

Chapter 3

Continuous In-stream Temperature Modeling: Integration with a Physically-based Subwatershed Hydrology Model

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In the past four years, several integrated watershed management studies (e.g. Laurel Creek; Hanlon Creek; Blair, Bechtel, and Bauman Creeks; and Mill Creek) have been conducted in southwestern Ontario. Elevated stream temperature is a key water quality stressor for causing degraded aquatic biota. Discharges from urban drainage and aggregate extraction activities contribute to aquatic biota degradation, since runoff and detention pond releases elevate in-stream temperatures. This chapter describes a simple continuous in-stream temperature model that has been integrated with the existing GAWSER (Guelph All-Weather Sequential-Events Runoff V6.4) model to evaluate the impacts of elevated stream temperatures on aquatic biota in developing subwatersheds.

The chapter gives a brief overview of the hydrologic computations available in GAWSER. The corresponding in-stream temperature (energy exchange) processes for the major hydrologic sources (and sinks) within a watershed (e.g. rain and snowmelt runoff, subsurface and groundwater baseflow, evapotranspiration, channel routing elements, reservoirs, and recharge ponds) are outlined in detail. The model uses vegetative canopy information in computing the energy exchange process at the air-water interface. Early results of applying the model to the Blair and Bechtel Creeks subwatersheds are presented.

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3.1 Blair, Bechtel, and Bauman Creeks Watersheds Study

Blair, Bechtel, and Bauman Creeks (Figure 3.1) drain a combined area of about 25.8 km² within the Regional Municipality of Waterloo, in southwestern Ontario. The diverse natural resources in the the creeks' watersheds provide important functions to meet ecological and human needs. Competing interests associated with these resources, particularly urban development and aggregate extraction activities, led to the present subwatershed planning study (CH2M HILL, 1995). The GAWSER model is being used to estimate changes in surface water quality resulting from existing or proposed land use activities in the area. Temperature calculations were included in the GAWSER model framework.

Blair Creek drains an approximate 18.5 km² area. It is about 9 km in length and originates in the ice-contact sands and gravels of the Waterloo Moraine. From its headwaters in the south end of Kitchener, it travels eastward through the Roseville Swamp and then in a northeastern direction through outwash terraces and kames in the village of Blair within the City of Cambridge (see Figure 3.1). Wetlands adjacent to the upper part of Blair Creek are part of the Class I Roseville Swamp-Cedar Creek wetland complex, whereas the wetlands in the lower section of Blair Creek are part of the Class 2 Blair Creek wetland. (The Ontario Ministry of Natural Resources classifies wetlands on their biological, social and hydrological value. The first three of the six classes are provincially significant).

Bechtel Creek drains an area of about 2 km² and travels primarily in a northern direction to the Grand River through surficial outwash terraces and kames with gravel in the south and sand in the north. The creek is about 4 km long. The Class 3 Orr's Lake/Bechtel Creek wetland is adjacent to the creek for much of its length. The creek is ephemeral throughout most of this wetland complex. Numerous aggregate extraction activities exist within the subwatershed area.

Figures 3.2 and 3.3 illustrate the variation in stream temperature throughout the length of Blair and Bechtel Creeks, for three dates in the 1994 sampling year. In Blair Creek (Figure 3.2), the water temperatures increase as the stream travels toward the Grand River. Around Roseville Swamp, temperatures are lower due to regional groundwater flow in this area. Runoff from the highway easement and several mill ponds elevate temperatures downstream of Highway 401. In Bechtel Creek (Figure 3.3), stream temperatures are highest in the headwaters due to Orr's Lake, low in the central part of the creek where groundwater discharge is predominant, and elevated near the outlet due to three man-made mill ponds.

3.2 Review of Processes

This review provides a framework for formulating the model. A brief overview of the GAWSER program is provided, followed by a qualitative description of the thermal budget within a subwatershed identifying the major energy exchange processes that need to be modeled.

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- Sources:
 1. 1:10 000 Digital Ontario Base Map Series (1983).
 2. O.M.N.R. 1:10 000 Mapping.
 3. Consultant Inventory/Air Photo Analysis.

