater (seepage banks) or coldwater releases from hypolimnia of deep reservoirs.

(2) All coolwater fish will also be threatened by elimination in the southern region of the state and some coolwater species will be threatened by elimination in the north.

(3) The species distribution in streams will become more similar to that in the mainstem of the Mississippi River.

Changes in *stream flow* are also very likely to occur with climate change. Stream temperatures in free flowing long streams will not be much affected by this as shown in Table 7.8. Most affected by flow rates will be the length of coldwater stream reaches, but stream reaches downstream from lake outlets and dams will also be affected. These effects will be discussed later. The analysis in this chapter is for free flowing streams only.

7.7. Validation of projections for fish presence

Projections of fish presence and growth potential under future climate scenarios are difficult if not impossible to validate, but fish surveys can be compared with simulation results for past climate conditions. Tables 7.5a to 7.5e provide such comparisons. It can be seen that agreement is very reasonable. Exceptions for coldwater fishes are found in the Baptism River for brook trout (1/7 i.e. caught in 1 of 7 surveys), Zumbro for rainbow trout (4/50). In the Mississippi River, white sucker was observed where simulations indicated that it could not be present. Those are the only three disagreements for streams. All other observations agree with model predictions. This is considered satisfactory or good. In addition, the trout observations may be the result of stocking or migration from upstream, colder tributaries.

Possible reasons for some disagreement between simulated and actually observed coldwater fish presence include the following:

(1) Fish collections may not have covered the same time period as the simulations (1955–1979).

(2) The water temperature criterion for fish presence or absence is subjectively chosen to be the upper 95% FTDMS temperature value. Fish can resist stressful temperatures for awhile and not be lost from the system, i.e. lethal temperatures are 2–3°C higher than the distribution limits.

Table 7.8. Effect of stream flow reduction to 50% of past values on fish parameters under $2xCO_2$ GISS climate scenario. (for acronyms see page v)

STREAM	FISH GUILD	SCL (days)			GSL (days)			GZERO (days)		
		min.	ave.	max.	min.	ave.	max.	min.	ave.	max.
STRAIGHT R.	COLD	-4	-2	0	-3	2	2	-1	2	3
	COOL	0	0	0	-1	0	3	0	0	0
	WARM	0	0	0	-4	3	4	0	0	0
BAPTISM R.	COLD	1	3	7	-12	3	0	2	5	14
	COOL	0	0	0	1	10	15	0	0	0
	WARM	0	0	0	1	5	8	0	0	0
ZUMBRO R.	COLD	0	2	7	-12	-2	4	2	5	13
	COOL	0	0	4	-5	0	4	3	3	6
	WARM	0	0	3	1	5	8	0	0	0
MISSISSIPPI R.	COLD	-1	0	3	-2	1	4	-2	1	1
	COOL	0	2	3	-4	-3	-1	1	3	5
	WARM	0	3	6	-2	-1	5	-3	0	3

(3) This temperature criterion is applied to the maximum of water temperatures averaged over 25 years. It is conceivable that fish presence and distribution is in response to water temperatures which occur less frequently.

(4) Stocking of streams with game fish species biases fish survey results.

(5) Refuges in areas of groundwater inflows/springs or downstream from reservoir outlets can provide cooler local habitat than free–flowing stream reaches unaffected by these local anomalies.

(6) Migration in streams with tributaries.

(7) Different thermal critical (i.e. UZNG) may give different predictions of fish distribution limits than used herein.

It has been shown that the model used herein is reasonable to determine fish presence. The model can probably be somewhat refined by incorporating water temperature fluctuations in addition to long–term averages. It is conceivable that fish presence or absence is in response to water temperature which occur at intervals of several years rather than in response to 25 year average conditions. As shown herein, the use of 25–year average temperatures leads to good predictions of fish presence for past conditions. It is extrapolated that it will do that also for future climate conditions. The authors believe that the uncertainty in climate scenarios is greater than that of the fish response model to temperature.

7.8. Conclusions

(1) The sensitivity of fishes to environmental temperature and parameters which are meaningful to characterize fish habitat have been derived from field and laboratory data banks. The parameters used herein define water temperature values for (a) survival, (b) good growth potential, and (c) restricted growth potential for different species or guilds of fishes. No claim is made that definition of the parameters used herein is optimal. The parameters used are, however, founded on large data bases and sound theoretical concepts and are considered to be meaningful and useful.

(2) Fish survival and growth parameters can be determined for long–time series of simulated water temperatures and dissolved oxygen under both past and future climate scenarios. Interpretation of these computed parameters indicates (a) which fish species or guilds will be threatened with extinction, (b) which others will become potential invaders, and (c) if the growth potential of a given species or guild increases or decreases.

(3) Further analysis of the survival and growth potential parameters indicates which stream characteristics cause most or least change for fishes and leads to the identification of management options for the mitigation of or adaptation to undesirable effects.

(4) Coldwater fish will be all but eliminated from free flowing streams, except those in the north which have and can maintain strong shading (40% or better). Streams with significant groundwater input or fed by water releases from deep reservoirs can continue to sustain coldwater fish if the streams maintain shading and if the cool reservoir and/or groundwater releases can be maintained throughout the summer.

(5) Coolwater fish will be eliminated from the Mississippi River in its central Minnesota reach (Anoka, MN and below), but will find improved growth potential in cold streams due to more shading. The extreme climate scenario (UKMO) predicts that even coolwater fish will be eliminated from all but the most shaded streams. Certain species or all of the coolwater fishes will also be eliminated from a great many streams which now carry them if riparian vegetation is lost. This is the case for the southern streams, such as the Zumbro River, which is projected to lose all coolwater fishes as well as the Straight River, which will lose walleye and yellow perch.

(6) Warmwater fishes will have unchanged growth conditions in the Mississippi River and improved ones in more shaded streams.

(7) If riparian shading trees are lost, species habitation in southern Minnesota streams will become similar to that currently found in the mainstem of the Mississippi River, which is a warmwater fishery. Riparian vegetation is vulnerable to loss as the potential for agriculture is moved northward due to global climate change. With intensive agriculture possibly advancing into areas now too cool for agriculture, demands for plowing up to the banks of streams and rivers now running through forested lands will increase and shading can be expected to diminish.

8. UPSTREAM BOUNDARY AND GROUNDWATER INFLOW EFFECTS ON STREAM WATER TEMPERATURES AND FISHES

8.1. Introduction

Stream water temperatures depend on the source of stream water. A stream can receive its water from one or more of the following: spring, reservoir (impoundment), lake, wetland, groundwater, tributary, overland flow and precipitation. These different sources will likely have different stream water temperatures.

So far, in this study, freely flowing (uniform) streams were considered. Freely flowing streams have temperatures independent of the upstream boundary conditions. Such a scenario requires a fairly long stream reach, typically of several miles length, and it does not describe the stream temperatures in tailwaters downstream from a dam, lake or spring. Effects of such upstream boundary conditions are considered in this chapter. The main upstream boundary conditions studied are (1) a reservoir or lake release and (2) groundwater inflow. In addition, the effect of lateral inflow of groundwater on stream water temperatures is studied because groundwater provides baseflow and moderates the effect of seasonal air temperature fluctuations in temperate climates (Ward, 1985). Groundwater discharge areas provide relatively stable thermal environments for developing fish eggs and fry and inhibit the formation of anchor ice (Needham and Jones, 1959). Anchor ice can cause high mortalities in post–emergent trout (Benson, 1953).

8.2. Reservoir release

Water temperatures of reservoir releases are known to vary widely depending on the depth from which the water is released, because reservoirs, especially deep ones, stratify thermally. Epilimnetic and hypolimnetic releases of lake water were studied as upstream boundary conditions. Epilimnetic (surface) water releases from a reservoir are usually warm and follow air temperatures and solar inputs closely. Hypolimnetic (submerged) water releases are usually cold, without diurnal fluctuations and small seasonal gradients. A one–dimensional, unsteady (daily timestep) lake and reservoir water temperature stratification model (Hondzo and Stefan, 1992) provided the water temperatures which were used as upstream boundary conditions for the stream water temperature model predictions. 25–year averages of daily water temperatures for a lake with 1.7 km^2 surface area and 13 m maximum depth were used. This is a median type lake within a classification scheme of 3002 Minnesota lakes (Stefan et al., 1991). The lake water temperatures were calculated using past records of weather data from either Minneapolis/St. Paul or Duluth, MN, depending on the location of the stream into which it discharged. Lake water temperatures were also calculated for the GISS ($2xCO_2$) climate scenario to study the effects of global climate change on stream water temperatures and stream fish habitat.

8.3. Groundwater release

Two groundwater release scenarios were considered. In the first (extreme) scenario, the entire stream flow was assumed to be of groundwater origin at the upstream end of the stream reach. The upstream boundary condition, in this case, is the temperature of groundwater.

Groundwater temperatures can be assumed equal to the temperatures of the geological formation from which the groundwater is originating. The seasonal fluctuation in ground temperature decreases with increasing depth (Meisner et al., 1988) until it remains constant, with no seasonal variation, below approximately 10m in Minnesota. This depth is known as the neutral zone (Mathess, 1982). Groundwater temperatures at the neutral depth can be estimated by adding 1–2 °C to the mean annual air temperature (Collins, 1925; Heath, 1964). Figure 8.1 shows the temperatures of groundwater, at the neutral zone, for the United States. The groundwater temperatures shown on the map should be corrected by adding 1–2 °C for the regions with continuous winter snow cover such as Minnesota (Meisner et al., 1988). Accordingly, a constant groundwater temperature of 7 °C was used in the simulations of stream water temperatures for historical (1953–1979) weather conditions. This agrees with Fig. 8.1 and with the measured groundwater temperatures at the Straight River (Stark, 1989). To study the anticipated effects of global climate change, the groundwater temperature was adjusted by the projected increase in average annual air temperature. The adjusted groundwater temperature under the GISS ($2xCO_2$) scenario was 10.4 °C and it was used in the simulations as the projected future upstream boundary condition.

The second scenario represents, perhaps, a more typical situation than the stream starting at a single source. Only 50% of the groundwater with 7 °C (past) or 10.4 °C (future) temperature is released at the upstream boundary. The remaining 50% of the total stream flow is assumed to be of groundwater origin too, but is distributed uniformly as a line source over the first 10 miles of the 40 mile stream reach investigated.

8.4. Stream water temperature results

The two upstream reservoir release scenarios were applied to four of the five selected streams: the Straight River, the Baptism River, the Clearwater River and the Zumbro River. The first groundwater release scenario was applied to the Straight and the Baptism Rivers while the second groundwater release scenario was applied to the Straight River only. These boundary conditions might not reflect the exact actual boundary conditions which exist on each of these streams but can serve nevertheless to explain some of the thermal characteristics of Minnesota streams because some of them have reservoirs (lakes) further upstream (e.g. the Straight River and the Zumbro River). Table 8.1 gives a summary of the different upstream boundary conditions studied. Figures 8.2 and 8.3 give the upstream water temperatures used as input in the model simulations. Model outputs are presented in the form of isotherm plots (Figs. 8.4, 8.5, 8.6 and 8.7). Isotherms are plotted in a distance versus time coordinate system to show variations throughout a season. Stream water temperatures using a lake epilimnetic release can either

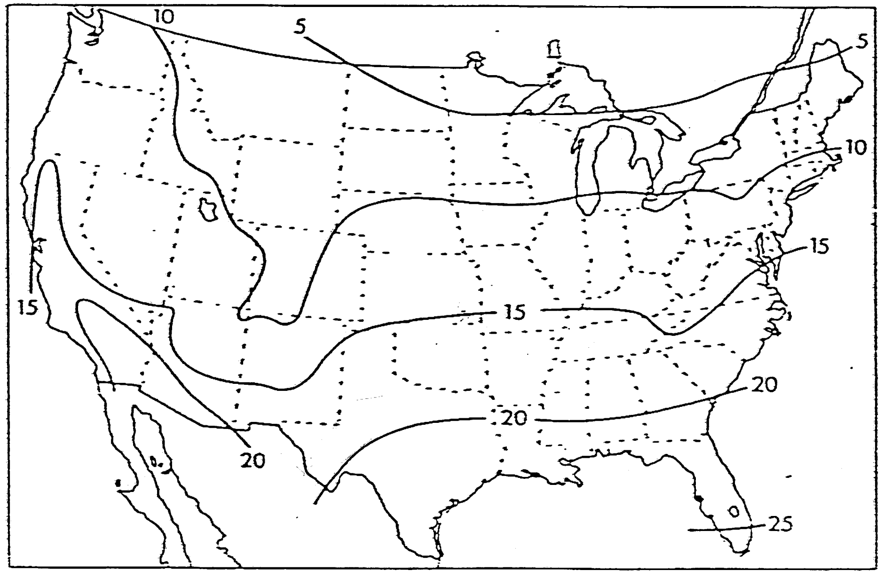


Figure 8.1. Approximate temperature (° C) of groundwater in the United States (from Todd 1980 after Collins 1925).

Table 8.1. Summary of upstream inflow scenarios.

STREAM	CLIMATE							
	PAST				GISS			
	Upstream boundary scenario							
	1	2	3	4	1	2	3	4
Straight	X	X	Y	X	X	X	Y	X
Baptism	X	Y	Y	▨	X	Y	Y	▨
Clearwater	X	Y	▨	▨	X	Y	▨	▨
Zumbro	X	X	▨	▨	X	X	▨	▨

Scenario 1: Upstream inflow from a lake epilimnion.
Scenario 2: Upstream inflow from a lake hypolimnion.
Scenario 3: Upstream inflow from a spring (groundwater).
Scenario 4: Upstream and lateral inflow form groundwater.
Note: Shaded boxes indicate no simulation.
X: Scenario might represent actual (existing) conditions.
Y: Hypothetical scenario.

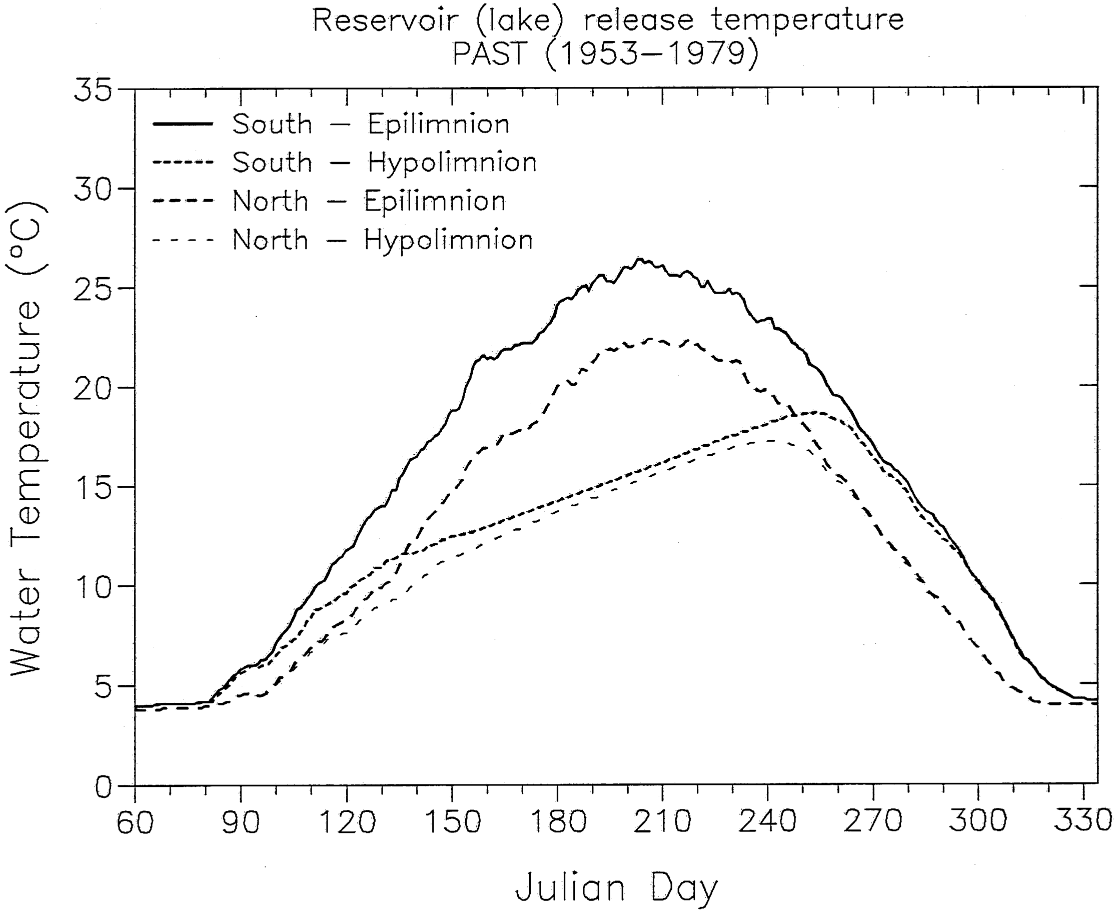


Figure 8.2. Temperature of a medium surface area and a medium average depth lake under past weather conditions.

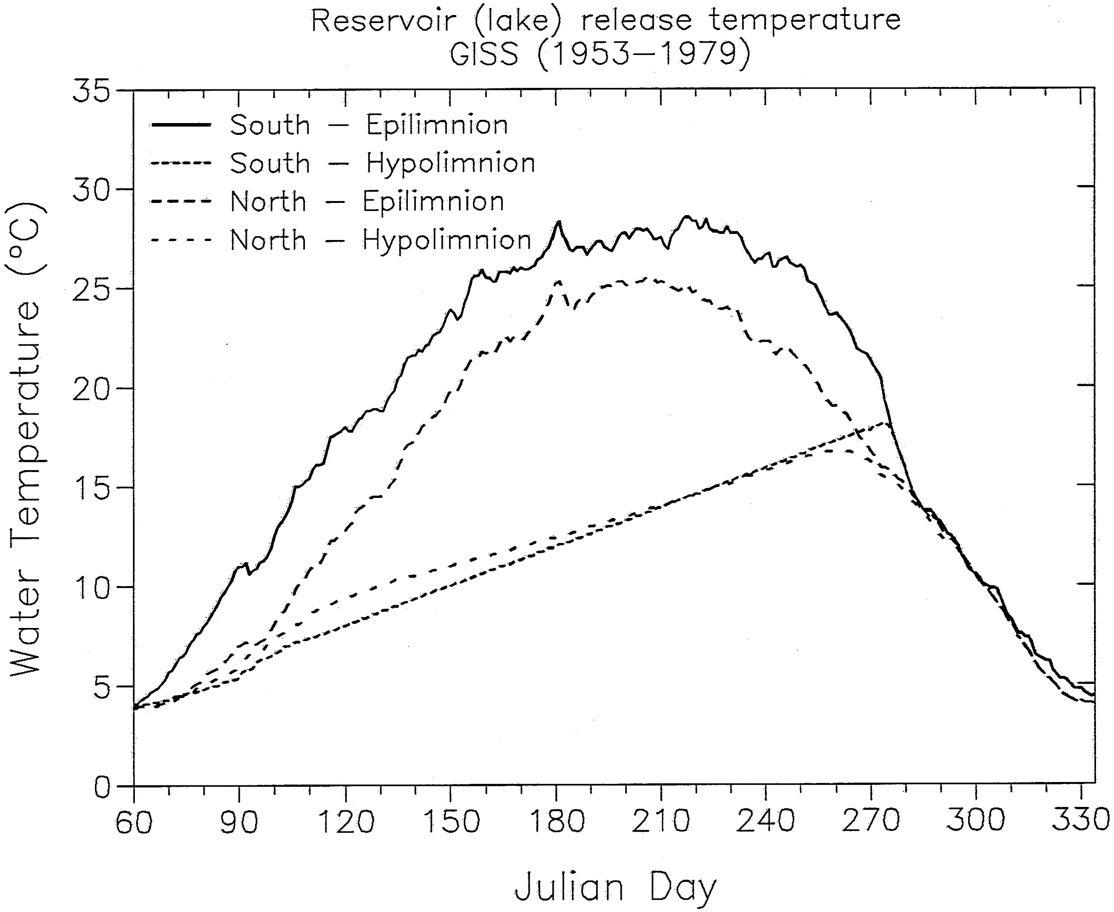
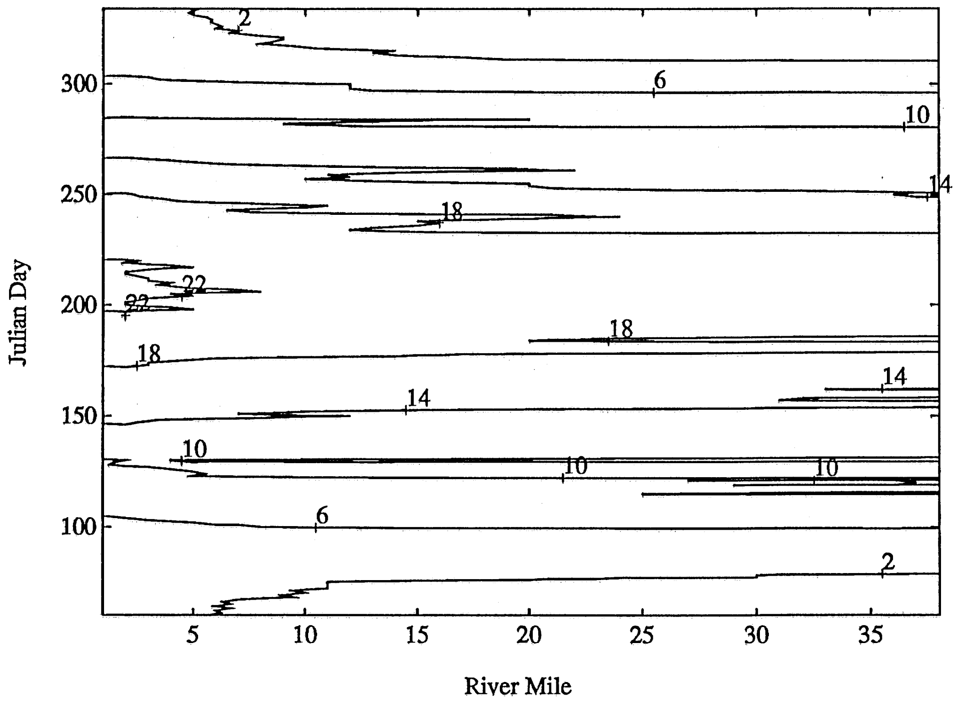


Figure 8.3. Temperature of a medium surface area and a medium average depth lake under future (GISS) weather conditions.

