Chapter 16

A Simplified Stream Temperature Model for Evaluating Urban Drainage Inputs

Donald G. Weatherbe

Donald G. Weatherbe Associates Inc.
1352 Safeway Crescent
Mississauga, Ontario, L4X 1H7

In carrying out watershed studies, one of the key parameters of concern for causing a degraded fishery is elevated temperatures. Urban drainage discharges contribute to the problem, since the runoff and stormwater pond releases often have elevated temperatures. This chapter presents a practical tool for evaluating these impacts for use on small watersheds. A simple equilibrium-based temperature model was applied in the Laurel Creek Study in southern Ontario. Practical examples are presented of temperature balance calculations at the head of a stream reach, longitudinal and diurnal variations in the reach, effects of varying canopy, and the impact of channel modifications.

16.1 Introduction

Urbanization typically proceeds with construction of buildings and roadways, which increase imperviousness, and reduces the amount of water infiltrating into the ground. Along with the construction of storm

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drainage systems this results in increased rates and volume of runoff. The increased runoff rate usually causes natural channels to increase in depth and width as banks are eroded by the greatly increased frequency of channel-full events.

Heated stormwater pond discharges and reductions to baseflow further elevate temperatures. For example, Gali (1990) reports that the baseflow temperature was elevated over 8 °C after flowing through an in-line stormwater detention pond. Measures to offset the temperature increases in ponds and to increase infiltration can improve the thermal regime. In addition it is often proposed that the stream banks be revegetated in order to provide canopy and shade from solar heat inputs.

Channel modifications are also often proposed to rehabilitate the fishery and reproduce a natural habitat. This could include addition of meanders, creation of a natural pool and riffle system, and addition of a low-flow channel that has the effect of narrowing and deepening the flow during baseflow conditions. All these changes to discharges, stream bank and channel can have an impact on the thermal regime.

Many species of fish are sensitive to elevated temperature levels in streams during various stages of their life cycle. Higher temperatures reduce dissolved oxygen saturation levels, and also increase the toxicity of some contaminants such as ammonia. Fish (and other organisms) respond to higher temperatures by increasing respiration, thus requiring more oxygen. These factors combined can cause worst-case conditions in streams for fish biota. The impact of urbanization on streams is summarized in Figure 16.1.

16.2 The Laurel Creek Watershed Study

The Laurel Creek watershed is a 75 km² tributary of the Grand River, located in southwestern Ontario. Approximately one half of the watershed is urbanized, with pressure to urbanize a large proportion of the remaining upper half. This development pressure led to the Laurel Creek Watershed Study (GRCA, 1993). Hydrologic and water quality models were used to estimate the changes in surface water quality resulting from urbanization, (Weatherbe *et al*, 1993). Since temperature impacts were considered important, calculation of temperature impacts were included in the study (Draper *et al*, 1992). This chapter describes the model used in the study, and presents examples of different applications.

Figure 16.1
Impact of urbanization on stream temperature.

Temperature targets used in the study are as follows:

For warmwater species: instream temperatures should be no greater than 29°C from Aug. 1 to October 31 (to protect adults), and no greater than 26°C from June 1 to Aug. 1 to protect embryos. These targets were applied to the areas already affected by urbanization.

For coldwater species: instream temperatures should be no greater than 22°C from April 1 to Oct. 31 (to protect adults, juveniles and fry). This target was applied to the reaches upstream of the existing urban area, including areas likely to be affected by future urban development.

Existing conditions upstream of the urbanized area showed maximum temperatures approximately at the target, during June 1991. As Laurel Creek enters the urbanized area, it flows through several impoundments, including a major flood control reservoir. Downstream from the Laurel Creek Reservoir, temperatures in June 1991 were up to 28°C which is in excess of the target. Urbanization without controls can be expected to further increase temperatures upstream. Since the downstream reaches are already exceeding the targets, remedial measures would have to be applied.

16.3 Heat Balance Considerations

16.3.1 Theoretical Heat Balance

The temperature of a body of water is dependent on the rate at which heat energy is exchanged between the water and the surroundings. If more heat energy is entering the water than leaving, then the temperature rises. The heat balance of a body of water, H , is expressed as the sum of all the energy input and output terms:

$$H = H_s + H_a - H_{br} - H_e \pm H_c - H_{sr} - H_{ar} \quad (16.1)$$

where:

- H = heat loss or gain, $\text{mj/m}^2/\text{day}$
- H_s = shortwave solar radiation, $\text{mj/m}^2/\text{day}$
- H_a = long-wave atmospheric radiation, $\text{mj/m}^2/\text{day}$
- H_{br} = long-wave back-radiation, $\text{mj/m}^2/\text{day}$
- H_e = evaporative heat loss, $\text{mj/m}^2/\text{day}$
- H_c = conductive heat loss or gain, $\text{mj/m}^2/\text{day}$
- H_{sr} = reflected solar radiation, $\text{mj/m}^2/\text{day}$
- H_{ar} = atmospheric reflection, $\text{mj/m}^2/\text{day}$

The sign indicates the typical direction of the heat flow. If the sum of positive terms (heat gain) is larger than the sum of negative terms (heat loss), then the temperature of the body of water rises. Models are available that account for all the terms in the heat balance, such as those described in Xie and James (1994). A simplified procedure, suitable for screening or planning purposes is described below.

16.3.2 Equilibrium Temperature

The concept of equilibrium temperature is used in a simplified modeling procedure recommended by the US EPA (EPA 1985). If all the heat terms are in balance, or equilibrium ($H = 0$), then the body of water is at the equilibrium temperature, E . Further, the concept assumes that the surface water temperature will move towards the equilibrium temperature as described in the excess temperature model (see following section). Edinger *et al* (1974) shows that the equilibrium temperature may be estimated by:

$$E = T_d + \frac{H_s}{K} \quad (16.2)$$

where:

$$\begin{aligned} T_d &= \text{the dewpoint temperature, Deg. C} \\ H_s &= \text{the net rate of solar radiation, mj/m}^2/\text{day} \\ K &= \text{the thermal exchange coefficient, mj/m}^2/\text{day}/^\circ\text{C} \end{aligned}$$

This formulation assumes that at night, evaporative heat losses would drive stream temperature towards the dew point temperature (where evaporation is zero). During the day, equilibrium temperature is increased by the net solar input, divided by the thermal exchange coefficient. The thermal exchange coefficient accounts for the rate of evaporation. The equation ignores several terms of the heat balance as it assumes that long-wave atmospheric radiation is approximately balanced by the back-radiation and conductive heat losses.

The thermal exchange coefficient, K , is dependent on wind speed and an empirically-derived relationship as follows:

$$K = [4.48 + (B + 0.47) \cdot f(w) + 0.05T_s] \cdot 0.0864 \frac{\text{mj}}{\text{m}^2 \cdot \text{day} \cdot ^\circ\text{C}} \quad (16.3)$$

where:

$$f(w) = 9.2 + .0355 w^2 \quad (16.4)$$

w = wind speed in km/hr

$$B = .35 + .015 T_m + .0012 T_m^2 \text{ mm-Hg}/^\circ\text{C} \quad (16.5)$$

T_s = surface water temperature, Deg. C

$$T_m = (T_s + T_d)/2 \quad (16.6)$$

The initial value of the surface water temperature term, T_s (which is unknown) may be approximated by the equilibrium temperature, E , thus setting up an equation that has the same term on both sides. This can be solved iteratively, with a guess at the initial value of E (suggested as $E = T_d$). This iterative solution was set up in a spreadsheet for the Laurel Creek study. In trials the result was stable after three iterations, consequently the spreadsheet was set up to complete four iterations routinely.

16.3.3 Excess Temperature Model

Once the equilibrium temperature is known, the steady state temperature distribution downstream from a point where initial temperatures are known can be estimated by an excess temperature model:

$$\frac{T_x - E}{T_o - E} = \exp\left(\frac{-0.011574Kx}{pC_pUD}\right) \quad (16.7)$$

where:

- T_x = Temperature (Deg.C) at any point x (km) downstream from the initial point, $x = 0$
- T_o = Temperature (Deg.C) at $x = 0$
- E = Equilibrium temperature Deg.C
- K = Thermal exchange coefficient
- pC_p = 4.186 mj/m³/Deg.C
- U = Stream velocity, m/s
- D = depth, m

All input data requirements were readily available from the Atmospheric Environment Service (AES) meteorological monitoring station located at Elora, Ontario, approximately 50 km from the watershed. The equations and terms are converted to hourly rates.

16.4 Hydraulic Relationships

Variations in velocity and depth with flow are given by:

$$U = aQ^b \quad (16.8)$$

$$D = cQ^d \quad (16.9)$$

$$W = eQ^f \quad (16.10)$$

where:

- W = width, m
- Q = flow, m³/s

a,b,c,d,e,f are dimensionless empirical coefficients, such that $ace = 1$, and $b + d + f = 1$

McCutcheon (1989) suggests values for the exponents. For example, for a rectangular channel, the velocity exponent, b, is 0.40, the depth exponent, d, is 0.60, and the width exponent, f, is 0.0. In the Laurel Creek Study, the coefficients were provided by the hydrologic/hydraulic model used in the study, GAWSER (OMNR, 1989).