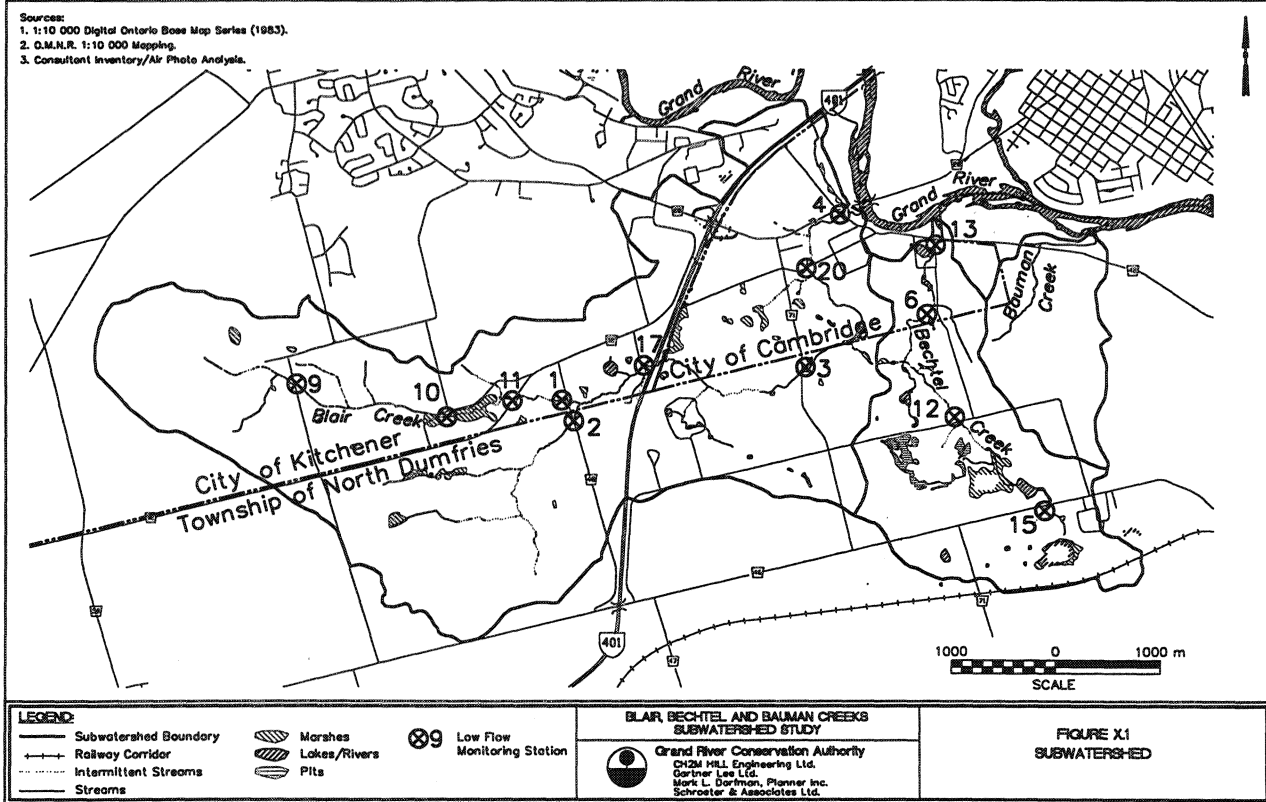


Figure 3.1 Blair, Bechtel and Bauman Creek area.

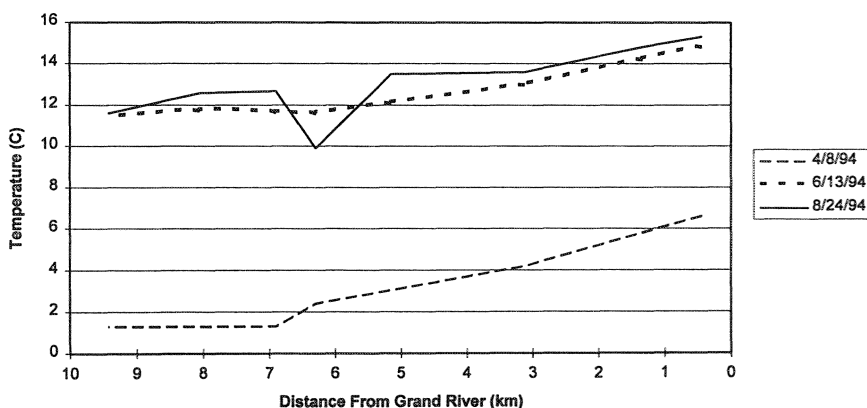


Figure 3.2 Blair Creek temperature profile.

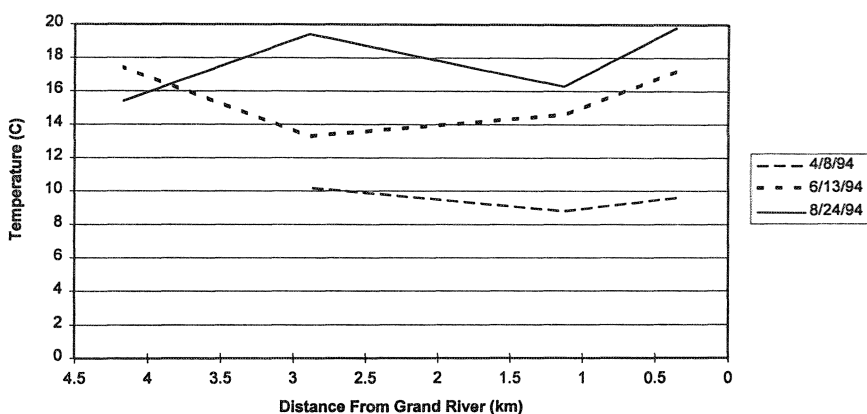


Figure 3.3 Bechtel Creek temperature profile.

3.2.1 Overview of GAWSER Program

The GAWSER model is a deterministic hydrologic model, based on the HYMO format (Ghate and Whiteley, 1982), that computes the total streamflow from rainfall and snowmelt. It has been applied in Ontario for planning, design, real-time flood forecasting, and evaluating the effects of physical changes in the drainage basin (e.g. Ecologistics Ltd., 1988; Charlton and Tufgar, 1991; Weatherbe et al., 1992; Schroeter and Whiteley, 1992). Three years ago, GAWSER was modified to operate in continuous simulation mode, model recharge ponds and to compute pollutant accumulation, washoff, and transport.

GAWSER can operate at variable time steps from as low as 1 minute to 24 hours, depending on the availability of meteorological inputs for the selected time interval. Readily available daily maximum and minimum temperatures are fitted to an assumed sinusoidal diurnal pattern to develop the temperature inputs for each time step. Daily snowfall depths are distributed evenly among time steps where the air temperature is less than 0°C, and a constant value for new snow relative density is applied to estimate the new snowfall equivalent water contents.

GAWSER calculations are based on ten processes: snow accumulation and ablation, infiltration, depression storage accounting, evapotranspiration, runoff estimates, overland flow routing, subsurface routing, baseflow routing, stream channel routing, and reservoir routing (with operations). The procedures for calculating these processes are outlined in the GAWSER Training Guide and Reference Manual (OMNR, 1989). The form of GAWSER used for continuous simulation and water quality modeling is described by Weatherbe et al. (1992).

The GAWSER snow accumulation and ablation sub-model is a simplified form of ASAAM (Areal Snow Accumulation-Ablation Model) (Schroeter et al., 1991), which uses one cell for each block of equivalent accumulation. Redistribution of snow after each snowfall is accounted for by assuming that all new snow deposited in each block in excess of its holding capacity is available for redistribution to linear edge blocks (e.g. fencelines, forest edges, or roadway easements). This assumption is valid only where blowing snow is common during and immediately following each snowfall (as in southern Ontario). No redistribution is estimated for snow in forest blocks.