Straight River : Epilimnion Release (PAST)



Straight River : Epilimnion Release (GISS)

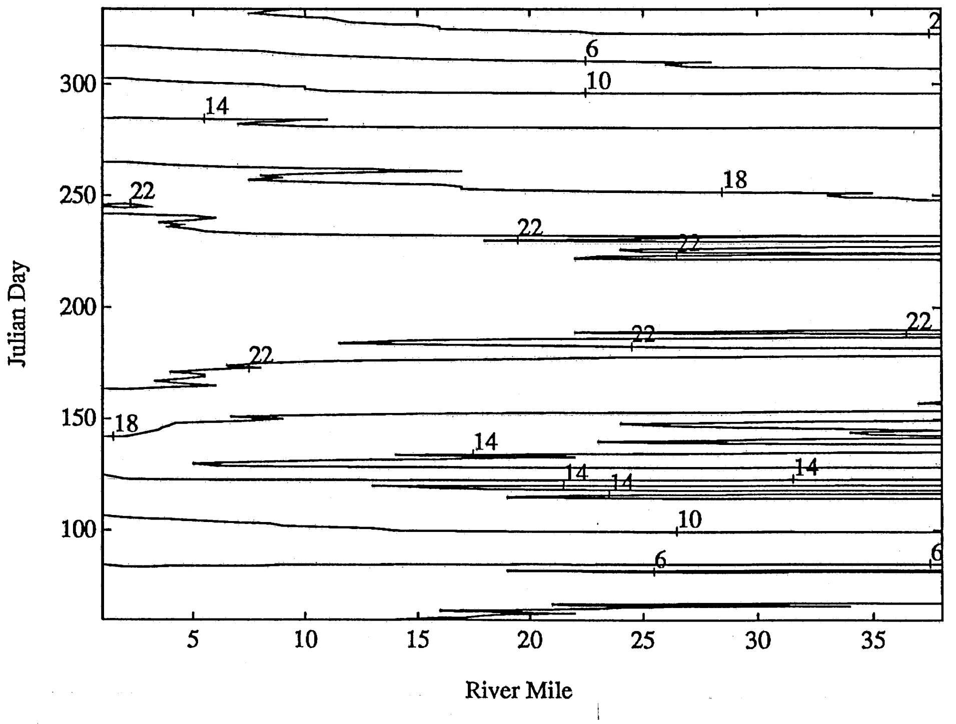
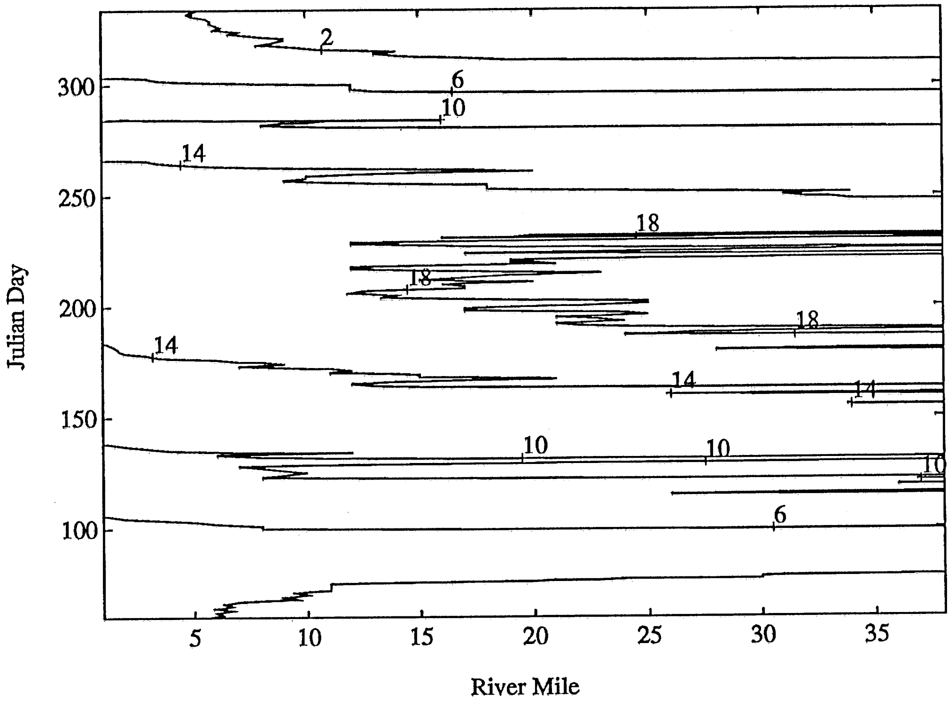
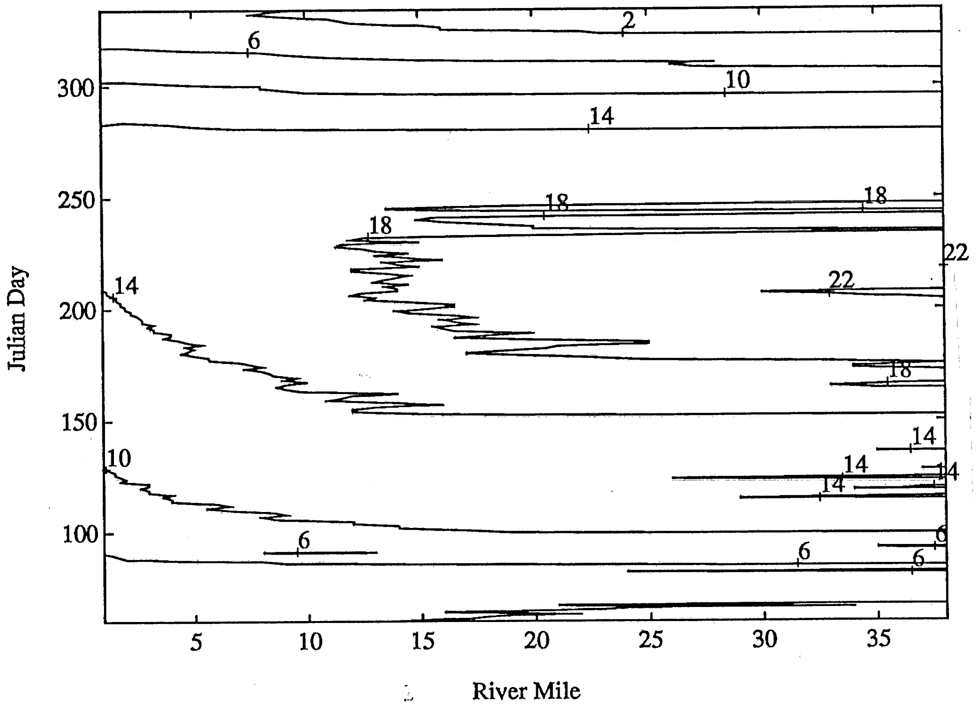
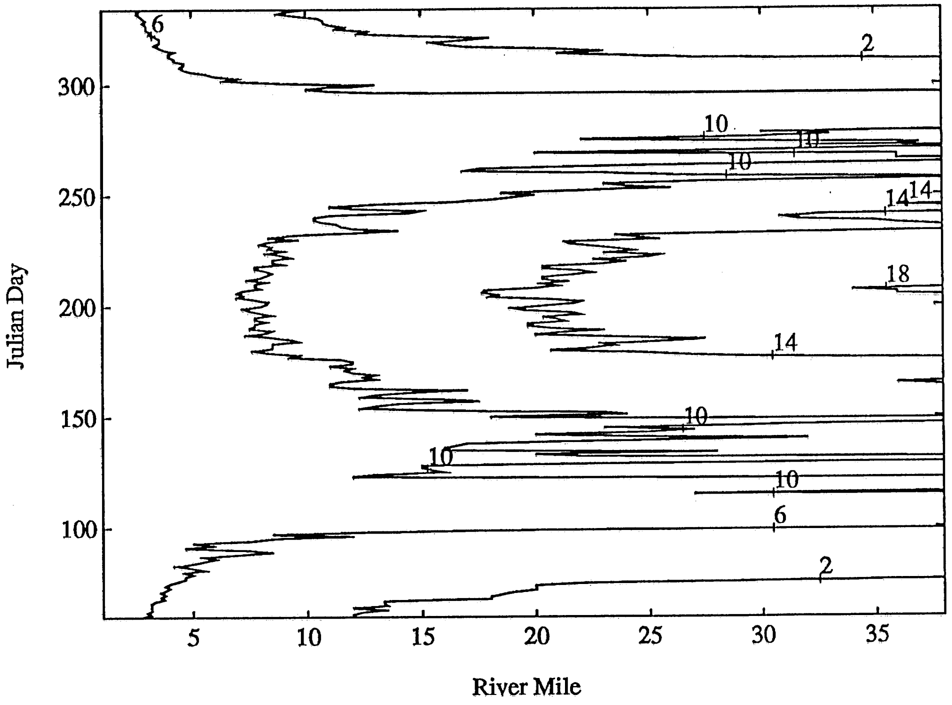
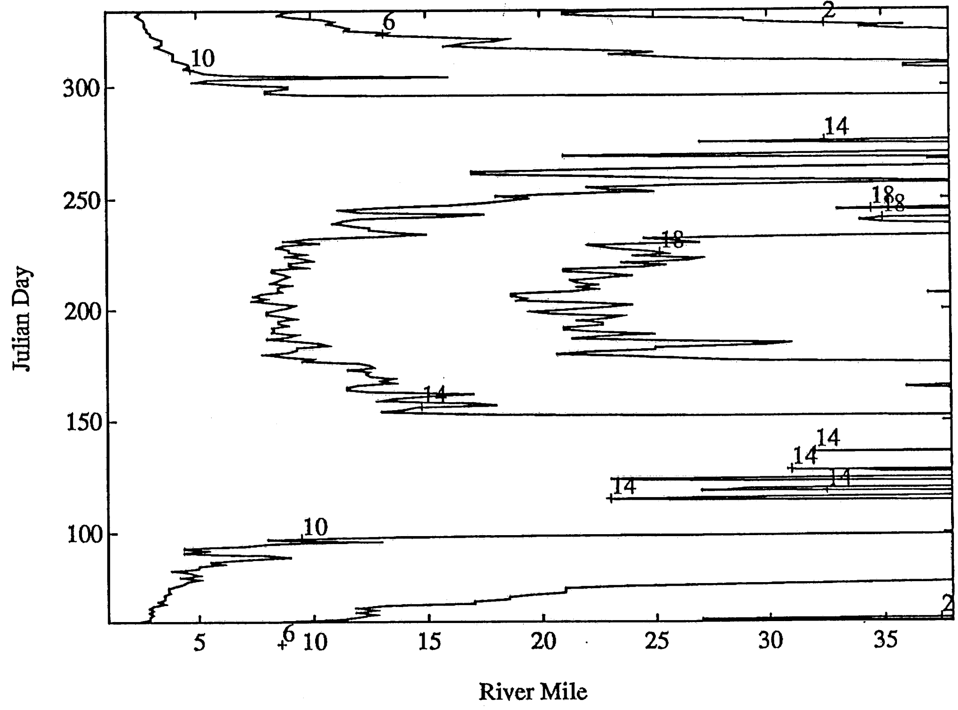


Figure 8.4. Straight River isotherms under different upstream boundary conditions.

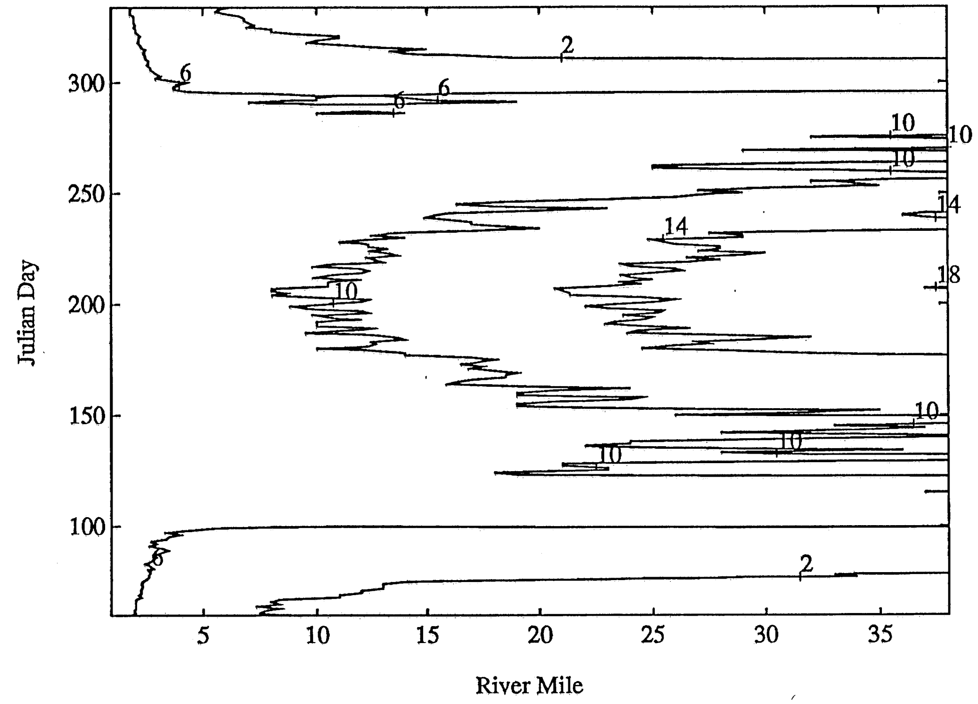

Straight River : Hypolimnion Release (PAST)


Straight River : Hypolimnion Release (GISS)

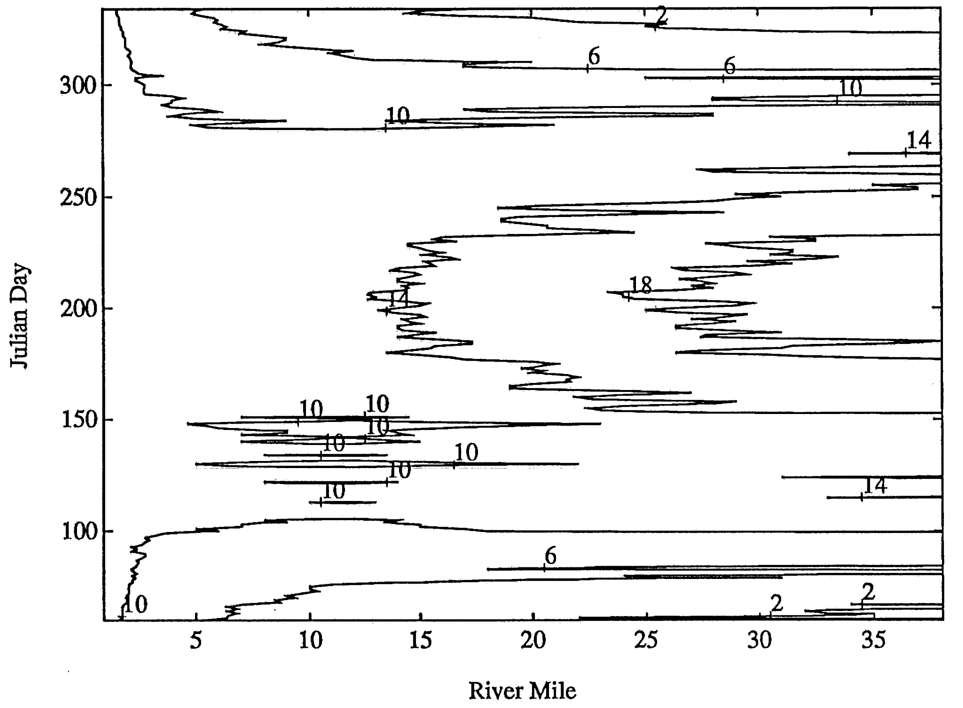

Straight River : Upstream Groundwater Inflow (PAST)


Straight River : Upstream Groundwater Inflow (GISS)

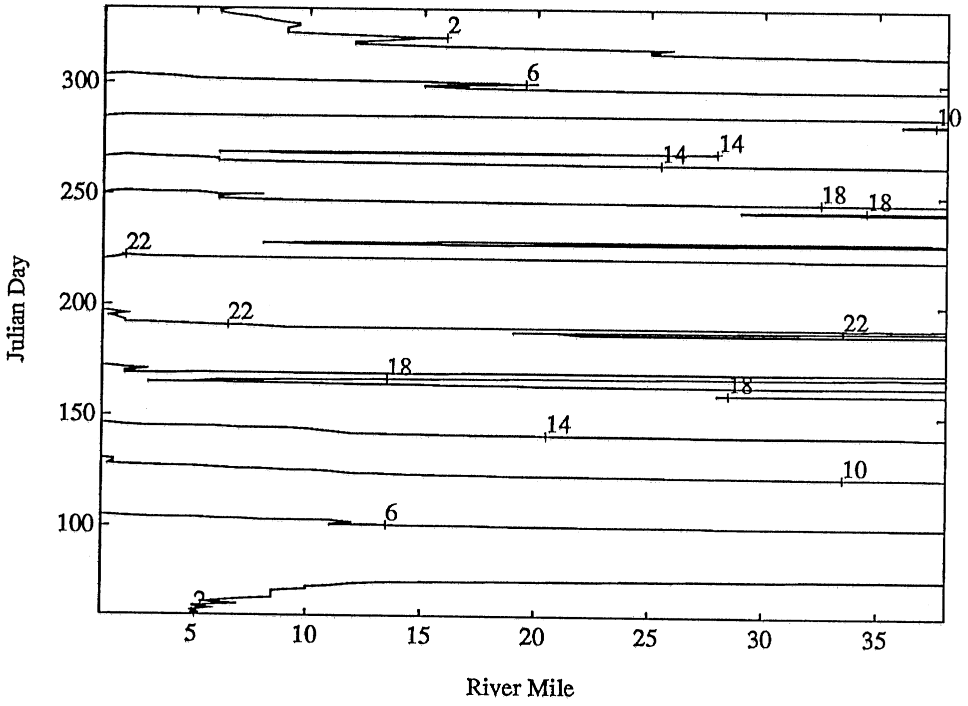
Straight River : Upstream and Lateral Groundwater Inflow (PAST)



Straight River : Upstream and Lateral Groundwater Inflow (GISS)



Baptism River : Epilimnion Release (PAST)



Baptism River : Epilimnion Release (GISS)

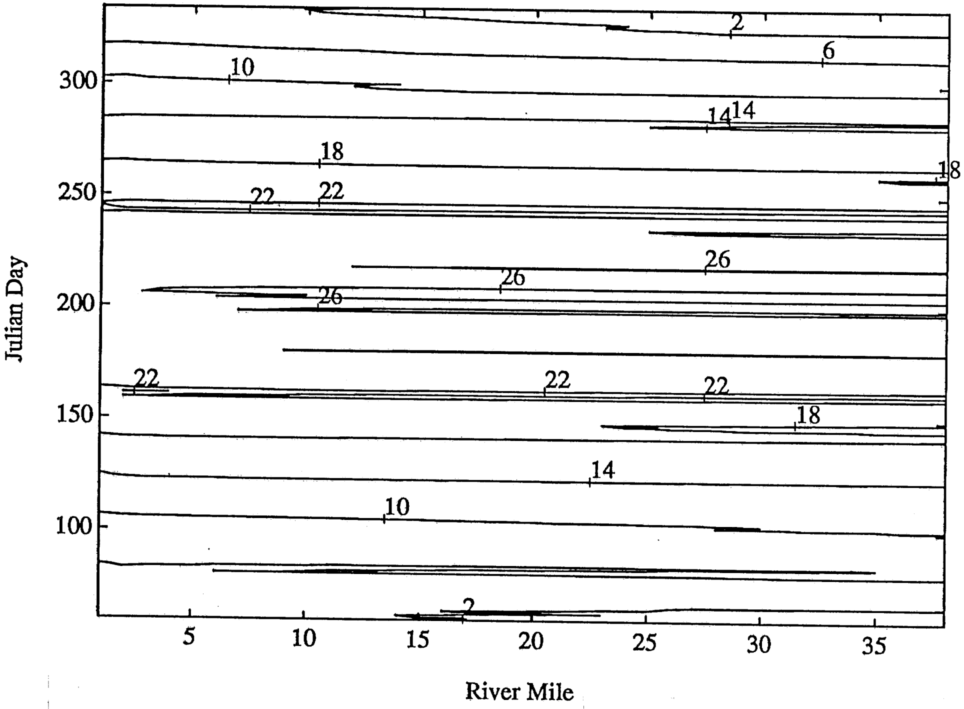
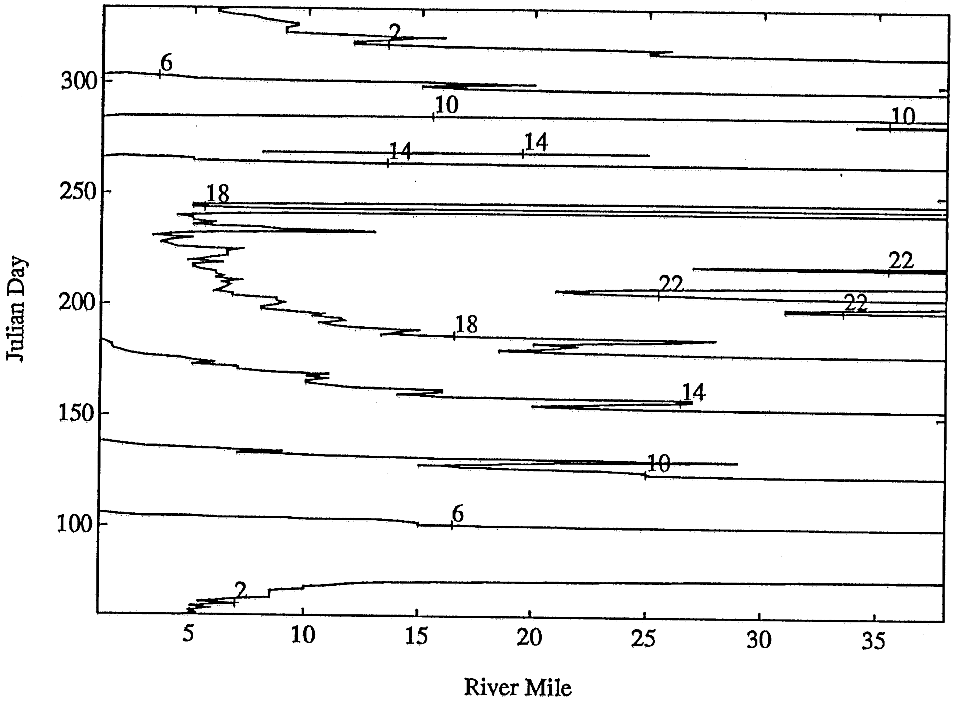
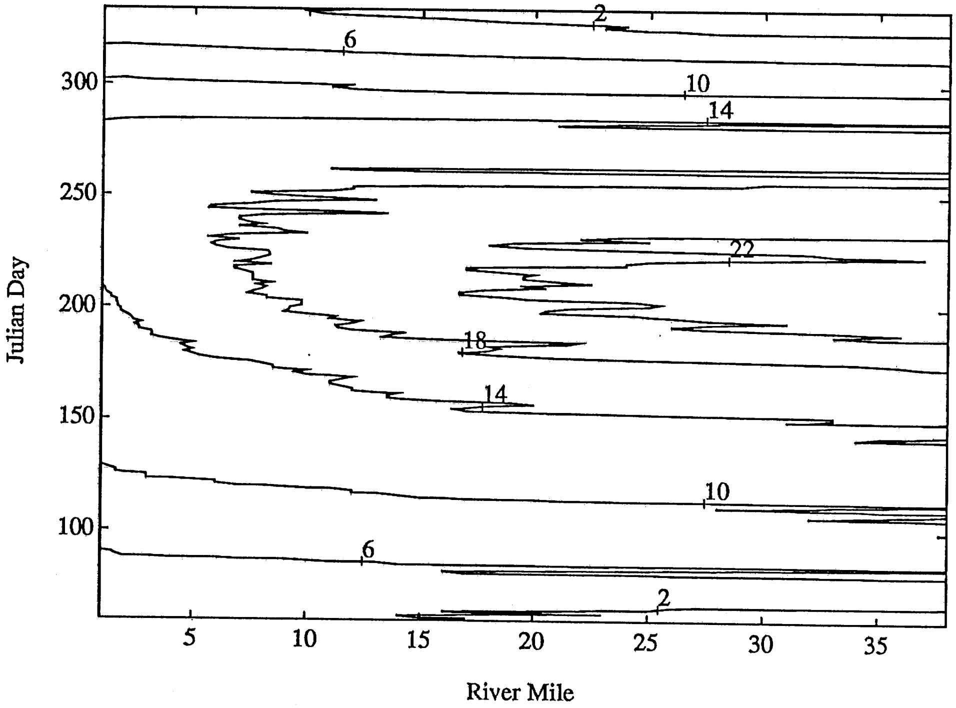


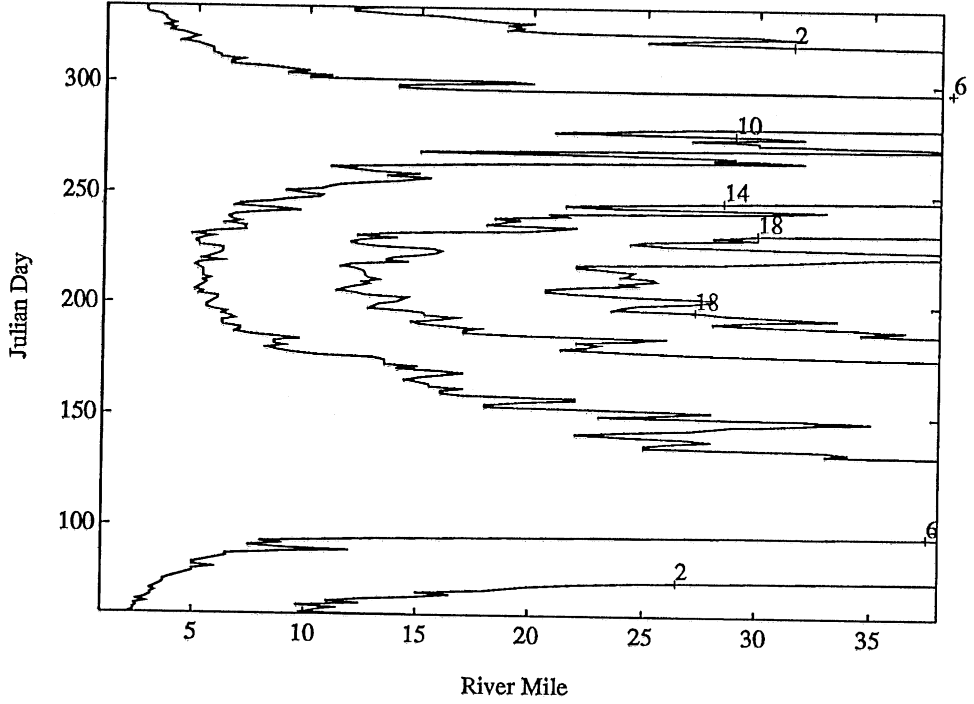
Figure 8.5. Baptism River isotherms under different upstream boundary conditions.

