Chapter 13

Modelling Solar Thermal Enrichment of Urban Stormwater

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This paper reviews some literature on solar thermal enrichment of stormwater due to urbanization, and summarises stormwater temperature modelling and existing model processes. It warns that thermal stormwater enrichment is certainly one of most important of the urbanization factors that destroy fish and aquatic ecosystems downstream.

13.1 Introduction

In recent years, considerable interest has been shown in stormwater pollution, but very few studies refer to thermal pollution of stormwater. The purpose of this paper is to present an overview of some recent studies on the effect of urban landscape interventions on stream temperature, and to present some useful modelling concepts and procedures.

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Why is it necessary to model solar thermal pollution of stormwater? Simply because urbanization raises the temperature of receiving streams significantly beyond lethal levels for certain aquatic ecosystems; water temperature is one of the most fundamental indicators of the water quality, especially the nature of an aquatic environment.

13.2 Background Review

Pluhowski (1970) analyzed the effect of anthropogenic changes on stream temperature and thermal patterns of five streams on Long Island, N. Y. Pluhowski indicated that man's tendency to cluster in urban environments, particularly during the past several decades, is probably the single most important factor governing the regimen of streams in recent geologic history. Widespread alterations in the natural environment have sharply reduced the infiltration capacity of soils, thereby increasing storm runoff to streams in urban areas. Not only has the volume of runoff increased, but there has been a reduction in the arrival time of runoff to watercourses. Pluhowski found that modifications of the natural environment of streams due to man's activities have increased average stream temperatures in summer by as much as 5°C to 8°C. Concurrent temperature differences between sites along the same stream of 8°C to 10°C have been observed in summer on days of high solar radiation. These large temperature differences are ascribed to a variety of urban factors, including the introduction of ponds and lakes, clearcutting of vegetation from streambanks, increased storm runoff to streams, and a reduction in the amount of ground-water inflow. By way of contrast, winter stream temperatures in man-affected reaches average about 1.5°C to 3°C lower than in unaffected reaches. During the spring and fall, changes in thermal patterns due to man's activities are minimal and barely identifiable. Analysis of variance indicated that the observed temperature patterns among the five study streams are significantly different during the summer.

The introduction of large quantities of storm water into watercourses from urbanized areas in Nassau County and southwestern Suffolk County may, under some meteorologic conditions, sharply alter stream-temperature patterns. Mixing of relatively large quantities of urban storm-water runoff with streamflow during August 25 and 26, 1967, raised temperatures 5.5°C at an upstream site on East Meadow Brook and 8.5°C at Swan River. The impact of streamflow on thermal patterns diminished downstream as the ratio of direct urban runoff to total streamflow decreases.

On-site observations at Connectquot River show that shading along this stream may reduce incoming solar radiation by as much as 70 percent. Energy-budget analyses on Connectquot River shows that short-wave (solar) radiation and ground-water seepage are among the most important heat sources controlling the thermal patterns in Long Island streams. These particular energy sources are

also most amenable to change due to man's activities.

Of the numerous factors affecting stream temperatures, Pluhowski stated that the most important include:

- 1) short-wave solar energy,
- 2) atmospheric long-wave energy,
- 3) back long-wave energy radiation from the stream,
- 4) advected heat from the ground-water reservoir; and
- 5) advected heat from direct (street) runoff where such runoff is a significant part of streamflow.

Items (1), (2) and (3) are highly stable, so that they are only slightly affected by urbanization. Item (4) is easily altered by a number of man's activities, particularly by the direct loss or recharge or through excessive withdrawals from the ground-water reservoir. In addition, the introduction of advected heat from storm sewers (item 5) can, under certain meteorologic conditions, materially change the energy budget of all streams.

In the summary of his paper, Pluhowski states that Long Island streams may be characterized as having low "thermal inertia"- that is, they possess only a small capacity for heat storage. In particular, the incoming energy from solar radiation under clear skies is relatively large when compared to the heat-storage capacity of the streams. Accordingly, nearly all Long Island streams tend to respond rapidly to heat inputs. On days of high solar radiation, large diurnal-temperature fluctuations may be observed in many streams. Moreover, under natural conditions, maximum temperatures tend to occur at nearly the same time everywhere along the streams. Urbanization causes stream-temperature patterns to change significantly both seasonally and diurnally.