Areal variability in infiltration rates, percolation rates within soil, and overland runoff rates are accounted for by conducting separate calculations within each subwatershed for one impervious area (including paved areas, lakes, buildings, etc.) and up to eight pervious areas. The Green-Ampt equation is used in the infiltration calculations with allowance for the recovery of infiltrability between events. Overland routing uses separate area/time versus time relationships for urban and rural areas depending on the hydraulics of the drainage network. The baseflow from subsurface and groundwater storage is simulated using a single linear reservoir. Channel routing is done by the Muskingum-Cunge method (Schroeter and Epp, 1988). Reservoir routing is by Puls method, allowing controlled releases.

The dry-weather accumulation of pollutants is represented by an exponential build-up function (Alley and Smith, 1981). The washoff and transport of up to four pollutants is modeled using the Equivalent Solids Reservoir (ESR) approach developed by Schroeter and Watt (1989). This method requires sediment characteristics (particle size and relative density) as inputs to the sediment washoff/transport calculations.

Seasonal changes in model parameters (e.g. effective soil hydraulic conductivity or snowmelt/refreeze factor) are specified on a monthly basis for long-term simulation periods.

3.2.2 Qualitative Description of Temperature Processes

The quantities in the thermal budget of a watershed are defined in Figure 3.4. Each quantity is discussed briefly below to identify the major processes that influence the thermal regime in a watershed.

Some of the precipitation that arrives at the ground surface, either as rainfall or snowmelt, will appear as *runoff water*, while the remaining water will either pond on the surface in depression storage or infiltrate into the ground. The rate of infiltration is controlled by the hydraulic conductivity of the soil and the intensity of the rain or snowmelt input. Runoff water temperatures will be close to precipitation temperatures, but they will be modified by the heat exchange (warming or cooling) occurring at the ground surface (conduction) and with the atmosphere (e.g. evaporation). The temperature of rain is usually assumed to be the same as the air near the ground surface. During snowmelt, runoff temperatures are usually close to 0°C. Ground surface temperatures are controlled by energy exchanges with the atmosphere, such as daytime solar heating and nighttime radiation cooling. In urban areas, paved surfaces are heated by direct sunlight, which elevates subsequent runoff temperatures by more than 5 to 15°C (see Xie, 1993).

As *infiltrated water* travels deeper into the soil, its temperature is modified by conductive energy exchanges with the surrounding soil. Generally, infiltrated water has the same temperature as the precipitation input, but will approach the temperature of the surrounding soil with distance travelled and time. When infiltrated water encounters the water table, it will mix with the groundwater. In the summer, infiltrated water will be cooled as it travels downward in the soil, while during spring snowmelt, it will warm up. Diurnal fluctuations in soil

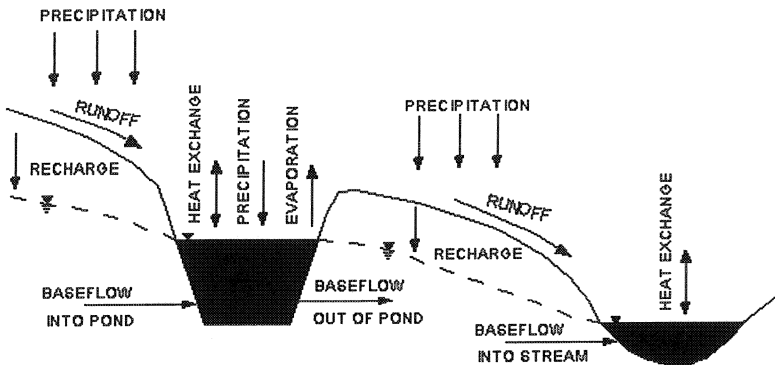


Figure 3.4 Thermal budget of watershed.

temperature caused by temperature variations at the ground surface are significant to a depth of about 1 m (Oke, 1978). Seasonal variations in soil temperature can occur to a depth of about 10 m (Oke, 1978).

Baseflow is water released from groundwater storage that may discharge to a stream reach or a detention pond (or swamp). Groundwater temperatures are modified by conduction with the surrounding soil/rock mass and any mixing with other underground heat sources or sinks. Groundwater temperatures in southern Ontario are typically about 10°C and show some seasonal variations. Generally, the depth of nearly uniform temperature occurs at about 10 m in the tropics and increases to about 20 m in polar regions, although influences such as rock type, elevation, and climate variables can produce local variations (Todd, 1980).

The thermal budget of a *detention pond* is influenced by several heat sources/sinks and heat exchange processes. Thermal sources to the pond include baseflow, runoff, and precipitation, whereas the heat sinks include evaporation and outflows (at outlet and baseflow recharge) from the pond. Heat exchanges occur between the water surface and the atmosphere (e.g. solar radiation) and at the pond walls and bottom. Heat transport through the pond may be modeled as plug flow or completely mixed conditions. In some instances, especially for deeper ponds or reservoirs, thermal stratification of the water profile may be significant and needs to be considered.

The thermal budget of a *stream segment* involves the same inputs and outputs as those for detention ponds. However, generally the evaporation output and precipitation input is assumed to be negligible for small streams (less than 5 m), leaving baseflow and runoff input as the two main heat sources and reach outflow as the only sink. Heat exchanges between the water surface and the atmosphere depend on the amount of riparian cover (which limits the amount of direct solar radiation). Thermal transport through a channel can be modeled as plug flow or a series of mixing cells.

3.3 Model Formulation

3.3.1 Practical Considerations

Whenever new process routines are considered for addition to an existing watershed model, their input data requirements and computational procedures must be reviewed in terms of the modeling philosophy adopted in the whole model. Anderson (1979) states that the process algorithms should be as simple as possible and involve parameters that have unique effects on the model output. Generally, development of these algorithms is accomplished through correct water budget (or energy) accounting and the timing involved in the movements

of the various parts of this budget. GAWSER was built with this philosophy; therefore, the new temperature model needs to harmonize with this approach.