Baptism River : Hypolimnion Release (PAST)

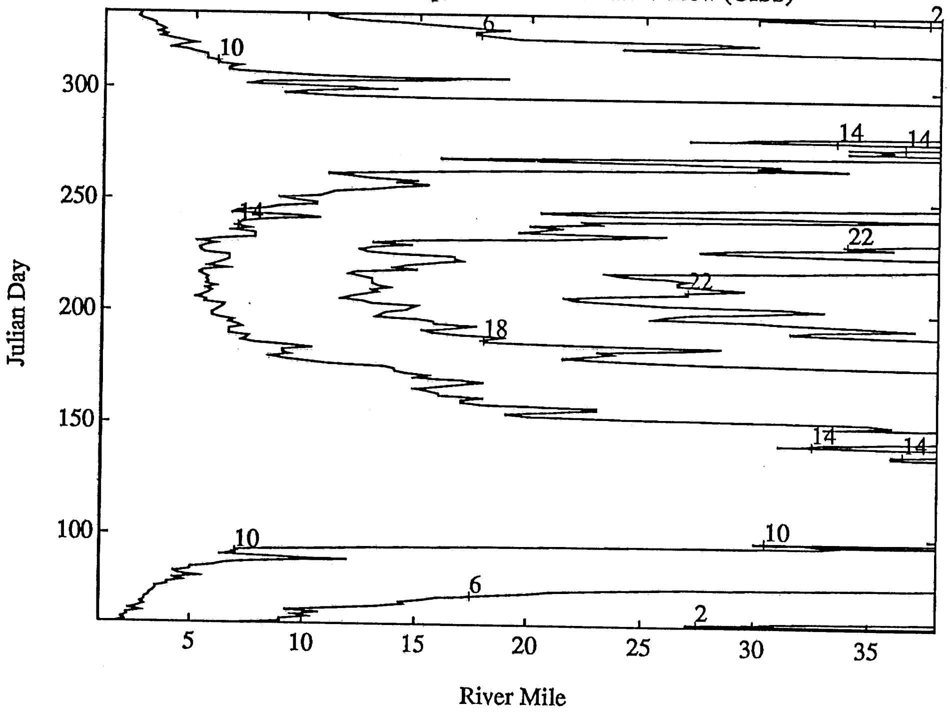


Baptism River : Hypolimnion Release (GISS)



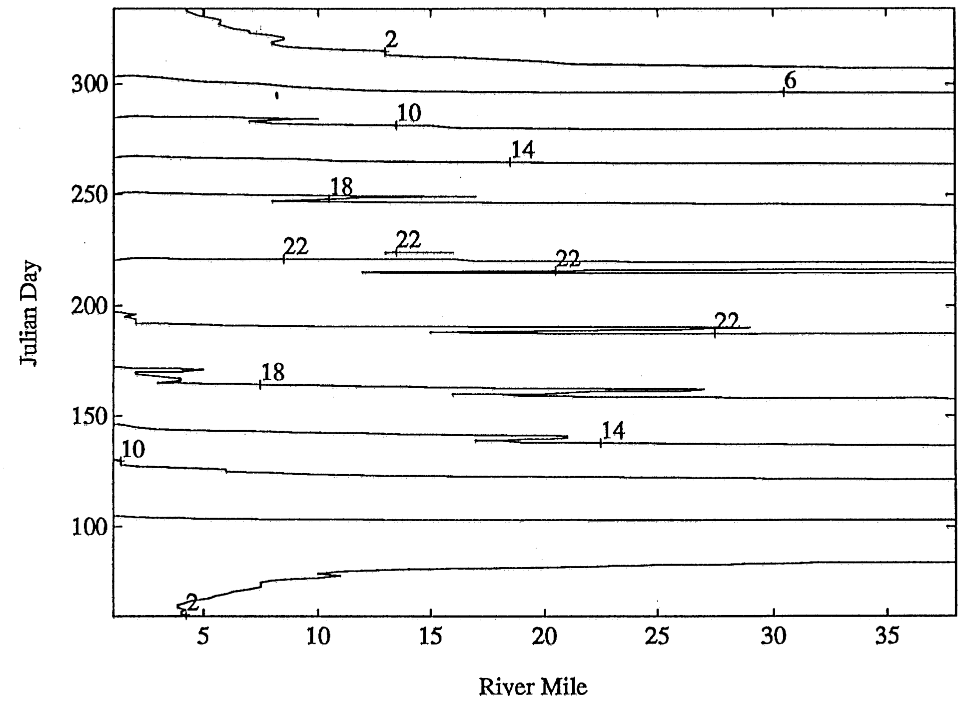


Baptism River : Upstream Groundwater Inflow (PAST)



Baptism River : Upstream Groundwater Inflow (GISS)

Clearwater River : Epilimnion Release (PAST)



Clearwater River : Epilimnion Release (GISS)

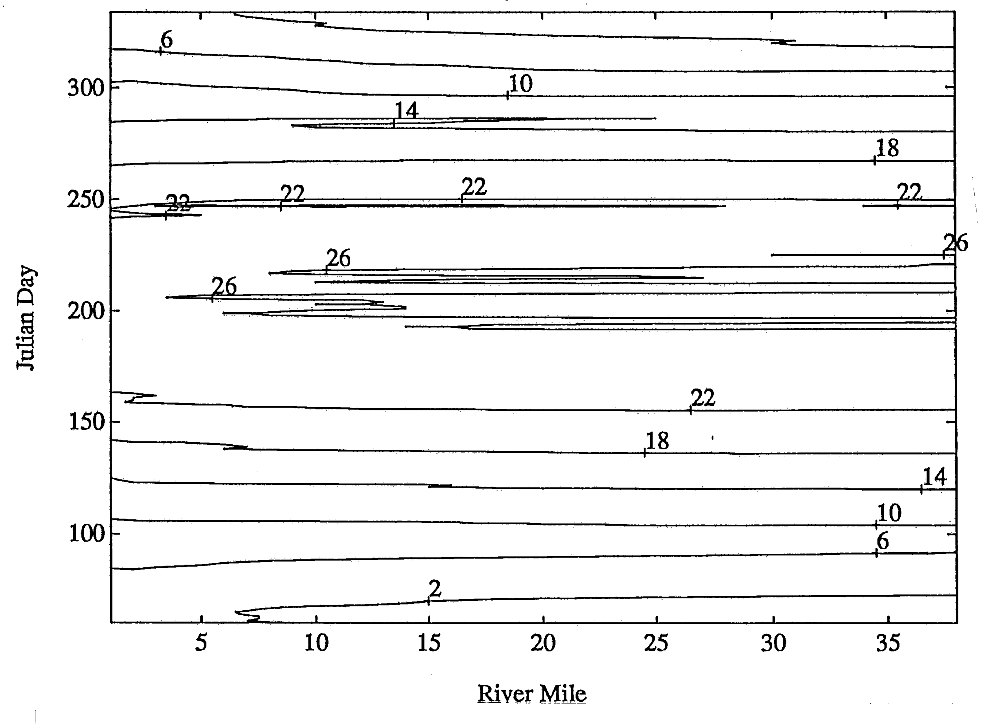
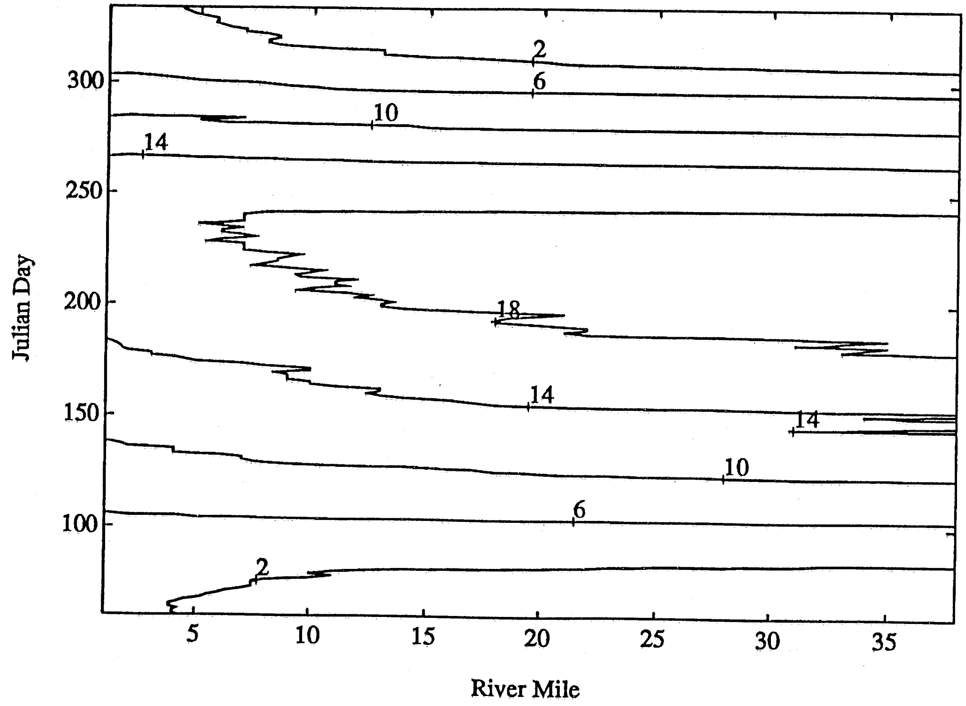
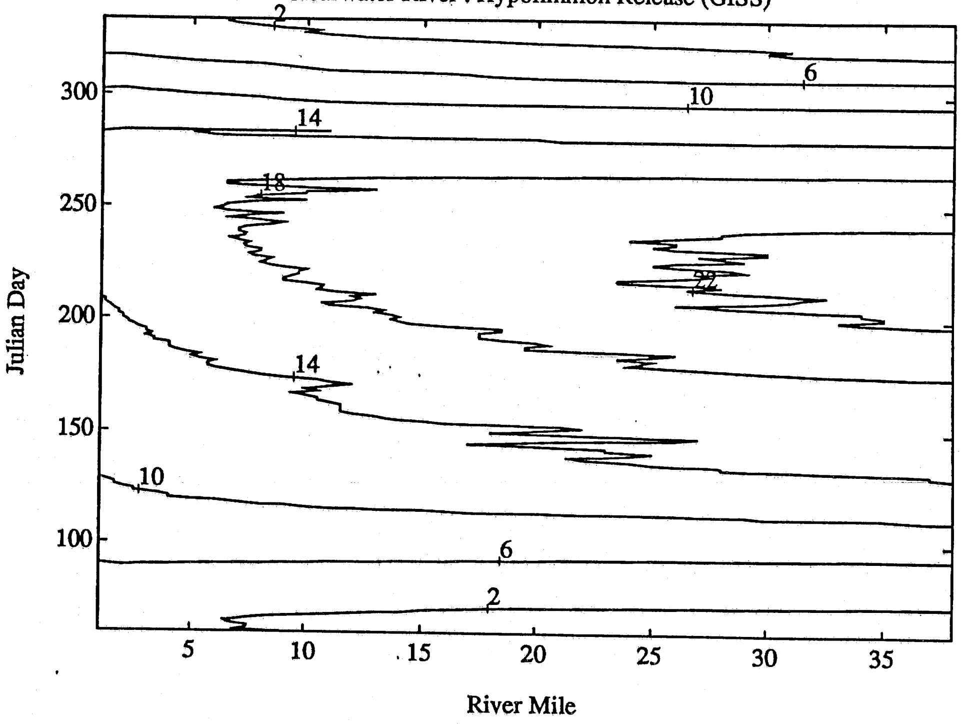


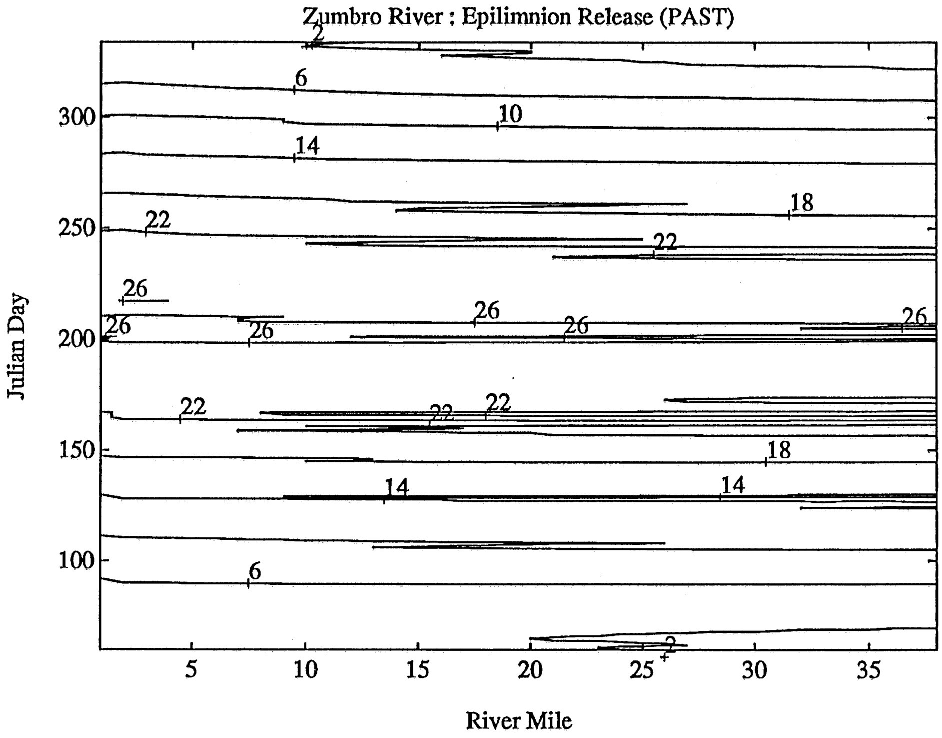
Figure 8.6. Clearwater River isotherms under different upstream boundary conditions.

Clearwater River : Hypolimnion Release (PAST)



Clearwater River : Hypolimnion Release (GISS)





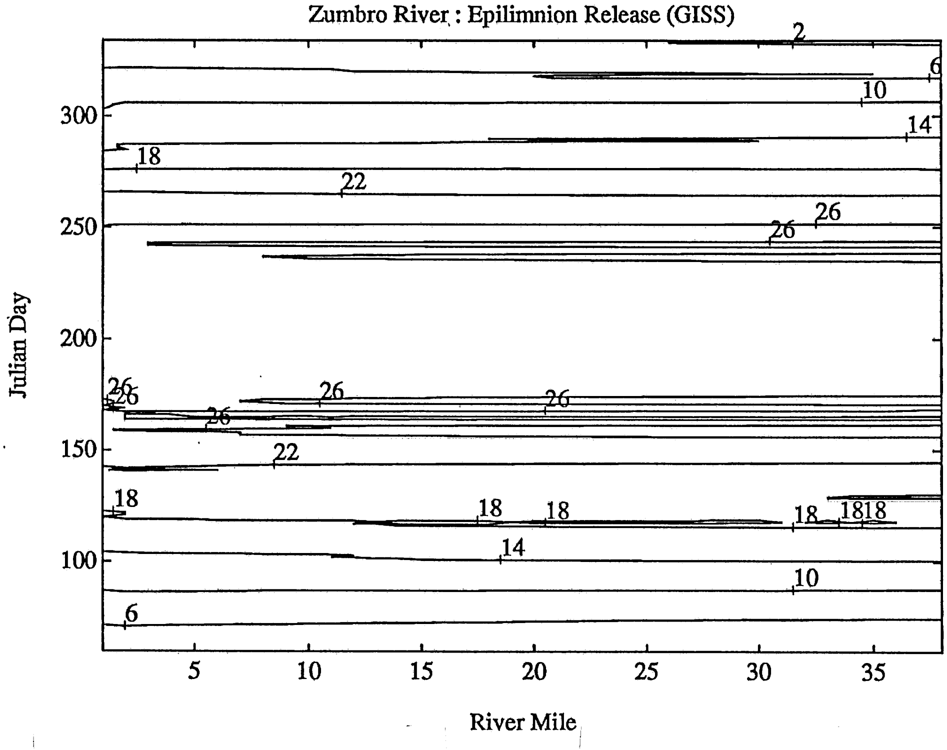
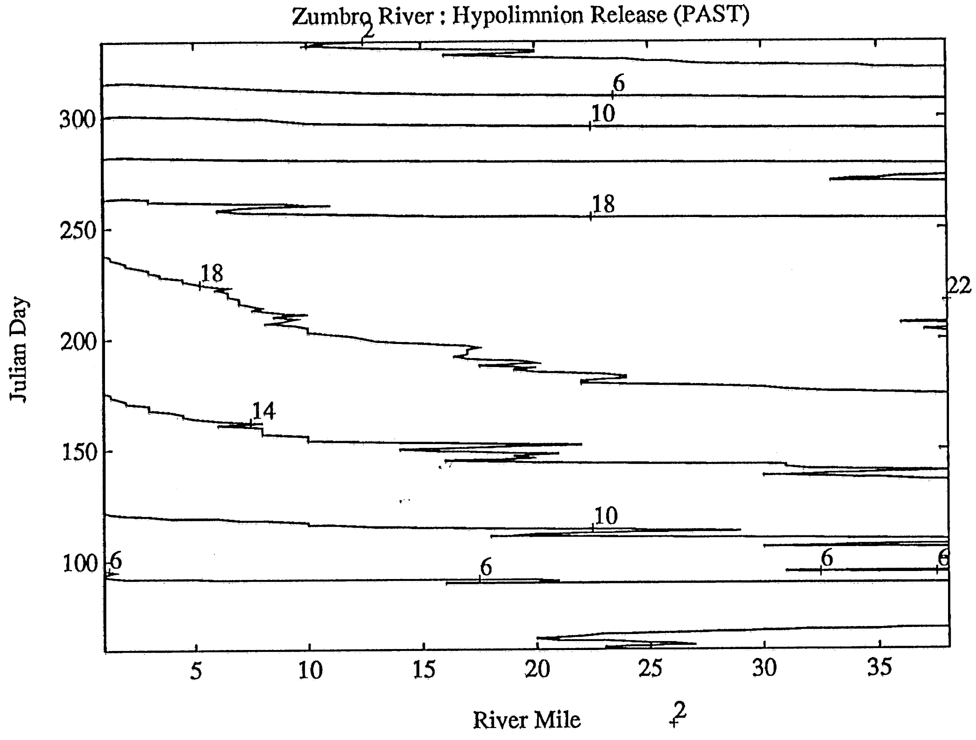
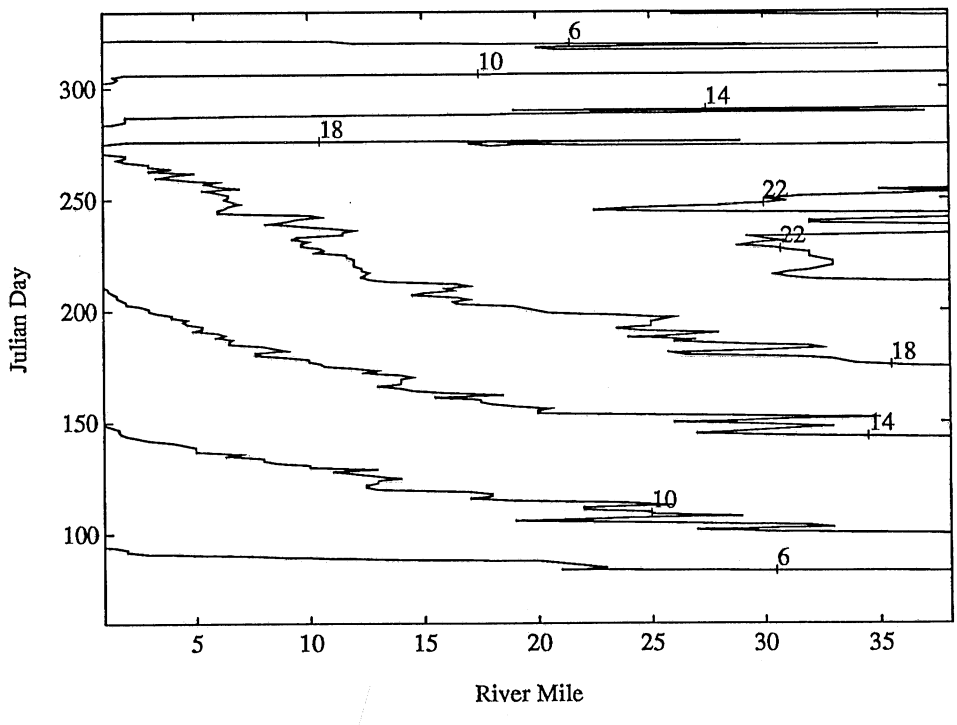


Figure 8.7. Zumbro River isotherms under different upstream boundary conditions.

Zumbro River : Hypolimnion Release (PAST)



Zumbro River ; Hypolimnion Release (GISS)



warm up, stay unchanged, or get colder (Figs. 8.4a through 8.7a). This behavior is directly dependent on the percentage of stream shading. The graphs show that stream water temperatures warm up in the downstream direction if the upstream release is from the hypolimnion of a reservoir (lake) or from groundwater (Figs. 8.4b,c,d through 8.7b). For all upstream boundary conditions studied, stream water temperatures, as expected, approach those of the freely flowing stream as the water travels downstream.