Galli (1990) pointed out that, through the process of urbanization:

- 1) vegetation is removed from watersheds,
- 2) formerly pervious surfaces are converted to impermeable (such as rooftops, streets and parking lots), and
- 3) natural drainage networks are modified to convey runoff more efficiently.

These processes act together to alter the thermal regime of urban, headwater streams.

Among the more enlightening results of his study, was the finding that the level of watershed development had the single, greatest anthropogenic influence enrichment on the temperature regime of urban, headwater streams.

Galli examined the relationship between water temperature and watershed imperviousness and the analysis of the data revealed a strong linear relationship between mean late spring-summer water temperatures and watershed

imperviousness, as shown in Figure 13.1. An estimate of the mean, late-spring/summer water temperature of small, heavily shaded, headwater Piedmont stream was derived from the following equation:

$$\text{Mean Summer Water Temp. (}^{\circ}\text{C)} = 15.8 + 0.076 (\text{watershed imperviousness})$$

This least squares linear regression yields a correlation coefficient (r^2), adjusted for degrees of freedom, of 0.95, indicating a strong general relationship between water temperature and watershed imperviousness.

The explanation of Figure 13.1 is as follows: Metropolitan Washington Council of Governments staff identified several representative study sites for continuous water temperature monitoring and water quality grab sampling, such as: wet pond, artificial wetland, detention dry pond, urban stream draining watershed with high imperviousness and a small undeveloped watershed. Each site was ranked according to drainage area, watershed land use, stream discharge, stormwater and stormdrain conveyance system, and representativeness and access. These sites are within the Maryland portion of the Anacostia River basin. The characteristics of each site are summarized in Table 13.1.

Galli also noted that many of the environmental problems caused by urbanization (e.g. stream warming), cannot be completely mitigated by engineering means. The results of his study showed that stream temperature regime changes occur at relatively low levels; trout and other coldwater biota will most likely be lost when watershed imperviousness exceeds 12 to 15 percent. For the effects of meteorological and watershed land use condition on stream temperature, Galli observed:

1) Air Temperature and Other Local Meteorological Conditions.

- Local air temperature had for approximately 90 to 95 percent of the time, a greater influence on stream temperature than did stormflow. Notably, the potential for major stream temperature increases grew dramatically when air temperatures remained at or above 26.7°C for long periods of time. In general, the critical thermal loading season for the streams studied was late May to late September.
- The amount and intensity of precipitation was an important, though somewhat smaller factor. During the study, small storms which produced little or no runoff generally had little effect on receiving stream temperatures. Sharp, rapid increases in stream temperature were not observed under steady, light precipitation conditions. They were, however, closely associated with warm air conditions which included heavy shower activity.

RELATIONSHIP BETW. WATERSHED IMPERVIOUS AND WATER TEMPERATURE

source: Galli J.1990. Thermal Impact Associated with Urbanization and Stormwater management Best Management Practices. Units have been changed to C.

Figure 13.1

Relationship between watershed imperviousness and water temperature.

2) Watershed Imperviousness.

- Imperviousness together with local meteorological conditions had the largest influence on urban stream temperatures. In general, the average water temperature of urban streams increased in a linear fashion with increasing levels of watershed imperviousness. Results indicated that the average rate of increase was 0.08°C per one percent increase in imperviousness.
- Stream temperatures at the undeveloped watershed responded to storm events by becoming slightly cooler. This was largely due to the drop in air temperatures which accompanied most rainfall events. While this was also generally true of urban streams, as the level of watershed imperviousness increased, the streams become progressively more responsive to inputs of stormwater runoff. With increasing imperviousness, the storm-size needed to produce large, stream temperature fluctuations decreased. At a watershed imperviousness of 12% over 1.8 mm of rainfall was generally required. In contrast, at 60% imperviousness, less than 0.5 mm of