GAWSER considers the major hydrologic sources (and sinks) of water in a subwatershed (e.g. rain and snowmelt runoff, subsurface and groundwater baseflow, evapotranspiration). Temperatures can be assigned or modeled for each of these sources (or sinks) and transported (routed) throughout the subwatershed assuming completely mixed conditions. GAWSER uses commonly available climate variables (e.g. hourly rainfall, daily maximum and minimum air temperature, daily rain and snowfall), which may appear to limit the temperature model, because inputs needed to predict the full heat balance such as wind speed, dew point temperature (or humidity), and solar radiation are not input. GAWSER has two other processes (snowmelt and evaporation) which could have been modeled more completely using an energy balance, but which it handles successfully using temperature index methods.

Temperature index methods are generally adequate for energy exchange calculations, because the various terms in the heat balance are strongly correlated with air temperature (e.g. Zuzel and Cox, 1975). This correlation is not surprising, because air temperature measured at a point ultimately responds to all the inputs in the heat balance. For example, net solar radiation heats a given surface, which transfers some of this heat to the air just above the ground. As the warmer air rises, its temperature is measured by a climate station thermometer. At night, with no solar input, air temperatures are cooler. During windy periods, air temperatures tend to be lower than for periods with no wind.

In addition, the formulated temperature model uses other deterministic information available within GAWSER. For example, any quantities associated with cross-sectional rating curve calculations, such as flow top width, surface areas, and flow areas, can be used directly in the new algorithm's calculations.

3.3.2 General Procedures: Continuous Stirred Reactors

The complex thermal processes occurring in a watershed are represented in GAWSER by assuming that each hydrologic element behaves like a continuous stirred reactor (CSTR). Consequently, a corresponding CSTR for subwatershed elements handles overland runoff and baseflow temperature contributions, channel reaches, and detention pond or reservoir elements. The computations considered in the CSTRs for each element are similar, but differ in their input requirements. For instance, inflows to a subwatershed element CSTR would include output from the baseflow and runoff calculations, whereas the channel CSTR receives input from an upstream hydrograph (e.g. output from another channel or subwatershed element).

Medina et al. (1981) give the governing equation for a completely mixed volume (modified here for temperature) during a given time step:

$$V*(dT/dt) = Q*(TI - T) - KT*V*(T - TREF) \quad (3.1)$$

where:

- V = the average volume [m³]
- Q = the average through-flow (average of inflow and out-flow)
- T = the temperature in the effluent and in the mixed volume [°C]
- TI = the inflow temperature
- KT = a first order reaction coefficient [s⁻¹]
- $TREF$ = a reference temperature
- t = time [s]

Equation 3.1 can be integrated between 0 and Δt to yield

$$T(t + \Delta t) = (B/C)*(1 - A) + A*T(t) \quad (3.2)$$

where:

$$\begin{aligned} A &= \exp[-(Q/V + KT)*\Delta t] \\ B &= Q*TI/V + KT*TREF \\ C &= Q/V + KT \end{aligned}$$

To account for canopy cover in channel and subwatershed elements, as well as surface area in pond elements, the reaction coefficient is expressed

$$KT = [RT + (1 - FC)*CT]*AS \quad (3.3)$$

where:

- RT = the regional part of the transfer coefficient for a fully forested area
- FC = the fraction of the element (e.g. subwatershed, channel, or pond) covered by a forest canopy
- CT = the wide-open or no canopy part of the transfer coefficient
- AS = the water surface area in the element during the calculation interval Δt .

Initial values for KT can be estimated from the literature. Final values can be established by calibration. Seasonal variations in KT can easily be accommodated in the GAWSER program.

The reference temperature, $TREF$, is computed

$$TREF = (1 - FC) * TE + FC * TAIR \quad (3.4)$$

where:

TE = the equilibrium temperature (Weatherbe, 1995) (the temperature at which net energy transfers are zero)

$TAIR$ = the air temperature.

TE is estimated from the observed daily maximum and minimum air temperatures and is assumed to have a sinusoidal distribution through the day-time with a maximum at noon and minimums at 6:00 and 18:00 hours. During the summer months, the mean daily TE is about 8°C higher than the mean daily air temperature, and the amplitude of a typical diurnal TE curve is about three times that of the corresponding air temperature curve. This amplitude ratio can be varied month to month during an annual simulation period.

The processes in CSTRs for channel and reservoir elements (including detention and recharge ponds) are computed in essentially the same manner. Both element types require an upstream inflow hydrograph as input and physical characteristics of the element (e.g. cross-section information, length, slope, surface area). The main difference in the CSTRs is the method used to compute inflow temperatures. These are dealt with in the next section.

3.3.3 Inflows to the Subwatershed Element CSTRs

Inflows to the subwatershed element CSTRs include contributions from each soil/land cover response unit, subsurface, and baseflow.

The ground surface temperature, $TGS(t, i)$ for soil/land cover response unit i is expressed

$$TGS(t, i) = A_1(i) + B_1(i) * TAIR(t) \quad (3.5)$$

where $A_1(i)$ and $B_1(i)$ are input constants for response unit i . Response unit 1 represents impervious surfaces in the subwatershed; response units 2 through 9 represent pervious surfaces.

Next, the flow-weighted average ground surface temperature is found using

$$RSUM(t) = \sum_{i=1}^n PCT(i) * SURF(t, i) \quad (3.6)$$

$$TAGS(t) = \sum_{i=1}^n PCT(i) * SURF(t, i) * TGS(t, i) / RSUM(t) \quad (3.7)$$

where:

- $PCT(i)$ = a fraction of the subwatershed area assigned to a soil zone or response unit i
 $SURF(t,i)$ = the computed runoff amount for response unit i at time interval t
 $TGS(t,i)$ is computed using Equation 3.5.

The precipitation temperature is estimated using air temperature as follows:

$$\begin{aligned} TP(t) &= TAIR(t) \text{ for rainfall only periods} \\ TP(t) &= 0 \text{ }^\circ\text{C for snowmelt periods} \end{aligned} \quad (3.8)$$

where:

- $TP(t)$ = the temperature of precipitation ground input at time t
 $TAIR(t)$ = the air temperature at time t .