8.5. Implications for stream fisheries

The simulated stream water temperatures were used to study the effects of different upstream boundary conditions and the effects of global climate change on fish survival. A fish species can not survive in a stream if the water temperature exceeds a limit for a period of time, chosen to be seven or more days.

An inhabitable stream reach length for 32 different fish species was calculated for each of the four aforementioned streams (Tables 8.2, 8.3, 8.4 and 8.5). In order to compute and compare the survival conditions for the different fish species, the water temperature criteria for inhabitable conditions used for the freely flowing stream scenario (Table 7.1) was used here. The calculated stream water temperature profiles (Figs. 8.4 through 8.7) were applied to find daily inhabitable stream reach lengths for each fish species. Because water temperatures were calculated on a daily basis the inhabitable stream reach lengths for sliding periods of seven days was examined and the maximum length for each seven–day period was retained as the inhabitable stream reach length for that period. The minimum of all the inhabitable stream reach lengths over a simulated season was selected as the inhabitable stream reach length for the entire simulation period (March 1 through November 30).

Lengths of river reaches, expressed as a percentage of total length (38 mi), in which the 32 fish species can survive under past and future projected climate conditions are given in Tables 8.2 through 8.5. The effect of upstream boundary condition on fish survival can be seen clearly. In the freely flowing stream scenario (chapter 7) the Baptism River, as an example, showed to be unable to support the survival of Brook trout (Table 7.5b) while here (Table 8.3b) the Baptism River showed to have a reach of at least 37.9 miles in length that is capable of supporting the survival of the same fish species if the water is hypolimnetic or groundwater release. Table 8.6 compares the inhabitable conditions in four streams under different upstream boundary condition scenarios.

8.6. Conclusions

(1) Stream water temperatures depend on the source of water.

(2) Water releases from lake epilimnion, lake hypolimnion or groundwater have different thermal characteristics.

Table 8.2. Inhabitable fraction (%) of river reach for the Straight River under different upstream boundary conditions.

Straight River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake epilimnion

FISH	OBS.	PAST	GISS
Brook Trout		94	▨
Brown Trout	22/22	100	100
Coho Salmon		100	41
Rainbow Trout	5/22	100	71
Lake Herring		100	54
Chinook Salmon		100	66
Chum Salmon		97	▨
Mountain Whitefish		100	59
Pink Salmon		100	▨
Lake Trout		100	54
Sockeye Salmon		100	41
Guild (Cold)		100	54
Northern Pike	8/32	100	100
Sauger		100	100
White Sucker	13/39	100	100
Yellow Perch	3/22	100	100
Walleye	1/22	100	100
Muskellunge		100	100
Black Crappie	2/7	100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner	1/22	100	100
Green Sunfish	1/22	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	2/22	100	100
Channel Catfish		100	100
Largemouth Bass	5/22	100	100
Bluegill	1/22	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.2.)

Straight River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake hypolimnion

FISH	OBS.	PAST	GISS
Brook Trout		100	100
Brown Trout	22/22	100	100
Coho Salmon		100	100
Rainbow Trout	5/22	100	100
Lake Herring		100	100
Chinook Salmon		100	100
Chum Salmon		100	100
Mountain Whitefish		100	100
Pink Salmon		100	100
Lake Trout		100	100
Sockeye Salmon		100	100
Guild (Cold)		100	100
Northern Pike	8/32	100	100
Sauger		100	100
White Sucker	13/39	100	100
Yellow Perch	3/22	100	100
Walleye	1/22	100	100
Muskellunge		100	100
Black Crappie	2/7	100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner	1/22	100	100
Green Sunfish	1/22	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	2/22	100	100
Channel Catfish		100	100
Largemouth Bass	5/22	100	100
Bluegill	1/22	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.2.)

Straight River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a spring (groundwater)[b]

FISH	OBS.	PAST	GISS
Brook Trout		100	100
Brown Trout	22/22	100	100
Coho Salmon		100	100
Rainbow Trout	5/22	100	100
Lake Herring		100	100
Chinook Salmon		100	100
Chum Salmon		100	100
Mountain Whitefish		100	100
Pink Salmon		100	100
Lake Trout		100	100
Sockeye Salmon		100	100
Guild (Cold)		100	100
Northern Pike	8/32	100	100
Sauger		100	100
White Sucker	13/39	100	100
Yellow Perch	3/22	100	100
Walleye	1/22	100	100
Muskellunge		100	100
Black Crappie	2/7	100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner	1/22	100	100
Green Sunfish	1/22	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	2/22	100	100
Channel Catfish		100	100
Largemouth Bass	5/22	100	100
Bluegill	1/22	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
b - Extreme scenario: all stream flow is originated at the upstream end.

Cont. (Table 8.2.)

Straight River : Inhabitable fraction (%) of river reach[a]
Upstream and lateral inflow from a spring
(groundwater)

FISH	OBS.	PAST	GISS
Brook Trout		100	100
Brown Trout	22/22	100	100
Coho Salmon		100	100
Rainbow Trout	5/22	100	100
Lake Herring		100	100
Chinook Salmon		100	100
Chum Salmon		100	100
Mountain Whitefish		100	100
Pink Salmon		100	100
Lake Trout		100	100
Sockeye Salmon		100	100
Guild (Cold)		100	100
Northern Pike	8/32	100	100
Sauger		100	100
White Sucker	13/39	100	100
Yellow Perch	3/22	100	100
Walleye	1/22	100	100
Muskellunge		100	100
Black Crappie	2/7	100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner	1/22	100	100
Green Sunfish	1/22	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	2/22	100	100
Channel Catfish		100	100
Largemouth Bass	5/22	100	100
Bluegill	1/22	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Table 8.3. Inhabitable fraction (%) of river reach for the Baptism River under different upstream boundary conditions.

Baptism River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake epilimnion

FISH	OBS.	PAST	GISS
Brook Trout	1/7	▨	▨
Brown Trout	2/7	100	100
Coho Salmon		100	▨
Rainbow Trout	7/10	100	▨
Lake Herring		100	▨
Chinook Salmon	5/7	100	▨
Chum Salmon		1	▨
Mountain Whitefish		100	▨
Pink Salmon		1	▨
Lake Trout		100	▨
Sockeye Salmon		100	▨
Guild (Cold)		100	▨
Northern Pike		100	100
Sauger		100	100
White Sucker	2/7	100	100
Yellow Perch	3/7	100	100
Walleye		100	100
Muskellunge		100	100
Black Crappie		100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner		100	100
Green Sunfish		100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass		100	100
Channel Catfish		100	100
Largemouth Bass		100	100
Bluegill		100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.3.)

Baptism River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake hypolimnion

FISH	OBS.	PAST	GISS
Brook Trout	1/7	100	51
Brown Trout	2/7	100	100
Coho Salmon		100	66
Rainbow Trout	7/10	100	94
Lake Herring		100	76
Chinook Salmon	5/7	100	86
Chum Salmon		100	51
Mountain Whitefish		100	79
Pink Salmon		100	54
Lake Trout		100	76
Sockeye Salmon		100	66
Guild (Cold)		100	76
Northern Pike		100	100
Sauger		100	100
White Sucker	2/7	100	100
Yellow Perch	3/7	100	100
Walleye		100	100
Muskellunge		100	100
Black Crappie		100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner		100	100
Green Sunfish		100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass		100	100
Channel Catfish		100	100
Largemouth Bass		100	100
Bluegill		100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.3.)

Baptism River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a spring (groundwater)[b]

FISH	OBS.	PAST	GISS
Brook Trout	1/7	100	69
Brown Trout	2/7	100	100
Coho Salmon		100	91
Rainbow Trout	7/10	100	100
Lake Herring		100	100
Chinook Salmon	5/7	100	100
Chum Salmon		100	69
Mountain Whitefish		100	100
Pink Salmon		100	71
Lake Trout		100	100
Sockeye Salmon		100	91
Guild (Cold)		100	100
Northern Pike		100	100
Sauger		100	100
White Sucker	2/7	100	100
Yellow Perch	3/7	100	100
Walleye		100	100
Muskellunge		100	100
Black Crappie		100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead		100	100
Carp		100	100
Freshwater Drum		100	100
Gizzard Shad		100	100
Golden Shiner		100	100
Green Sunfish		100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass		100	100
Channel Catfish		100	100
Largemouth Bass		100	100
Bluegill		100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
b - Extreme scenario: all stream flow is originated at the upstream end.

Table 8.4. Inhabitable fraction (%) of river reach for the Clearwater River under different upstream boundary conditions.

Clearwater River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake epilimnion

FISH	OBS.	PAST	GISS
Brook Trout		▨	▨
Brown Trout	11/13	100	100
Coho Salmon		64	▨
Rainbow Trout	11/13	100	▨
Lake Herring		100	▨
Chinook Salmon		100	▨
Chum Salmon		1	▨
Mountain Whitefish		100	▨
Pink Salmon		1	▨
Lake Trout		100	▨
Sockeye Salmon		64	▨
Guild (Cold)		100	▨
Northern Pike	5/18	100	100
Sauger		100	100
White Sucker	8/18	100	100
Yellow Perch	2/13	100	100
Walleye	3/18	100	100
Muskellunge		100	100
Black Crappie		100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead	1/13	100	100
Carp	1/13	100	100
Freshwater Drum	2/13	100	100
Gizzard Shad		100	100
Golden Shiner		100	100
Green Sunfish	1/13	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	6/18	100	100
Channel Catfish	2/13	100	100
Largemouth Bass		100	100
Bluegill	1/13	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.4.)

Clearwater River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake hypolimnion

FISH	OBS.	PAST	GISS
Brook Trout		100	69
Brown Trout	11/13	100	100
Coho Salmon		100	89
Rainbow Trout	11/13	100	96
Lake Herring		100	100
Chinook Salmon		100	71
Chum Salmon		100	99
Mountain Whitefish		100	74
Pink Salmon		100	96
Lake Trout		100	89
Sockeye Salmon		100	96
Guild (Cold)		100	100
Northern Pike	5/18	100	100
Sauger		100	100
White Sucker	8/18	100	100
Yellow Perch	2/13	100	100
Walleye	3/18	100	100
Muskellunge		100	100
Black Crappie		100	100
White Crappie		100	100
Guild (Cool)		100	100
Smallmouth Bass		100	100
Brown Bullhead	1/13	100	100
Carp	1/13	100	100
Freshwater Drum	2/13	100	100
Gizzard Shad		100	100
Golden Shiner		100	100
Green Sunfish	1/13	100	100
White Bass		100	100
Lake Sturgeon		100	100
Rock Bass	6/18	100	100
Channel Catfish	2/13	100	100
Largemouth Bass		100	100
Bluegill	1/13	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Table 8.5. Inhabitable fraction (%) of river reach for the Zumbro River under different upstream boundary conditions.

Zumbro River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake epilimnion

FISH	OBS.	PAST	GISS
Brook Trout		▨	▨
Brown Trout	1/50	100	▨
Coho Salmon		▨	▨
Rainbow Trout	4/50	▨	▨
Lake Herring		▨	▨
Chinook Salmon		▨	▨
Chum Salmon		▨	▨
Mountain Whitefish		▨	▨
Pink Salmon		▨	▨
Lake Trout		▨	▨
Sockeye Salmon		▨	▨
Guild (Cold)		▨	▨
Northern Pike	6/50	100	100
Sauger	17/50	100	100
White Sucker	16/67	100	4
Yellow Perch	4/50	100	100
Walleye	14/54	100	100
Muskellunge		100	100
Black Crappie	15/50	100	100
White Crappie	10/50	100	100
Guild (Cool)		100	100
Smallmouth Bass	35/54	100	100
Brown Bullhead		100	100
Carp	11/50	100	100
Freshwater Drum	5/50	100	100
Gizzard Shad	2/50	100	100
Golden Shiner		100	100
Green Sunfish	5/50	100	100
White Bass	16/63	100	100
Lake Sturgeon		100	100
Rock Bass		100	100
Channel Catfish	16/63	100	100
Largemouth Bass	25/50	100	100
Bluegill	14/50	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Cont. (Table 8.5.)

Zumbro River : Inhabitable fraction (%) of river reach[a]
Upstream inflow from a lake hypolimnion

FISH	OBS.	PAST	GISS
Brook Trout		100	76
Brown Trout	1/50	100	100
Coho Salmon		100	100
Rainbow Trout	4/50	100	100
Lake Herring		100	100
Chinook Salmon		100	100
Chum Salmon		100	79
Mountain Whitefish		100	100
Pink Salmon		100	81
Lake Trout		100	100
Sockeye Salmon		100	100
Guild (Cold)		100	100
Northern Pike	6/50	100	100
Sauger	17/50	100	100
White Sucker	16/67	100	4
Yellow Perch	4/50	100	100
Walleye	14/54	100	100
Muskellunge		100	100
Black Crappie	15/50	100	100
White Crappie	10/50	100	100
Guild (Cool)		100	100
Smallmouth Bass	35/54	100	100
Brown Bullhead		100	100
Carp	11/50	100	100
Freshwater Drum	5/50	100	100
Gizzard Shad	2/50	100	100
Golden Shiner		100	100
Green Sunfish	5/50	100	100
White Bass	16/63	100	100
Lake Sturgeon		100	100
Rock Bass		100	100
Channel Catfish	16/63	100	100
Largemouth Bass	25/50	100	100
Bluegill	14/50	100	100
Guild (Warm)		100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.

Table 8.6a.

Straight River : Inhabitable fraction (%) of river reach[a]

FISH	OBS.	Uniform	1	2	3	4
Brook Trout		Yes	94	100	100	100
Brown Trout	22/22	Yes	100	100	100	100
Coho Salmon		Yes	100	100	100	100
Rainbow Trout	5/22	Yes	100	100	100	100
Lake Herring		Yes	100	100	100	100
Chinook Salmon		Yes	100	100	100	100
Chum Salmon		Yes	97	100	100	100
Mountain Whitefish		Yes	100	100	100	100
Pink Salmon		Yes	100	100	100	100
Lake Trout		Yes	100	100	100	100
Sockeye Salmon		Yes	100	100	100	100
Guild (Cold)		Yes	100	100	100	100
Northern Pike	8/32	Yes	100	100	100	100
Sauger		Yes	100	100	100	100
White Sucker	13/39	Yes	100	100	100	100
Yellow Perch	3/22	Yes	100	100	100	100
Walleye	1/22	Yes	100	100	100	100
Muskellunge		Yes	100	100	100	100
Black Crappie	2/7	Yes	100	100	100	100
White Crappie		Yes	100	100	100	100
Guild (Cool)		Yes	100	100	100	100
Smallmouth Bass		Yes	100	100	100	100
Brown Bullhead		Yes	100	100	100	100
Carp		Yes	100	100	100	100
Freshwater Drum		Yes	100	100	100	100
Gizzard Shad		Yes	100	100	100	100
Golden Shiner	1/22	Yes	100	100	100	100
Green Sunfish	1/22	Yes	100	100	100	100
White Bass		Yes	100	100	100	100
Lake Sturgeon		Yes	100	100	100	100
Rock Bass	2/22	Yes	100	100	100	100
Channel Catfish		Yes	100	100	100	100
Largemouth Bass	5/22	Yes	100	100	100	100
Bluegill	1/22	Yes	100	100	100	100
Guild (Warm)		Yes	100	100	100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
Uniform - Freely flowing stream scenario (Yes indicates inhabitable conditions).
1 - Upstream inflow from a lake epilimnion.
2 - Upstream inflow from a lake hypolimnion.
3 - Upstream inflow from a spring (groundwater).
4 - Upstream and lateral inflow from a spring (groundwater).

Table 8.6b.

Baptism River : Inhabitable fraction (%) of river reach[a]

FISH	OBS.	Uniform	1	2	3
Brook Trout	1/7	▨	▨	100	100
Brown Trout	2/7	Yes	100	100	100
Coho Salmon		Yes	100	100	100
Rainbow Trout	7/10	Yes	100	100	100
Lake Herring		Yes	100	100	100
Chinook Salmon	5/7	Yes	100	100	100
Chum Salmon		▨	1	100	100
Mountain Whitefish		Yes	100	100	100
Pink Salmon		▨	1	100	100
Lake Trout		Yes	100	100	100
Sockeye Salmon		Yes	100	100	100
Guild (Cold)		Yes	100	100	100
Northern Pike		Yes	100	100	100
Sauger		Yes	100	100	100
White Sucker	2/7	Yes	100	100	100
Yellow Perch	3/7	Yes	100	100	100
Walleye		Yes	100	100	100
Muskellunge		Yes	100	100	100
Black Crappie		Yes	100	100	100
White Crappie		Yes	100	100	100
Guild (Cool)		Yes	100	100	100
Smallmouth Bass		Yes	100	100	100
Brown Bullhead		Yes	100	100	100
Carp		Yes	100	100	100
Freshwater Drum		Yes	100	100	100
Gizzard Shad		Yes	100	100	100
Golden Shiner		Yes	100	100	100
Green Sunfish		Yes	100	100	100
White Bass		Yes	100	100	100
Lake Sturgeon		Yes	100	100	100
Rock Bass		Yes	100	100	100
Channel Catfish		Yes	100	100	100
Largemouth Bass		Yes	100	100	100
Bluegill		Yes	100	100	100
Guild (Warm)		Yes	100	100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
Uniform - Freely flowing stream scenario (Yes indicates inhabitable conditions).
1 - Upstream inflow from a lake epilimnion.
2 - Upstream inflow from a lake hypolimnion.
3 - Upstream inflow from a spring (groundwater)

Table 8.6c.

Clearwater River : Inhabitable fraction (%) of river reach[a]

FISH	OBS.	Uniform	1	2
Brook Trout		▨	▨	69
Brown Trout	11/13	Yes	100	100
Coho Salmon		Yes	64	89
Rainbow Trout	11/13	Yes	100	96
Lake Herring		Yes	100	100
Chinook Salmon		Yes	100	71
Chum Salmon		▨	1	99
Mountain Whitefish		Yes	100	74
Pink Salmon		▨	1	96
Lake Trout		Yes	100	89
Sockeye Salmon		Yes	64	96
Guild (Cold)		Yes	100	100
Northern Pike	5/18	Yes	100	100
Sauger		Yes	100	100
White Sucker	8/18	Yes	100	100
Yellow Perch	2/13	Yes	100	100
Walleye	3/18	Yes	100	100
Muskellunge		Yes	100	100
Black Crappie		Yes	100	100
White Crappie		Yes	100	100
Guild (Cool)		Yes	100	100
Smallmouth Bass		Yes	100	100
Brown Bullhead	1/13	Yes	100	100
Carp	1/13	Yes	100	100
Freshwater Drum	2/13	Yes	100	100
Gizzard Shad		Yes	100	100
Golden Shiner		Yes	100	100
Green Sunfish	1/13	Yes	100	100
White Bass		Yes	100	100
Lake Sturgeon		Yes	100	100
Rock Bass	6/18	Yes	100	100
Channel Catfish	2/13	Yes	100	100
Largemouth Bass		Yes	100	100
Bluegill	1/13	Yes	100	100
Guild (Warm)		Yes	100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
Uniform - Freely flowing stream scenario (Yes indicates inhabitable conditions).
1 - Upstream inflow from a lake epilimnion.
2 - Upstream inflow from a lake hypolimnion.

Table 8.6d.

Zumbro River : Inhabitable fraction (%) of river reach[a]

FISH	OBS.	Uniform	1	2
Brook Trout		▨	▨	100
Brown Trout	1/50	Yes	100	100
Coho Salmon		▨	▨	100
Rainbow Trout	4/50	▨	▨	100
Lake Herring		▨	▨	100
Chinook Salmon		▨	▨	100
Chum Salmon		▨	▨	100
Mountain Whitefish		▨	▨	100
Pink Salmon		▨	▨	100
Lake Trout		▨	▨	100
Sockeye Salmon		▨	▨	100
Guild (Cold)		▨	▨	100
Northern Pike	6/50	Yes	100	100
Sauger	17/50	Yes	100	100
White Sucker	16/67	Yes	100	4
Yellow Perch	4/50	Yes	100	100
Walleye	14/54	Yes	100	100
Muskellunge		Yes	100	100
Black Crappie	15/50	Yes	100	100
White Crappie	10/50	Yes	100	100
Guild (Cool)		Yes	100	100
Smallmouth Bass	35/54	Yes	100	100
Brown Bullhead		Yes	100	100
Carp	11/50	Yes	100	100
Freshwater Drum	5/50	Yes	100	100
Gizzard Shad	2/50	Yes	100	100
Golden Shiner		Yes	100	100
Green Sunfish	5/50	Yes	100	100
White Bass	16/63	Yes	100	100
Lake Sturgeon		Yes	100	100
Rock Bass		Yes	100	100
Channel Catfish	16/63	Yes	100	100
Largemouth Bass	25/50	Yes	100	100
Bluegill	14/50	Yes	100	100
Guild (Warm)		Yes	100	100

Shaded boxes indicate uninhabitable conditions.
OBS. = Observed in fish surveys. 1/7 means fish species observed in 1 of 7 surveys.
a - Total length of river reach investigated is 37.9 mi.
Uniform - Freely flowing stream scenario (Yes indicates inhabitable conditions).
1 - Upstream inflow from a lake epilimnion.
2 - Upstream inflow from a lake hypolimnion.

(3) Stream water temperatures in tailwaters below different release conditions were studied. For all upstream boundary conditions studied, stream water temperatures, as expected, approach those of the freely flowing stream as the water travels downstream.

(4) To accurately estimate stream water temperatures, actual upstream and lateral inflow boundary conditions need to be considered when modeling a specific reach of any stream. This kind of information is usually difficult to obtain. Therefore, an approximation of such boundary conditions is necessary.

(5) The effect of cold water originated from a lake hypolimnion or from groundwater was still observed 30 miles downstream from its origin. This could explain the existence of some fish species, observed in different fish surveys, that could not survive under the freely flowing stream conditions.

(6) Stream water temperatures were increased by approximately 4 °C, regardless of the upstream boundary conditions, as a result of the projected climate change.

(7) Streams with significant groundwater input or those fed by water releases from deep reservoirs (hypolimnion release) will continue to sustain coldwater fish even after climate change. At least 76% of the modeled stream reach length will have inhabitable conditions for coldwater fish if the stream water was from a lake (reservoir) hypolimnion or from groundwater.

9. SUMMARY AND CONCLUSIONS

Water temperatures in streams vary in time depending on atmospheric conditions. Herein stream water temperatures have been simulated by a one–dimensional unsteady advection–dispersion model. Heat exchange between the atmosphere and the water is crucial but in shallow streams the stream bed, as a heat source or sink, is also important. Streams differ from other open water bodies (lakes for example) by their narrow width, and if banks are lined by trees, streams will experience sun–shading and wind–sheltering. The model presented herein accounts for sun–shading and wind–sheltering by coefficients which are a function of bank vegetation, especially height and density, stream valley topography and stream width, and were determined through model calibration. The exposure of a stream surface to sun is greater in spring before leaves grow on trees or in fall after leaves fall from trees. Therefore, different shading percentages for several streams (Straight, Baptism, Clearwater, Zumbro and Mississippi Rivers) were established through separate seasonal model calibrations using stream water temperatures measured in spring, summer and fall. Summer shading percentages ranged from 0% to 60% depending on stream width. The widest stream (Mississippi) had 0% shading, and the narrowest (Straight) had 60% shading.