Table 13.1
Site characteristics

Study Location	Station Type	Watershed Drainage Area (acre)	Major Land Uses	Watershed Imperviousness(%)	Stream Gradient	Avg.Stream Width (m)	Avg.Baseflow cms
Lakemont	Reference Stream	400.0	F; OF	1	1.5	2.5	0.024
Okspring	Artificial Wetland	140.0	TH, SFR	18	2.7	1.2	0.003
Gum Spring	Trout Stream	620.0	SFR,F,OF,TH	12	2	2.7	0.028
Countryside	Wet Pond	165.0	SFR,LE,F,C	12	2.3	1.2	0.007
Tanglewood	Dry Pond	195.0	TH,SFR,O,F	30	2.3	2.3	0.007
Fairland Ridge	Dry Pond W/Infil.Tren.	25.0	SFR	18	4.7	0.8	0.001
White Oak	Urban Stream	225.0	C,GA,F	60	3.9	3	0.01

key abbreviations:

P = Piedmont; C = Coastal Plain; F = Forest;

OF = Old Field; TH = Townhouse; SFR = Single Family Residential(0.25 -.05 ac. lot);

C = Commercial; GA = Garden Apts;

LE = Large Estates (>2ac); O = Office Park;

Source: Galli J.1990. Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices. 7pp.

The units have been changed into metric system.

precipitation was needed to produce a comparable temperature change. It should be noted that stormwater runoff on receiving streams increased as the runoff (Q_{in}) to receiving stream flow (Q_r) ratio increased.

3) Riparian Canopy Coverage.

- Riparian vegetation plays a key role in insulating small streams from the warming effect of solar radiation. Other studies have shown that the removal of riparian vegetation can raise the summer water temperature of small streams by 6 to 11°C, and can lower winter water temperatures by 3 to 4°C. Results from this study revealed an average enrichment of 0.8°C per 30 meter of flow through either open or poorly-shaded reaches.

4) Stream Order/Size.

- It is well known that stream temperature naturally increases in a downstream direction with increasing stream order/distance from the source. In urban watersheds a variety of anthropogenic factors, such as the removal of riparian vegetation, micro-climate changes, and reduction of groundwater inflow, add to the so-called “watershed Delta-T” effect. Monitoring results indicated that the watershed Delta-T effect for a 18% impervious, urban third order stream system, is 0.6 to 1°C per stream mile. In addition, smaller lower-order urban streams are more responsive to this background watershed effect.

Galli also indicated that coldwater species such as trout would not be expected to survive at temperature levels observed at either the moderately or highly developed watershed sites. All trout species are extremely sensitive to thermal pollution/stress. Sustained elevated water temperatures over 21°C are generally considered to be stressful, while those at or above 25°C are usually lethal. Water temperature monitoring results from the 12% impervious Gum Springs tributary indicate that baseflow water temperatures remain safely below levels considered to be stressful to trout. However, under stormflow conditions, water temperature exceeds 21°C.

Klein (1977, cited by Klein, 1979) documented an 11°C difference between a wooded section along a Harford County, Maryland, stream and a poorly shaded pasture section of the same stream located 1.2 km below the woodland measurement point. Gray (1969) found an increase of 6.5°C in the summer stream water temperature after the trees were felled.

Klein (1979) also found that the differences between daily minimum

and maximum temperatures along a Harford County, Maryland, stream were 1.9°C in a wooded section, 4.3°C in a shrub lined section, and 8.3 °C in a pasture.

Schueler (1987) indicated that a number of factors can increase summertime water temperatures in urban headwater streams. Of these, three factors often act synergistically to increase water temperatures. First, as the urban landscape heats up on warm summer days, it tends to impart a great deal of heat to any runoff passing over it. Second, fewer trees are present on the streambank to shade the stream channel, adding to the warming effect. Third, runoff stored in shallow wet ponds and other impoundments is heated between storms, and then may be released in a rapid pulse, following a storm.

13.3 Recommended Modelling Procedures

13.3.1 HSPF

The Hydrology Simulation Program-Fortran (Johanson et al, 1984) can simulate the hydrologic and associated water quality processes in pervious and impervious land surfaces, in the soil profile, and in stream and well mixed impoundments. Routines HTRCH of the RCHRES module simulate the processes which determine the water temperature in a reach or mixed reservoir. It considers two major processes: heat transfer by advection, and heat transfer across the air-water interface as shown in Figure 13.2. The processes of diffusion and dispersion are not considered in HSPF.

Heat transfer by advection is simulated by treating water temperature as a thermal concentration. Heat is transported across the air-water interface by a number of mechanisms, and each must be evaluated individually. Mechanisms which can increase the heat content of the water are absorption of solar radiation, absorption of longwave radiation, and conduction-convection. Mechanisms which decrease the heat content are emission of longwave radiation, conduction-convection, and evaporation.