The surface runoff temperature (TSR) will initially be about the same as the surface temperature. However, as rain or snowmelt continues to be supplied at the ground surface, the surface runoff temperature approaches that of the precipitation due to cooling of the ground surface, which is represented in the model by

$$\begin{aligned} TSR(t) &= FR * TAGS(t) + (1 - FR) * TP(t) \\ FR &= \exp[-(VR / KR)^M] \end{aligned} \quad (3.9)$$

where:

- VR = the accumulated rain (or snowmelt) volume
 KR = a type of reaction coefficient
 M = an exponent.
 VR = 0 when there is no ground input (rain or snowmelt) for at least 12 hours during the simulation.

Generally, the temperature of groundwater discharge and interflow can be taken as a constant throughout the year. However, to account for some seasonal variation in the groundwater discharge (baseflow) temperatures, a first order linear delay (diffusion-like) relationship is used (Todd, 1980).

$$TGW(t+1) = C_1 * TGW(t) + (1 - C_1) * [TAIR(t) - TGWC] \quad (3.10)$$

where:

- C_1 = $\exp[-(\Delta t / KGW)]$
 $TGWC$ = the mean annual groundwater temperature (taken to be constant)

KGW = a recession constant (KSS represents the subsurface recession constant).

In summary, the inflow temperature (TI in Equation 3.1) to the subwatershed element CSTR becomes

$$TI(t) = \frac{TSR(t)*IR(t) + TGW(t)*QGW(t) + TSS(t)*QSS(t)}{IR(t) + QGW(t) + QSS(t)} \quad (3.11)$$

$$IR(t) = RSUM(t)*AREA$$

where:

$IR(t)$ = the total runoff inflow
 $QGW(t)$ = the groundwater flow
 $QSS(t)$ = the subsurface inflow
 $AREA$ = the drainage of the catchment.

3.3.4 Temperature Mixing at Hydrograph Addition Points

At hydrograph addition points, the resulting temperature from mixing any two flow streams is

$$TSUM(t) = \frac{[T_1(t)*Q_1(t) + T_2(t)*Q_2(t)]}{Q_1(t) + Q_2(t)} \quad (3.12)$$

where:

Q_1 and Q_2 = the flows for the two streams being combined
 T_1 and T_2 = the corresponding temperatures.

3.4 Model Application

The temperature model was tested against data from the Blair and Bechtel Creek watersheds as described earlier. In-stream temperature data were available at two locations for two periods: June 9 to July 3, 1994 and July 14 to August 7, 1994. Although this database is not sufficient for complete testing of the model, it did provide early indications of the temperature model's performance. Additional data for more complete testing will be available from the Mill Creek subwatershed near Cambridge, Ontario later this year.

3.4.1 Instrumentation

Rainfall was measured by a single MSC (Meteorological Service of Canada) tipping-bucket raingage located on Blair Creek just upstream of Roseville Swamp. Depth measurements for recorded flow values were measured using Lakewood RX Ultra-loggers and Terra Science Gnome data loggers with PS9000 0-15 psi and -30 psi pressure transducers respectively. Stream temperatures were measured using HOBO XT -5°C to 37°C data loggers. Stream temperature data was collected at stations 1, 2 and 4 (see Figure 3.1) on Blair Creek with a maximum of two of these stations gaged simultaneously. Stream temperature data was collected at station 6 on Bechtel Creek. All stream temperature data was collected at hourly intervals.

3.4.2 Parameter Determination

Whenever possible, previously published values were used for most parameters. Where published values did not exist, starting values were assumed, based on field observations and experience, which are noted below. Although not currently fully calibrated, the values used in the applications reported here are summarized in Table 3.1.

Initially, some parameters (e.g. the no-canopy part of the CSTR reaction coefficient or ground surface temperature estimation constants) were believed to have different values for each hydrologic element (or response unit in the runoff calculations). The model was structured to allow independent specification of such parameters for each element (or response unit), but as a first estimate (except where obvious differences for each element were identified, e.g. mean ground surface temperature adjustment constant), the same parameter values were used for all elements. The other parameters that are held constant for all elements (e.g. the wide open part of the CSTR reaction coefficient) are noted as well.

The hydrologic model parameters are described in the *GAWSER Training Guide and Reference Manual* (OMNR, 1989) and have been established from applications of GAWSER in southwestern Ontario over the past nine years as reported recently by Schroeter and Associates (1995).

CSTR Reaction or Transfer Coefficients, RT and CT. Observed values for these parameters were not available in the literature. However, the range of possible values can be determined by sensitivity analyses (i.e. varying RT and CT, and checking computed outflow temperature response through the different elements). Equations 3.1 and 3.3 indicate that for high values of RT and CT, the computed outflow temperatures from shallow reservoirs or wide channels (with no canopy) will tend toward the reference temperature, which in this case is TE. Consequently, when RT and CT were greater than 2.0/ha-d, the stream temperature became TE. Based on this information, initial values of RT and CT that were about half to a quarter of these limiting values were chosen.

Table 3.1 Temperature model parameters.

Hydrologic Element													
Parameter	Symbol	Subwatershed Response Units									Channels	Ponds	
		1	2	3	4	5	6	7	8	9			
CSTR Reaction or Transfer Coefficient (see Eq. 3)													
Wide-open	RT	←----- 0.8/ha - d -----→											
No Canopy	CT	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3		0.3
% Canopy	FC	0	0	50	10	5	5	100	100	20			
Ground Surface Temperature Constants (Eq. 5)													
Mean Adjustment	A1	6	4	-2	4	4	4	-2	-2	4	n/a		n/a
Scaling Factor	B1	←----- 1.0 -----→									n/a		n/a
Ground Surface Cooling Constants (Eq. 9)													
Reaction	KR	5	5	5	5	5	5	5	5	5	n/a		n/a
Exponent	M	←----- 0.5 -----→									n/a		n/a
Constant Subsurface Storage Temperatures (see Eq. 10)													
Subsurface	SST	←----- 12°C -----→									n/a		n/a
Groundwater	GWT	←----- 10°C -----→									n/a		n/a
Subsurface Storage Recession Constants (see Eq. 10)													
Subsurface	KSS	←----- 5°C -----→									n/a		n/a
Groundwater	KGW	←----- 384°C -----→									n/a		n/a
Note: The subwatershed response units or zones are defined as:													
1 = Impervious areas													
2 = Low infiltrability, no forest													
3 = Medium infiltrability, no forest, swamplands													
4 = Medium infiltrability, no forest (contributes to groundwater storage)													
5 = High infiltration, no forest (contributes to subsurface storage)													
6 = High infiltration, no forest (contributes to groundwater storage)													
7 = Low infiltration forest cover													
8 = High infiltration forest cover													
9 = Aggregate extraction areas (gravel pits)													

Ground Surface Temperature Estimation Constants, A_i and B_i . Based on information given in Xie (1993), $A_i = 4^\circ\text{C}$ and $B_i = 1$ were used for all the response units. Because ground temperatures in forests are typically less than the air temperature, B_i was set to -2°C for response units 7 and 8 (see Table 3.1). For paved or impervious areas, A_i was set to 6°C .