Sensitivity of the model to several weather parameters (air temperature, solar radiation, relative humidity, wind speed, cloud cover and barometric pressure) was established using the influence coefficient method and the sensitivity equation method. Both methods gave results on the same order of magnitude and showed that the model is most sensitive to air temperature and solar radiation (according to the sensitivity equation method, the model output sensitivities to air temperature, solar radiation, relative humidity, cloud cover and wind speed were 3.8, 2.9, 0.7, 0.6 and 0.3 °C, respectively). This means that representative and reliable information on air temperature, solar radiation and stream bank vegetation (sun–shading) are necessary to accurately predict stream water temperatures. On the other hand, sensitivity of the model to barometric pressure (used to calculate convective heat transfer) is very small and, therefore, the barometric pressure can be assumed constant in all cases. Water temperatures for the Straight, Baptism, Clearwater, Zumbro and Mississippi Rivers in Minnesota were predicted at time steps ranging from 1–hour to 1–day with accuracies (standard errors compared to measurements) on the order of 0.2 to 1°C.

The stream water temperature model was used to project global climate change impacts on stream water temperatures. Climate parameter projections from four General Circulation Models (GCM's) developed by the Columbia University Goddard Institute for Space Studies (GISS), Princeton University Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO) and Oregon State University (OSU), were used as model input. Summer time stream water temperatures were projected to increase by 2.4 to 4.7 °C in the five streams studied as a result of global climate change due to doubling of atmospheric CO_2. Rises in stream water temperatures up to 6 °C are projected if the stream bank vegetation were lost due to climate change.

A simplified relationship between water temperature, air temperature and solar radiation applied at the water surface was derived from the complete heat budget model. This relationship requires only three independent input variables instead of seven used in the complete heat budget model. It can be used to estimate approximate stream water temperatures if air temperature, solar radiation and information about stream bank vegetation (shading) are available.

An additional objective of this research was to estimate global climate change effects on fish habitat in streams. Fish survival and growth are directly influenced by the temperature of their environment. The sensitivities of fish species to environmental temperatures have been derived from field and laboratory data by the USEPA (Environmental Protection Agency). The stream temperature model output was combined with thermal criteria for different fish species to determine survival and growth parameters. Time series over 25 years of simulated water temperatures under past and future climate scenarios were generated and interpreted to determine if a fish species or guild will be threatened with extinction, and whether its good growth habitat, defined as the range within which the most rapid growth should occur, will increase or decrease. According to these estimates coldwater fish will be eliminated in four out of the five freely flowing streams studied in Minnesota after climate change. Streams located in northern Minnesota will continue to sustain coldwater fish if trees on stream banks are not lost to climate change. Another projection is that coolwater fish will be eliminated from the Mississippi River in its central Minnesota reach (south of Anoka), but will find improved growth potential in smaller streams with more shading. Therefore, a regional redistribution of fish guilds/species in streams is expected as a consequence of projected global climate change.

Upstream boundary conditions, i.e. the origin of the stream water, and lateral groundwater inflow along the stream banks play an important role in controlling stream water temperatures and fish habitat. Streams with significant groundwater input or those fed by water releases from deep reservoirs (hypolimnion release) will continue to sustain coldwater fish even after climate change (based on the GISS model). The study showed that at least 76% (29 miles) of the stream reaches studied will have inhabitable conditions for coldwater fish.

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Appendix A – List of Symbols

A = Coefficient for the calculation of reflectivity.
A_s = Stream cross–sectional area.
B = Coefficient for the calculation of reflectivity.
B_i = Biot number.
B_s = Stream surface width.
C_c = Fraction cloud cover.
C_p = Heat capacity of water.
C_r = Cloudiness ratio.
D_L = Dispersion coefficient.
F_o = Fourier number.
H_c = Convective heat flux.
H_e = Evaporative heat flux.
H_l = Longwave radiation.
H_s = Shortwave radiation
H_{si} = Measured incoming shortwave radiation.
H_{sm} = Clear sky radiation.
H_{sr} = Reflected solar radiation.
K = Coefficient (0.17).
L = Latent heat of vaporization.
P_a = Atmospheric pressure.
Q = Stream flow rate.
RH = Relative humidity.
S = Heat flux (Source) term.
S_a = Water/air heat flux.
S_b = Streambed heat flux.
SEE = Standard error of estimate.
SF = Sun–shading factor.
T = Stream water temperature.
T_a = Air temperature.
T_b = Streambed temperature.
T_c = Computed stream water temperature.

T_m = Measured stream water temperature.

T_s = Stream surface water temperature.

U = Average stream velocity.

Wftn = Wind function.

e_{az} = Vapor pressure at height z.

e_s = Saturation vapor pressure.

e_{sw} = Saturation vapor pressure at water surface.

h = Average stream depth.

k_b = Thermal conductivity of streambed material.

q_b = Streambed heat flux.

r = Total reflectivity of the water surface.

t = Time.

x = Distance downstream.

z = Vertical distance.

α = Thermal diffusivity of streambed material.

α_r = Solar radiation angle.

ϵ_a = Atmospheric emissivity with cloud cover.

ϵ_{ac} = Atmospheric emissivity without cloud cover.

ϵ_w = Emissivity of water.

ρ = Density of water.

σ = Stefan Boltzman constant.

Regional fish survival and growth parameters:

SCB – Earliest Julian date when the water temperature exceeds the survival temperature.

SCE – Latest Julian date when the water temperature exceeds the survival temperature.

SCL – Total number of days when the stream water temperature exceeds the survival temperature.

GSB – Earliest Julian date when the water temperature exceeds the lower bound growth temperature.

GSE – Latest Julian date when the water temperature exceeds the lower bound growth temperature.

GSL – Total number of days when the stream water temperature is within lower and upper growth limits.

GZER– Total number of days when the upper bound growth temperature is exceeded. This is the midsummer reduced growth potential and stress (or even death), period, which includes non–survival (SCL) period.

R – Ratio between (GSL+1) and (GZER+1) : [$R = (GSL+1)/(GZER+1)$]

Appendix B

Diurnal Stream Water Temperature Fluctuations

I. Introduction

Stream water temperatures fluctuate mostly in response to weather conditions and flow. Seasonal and diurnal periodicities in stream water temperature records are the most obvious in temperate climates. Most streams are well–mixed water bodies. It can be shown by a simple heat transfer analysis that the amplitudes of diurnal stream water temperature variations are therefore directly dependent on stream depth. Song et al. (1973) related the amplitude of reported stream temperature maxima and minima to the average depth of the stream system considered. Herein we will try to find a relation between the diurnal amplitude of continuously recorded stream water temperatures and the stream depth for several different streams. The analysis uses continuous records of measured water temperatures, and in addition air temperature, solar radiation and measurements of average stream depth. Water temperatures and stream depths were obtained by direct field measurements as discussed earlier. The air temperature and solar radiation data were obtained from the National Weather Service and from the files of Prof. Donald Baker from the Soil Science department at the University of Minnesota, St. Paul, MN.

II. Data analysis

II.1. Spectral analysis

Although the diurnal variations in water and air temperatures can be clearly seen in the time plots of such data (Fig. 2.2), a power spectral analysis was conducted to determine if other dominant periodicities existed in the records. The power spectra of hourly measured air and stream water temperatures were calculated using the fast fourier transform technique available with the statistical software PlotIT (Scientific Programming Enterprises). Two peaks can be seen clearly in the results (Fig. B.1) in all the cases plotted. One was at a frequency of 1 cycle per day. This corresponds, as expected, to the diurnal variation of air and stream water temperatures. The other peak was at a frequency of approximately 0.3 cycles per day. This means that there is a pattern that repeats itself every 3 or 4 days. Stefan and Chau (1976) had found a similar periodicity by autocovariance analysis of measured water temperatures for the Mississippi River at St. Paul (MN.). It is believed that this periodicity indicates predominant weather patterns in the flat topography of the north central United States.

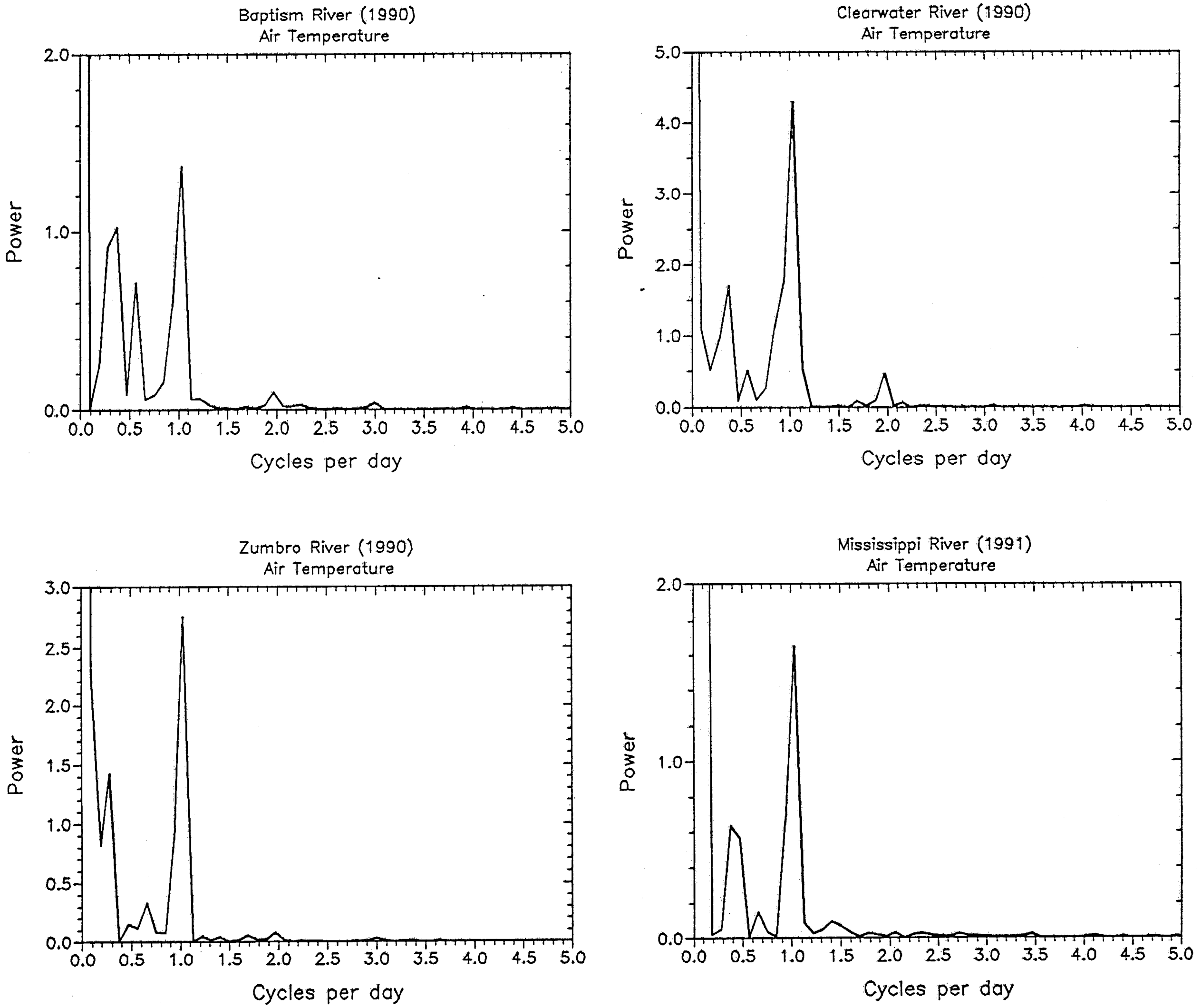
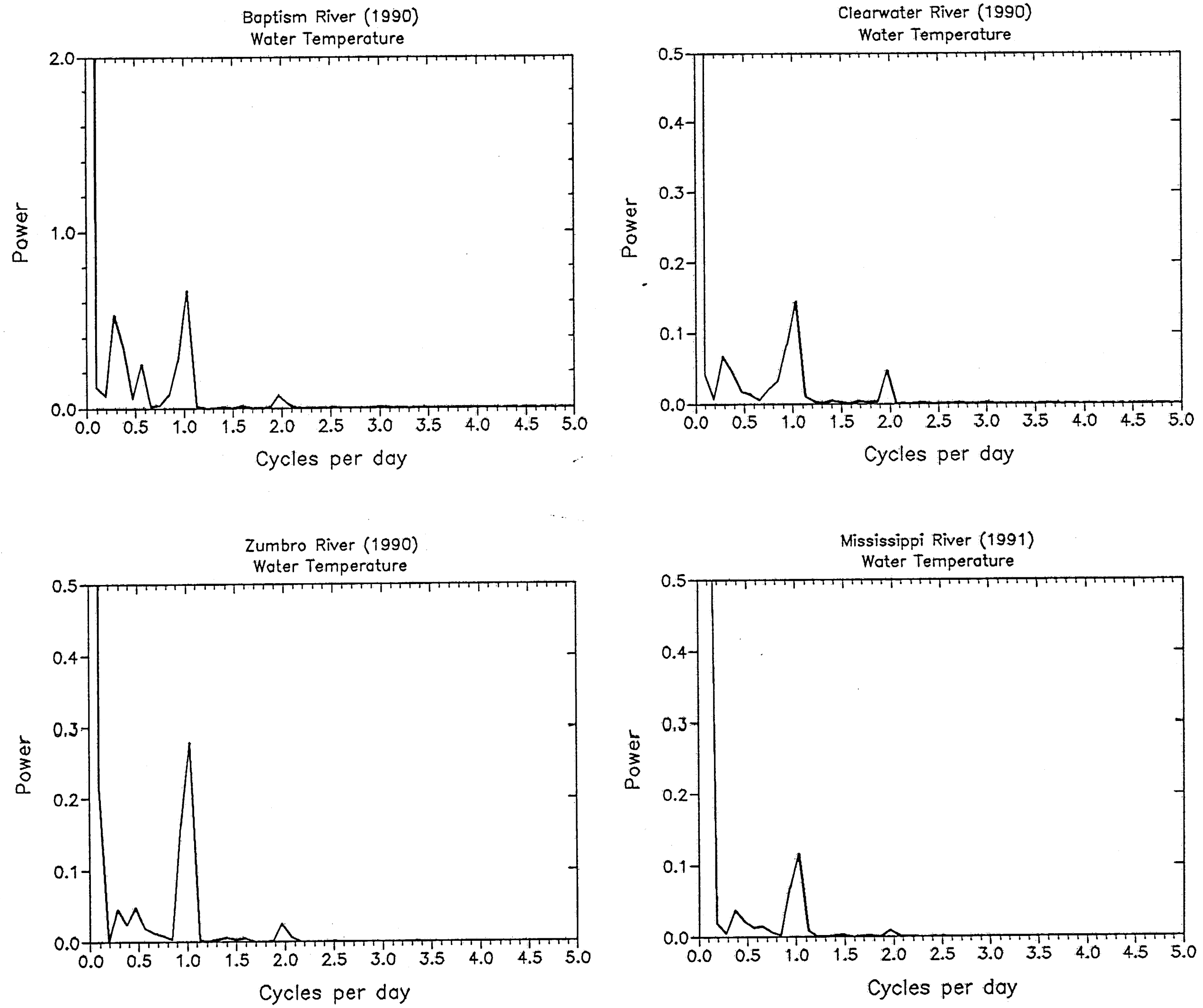


Figure B.1a. Power spectrum for measured air temperatures.



Baptism River (1990) Water Temperature

Clearwater River (1990) Water Temperature

Zumbro River (1990) Water Temperature

Mississippi River (1991) Water Temperature

Figure B.1b. Power spectrum for measured water temperatures.

II.2. Trend analysis

Trend in the records of measurements could affect the amplitude values. To examine the effect of a trend (over at least several days) on diurnal water temperature amplitudes the trend was eliminated using a moving average technique. A six day moving average was selected. The moving average was subtracted from the original records of measured stream water temperatures to produce residuals (Fig. B.2). New amplitudes were found by taking half the difference between the daily maxima and minima of the residuals. The diurnal amplitudes of stream water temperatures before and after the removal of trend were plotted for the purpose of comparison (Fig. B.3). No significant difference between the two amplitudes can be seen and one can conclude that the trend has no strong effect on the diurnal amplitude of stream water temperatures as defined.

II.3. Diurnal stream water temperature amplitude analysis

Diurnal stream temperature amplitudes were calculated from all the records and plotted against stream depth in Fig. B.4. The diurnal water temperature amplitude was defined as half the difference between daily maximum and minimum temperatures regardless of whether temperatures were in a low term rising or falling pattern. Despite considerable scatter of the data it is evident that the diurnal stream water temperature amplitude is inversely proportional to the streams depth. This result agrees with a simple heat transfer analysis of a well–mixed water column subjected to periodic heating and cooling. In such analysis the water temperature in the water water column (T) is the solution of the heat transfer equation

$$\rho c_p h \frac{dT}{dt} = K\,(T_a - T) \qquad \text{(B.1)}$$

where ρc_p = specific heat of water per unit volume, T_a = air temperature, h = water depth and K is a bulk coefficient of surface heat transfer. T_a is the forcing temperature outside the water surface and varies with time. We use air temperature as the forcing function and K as the bulk coefficient of heat transfer as if the entire heat transfer process were controlled by conduction only. In reality heat transfer from the atmosphere to the water also includes radiation and evaporative components. For the purpose of this analysis their contributions are considered in the value of K. This is sufficient for the analysis which we propose here but a more rigorous derivation of the heat transfer processes through a water surface has been given e.g. by Edinger et al. (1968), Raphael (1962), Jobson (1973) and Stefan et al., (1980).

If in equation (B.1) the forcing function $T_a(t)$ is a periodic function with a period T (of 1 day) and an amplitude ΔT_a, one can show (e.g. Stefan and Preud'homme, 1992) that the water temperature will respond with a periodic function of amplitude ΔT_w given by the equation

$$\frac{\Delta T_w}{\Delta T_a} = \frac{1}{\sqrt{1 + (\omega h/\alpha)^2}} \qquad \text{(B.2)}$$

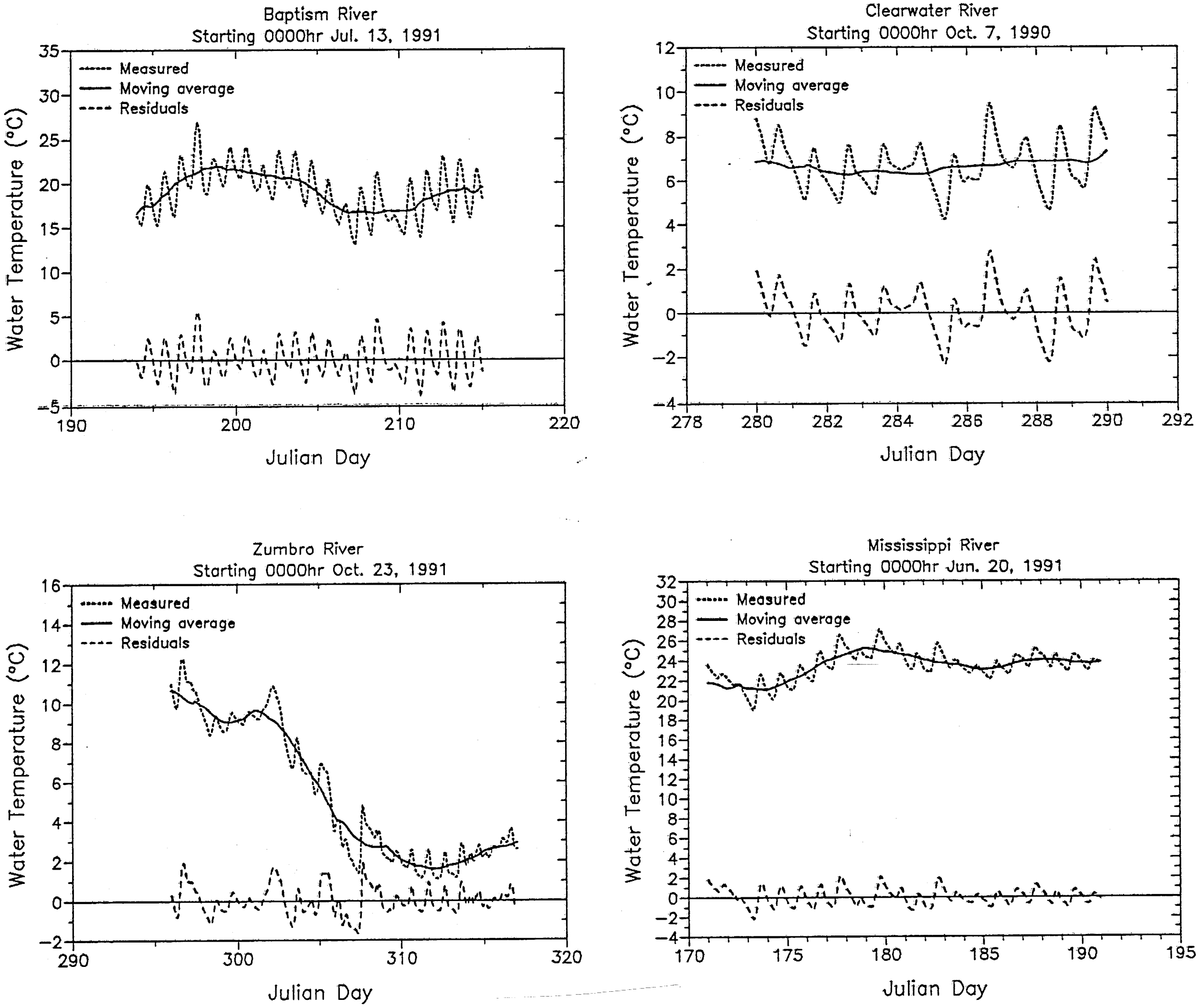


Figure B.2. Measured water temperature records before and after the removal of trend (using the moving average technique).

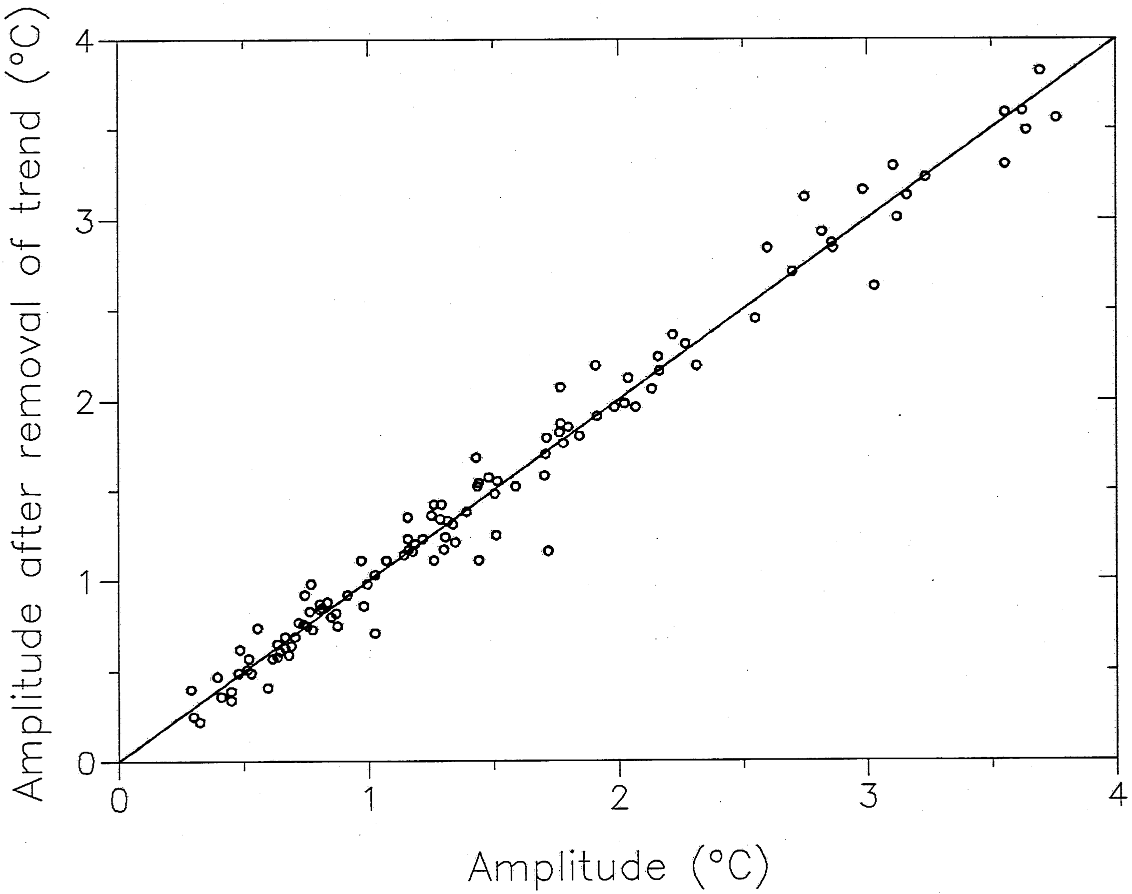


Figure B.3. Comparison between stream water temperature amplitudes before and after the removal of trend.