In considering channel modifications, the velocity and depth coefficients must be modified. The Manning equation (Chow, 1959) can be restated for a rectangular channel, in terms of the above coefficients, as follows:

$$Q = \frac{S^{0.5}}{n} \cdot WD^{1.5} \quad (16.11)$$

where:

S = channel slope
n = dimensionless roughness coefficient

One of the effects of urbanization is that the increased rate and volume of runoff cuts a wider channel destroying the pre-development natural channel. During the summer period, the low-flow channel is wider and shallower than the natural condition. This exposes the water to increased heat inputs. In rehabilitating channels, it is often proposed that a narrow low flow channel be constructed to provide for increased depth and velocity.

If we alter channel geometry by narrowing and deepening the low flow channel, we can calculate new values of coefficients. From Equation 16.11, for the same flow and channel material and slope, we can assume that the S, n and Q terms are constant. Thus,

$$W_1 D_1^{1.5} = W_2 D_2^{1.5} \quad (16.12)$$

where the subscript, 1, refers to the before construction case, and 2, to after construction.

16.5 Spreadsheet Model

The calculations in the spreadsheet model proceed in three steps, given below and also shown in Figure 16.2.

1. A temperature balance calculation (similar to a mass balance) takes place at the head of a reach to mix upstream channel flow, Q_u , with runoff, Q_r , and groundwater, Q_{gw} , to calculate an initial temperature, T_o .

$$T_o = \frac{Q_u T_u + Q_r T_r + Q_{gw} T_{gw}}{Q_u + Q_r + Q_{gw}} \quad (16.13)$$

Similarly, the water balance is calculated:

$$Q_o = Q_u + Q_r + Q_{gw} \quad (16.14)$$

2. Equilibrium temperature, E , is calculated for a two-hour steady-state condition using Equations 16.3 to 16.6 (repeated iteratively as described above). This is repeated each two hours during the day to give a 24-hour temperature variation.
3. Temperature, T_x , is calculated using Equation 16.7 for each 2 hour time-of-travel (x/U) step in the reach and at the end of the reach, assuming a steady-state plug flow. Hydraulic coefficients are stored in a table in the spreadsheet and used in the calculations for the resulting channel flow (Equation 16.14). The calculation of T_x is repeated for every two-hour time period, producing a diurnal curve for each time step.

16.6 Application of the Model

16.6.1 Temperature Balance

The immediate impact of urbanization on temperature can be calculated by the temperature balance calculation shown above. For example, the groundwater flow contributions from the subwatershed

tributary to reach 111 were calculated (Figure 16.3) for existing conditions, a development scenario with conventional stormwater controls (i.e. no controls with respect to groundwater infiltration), and development with use of recharge ponds. Assuming ground water flows are 10 Deg. C in the middle of summer, we can calculate the immediate impact of mixing

Figure 16.2
Calculation steps in the spreadsheet model.

Figure 16.3
Estimates of groundwater flow with different control measures.

groundwater flow and channel flows at a single point, as shown in Table 16.1. The impact of reduced base flow due to the development is limited (0.2 Deg. C), but coupled with a stormwater pond release, following a storm, the impact increases to 0.67 Deg. C. Also shown is the impact of the recharge pond. The difference in using so-called wet stormwater ponds compared to infiltration ponds to recharge local aquifers could be as high as 1.0 Deg. C (ie. net effect of sum of delta T's).

Table 16.1
Temperature balance calculations for Laural Creek - base flow conditions.

Reach 111 Case	Qu m ³ /s	Tu °C	Qr m ³ /s	Tr °C	Qgw m ³ /s	Tgw °C	Qo m ³ /s	To °C	Delta T °C
Existing	0.081	20	0	0	0.010	10	0.091	18.90	
Development	0.081	20	0	0	0.008	10	0.089	19.10	0.20
Dev. + Recharge	0.081	20	0	0	0.013	10	0.094	18.62	-0.28
Dev. + SW Pond	0.081	20	0.005	28	0.008	10	0.094	19.57	0.67

where:

- Qu = upstream channel flow
- Tu = temperature upstream
- Qr = stormwater management pond release
- Tr = temperature of runoff or release
- Qgw = groundwater or baseflow
- Tgw = temperature of groundwater

16.6.2 Longitudinal Variation

Figure 16.4, shows the longitudinal temperature variation for reaches 102, 104, and 109, estimated using the model. These three reaches represent the main channel of Laurel Creek from the headwaters to the first impoundment at Laurel Creek Reservoir. Table 16.2 gives the reach characteristics used in the model. All inputs, including groundwater, are assumed to be introduced at the head of the reach.