Ground Surface Cooling Constants, KR and M . The KR parameter in Equation 3.9 was established by assuming that the surface runoff temperature, $TSR(t,i)$, for a given response unit, should be equal to the precipitation (air) temperature (TP) when the accumulated rainfall depth (VR) is about 3 times KR . Equation 3.9 shows that this occurs when $VR = 15$ mm and $KR = 3$ mm. Using this value for KR , a value for the exponent M was chosen so that the surface runoff temperature was the average of the ground surface and precipitation temperatures (i.e. $TSR = 0.5TG_S + 0.5TP$). This occurs when $VR = 2.5$ mm and $M = 0.5$.

Constant Subsurface Storage Temperatures, SST and GWT . From field observations, the groundwater storage temperature GWT was set initially to 10°C . SST was assumed to be about 2°C higher, because of the faster response time of the subsurface reservoirs relative to groundwater storage.

Subsurface Storage Recession Constants, KSS and KGW . From previous applications, $KSS = 5$ h and $KGW = 384$ hours (or 16 days).

3.4.3 Temperature Model Parameter Sensitivity

During initial application of the model, a sensitivity analysis proved to be valuable in the calibration process. This analysis revealed that the CSTR reaction or transfer coefficients (Equation 3.3) exerted the greatest influence on the simulation results. The ground surface temperature constants (Equation 3.5) and the ground surface cooling constants exerted secondary influence, primarily during runoff events, and are, therefore, considered fine tuning parameters.

Although the constant subsurface storage (e.g. baseflow, GWT) and equilibrium temperatures (TE) are considered input variables rather than model parameters, they strongly influenced the simulation results. The temperature of any water flowing through a reservoir or channel element was strongly influenced by the CSTR reaction coefficient (KT , see Equation 3.3), which is determined as a function of the flow surface area and the vegetative canopy cover. For very large values of KT , the stream temperature will approach the equilibrium temperature (TE).

3.4.4 Simulation Results

The temperature model was initially tested against data for the period June 9 to July 3, 1994. This simulation provided the first rough calibration of the model parameters. Next, the final calibrated parameters from the June period were applied directly in the simulation of the July 14 to August 7, 1994 period to test

the robustness of the model for other events. These data represent the only periods for which complete records of rainfall, air temperature, discharge, and in-stream temperature were available for at least two locations in each of the study subwatersheds. Observed and simulated hydrographs and water temperature time-series plots for the two gage locations in each simulation period are presented in Figures 3.5 to 3.8.

Figure 3.5a shows the observed and computed discharge hydrograph at the outlet of Roseville Swamp (Gage No. 7), a major tributary of Blair Creek, for the period June 9 to July 3, 1994. The corresponding water temperature time-series plots are shown in Figure 3.5b. In general, there is fairly good agreement between the measured and computed discharges from the swamp throughout the simulation period, with the exception that the flows for a runoff event occurring on June 24 are overestimated by about 65%. This discrepancy is attributed to the rainfall

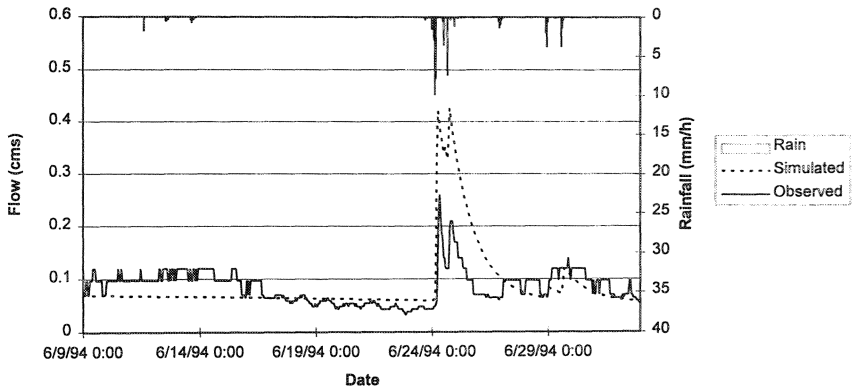


Figure 3.5a Roseville Swamp stream flow.

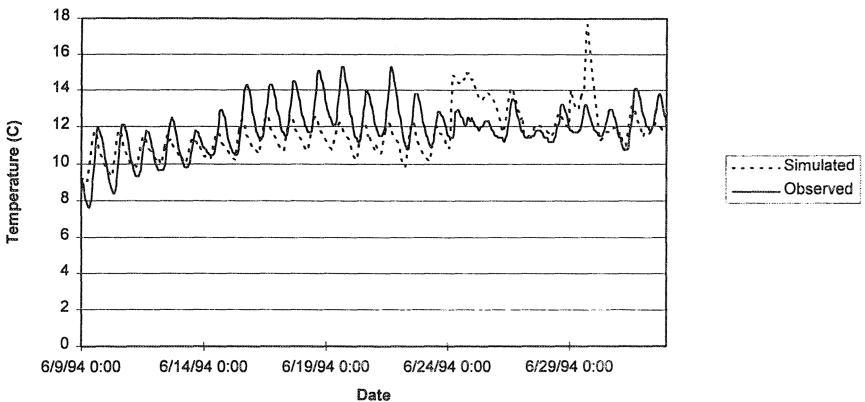


Figure 3.5b Roseville Swamp stream temperature.