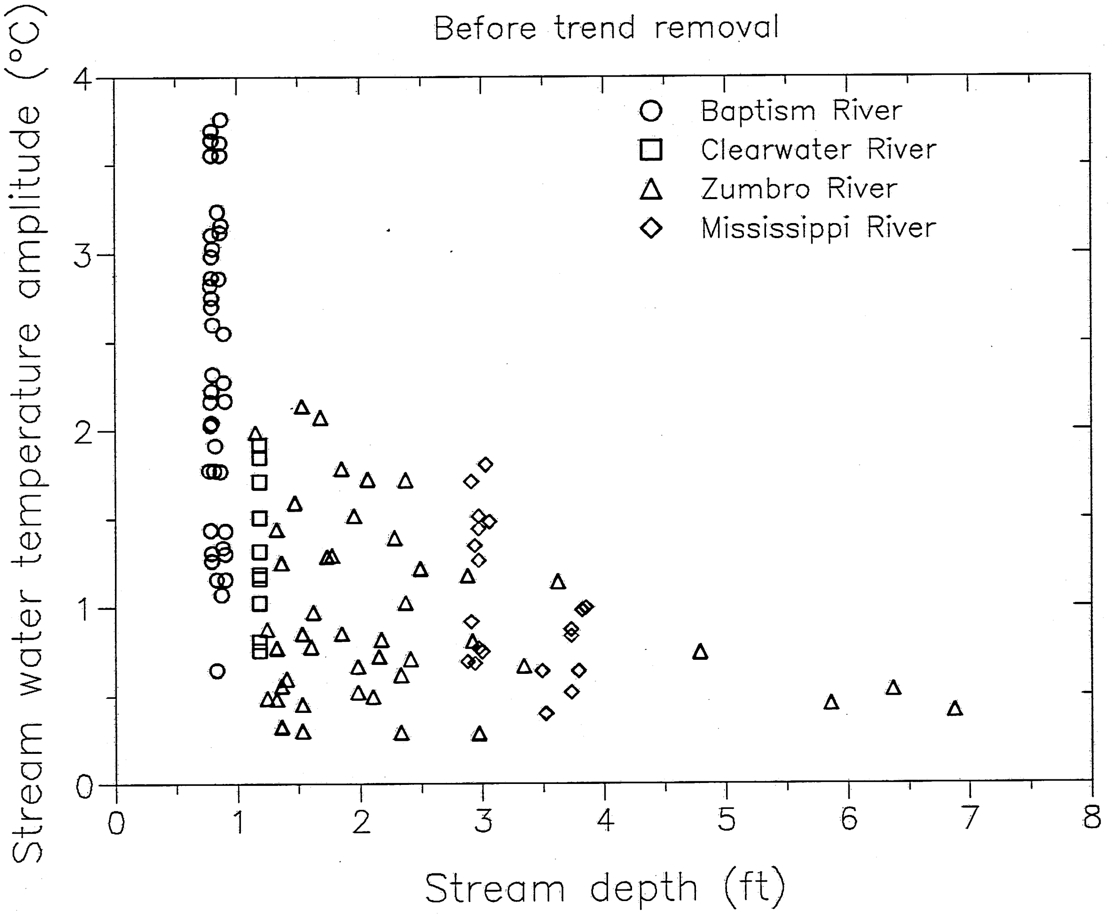


Figure B.4. Relationship between stream water temperature amplitude and stream depth.

where $\omega = 2\pi/T$ and $\alpha = K/\rho c_p$. This relationship was plotted with the measurements in Fig. B.5. Most of the measurements were within the range of the theoretical boundaries. Scatter is still obvious. Several shortcomings of the theory can be called upon to explain the scatter. For example the daily amplitude in air temperature ΔT_a may not reflect the full effect of solar radiation. Therefore, daily total solar radiation was introduced as an additional independent variable. The diurnal water temperature amplitudes ΔT_w were divided by the daily solar radiation but the scatter was not reduced significantly.

III. Conclusions

1) Power spectral analysis of hourly water temperature records and air temperature records of four streams in Minnesota showed clearly that diurnal fluctuations in air and stream water temperatures are present. In addition an unobvious pattern in air and stream water temperatures that is repeated every 3 to 4 days was revealed.

2) Diurnal stream water temperature amplitude can be calculated as one half the difference between daily maximum and minimum water temperatures, regardless of trend.

3) Diurnal amplitude of stream water temperature defined as one half the difference between daily maximum and minimum water temperatures is inversely proportional to stream depth.

4) Introduction of the amplitude of air temperature and/or solar radiation as additional independent variables may improve the relationship between diurnal stream water temperature amplitude and stream depth. Further analysis of this approach will require extensive measurements of stream depths, stream water temperatures, air temperatures and solar radiation.

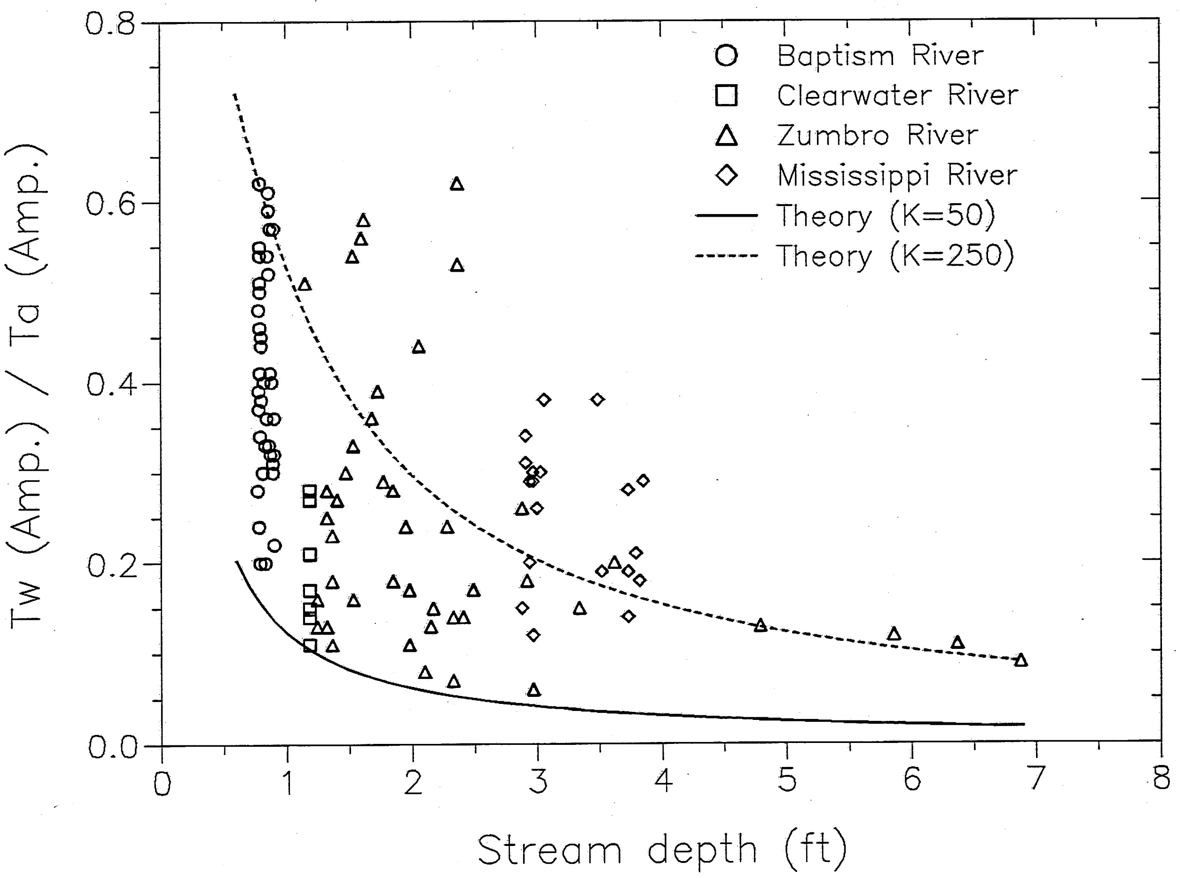


Figure B.5. Comparison between computed (theory) and measured ratios of water and air temperature amplitudes.

Appendix C

Streambed Heat Transfer

The calculations of streambed heat flux requires a temperature profile at the streambed surface. Brown (1969) used measured temperature profiles at the surface of his modeled stream to calculate the streambed heat flux. Often such measurements are not available. So, to be able to incorporate the streambed heat flux into the stream water temperature model a subroutine that calculates streambed temperature profiles is required.

In order to study streambed heat transfer, the streambed geometry can be approximated by a semi–infinite solid body. Semi–infinite solids can be used to determine heat transfer near the surface of the earth (Incropera and De Witt, 1990). Since semi–infinite solid extends to infinity in all but one direction, it is characterized by a single identifiable surface. If a sudden change of conditions is imposed at this surface, transient, one dimensional conduction will occur within the solid.

The heat equation for transient conduction in a semi–infinite solid is given by

$$\frac{1}{\alpha}\frac{\partial T_b}{\partial t} = \frac{\partial^2 T_b}{\partial z^2} \qquad \text{(C–1)}$$

where T_b is the streambed temperature, α is the thermal diffusivity of the streambed material, t is time and z is a vertical coordinate starting at the streambed surface.

Analytical solutions to transient problems (Eqn. C–1) are restricted to simple boundary conditions. In the case where the boundary conditions are complex, numerical solutions should be selected. Finite–difference methods in the explicit or implicit forms are used in these cases (Incropera and De Witt, 1990). The explicit finite–difference scheme is not unconditionally stable. It frequently requires the use of extremely small time increment (Δt) and a very large number of time intervals to obtain a solution for a given space increment (Δz).

The implicit finite–difference scheme, on the other hand, is unconditionally stable. Therefore, a reduction in the amount of computation time can be obtained by employing such scheme.

The implicit finite–difference form of equation (C–1) for an interior grid point (i) shown in Fig. C.1 is

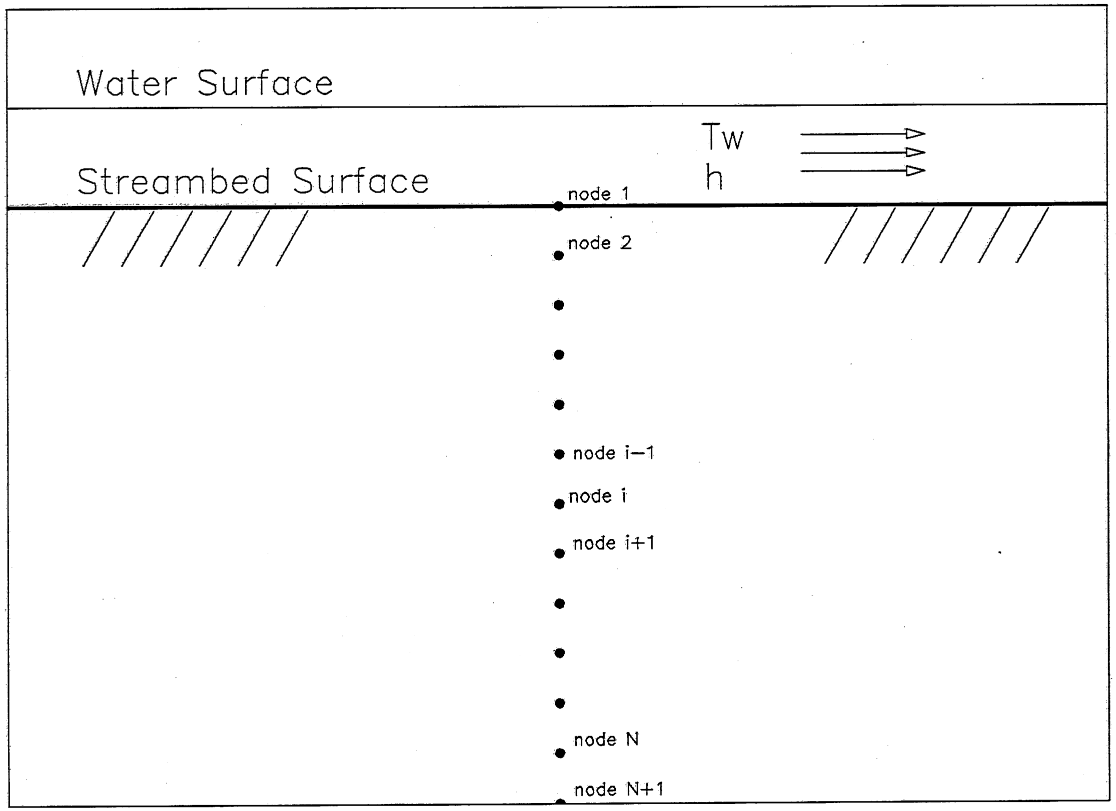


Figure C.1. Schematic diagram of a half–body with the location of different nodes used in the numerical solution.

$$\frac{1}{\alpha}\frac{T_i^{t+1}-T_i^t}{\Delta t} = \frac{T_{i+1}^{t+1}+T_{i-1}^{t+1}-2T_i^{t+1}}{(\Delta z)^2} \qquad \text{(C–2a)}$$

or

$$T_i^{t+1} = \frac{\alpha\Delta t}{(\Delta z)^2}\left[\,T_{i+1}^{t+1} + T_{i-1}^{t+1} - T_i^{t+1}\,\right] + T_i^t \qquad \text{(C–2b)}$$

or

$$-F_0\, T_{i-1}^{t+1} + (1+2F_0)\, T_i^{t+1} - F_0\, T_{i+1}^{t+1} = T_i^t \qquad \text{(C–2c)}$$

where F_0 = Fourier number = $\frac{\alpha\Delta t}{(\Delta z)^2}$ and i is the node number.

For the last grid node no heat flux boundary is assumed $(T_N = T_{N+1})$ equation (C–2c) will take the following form

$$-F_0\, T_{i-1}^{t+1} + (1+F_0)\, T_i^{t+1} = T_i^t \qquad \text{(C–3)}$$

and for the surface grid node, equation (C–2c) will take the following form (Incropera and De Witt, 1990):

$$(1+2F_0+2F_0B_i)\, T_i^{t+1} - 2F_0\, T_{i+1}^{t+1} = 2F_0B_i\, T_w + T_i^t \qquad \text{(C–4)}$$

where B_i = Biot number = $\frac{h\Delta z}{k}$, h is the convective heat transfer coefficient, k is the thermal conductivity of the streambed material and T_w is the stream water temperature.

Equations (C–2) through (C–4) show that the new temperature at node i depends on the new temperatures of its neighboring nodes which are unknown. Therefore, a simultaneous solution of all the nodal equations is necessary to determine the unknown nodal temperatures.

The system of equations in question is most conveniently solved using a tridiagonal matrix algorithm. An initial streambed temperature profile is required to successfully solve this transient heat conduction problem. In addition, two boundary conditions has to be specified: (1) an adiabatic boundary condition at a depth of 6m and (2) the water temperature and convective heat transfer coefficient at the streambed surface.

The convective heat transfer coefficient between the stream water and the streambed can be calculated using the analogy of turbulent flow on a flat plate. Measurements of streambed temperature profiles on the Rum River showed that the temperature of the streambed surface is almost equal to the temperature of the stream water. This means that the streambed surface temperature (water temperature) can be assumed as the surface boundary condition which is equivalent to the old boundary condition with a large convective heat transfer coefficient.

After solving for the entire streambed temperature profile at each time step, the streambed heat flux (q_b) can be calculated using the following equation

$$q_b = -k \left. \frac{\partial T_b}{\partial z} \right|_{z=0} \tag{C-5}$$

The streambed heat flux is calculated every time step in the model and it is added to the atmospheric source term to form a total source term which represents the heat exchange between the stream water and its surrounding environment.

As mentioned earlier, the solution of the streambed heat flux requires an initial temperature profile in the streambed. Since no measurements of such profile exist, approximate profiles of streambed temperatures were calculated using long–term averaged water temperatures at the Kawishiwi River (MN.). The daily measured water temperatures were applied as a boundary condition and the streambed temperature profiles were calculated using daily time step increments for a period of 10–years after which no change in the temperature profiles from one year to another were found. Daily temperature profiles in the streambed were the results of such computations (Fig. C.2). These temperature profiles can be used as an initial streambed temperature profiles for streams in the north–central US.

Wet sand, gravel, mud, peat and rocks were the main materials covered the beds of the streams modeled. Thermal characteristics of these materials in addition to some other materials were found in the literature and are listed in Table C–1.

Measured streambed temperature profiles at the Rum River were used to validate the accuracy of the streambed heat flux subroutine. An initial measured temperature profile was used as an input in the simulations. An adiabatic boundary condition was assumed at a depth of 6m. Measured water temperatures at the streambed surface were used as the other boundary condition. The thermal characteristics (thermal diffusivity) of the streambed material were initially assumed using the values in Table C–1 as a guideline. The thermal diffusivity was then changed to minimize the error between measured and computed temperature profiles and its value was within the limits listed in Table C–1.

The streambed temperature profile was calculated at different times and it was compared to measured temperature profiles as shown in Figure C.3. Figure C.4 shows the time variation of streambed temperature at three different depths. Figures C.3 and C.4 show that the model accurately estimates the streambed temperature profiles. Some discrepancies were found between measured and computed streambed temperatures and they could be due to the assumption that the streambed material is homogeneous and has the same water content.

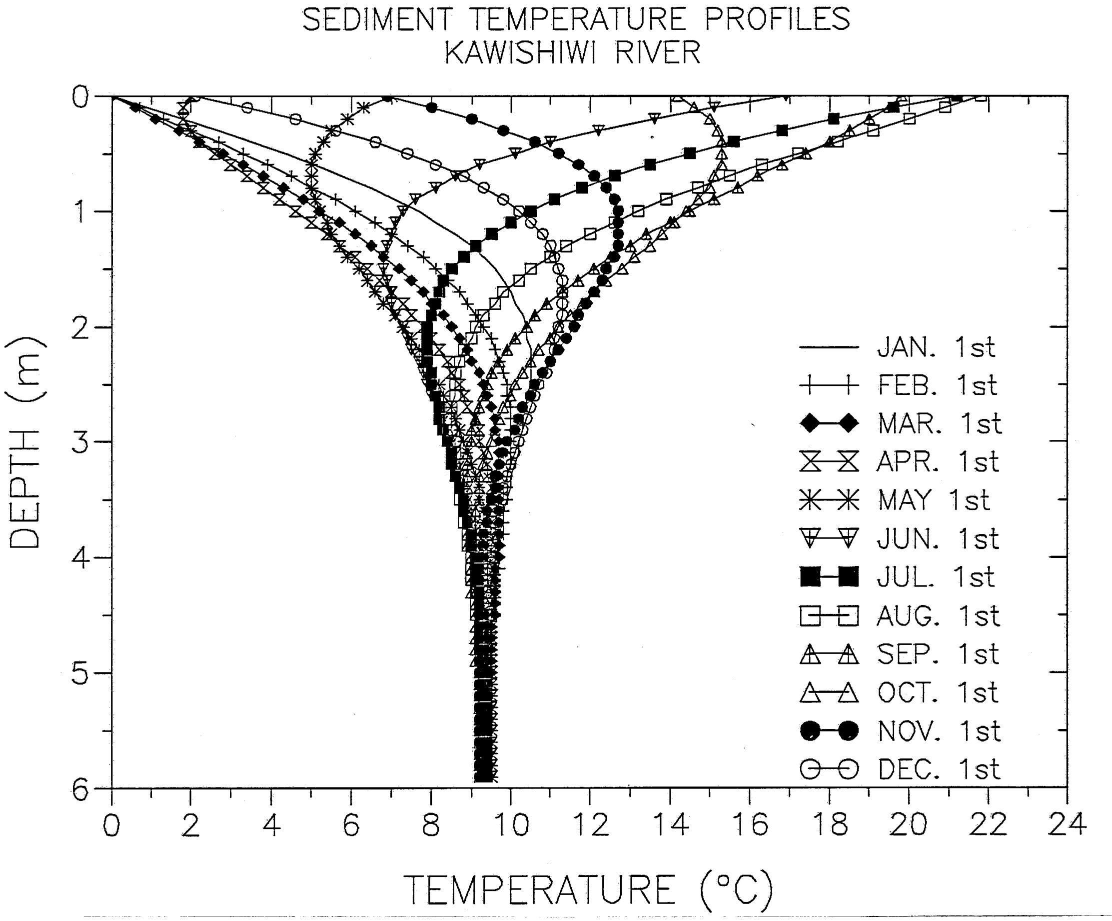


Figure C.2. Calculated streambed temperature profiles for the Kawishiwi River.