Table 16.3 gives the meteorological data used for August 7. This day was chosen as representative of a sunny day with high solar radiation input.

Table 16.2
Laurel Creek reach characteristics.

Reach (No.)	Length (m)	Hydraulic Coefficients *					
		a	b	c	d	e	f
102	4115	0.786	0.272	0.606	0.38	3.285	0.321
104	2450	0.786	0.272	0.606	0.38	3.285	0.321
109	2700	0.804	0.268	0.511	0.373	4.233	0.321
111	3150	0.602	0.251	0.421	0.375	7.844	0.373

$$* \quad U = aQ^b \quad D = cQ^d \quad W = eQ^f$$

Figure 16.4
Longitudinal temperature computation for Laurel Creek.

16.6.3 Effect of Canopy

The model was applied to a headwater reach to show the impact of various levels of canopy, or tree cover, shading the water surface. In the model, the solar radiation is modified by the percent canopy, eg. 65% canopy is assumed to intercept 65% of the incoming solar radiation for each time step.

Figure 16.5 indicates the computed result from discharges of cool groundwater to the head of reach 102 with various percentages of canopy. The channel is shallow, about 4 km long, with a 6 hour travel time. As shown, the change in 90% canopy to 15% canopy can result in a 17 Deg. C increase in surface temperature, on a hot day in August. Note that the estimated canopy level for reach 102 is 65%.

Table 16.3
Meteorological data from Elora, Ontario.

Hour	Air Temp. Deg. C	Dewpoint Deg. C	Wind km/hr	Sol. Rad. mJ/m ² /hr
1	13.1	10.7	10	0
2	13.7	11.1	12	0
3	14	11.8	9	0
4	13.8	10.8	10	0
5	13	10.7	14	0
6	13.3	11.1	15	0.33
7	15	11.1	9	0.93
8	17.9	11.9	9	1.72
9	20.5	12.1	10	2.3
10	21.5	11.9	10	2.88
11	22.1	12.4	11	2.3
12	23.1	12.3	13	4.16
13	22.8	12	10	3.94
14	23.8	11.8	15	4.12
15	23.4	11.9	11	3.17
16	24.4	11.5	17	2.4
17	24.2	12.1	9	1.14
18	23	12.7	12	0.26
19	22	14.6	13	0.16
20	19.9	15.1	19	0
21	18.5	14.1	12	0
22	17	12.3	10	0
23	16.2	11.2	10	0
24	14.9	10.7	13	0

16.6.4 Effect of Channel Modifications

The effect of channel modifications can be estimated by altering depth and width in the model as described above. For example, assuming that the channel is a rectangle, we can construct a narrower channel such that $W_2 = 0.25 W_1$. Solving Equation 16.12, and the continuity equation ($Q = WDU$) gives us $D_2 = 2.52 D_1$, and $U_2 = 1.59 U_1$. Thus the reduced width increases both the depth and velocity. The effect of the modified geometry on temperature can now be tested in the spreadsheet model by altering the U and D terms in Equation 16.7.

Figure 16.6 shows the effect of modifying a reach by reducing the width to 1/4 of the existing width. The reach modeled in this example is

Figure 16.5
Effect of canopy on temperature.

Figure 16.6
Effect of channel modifications on temperature.

a hypothetical channel, similar to reach 109, but with longer travel time, and no canopy. The effect of the channel narrowing for the low flow condition is to decrease maximum temperatures at the end of the reach by approximately 5 Deg. C. Note that the plotting positions are not strictly equivalent, given that the velocity and thus the time of travel to a given location is different for each case.

16.7 Conclusions

The spreadsheet model described is useful as a screening tool, primarily to evaluate the importance of major inputs. It should be noted here that the model was included in an earlier report (US EPA, 1985).

The model is sensitive to solar radiation inputs, input flows of different temperatures, variations in flow, changes in canopy and channel modifications.

The model formulation makes simplifying assumptions that ignore several heat sources and sinks. The assumption that the ignored terms cancel out is suitable for a screening model; however it may not be suitable if absolute values of temperature are required. The estimation of equilibrium temperature, E , is thought to be within 2° C or less, of more complicated approaches (EPA, 1985).

The model was not formally calibrated, due to the lack of suitable data. In spite of these limitations, the model appears to give reasonable results, and responds to inputs in a realistic manner. Confidence in the model could be improved in future calibration studies.

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