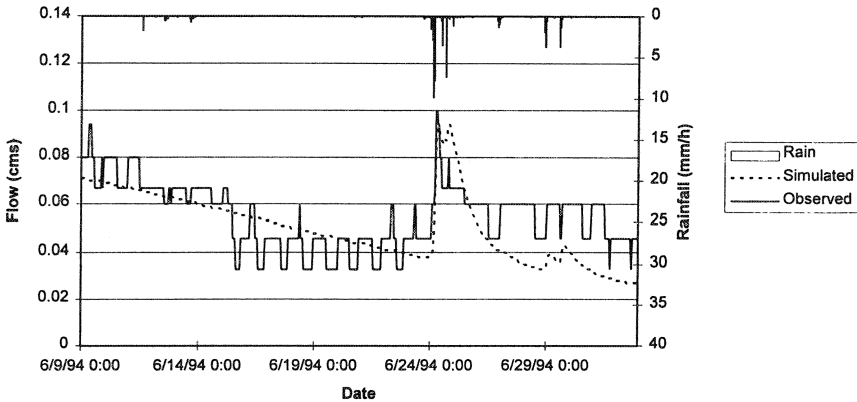


Figure 3.6a Bechtel Creek stream flow.

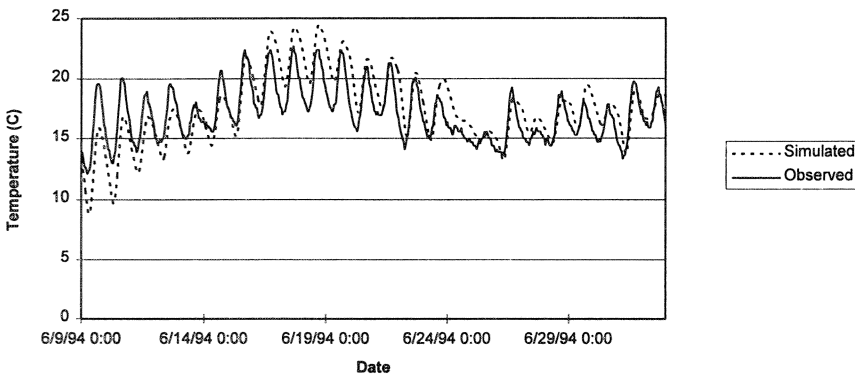


Figure 3.6b Bechtel Creek stream temperature.

measurements not being representative of the entire Roseville Swamp subwatershed. This is a common problem when computing runoff from early summer thunderstorms. When the three hours of highest rain depth for this 24-hour day period were reduced by 50%, the agreement between the observed and computed hydrographs was greatly improved.

Figure 3.5b shows the agreement between the observed and computed water temperature curves is poor, in terms of matching the individual diurnal patterns for each date in the modeling period. The model computed the water temperature for the runoff event on June 24 and 25 high by about 3°C; however, the computed mean water temperature for the entire 24-day period was within 0.5°C of the mean observed water temperature. These discrepancies are unexplained, but further calibration of the CSTR reaction coefficients for the individual land cover types within the Roseville Swamp should improve the results. The representative

channel cross-sections used for overland routing calculations may not yield large enough flow surface areas to allow the model to match the observed diurnal patterns shown in Figure 3.5.

The observed and simulated discharge and water temperature plots at the Bechtel Creek gage (No. 6) for the period June 9 to July 3, 1994 are summarized in Figure 3.6. There is good agreement between the measured and modeled results for discharge and water temperature. The magnitude of the flow units in the discharge hydrograph plot indicates that the observed values are close to the lower limit of accuracy for flow measurements. For water temperature, the overall trend in the observed patterns has been reproduced by the GAWSER model, with some slight underestimates (by about 2°C) early in the simulation period (June 9 to 12) and some overestimates (about 1 or 2°C) for June 16 to 20. There is very good agreement between the measured and computed temperature plots for the runoff event occurring on June 23 and 24.

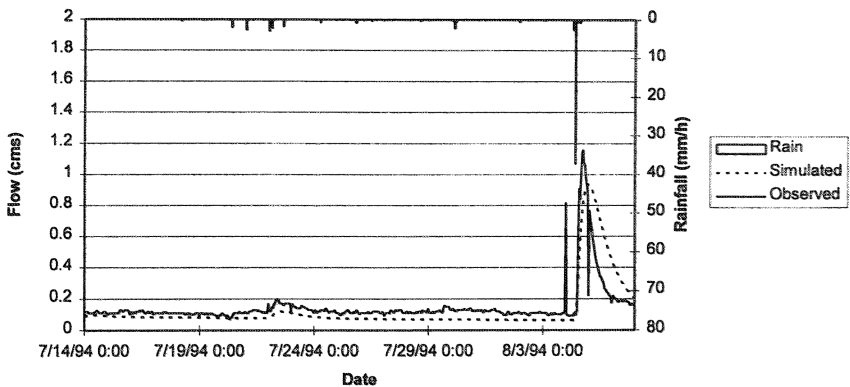


Figure 3.7a Blair Creek stream flow

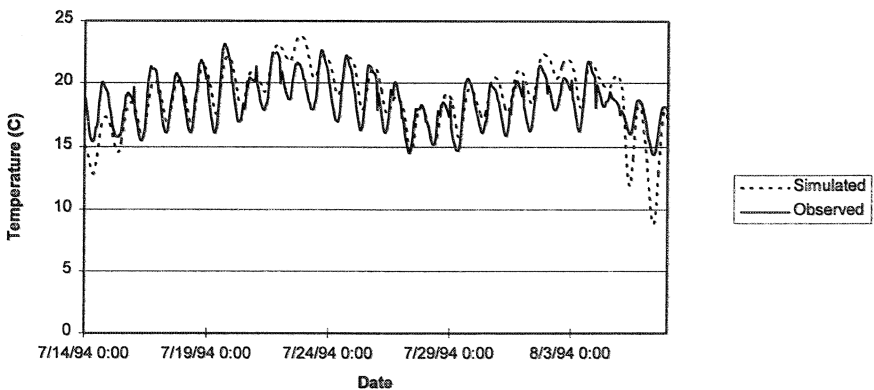


Figure 3.7b Blair Creek stream temperature.