Table C-1. Physical properties of different materials

TYPE OF MATERIAL	THERMAL CONDUCTIVITY (W/m.K)	THERMAL DIFFUSIVITY $*10^6$ (m^2/s)	REFERENCE
MUD FLAT	1.82	0.48	Andrews and Rodvey (1980)
SAND	2.5	0.79	
MUD SAND	1.8	0.51	
MUD	1.7	0.45	
WET SAND	1.67	0.70	Geiger (1965)
SAND 23% SATURATION WITH WATER	1.82	1.26	Nakshabandi and Kohnke (1965)
WET PEAT	0.36	0.12	Geiger (1965)
ROCK	1.76	1.18	Chow (1964)
	1.76	1.18	Carslaw and Jaeger (1959)
LOAM 75% SATURATION WITH WATER	1.78	0.60	Nakshabandi and Kohnke (1965)
WATER @ 17°C	0.60	0.14	Incropera and De Witt (1985)
AIR @ 27°C	0.03	22.5	Incropera and De Witt (1985)

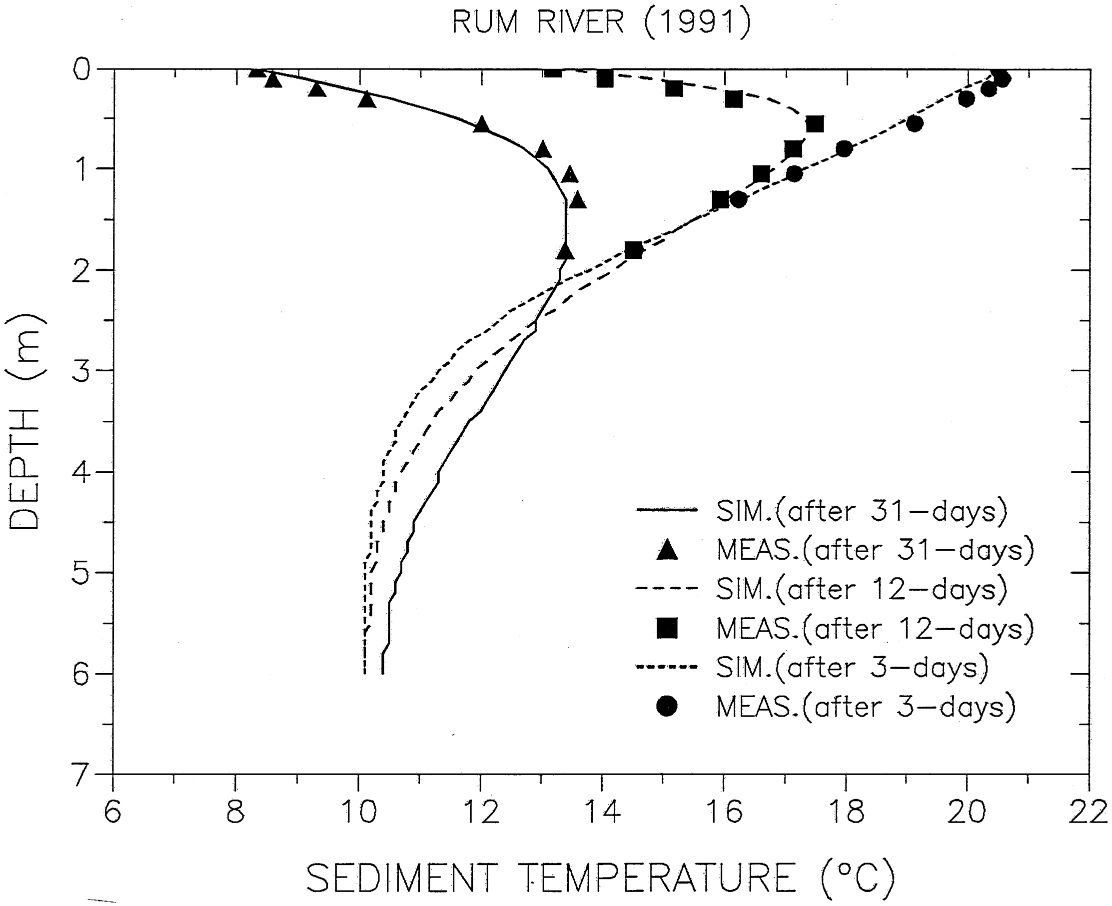


Figure C.3. Comparison between measured and computed streambed temperature profiles on the Rum River.

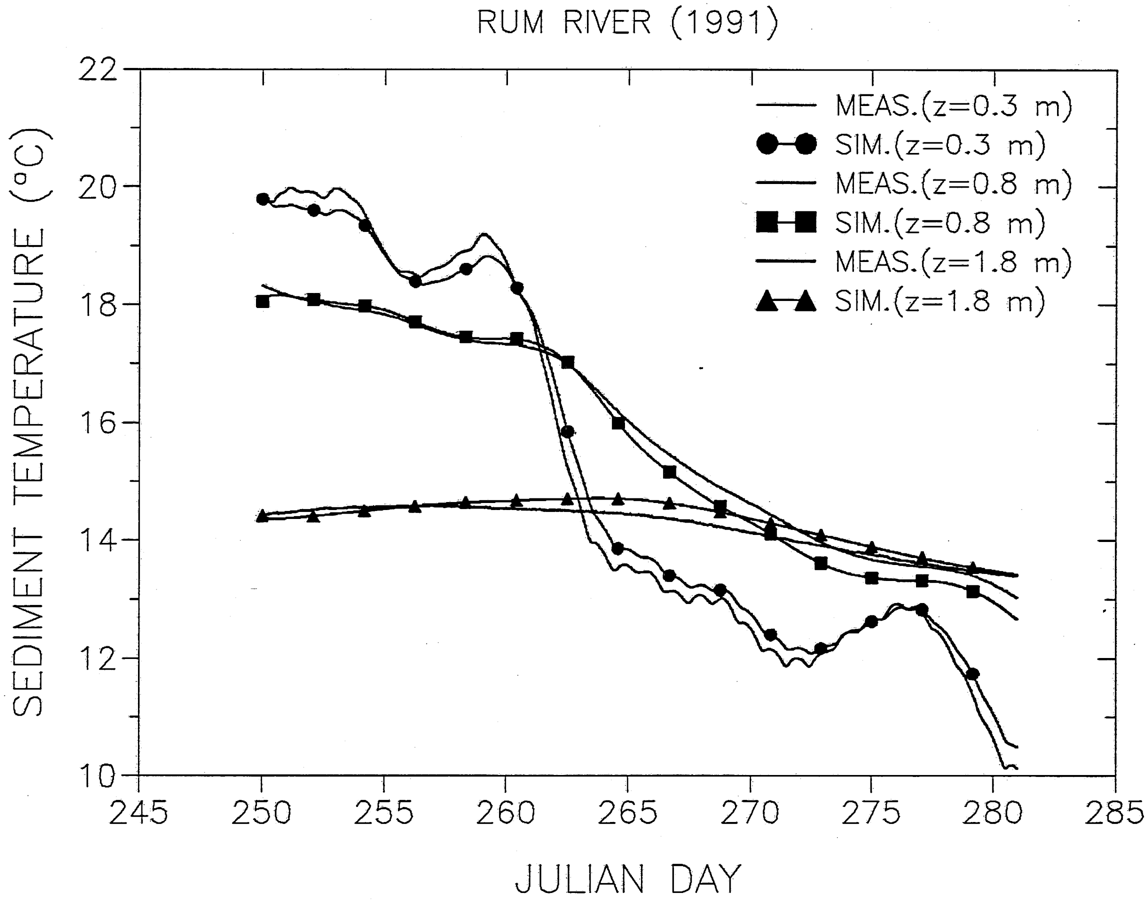


Figure C.4. Comparison between measured and computed streambed temperatures at three different depths (Rum River).

Appendix D

Heat Flux Sensitivity to Weather Parameters

1. Short wave radiation H_s

$$H_s = H_{si}(1-r)\ (1-SF) \qquad \text{(D-1a)}$$

$$\frac{\partial H_s}{\partial T_a} = 0 \qquad \text{(D-1b)}$$

$$\frac{\partial H_s}{\partial RH} = 0 \qquad \text{(D-1c)}$$

$$\frac{\partial H_s}{\partial H_{si}} = (1-r)\ (1-SF) \qquad \text{(D-1d)}$$

$$\frac{\partial H_s}{\partial WS} = 0 \qquad \text{(D-1e)}$$

$$\frac{\partial H_s}{\partial C_c} = 0 \qquad \text{(D-1f)}$$

$$\frac{\partial H_s}{\partial P_a} = 0 \qquad \text{(D-1g)}$$

2. Long wave radiation H_l

$$H_l = \sigma\ (\epsilon_w\ (T_s+273)^4 - \epsilon_a\ (T_a+273)^4\ ) \qquad \text{(D-2a)}$$

$$\frac{\partial H_l}{\partial T_a} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial T_a} - 4\ \sigma\ \epsilon_a\ (T_a+273)^3 \qquad \text{(D-2b)}$$

$$\frac{\partial H_l}{\partial RH} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial RH} \qquad \text{(D-2c)}$$

$$\frac{\partial H_l}{\partial H_{si}} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial H_{si}} \qquad \text{(D-2d)}$$

$$\frac{\partial H_l}{\partial WS} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial WS} \qquad \text{(D-2e)}$$

$$\frac{\partial H_l}{\partial C_c} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial C_c} \qquad \text{(D-2f)}$$

$$\frac{\partial H_s}{\partial P_a} = 4\ \sigma\ \epsilon_w\ (T+273)^3\ \frac{\partial T}{\partial P_a} \qquad \text{(D-2g)}$$

3. Evaporative heat transfer H_e

$$H_e = \rho L(Wftn)_z \, (e_s - e_a) \tag{D-3a}$$

$$\frac{\partial H_e}{\partial T_a} = Wftn\ (L'\ es + L\ es') - Wftn\ (L'\ ea + L\ ea') \tag{D-3b}$$

$$\frac{\partial H_e}{\partial RH} = Wftn\ (L'\ es + L\ es') - Wftn\ (L'\ ea + L\ ea') \tag{D-3c}$$

$$\frac{\partial H_e}{\partial H_{si}} = Wftn\ (L'\ es + L\ es') - Wftn\ (L'\ ea) \tag{D-3d}$$

$$\frac{\partial H_e}{\partial WS} = Wftn\ (L'\ es + L\ es') + Wftn'\ L\ es - Wftn'\ L\ ea - Wftn\ L'\ ea \tag{D-3e}$$

$$\frac{\partial H_e}{\partial C_c} = Wftn\ (L'\ es + L\ es') - Wftn\ (L'\ ea) \tag{D-3f}$$

$$\frac{\partial H_e}{\partial P_a} = Wftn\ (L'\ es + L\ es') - Wftn\ (L'\ ea) \tag{D-3g}$$

$$es' = \frac{\partial es}{\partial p} = es \left[\frac{17.27\ T}{(T + 309)^2} \right] \frac{\partial T}{\partial p} \tag{D-4a}$$

$$ea' = \frac{\partial e a}{\partial RH} = \frac{e_s}{100} + \frac{RH}{100} \frac{\partial e s}{\partial RH} \tag{D-5a}$$

$$L' = \frac{\partial L}{\partial p} = -\ 0.592 \frac{\partial T}{\partial p} \tag{D-6a}$$

$$Wftn' = \frac{\partial Wftn}{\partial WS}\ 0.0053 * (\text{Fraction wind speed}) \tag{D-7a}$$

4. Convective heat transfer H_c

$$H_c = 0.61 \frac{P_a\ (mb)}{1000} \rho L\ Wftn\ (T_s - T_a) \tag{D-8a}$$

$$\frac{\partial H_c}{\partial T_a} = 0.61 \frac{P_a\ (mb)}{1000} Wftn\ (L'\ T + L \frac{\partial T}{\partial T_a}) - 0.61 \frac{P_a\ (mb)}{1000} Wftn\ (L + L'\ T_a) \tag{D-8b}$$

$$\frac{\partial H_c}{\partial RH} = 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ \left(L'\ T + L \frac{\partial T}{\partial RH}\right)$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L'\ T_a \qquad \text{(D–8c)}$$

$$\frac{\partial H_c}{\partial H_{si}} = 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ \left(L'\ T + L \frac{\partial T}{\partial H_{si}}\right)$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L'\ T_a \qquad \text{(D–8d)}$$

$$\frac{\partial H_c}{\partial WS} = 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ \left(L'\ T + L \frac{\partial T}{\partial WS}\right)$$

$$+ 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L\ T$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L'\ T_a$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}'\ L\ T_a \qquad \text{(D–8e)}$$

$$\frac{\partial H_c}{\partial C_c} = 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ \left(L'\ T + L \frac{\partial T}{\partial C_c}\right)$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L'\ T_a \qquad \text{(D–8f)}$$

$$\frac{\partial H_c}{\partial P_a} = 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ \left(L'\ T + L \frac{\partial T}{\partial P_a}\right)$$

$$- 0.61 \frac{P_a\ (mb)}{1000}\ \text{Wftn}\ L'\ T_a$$

$$+ \frac{0.61}{1000}\ \text{Wftn}\ L\ (T - T_a) \qquad \text{(D–8g)}$$

APPENDIX E

PROGRAM LISTING AND EXAMPLES OF INPUT DATA FILES

```
      PROGRAM MNSTREM
      COMMON/A/T(12000,2),TG(1500),TIME,IX,IPOOL,KPOOL,MHOUR
      COMMON/B/TF(12000),TFF(12000,500),TT(12000),RESID(12000),
     &TAV(500,25)
      COMMON/C/TSTART,TLNGTH,IFLAG,JFLAG,KFLAG,JTIME,NSECT,NDELEAT
      COMMON/D/TO(12000),TI(500),TU(500)
      COMMON/E/Q(500),IF(500),NF
      COMMON/F/TA(500),RH(500),RAD(500),W(500),WDIR(500),P(500),CC(500)
      COMMON/G/S(500),SIGMA,DAY1,LAT,ALT,TOLD(600),HS,HE,HLR,HC
      COMMON/H/A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      COMMON/L/AS(90),BS(90),CS(90),FS(90),SS,h,Cks,Fo,Bi
      DIMENSION HEAD(10)
      REAL LAT
C General input data file
      OPEN(UNIT=9,FILE='stractgw.geo',STATUS='OLD')
C Streambed initial temperature profile
      OPEN(UNIT=7,FILE='sinp.prn',STATUS='OLD')
C Weather data file
      OPEN(UNIT=3,FILE='str.dul',STATUS='OLD')
C Upstream inflow temperatures (Optional)
      OPEN(UNIT=8,FILE='lake.prn')
      READ(9,*) DSTAR,TSTART,DELX,DTIME,DAY1,TLNGTH,LAT,ALT
      READ(9,*) DATE,CHDATE,FI
      Cks=1.7          {Thermal conductivity of streambed material}
      ALPHA=1.2E-6     {Thermal diffusivity of streambed material}
      Ckw=0.606        {Thermal conductivity of water}
      DEC=1            {IF 1 then streambed heat flux is included}
      DT=24
      h=1000000000     {Heat convection coefficient}
      Fo=ALPHA*DT*3600/0.1/0.1     {Forier No.}
      Bi=h*0.1/Ckw                 {Biot No.}
C Read initial streambed temperature profile
      DO 101 J=1,61
 101  READ(7,*) FS(J)
C Calculate initial streambed source term
      SS=(FS(2)-FS(1))*Cks*0.23884*0.001/0.1
      LAT=LAT*3.14/180.
      DELX=DELX*.3048
      TLNGTH=TLNGTH*.3048
      READ(9,*) NHOUR,MHOUR,NF,NSECT,IFLAG,JFLAG,KFLAG,LFLAG,NITER
C Read lateral inflow temperature and flow rate
      READ(9,*) GWT,(GWF(I),I=1,NSECT)
      SIGMA=1.17E-7
      NT=NHOUR/MHOUR
      ITEST=0
      ITER=0
      NDELEAT=0
C Read initial temperature
      READ(9,*) TO(1),(TI(I),I=1,NSECT)
      READ(9,830) (HEAD(I),I=1,10)
C Read Global Climate Change coefficients
      READ(9,*) TA3,TA4,TA5,TA6,TA7,TA8,TA9,TA10,TA11
      READ(9,*) SR3,SR4,SR5,SR6,SR7,SR8,SR9,SR10,SR11
```

```
      READ(9,*) RH3,RH4,RH5,RH6,RH7,RH8,RH9,RH10,RH11
      READ(9,*) CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC11
      READ(9,*) WS3,WS4,WS5,WS6,WS7,WS8,WS9,WS10,WS11

C Seasonal variations in sun-shading and wind-sheltering
      READ(9,*) SP1,SP2,FA1,FA2
      READ(9,*) SF1,SF2,WF
      TIME=TSTART+FLOAT(MHOUR)
      DO 4 J=1,NT
      NH=J*MHOUR
      ITER=ITER+1
      IF(TIME.GE.24.) TIME=TIME-24.
C Read weather parameters
      READ(3,*) TA(J),RH(J),W(J),WDIR(J),RAD(J),CC(J)
      P(J)=990.0
      TA(J)=(TA(J)-32.0)*5.0/9.0
      W(J)=W(J)*0.44803
      IF(CC(J).GT.100) CC(J)=100
      CC(J)=CC(J)/100.0
C
      IF (J.LE.SP1)             SFF=SF1
      IF (J.GT.SP1.AND.J.LE.SP2) SFF=SF1-(J-SP1)*(SF1-SF2)/(SP2-SP1)
      IF (J.GT.SP2.AND.J.LE.FA1) SFF=SF2
      IF (J.GT.FA1.AND.J.LE.FA2) SFF=SF2+(J-FA1)*(SF1-SF2)/(FA2-FA1)
      IF (J.GT.FA2)             SFF=SF1
      RAD(J)=RAD(J)*SFF*24.0/DT
      W(J)=W(J)*WF
C
C            ***  FUTURE  CLIMATE  SCENARIO  ***
C
      IF(J.GE.1.AND.J.LE.31) THEN
      TA(J)=TA(J)+TA3
      RAD(J)=RAD(J)*SR3
      RH(J)=RH(J)*RH3
      W(J)=W(J)*WS3
      CC(J)=CC(J)*CC3
      ENDIF
      IF(J.GE.32.AND.J.LE.61) THEN
      TA(J)=TA(J)+TA4
      RAD(J)=RAD(J)*SR4
      RH(J)=RH(J)*RH4
      W(J)=W(J)*WS4
      CC(J)=CC(J)*CC4
      ENDIF
      IF(J.GE.62.AND.J.LE.92) THEN
      TA(J)=TA(J)+TA5
      RAD(J)=RAD(J)*SR5
      RH(J)=RH(J)*RH5
      W(J)=W(J)*WS5
      CC(J)=CC(J)*CC5
      ENDIF
      IF(J.GE.93.AND.J.LE.122) THEN
      TA(J)=TA(J)+TA6
      RAD(J)=RAD(J)*SR6
```

```
      RH(J)=RH(J)*RH6
      W(J)=W(J)*WS6
      CC(J)=CC(J)*CC6
      ENDIF
      IF(J.GE.123.AND.J.LE.153) THEN
      TA(J)=TA(J)+TA7
      RAD(J)=RAD(J)*SR7
      RH(J)=RH(J)*RH7
      W(J)=W(J)*WS7
      CC(J)=CC(J)*CC7
      ENDIF
      IF(J.GE.154.AND.J.LE.184) THEN
      TA(J)=TA(J)+TA8
      RAD(J)=RAD(J)*SR8
      RH(J)=RH(J)*RH8
      W(J)=W(J)*WS8
      CC(J)=CC(J)*CC8
      ENDIF
      IF(J.GE.185.AND.J.LE.214) THEN
      TA(J)=TA(J)+TA9
      RAD(J)=RAD(J)*SR9
      RH(J)=RH(J)*RH9
      W(J)=W(J)*WS9
      CC(J)=CC(J)*CC9
      ENDIF
      IF(J.GE.215.AND.J.LE.245) THEN
      TA(J)=TA(J)+TA10
      RAD(J)=RAD(J)*SR10
      RH(J)=RH(J)*RH10
      W(J)=W(J)*WS10
      CC(J)=CC(J)*CC10
      ENDIF
      IF(J.GE.245.AND.J.LE.275) THEN
      TA(J)=TA(J)+TA11
      RAD(J)=RAD(J)*SR11
      RH(J)=RH(J)*RH11
      W(J)=W(J)*WS11
      CC(J)=CC(J)*CC11
      ENDIF
      IF(CC(J).GT.1.0) CC(J)=1.0
C
C
      TIME=TIME+FLOAT(MHOUR)
 4    CONTINUE
      IF(IFLAG.EQ.0) GOTO 7
      IT=0
      DO 5 J=1,NT
      NH=J*MHOUR
      READ(9,*) TO(NH+1),(TT(I),I=IT+1,IT+NSECT)
 5    IT=IT+NSECT
C Input or read upstream water temperatures
 7    DO 33 JJ=1,NHOUR+1
 33   TO(JJ)=TO(1)
C 7    DO 33 JJ=1,NT
```

```
C      READ(5,*) JD,EP,TU(JJ)
C      DO 33 I=1,24
C      J=(JJ-1)*24+I
C      TO(J)=TU(JJ)
C 33   CONTINUE
C      TO(NHOUR+1)=TO(NT)
      DO 10 I=1,NT
      IF(I)=24
 10   Q(I)=24.0
      IF(JFLAG.EQ.1) GO TO 40
      IF(KFLAG.NE.1) GO TO 40
      READ(9,*) (DL(I),I=1,NSECT)
 40   CONTINUE
      CALL TEMP(NT,DSTAR,ITEST,ERRMAX,SUMERR,IT,NITER)
      M=NT*NSECT-NDELEAT
      CALL PRNOUT(NT,M,DATE,CHDATE)
      IF(LFLAG.NE.1) STOP
      ITEST=1
      SUMERR=0.0
      ERRMAX=0.0
      DTIME=DTIME/2.
      CALL TEMP(NT,DSTAR,ITEST,ERRMAX,SUMERR,IT,NITER)
      ERRMEAN=SQRT(SUMERR/FLOAT(IT))
      STOP
 830  FORMAT(10A8)
      END
C
      SUBROUTINE PRNOUT(NT,M,DATE,CHDATE)
      COMMON/A/ T(12000,2),TG(1500),TIME,IX,IPOOL,KPOOL,MHOUR
      COMMON/B/ TF(12000),TFF(12000,500),TT(12000),RESID(12000),
     &TAV(500,25)
      COMMON/C/ TSTART,TLNGTH,IFLAG,JFLAG,KFLAG,JTIME,NSECT,NDELEAT
      COMMON/D/ TO(12000),TI(500),TU(500)
      COMMON/G/S(500),SIGMA,DAY1,LAT,ALT,TOLD(600),HS,HE,HLR,HC
      COMMON/H/ A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME ,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      MONTH=DATE
      IT=1
      TIME=TSTART
      WRITE(8,*) (I,I=0,300,5)
   9  FORMAT(61I4)
      DO 120 L=1,NT
      TIME=TIME+FLOAT(MHOUR)
      IF(TIME.LT.24.) GO TO 112
      TIME = TIME-24.
      DATE=DATE+0.01
      IF (DATE-FLOAT(MONTH).GT.CHDATE) DATE=FLOAT(MONTH)+1.01
      MONTH =DATE
 112  NH=L*MHOUR
      JD=L+59
      WRITE (8,8) JD,TO(1),(TFF(I,L),I=5,150,5)
 8    FORMAT(I4,31(1xF4.1))
      IF(IFLAG.EQ.0) GO TO 115
 115  IT=IT+NSECT
```

```
 120  CONTINUE
      DO 121 L=1,NT
      JD=L+59
      WRITE (8,81) JD,(TFF(I,L),I=155,300,5)
 81   FORMAT(I4,30(1xF4.1))
 121  CONTINUE
      IF(IFLAG.EQ.0) RETURN
      SUM=0.0
      DO 140 I=1,M
 140  SUMF=SUMF+RESID(I)**2
      VAR=SUMF/(M-1)
      STD=SQRT(VAR)
      RETURN
      END
C
      SUBROUTINE TEMP(NT,DSTAR,ITEST,ERRMAX,SUMERR,IT,NITER)
      EXTERNAL ITEMP,QRATE,HFLUX,DISPERS,UPSTREM
      COMMON/A/ T(12000,2),TG(1500),TIME,IX,IPOOL,KPOOL,MHOUR
      COMMON/B/ TF(12000),TFF(12000,500),TT(12000),RESID(12000),
     &TAV(500,25)
      COMMON/C/ TSTART,TLNGTH,IFLAG,JFLAG,KFLAG,JTIME,NSECT,NDELEAT
      COMMON/D/ TO(12000),TI(500),TU(500)
      COMMON/G/ S(500),SIGMA,DAY1,LAT,ALT,TOLD(600),HS,HE,HLR,HC
      COMMON/H/ A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME ,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      COMMON/L/AS(90),BS(90),CS(90),FS(90),SS,h,Cks,Fo,Bi
      DIMENSION Z(500),G(500),F(500),TITER(600)
C
      DO 303 J=2,60
      AS(J)=-Fo
      CS(J)=-Fo
      BS(J)=1+2*Fo
 303  CONTINUE
      AS(1)=0.0
      AS(61)=-Fo
      CS(1)=-2*Fo
      CS(61)=0.0
      BS(1)=1+2*Fo+2*Fo*Bi
      BS(61)=1+Fo
C
      ISED=0
 111  ROECP=1000.
      IX=TLNGTH/DELX+.1
      IPOOL=IX/NSECT
      KPOOL=FLOAT(IPOOL)/2.+.6
      JJ=1
      TIME=TSTART
      IT=1
      CALL ITEMP
      NH=0
      DO 300 LOOP=1,NT
      ISED=ISED+1
      MFLAG=0
      DO 5 I=1,IX
```

```
      TITER(I)=T(I,1)
    5 TOLD(I)=T(I,1)
      CALL HFLUX(LOOP,MFLAG)
      MFLAG=1
C       WRITE(8,88)HS,HE,HLR,HC
   88  FORMAT(4F10.2)
   89  DO 98 I=1,IX
   98  TAV(I,1)=0.
      DO 200 ILOOP=1,MHOUR
      NH=NH+1
      DTIME=3600.
      JTIME=3600./DTIME+.1
      CALL QRATE(FLOW,NH)
      QT=FLOW
      DO 12 MM=1,NSECT
      DO 12 MMM=1,IPOOL
      M=MMM+IPOOL*(MM-1)
      IF(M.EQ.1)THEN
      QQ(M)=QT
      ELSE
      QQ(M)=QQ(M-1)+GWF(MM)/FLOAT(IPOOL)
      ENDIF
   12  CONTINUE
      QQ(IX+1)=QQ(IX)+GWF(NSECT)/FLOAT(IPOOL)
      SUMB=0.0
      DO 13 IAB=1,IX+1
      QGWF=QQ(IAB)/45.0
      A(IAB)=(39.0*QGWF**(3/5))*0.3048*0.3048
      B(IAB)=(45.0)*0.3048
      SUMB=B(IAB)+SUMB
      QQ(IAB)=QQ(IAB)*0.3048**3
   13  CONTINUE
      BBAR=SUMB/(IX+1)
      IF(KFLAG.EQ.1) GO TO 25
      DO 20 K=1,IX
   20  DL(K)=DSTAR*QQ(K)/BBAR
   25  DO 30 K=1,IX
      FC(K)=DTIME/A(K)/DELX*FI
      PE(K)=QQ(K)*DELX/A(K)/DL(K)
   30  CONTINUE
   35  DO 200 J=1,JTIME
      TIME=TIME+1./FLOAT(JTIME)
      IF(TIME.GE.24.) TIME=TIME-24.
      R=1.-FLOAT(J)/FLOAT(JTIME)
C       T(1,JJ+1)=R*NT+(1.-R)*TO(NH+1)
      T(1,JJ+1)=R*TO(NH)+(1.-R)*TO(NH+1)
      T(1,JJ+1)=T(1,JJ+1)+0.2
      I=2
      K=1
      L=0
      IF(JFLAG.EQ.0) CALL DISPERS(K,L)
      IF(JFLAG.NE.0) CALL UPSTREM(K)
      Z(I)=T(I,1)+(1.-FI)/FI*(AK(K)*QQ(I-1)*T(I-1,1)-
     1 (AK(K)+CK(K))*QQ(I)*T(I,1)+
```

```
    2 CK(K)*QQ(I+1)*T(I+1,1))+S(K)*B(I)*DTIME/(A(I))/ROECP
     G(2)=(Z(2)+AK(K)*QQ(1)*T(1,2))/BK(K)/QQ(1)
     F(2)=-CK(K)/BK(K)
     DO 110 I=3,IX-1
     K=I-1
     L=0
     IF(I.EQ.IPOOL*(K-1)+1) L=1
     IF(JFLAG.EQ.0) CALL DISPERS(K,L)
     IF(JFLAG.NE.0) CALL UPSTREM(K)
     Z(I)=T(I,1)+(1.-FI)/FI*(AK(K)*QQ(I-1)*
    1 T(I-1,1)-(AK(K)+CK(K))*QQ(I)*T(I,1)+CK(K)
    2 *QQ(I+1)*T(I+1,1))+S(K)*B(I)*DTIME/(A(I))/ROECP
     G(I)=(Z(I)+AK(K)*QQ(I-1)*G(I-1))/(BK(K)+AK(K)*F(I-1))/QQ(I-1)
110  F(I)=-CK(K)/(BK(K)+AK(K)*F(I-1))
     I=IX
     K=IX-1
     L=0
     IF(JFLAG.EQ.0) CALL DISPERS(K,L)
     IF(JFLAG.NE.0) CALL UPSTREM(K)
     T(I+1,1)=T(I,1)*2.-T(I-1,1)
     Z(I)=T(I,1)+(1.-FI)/FI*(AK(K)*QQ(I-1)*T(I-1,1)-
    1 (AK(K)+CK(K))*QQ(I)*T(I,1)+
    2 CK(K)*QQ(I+1)*T(I+1,1))+S(K)*B(I)*DTIME/(A(I))/ROECP
     G(I)=((AK(K)-CK(K))*QQ(I-1)*G(I-1)+Z(I))/
    1 (BK(K)-2.*CK(K)+(AK(K)-CK(K))*F(I-1))/QQ(I-1)
     T(IX,JJ+1)=G(IX)
     DO 130 I=1,IX-2
130  T(IX-I,JJ+1)=G(IX-I)-F(IX-I)*T(IX-I+1,JJ+1)
     DO 333 I=2,IX
333  T(I,JJ+1)=((QQ(I)-QQ(I-1))*GWT+QQ(I-1)*T(I,JJ+1))/QQ(I)
     DO 140 I=1,IX
C
     IF(T(I,JJ+1).LT.0) T(I,JJ+1)=0.0
C
140  T(I,JJ)=T(I,JJ+1)
     DO 141 I=1,IX
141  TAV(I,ILOOP+1)=TAV(I,ILOOP)+T(I,JJ)
     CALL HFLUX(LOOP,MFLAG)
200  CONTINUE
     IF(MFLAG.EQ.NITER) GO TO 202
     NFLAG=0
     DO 2005 I=1,IX
2005 IF(ABS(T(I,2)-TITER(I)).GT.0.1) NFLAG=1
     IF(NFLAG.EQ.0) GO TO 202
     MFLAG=MFLAG+1
     TIME=TIME-FLOAT(MHOUR)
     NH=NH-MHOUR
     CALL HFLUX(LOOP,MFLAG)
     DO 201 I=1,IX
     TITER(I)=T(I,2)
201  T(I,1)=TOLD(I)
     GO TO 89
202  IF(ISED.EQ.1) GO TO 222
C     WRITE(3,*) S(1)
```

```
222  CONTINUE
     DO 220 I=IT,IT+NSECT-1
     II=(I-IT+1)*IPOOL-KPOOL+1
     IF(ITEST.NE.1) GO TO 205
     ERR=ABS(T(II,JJ)-TF(I))
     IF(ERR.GT.ERRMAX) ERRMAX=ERR
     SUMERR=SUMERR+ERR**2
     GO TO 220
205  DO 207 IJI=1,IX
207  TFF(IJI,LOOP)=TAV(IJI,MHOUR+1)/MHOUR
C
C   SEDIMENT HEAT FLUX CALCULATIONS
C
     FS(1)=2*Fo*Bi*TFF(I,LOOP)+TFF(I,LOOP)
     DO 102 J=2,61
     AS(J)=AS(J)/BS(J-1)
     BS(J)=BS(J)-AS(J)*CS(J-1)
102  FS(J)=FS(J)-AS(J)*FS(J-1)
     FS(61)=FS(61)/BS(61)
     DO 103 J=60,1,-1
103  FS(J)=(FS(J)-CS(J)*FS(J+1))/BS(J)
     SS=(FS(2)-FS(1))*Cks*0.23884*0.001/0.1
     IF(DEC.EQ.0) THEN
     SS=0.0
     ENDIF
     FS(1)=FS(1)+2*Fo*Bi*TFF(I,LOOP)
C
     DO 306 J=2,60
     AS(J)=-Fo
     CS(J)=-Fo
     BS(J)=1+2*Fo
306  CONTINUE
     AS(1)=0.0
     AS(61)=-Fo
     CS(1)=-2*Fo
     CS(61)=0.0
     BS(1)=1+2*Fo+2*Fo*Bi
     BS(61)=1+Fo
C
     IF(ISED.EQ.1) GO TO 111
C
C END OF SEDIMENT HEAT FLUX CALCULATIONS
C

     TF(I)=T(II,JJ)
     IF(IFLAG.EQ.0) GO TO 220
     RESID(I)=TF(I)-TT(I)
     IF(TT(I).GT.4.5) GO TO 220
     RESID(I)=0.0
     NDELEAT=NDELEAT+1
220  CONTINUE
     IT=IT+NSECT
300  CONTINUE
     RETURN
```

```
      END
C


      SUBROUTINE ITEMP
      COMMON/A/ T(12000,2),TG(1500),TIME,IX,IPOOL,KPOOL,MHOUR
      COMMON/D/ TO(12000),TI(500),TU(500)
      I=1
      II=1
      DO 40 J=2,IX
      R=FLOAT(J-1)/FLOAT(IX-1)
      T(J,1)=TO(1)*(1.-R)+R*TI(I)
      GO TO 40
 40   CONTINUE
      RETURN
      END
C
      SUBROUTINE QRATE(FLOW,NH)
      COMMON/C/ TSTART,TLNGTH,IFLAG,JFLAG,KFLAG,JTIME,NSECT,NDELEAT
      COMMON/H/ A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME ,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      COMMON/E/ Q(500),IF(500),NF
      IFF=1
      DO 10 I=1,NF+1
      IF(IFF+IF(I).LT.NH) GO TO 5
      IF(IFF.GT.NH) GO TO 10
      FLOW=Q(I)
 5    IFF=IFF+IF(I)
 10   CONTINUE
      RETURN
      END
C
      SUBROUTINE HFLUX(NH,MFLAG)
      COMMON/A/ T(12000,2),TG(1500),TIME,IX,IPOOL,KPOOL,MHOUR
      COMMON/C/TSTART,TLNGTH,IFLAG,JFLAG,KFLAG,JTIME,NSECT,NDELEAT
      COMMON/F/TA(500),RH(500),RAD(500),W(500),WDIR(500),P(500),CC(500)
      COMMON/G/S(500),SIGMA,DAY1,LAT,ALT,TOLD(600),HS,HE,HLR,HC
      COMMON/L/AS(90),BS(90),CS(90),FS(90),SS,h,Cks,Fo,Bi
      REAL LAT
      IF(MFLAG.GE.1) GO TO 8
      C1=1.0
      C2=1.0
      IF(RAD(NH).GE.0.0) GO TO 5
      HS=RAD(NH)
      GO TO 7
 5    HOUR1=0.262*(TIME-12.)
      IF(HOUR1.LT.0.0) C1=-C1
      HOUR2=0.262*(TIME+FLOAT(MHOUR)-12.)
      IF(HOUR2.LT.0.0) C2=-C2
      DAY=DAY1+FLOAT(NH*MHOUR/24)
      SUNDEC=0.409*COS(0.0172*(172.-DAY))
      HOURO=ACOS(-SIN(LAT)*SIN(SUNDEC)/COS(LAT)/COS(SUNDEC))
      IF(COS(HOUR1).LT.COS(HOURO)) HOUR1=C1*HOURO
      IF(COS(HOUR2).LT.COS(HOURO)) HOUR2=C2*HOURO
```

```
      SINA=((HOUR2-HOUR1)*SIN(LAT)*SIN(SUNDEC)+(SIN(HOUR2)-
     &SIN(HOUR1))*COS(LAT)*COS(SUNDEC))/FLOAT(MHOUR)/0.262
      IF(SINA.LE.0.0) SINA=1.E-40
      HSO=2880.*SINA/(1.+0.017*COS(0.0172*(186.-DAY)))**2
      FALT=(1.-2.26E-5*ALT)**5.256
      AMASS=FALT/(SINA+0.15/(ASIN(SINA)+3.885)**1.253)
      CRH=1.-RH(NH)/100.
      TDEW=TA(NH)-CRH*(14.55+0.114*TA(NH))-
     &(CRH*(2.5+.007*TA(NH)))**3-(15.9+0.117*TA(NH))*CRH**14
      AMC=0.85*EXP(0.11+0.0614*TDEW)
      A1=EXP(AMASS*(-0.465-0.130*AMC)*(0.179+0.421
     &*EXP(-.721*AMASS)))
      A2=EXP(AMASS*(-0.465-0.134*AMC)*(0.129+0.171
     &*EXP(-.880*AMASS)))
      HSM=HSO*(A1+0.5*(1.-A2))
      IF(RAD(NH).GT.HSM) GO TO 6
      CR=1.-RAD(NH)/HSM
    6 IF(RAD(NH).GT.HSM) CR=0.0
      A=2.20+CR**0.7/4.-(CR**0.7-0.4)**2/0.16
      B=-1.02+CR**0.7/16.+(CR**0.7-0.4)**2/0.64
      R=A*(ASIN(SINA)*57.3)**B
      IF(R.GT.1.0) R=1.0
      HS=(1.-R)*RAD(NH)
    7 ESA=6.1078*EXP(17.26939*TA(NH)/(TA(NH)+309.))
      EA=ESA*RH(NH)/100.
      EPS=(1.+0.17*CC(NH)**2)*(1.-0.261*EXP(-7.77E-4*TA(NH)**2))
    8 DO 10 I=1,IX
      II=I
      TWS=(T(II,1)+TOLD(II))/2.
      HLR=SIGMA*0.97*((TWS+273.)**4-EPS*(TA(NH)+273.)**4)
      ES=6.1078*EXP(17.26939*TWS/(TWS+309.))
      DELTV=(TWS+273.2)*(1.+0.378*ES/P(NH))-(TA(NH)+273.2)
     $*(1.+0.378*EA/P(NH))
      IF(DELTV.LE.0.0) DELTV=1.E-40
      WFTN=0.0096*DELTV**(1./3.)+0.0053*W(NH)
      E=WFTN*(ES-EA)
      CL=597.5-0.592*TWS
      HE=E*CL
      HC=0.61*P(NH)/1000.*WFTN*(TWS-TA(NH))*CL
      S(I)=(HS-HE-HLR-HC)*10./3600./24.
      S(I)=S(I)+SS
C       TO USE THE MODEL FOR ROUTING SET : S(I)=0
C        S(I)=0
   10  CONTINUE
      RETURN
  100  FORMAT(I5,13F10.4)
      END
C
      SUBROUTINE DISPERS(K,L)
      COMMON/H/A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME ,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      AK(K)=FC(K)*(1.+AMAX1(0.,(1.-0.1*PE(K-L))**5/PE(K-L)))
      CK(K)=FC(K)*AMAX1(0.,(1.-0.1*PE(K))**5/PE(K))
      BK(K)=1./QQ(K)+AK(K)+CK(K)
```

```
      RETURN
      END
C
      SUBROUTINE UPSTREM(K)
      COMMON/H/A(500),B(500),AK(500),BK(500),CK(500),DL(500),DELX,
     $DTIME ,PE(500),FC(500),FI,DEC,GWF(3000),GWT,QQ(6000)
      AK(K)=FC(K)
      CK(K)=0.0
      BK(K)=1./QQ(K)+AK(K)
      RETURN
      END
```

General input data file

```
DSTAR,TSTART,DELX,DTIME,DAY1,TLNGTH,LAT,ALT
DATE,CHDATE,FI
NHOUR,MHOUR,NF,NSECT,IFLAG,JFLAG,KFLAG,LFLAG,NITER
GWT,(GWF(I),I=1,NSECT)
TO(1),(TI(I),I=1,NSECT)
HEADING (TITLE)
GLOBAL CLIMATE CHANGE COEFFICIENTS (OPTIONAL)
SEASONAL VARIATIONS IN SUN-SHADING AND WIND-SHELTERING
```

Example 1: Straight River (August 1-20, 1989)

```
 7.47  0    1000  3600  213  16000  46.91  1460
 8.1   0.31  0.5
 480   24   20    1    0  1    0      0      50
 23.35  22.99
AUG 1-20, 1989
Note: Weather data
   28.61    75.00   574.20    5.02    24.25   990.00    0.26
   28.24    70.63   568.39    5.78    22.38   990.00    0.16
   30.24    76.63   331.28    5.34    21.13   990.00    0.43
   26.20    67.50   519.02    4.00    25.75   990.00    0.41
   18.07    75.13   561.02    5.65    26.38   990.00    0.58
   16.46    70.25   466.59    3.88    25.63   990.00    0.33
   17.93    62.63   601.82    3.62    32.00   990.00    0.51
   20.24    69.38   559.30    2.03    24.38   990.00    0.76
   21.18    68.50   575.59    1.27    11.00   990.00    0.26
   22.94    55.25   569.01    2.80    19.13   990.00    0.20
   22.25    59.75   538.31    2.79    16.88   990.00    0.36
   22.60    75.38   184.81    3.49    15.88   990.00    0.84
   20.92    89.13   500.09    1.84     8.50   990.00    0.96
   19.71    95.13   201.98    2.67     4.63   990.00    1.00
   18.53    82.25   336.03    1.97    17.88   990.00    0.55
   18.14    72.50   569.76    2.35    18.50   990.00    0.06
   20.55    78.88   538.99    3.69    11.75   990.00    0.70
   23.93    69.75   507.51    4.32    15.88   990.00    0.59
   21.77    88.75   126.54    4.45    21.88   990.00    1.00
   16.32    85.50   528.29    3.62    30.50   990.00    0.73
```

Note: Upstream inflow temperatures

```
23.35  23.35  22.78  22.78  22.16  22.16  21.51  21.51  21.05  21.05  21.58  21.58
23.01  23.01  24.76  24.76  26.04  26.04  26.49  26.49  26.16  26.16  25.64  25.64
25.05  25.05  24.32  24.32  23.51  23.51  22.67  22.67  22.12  22.12  22.53  22.53
23.59  23.59  24.95  24.95  26.24  26.24  26.51  26.51  26.23  26.23  25.71  25.71
25.2   25.2   24.49  24.49  23.83  23.83  23.26  23.26  22.76  22.76  22.86  22.86
24.42  24.42  26.26  26.26  27.66  27.66  28.12  28.12  27.83  27.83  27.38  27.38
26.51  26.51  25.37  25.37  24.33  24.33  23.29  23.29  22.65  22.65  22.88  22.88
23.44  23.44  24.21  24.21  24.85  24.85  25.23  25.23  24.79  24.79  24.18  24.18
23.43  23.43  22.45  22.45  21.36  21.36  20.35  20.35  19.54  19.54  19.03  19.03
18.97  18.97  19.31  19.31  19.26  19.26  19.06  19.06  18.56  18.56  17.95  17.95
17.26  17.26  16.49  16.49  15.69  15.69  14.94  14.94  14.54  14.54  15.2   15.2
16.52  16.52  17.71  17.71  18.86  18.86  19.56  19.56  19.37  19.37  18.78  18.78
18.05  18.05  17.14  17.14  16.12  16.12  15.08  15.08  14.46  14.46  15.1   15.1
16.77  16.77  18.89  18.89  20.62  20.62  21.04  21.04  20.84  20.84  20.33  20.33
19.61  19.61  18.63  18.63  17.58  17.58  16.61  16.61  16.07  16.07  16.69  16.69
18.38  18.38  20.38  20.38  22.03  22.03  22.67  22.67  22.48  22.48  21.95  21.95
21.03  21.03  19.81  19.81  18.51  18.51  17.27  17.27  16.46  16.46  16.98  16.98
18.79  18.79  21.04  21.04  22.87  22.87  23.4   23.4   23.15  23.15  22.4   22.4
21.58  21.58  20.55  20.55  19.28  19.28  17.99  17.99  17.17  17.17  17.73  17.73
19.45  19.45  21.63  21.63  23.13  23.13  23.81  23.81  23.64  23.64  23.06  23.06
22.25  22.25  21.29  21.29  20.2   20.2   19.13  19.13  18.43  18.43  18.74  18.74
20.12  20.12  22.06  22.06  22.62  22.62  22.09  22.09  21.86  21.86  21.35  21.35
20.68  20.68  20     20     19.34  19.34  18.62  18.62  18.18  18.18  18.92  18.92
20.44  20.44  22.29  22.29  24.22  24.22  24.79  24.79  24.22  24.22  23.46  23.46
22.47  22.47  21.2   21.2   19.93  19.93  18.82  18.82  18.17  18.17  18.73  18.73
20.33  20.33  22.37  22.37  22.64  22.64  21.98  21.98  21.55  21.55  20.86  20.86
20.04  20.04  19.3   19.3   18.65  18.65  18.11  18.11  17.76  17.76  17.8   17.8
18.73  18.73  19.97  19.97  21.26  21.26  21.72  21.72  21.23  21.23  20.32  20.32
19.26  19.26  18.33  18.33  17.58  17.58  16.97  16.97  16.6   16.6   16.92  16.92
17.69  17.69  19.47  19.47  21.41  21.41  21.91  21.91  21.71  21.71  20.81  20.81
19.45  19.45  18.09  18.09  16.86  16.86  15.76  15.76  15.05  15.05  15.69  15.69
17.57  17.57  19.93  19.93  21.95  21.95  22.88  22.88  22.55  22.55  21.52  21.52
20.23  20.23  18.89  18.89  17.6   17.6   16.43  16.43  15.67  15.67  16.23  16.23
18.02  18.02  20.25  20.25  21.76  21.76  22.46  22.46  22.05  22.05  21.26  21.26
20.2   20.2   19.11  19.11  18.12  18.12  17.27  17.27  16.73  16.73  17.26  17.26
18.97  18.97  21.13  21.13  22.78  22.78  23.26  23.26  22.73  22.73  21.77  21.77
20.74  20.74  19.74  19.74  18.82  18.82  18.25  18.25  17.9   17.9   17.88  17.88
18.57  18.57  20.5   20.5   22.24  22.24  22.8   22.8   22.43  22.43  21.56  21.56
20.48  20.48  19.38  19.38  18.39  18.39  17.47  17.47  16.73  16.73  16.78  16.78
17.95  17.95  19.86  19.86  21.58  21.58  22.11  22.11  21.54  21.54  20.41  20.41
20.41
```

Note: Stream flow rate (cfs)

```
35    35.5  34.5  36    38    36    34.5  33.5  34    34
35.5  36    38    42    40    38    39    37    40.5  41
```

Note: Stream flow rate duration (hours)

```
24    24    24    24    24    24    24    24    24    24
24    24    24    24    24    24    24    24    24    24
```

Note: Stream surface width (ft) and cross-sectional area (ft^2)

```
39
45
```

Note: Sun-shading and wind-sheltering coefficients have to specified

Example 2: Straight River (stractgw.geo)

Simulation of the Straight River water temperature profile under GISS ($2xCO_2$) climate scenario with upstream and lateral groundwater inflow.

```
7.47  0  1000  3600  60  320000  46.91  1460
4.1  0.3  0.5
6600  24  275  40  0  1  0  0  50
10.8  3.0 3.0 3.0 3.0 3.0 3.0 3.0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
10.8  1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
      1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
MAR.1-NOV.30
      4.80    4.97    1.54    3.51    2.59    2.80    3.96    3.89    5.93
      1.04    1.00    1.04    1.00    0.97    0.98    1.01    0.97    0.95
      1.24    1.00    1.04    1.15    0.99    1.04    0.94    1.02    1.00
      0.86    0.93    0.90    0.95    1.11    1.04    0.99    0.95    1.01
      0.82    0.85    0.57    0.74    0.75    0.88    0.81    0.73    1.06
64 84 193 213
0.9 0.4 0.35
```

APPENDIX F

Coefficients (a and n) for $X=aQ^n$

River	Width (W)		Cross-sectional Area (A)	
	a	n	a	n
Baptism	3.36	0.26	1.73	0.71
Clearwater	5.32	0.13	2.50	0.65
Zumbro	5.52	0.10	1.81	0.69
Mississippi	4.24	0.36	0.51	1.00

$W(ft) = aQ^n$

$A(ft^2) = aQ^n$

Q is flow rate in cfs.