The measured and computed discharge and water temperature plots at the outlet of Blair Creek (Gage No. 4) are displayed in Figure 3.7 for the period July 14 to August 7, 1994. For simulating this period, the final calibrated parameters from the June 9 to July 3 model run were used. This provided an opportunity to test, although in a limited way, the robustness of the model parameters. The model parameters (e.g. RT , CT and A , and B) did not differ significantly between the two simulation periods. In general, there is good agreement between the observed and computed results for discharge and water temperature. For water temperature, the overall trend in the measured diurnal patterns has been reproduced by the GAWSER model, with slight overestimates (by about 2°C) around July 22 and 23 and August 1 and 2. The large deviation for August 6 and 7 is likely due to an incorrect estimate of equilibrium temperature for early August. Further calibration of the model will reduce deviations.

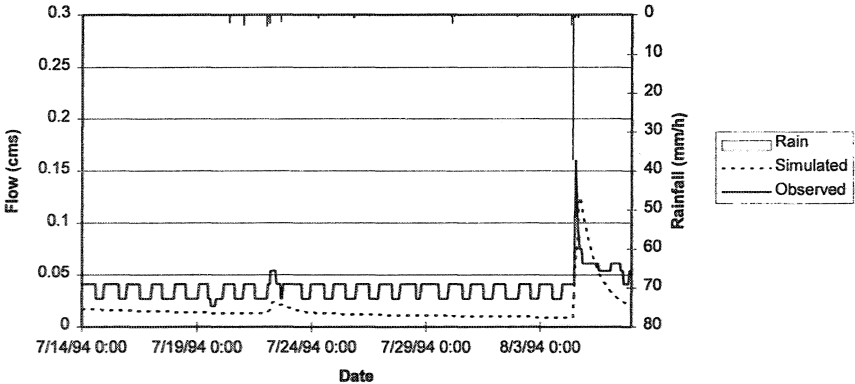


Figure 3.8a Bechtel Creek stream flow.

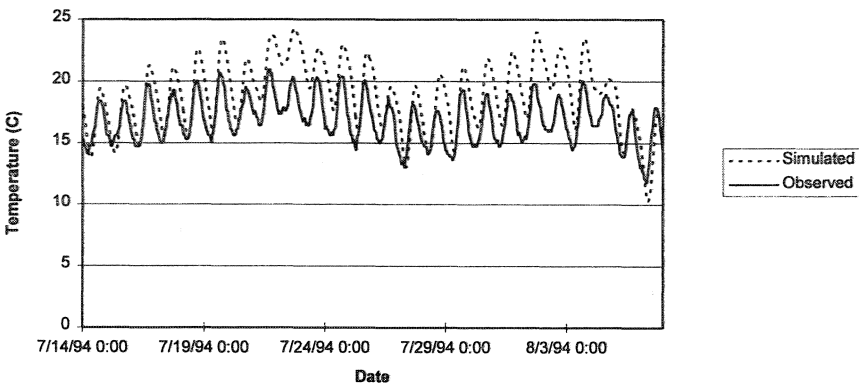


Figure 3.8b Bechtel Creek stream temperature

The computed and observed results for the July 14 to August 7, 1994 period at the Bechtel Creek gage (No. 6) are summarized in Figure 3.8. As noted previously, the agreement between measured and computed discharge is good, especially considering that the noted flow magnitudes are near the lower limit of accuracy for this type of stream flow gaging station. Overall, the computed water temperatures are in good agreement with the measured values, with some slight overestimates where runoff events occur (e.g. July 21 to 24 and August 1 to 4) by about 1 or 2°C.

Despite the discrepancies noted above, the results presented in this section are encouraging. With additional testing of the model with other datasets, the temperature modeling results should improve.

3.5 Critical Evaluation of Temperature Modeling Concept

3.5.1 Reliability

The limited testing to date suggests that the GAWSER temperature model is robust and reliable. The same parameters were applied in two 24-day simulation periods for two separate subwatersheds, and the model performed consistently in each case. At present, the model is valid for summer periods between June and August on watersheds similar to the Blair and Bechtel Creeks. The model needs to be tested on larger watersheds, on other areas with differing land cover types, and for other times of the year (i.e. early spring and late summer). At present, the model is not strictly correct during times when ice is present. However, a critical period for watershed management planning when considering temperature impacts is during low-flow, warm summer periods. Additional testing should include more upstream and downstream gage combinations for the same simulation periods.

3.5.2 Utility for Planning and Management

Subject to the qualifications noted above, the temperature model concept outlined here, either as part of GAWSER or other hydrology models with comparable subwatershed discretization, input data requirements and modeling accuracy (e.g. HSP/F, OTTHYMO), can be used to predict in-stream temperatures. Although parallel testing with other temperature models has not been undertaken, the two separate subwatershed tests indicate that the temperature algorithm, in combination with GAWSER, provides a realistic simulation. Because the model uses physical characteristics of the watershed (e.g. cross-sections, land cover information) as direct inputs to the temperature model calculations, it provides a practical tool for watershed planning and management during critical low-flow, warm periods.

3.6 Conclusion

A simple continuous in-stream temperature model has been successfully integrated with the existing GAWSER model (V6.4). This model provides a practical tool for evaluating the impacts of elevated stream temperatures on the aquatic biota in developing subwatersheds.

The input requirements for the temperature model are limited: air temperature, discharge from hydrology elements (the existing model), land cover and channel canopy information, channel and reservoir surface area, initial or constant subsurface storage temperatures, two CSTR reaction coefficients, and four surface temperature estimate parameters. Initial testing of the temperature model for Blair and Bechtel Creeks was very encouraging because the modeling parameter values were transferrable between basins and simulation periods. Computed temperatures during runoff events tended to be overestimated. Further testing of the model is required to resolve these discrepancies.

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