The shortwave radiation absorbed by a RCHRES is approximated by the following equation:

$$QSR = 0.97 * CFSAXE * SOLARD * 10.0$$

where:

- QSR = shortwave radiation in kcal/m².interval
- 0.97 = fraction of incident radiation which is assumed absorbed (3 percent is assumed reflected)
- CFSAXE = ratio of radiation incident to water surface to radiation incident to gage where data were collected. This factor also accounts for shading of the water body, e.g. by trees
- SOLARD = solar radiation in langleys/interval
- 10.0 = conversion factor from langleys to kcal/m²

Figure 13.2

All terrestrial surfaces, as well as the atmosphere, emit longwave radiation. The rate at which each source emits longwave radiation is dependent upon its temperature. The longwave radiation exchange between the atmosphere and the RCHRES is estimated using the formula:

$$QB = \text{SIGMA} * ((\text{TWKELV}^{**4}) - \text{KATRAD} * (10^{**-6}) * \text{CLDFAC} * (\text{TAKELV}^{**6})) * \text{DELT60}$$

where:

- QB = net transport of longwave radiation in kcal/m².interval
- SIGMA = Stephan-Boltzman constant multiplied by 0.97 to account for emissivity of water
- TWKELV = water temperature in degrees Kelvin
- KATRAD = atmospheric longwave radiation coefficient with a typical value of 9.0
- CLDFAC = 1.0 + (.0017*C**2)
- TAKELV = air temperature in degrees Kelvin corrected for elevation difference
- C = cloud cover, expressed as tenths (range 0 through 10)
- DELT60 = DELT(mins) divided by 60

Both atmospheric radiation to the water body and back radiation from the water body to the atmosphere are considered in this equation.

Conductive-convective transport of heat is caused by temperature differences between the air and water. Heat is transported from the warmer medium to the cooler medium; heat can therefore enter or leave a water body, depending upon its temperature relative to air temperature. HSPF assumes that the heat transport is proportional to the temperature difference between the two media:

$$QH = CFPRES * (KCOND * 10^{-4}) * WIND * (TW - AIRTMP)$$

where:

QH	=	conductive-convective heat transport in kcal/m ² .interval
CFPRES	=	pressure correction factor dependent on elevation
KCOND	=	conductive-convective heat transport coefficient (typically in the range of 1 to 20)
WIND	=	windspeed in m/interval
TW	=	water temperature in degree C
AIRTMP	=	air temperature in degree C

HTRCH also considers the evaporative heat loss, heat content of precipitation and correction of air temperature for elevation difference between the gage and simulation site.

13.3.2 SNTEMP

The Instream Water Temperature Model (Theurer et al, U.S.Fish & Wildlife Service, 1984) predicts instream water temperatures based on either historical or synthetic hydrological, meteorological, and stream geometry conditions. The model is applicable to any size watershed or river basin with a stream network of any stream order and complexity.

The following are some of the physical processes that affect instream water temperatures and their mathematical descriptions. The instream water temperature model (as shown in Figure 13.3) incorporates:

- 1) a solar model that includes both topographic and riparian vegetation shade,
- 2) an adiabatic meteorological correction model to account for the change in air temperature, relative humidity, and atmospheric pressure as a function of elevation,
- 3) a set of heat flux components to account for all significant heat sources,
- 4) a heat transport model to determine longitudinal water temperature changes,

Figure 13.3
HSPF

- 5) regression models to smooth or complete a known water temperature data set at measured point for starting or interior validation/calibration temperatures,
- 6) a flow mixing model at tributary junctions, and
- 7) calibration equations and tips to help eliminate bias and/or reduce the probable errors at interior calibration nodes.

The solar radiation model has two parts: (1) solar radiation; and (2) corrections for atmospheric conditions, for cloud cover, and for reflection from the water surface. The solar radiation at a site is a function of the latitude, general topographic features, and time of year. The solar radiation equation is:

$$H_{sx,i} = (q_s/\pi) \{ [(1 + \cos\theta_i)^2 / (1 - e^2)] \} \\ \{ [h_{s,i} \sin\phi \sin\delta_i] + [\sinh_{s,i} \cos\phi \cos\delta_i] \}$$

where:

- q_s = solar constant = 1377 (J/m²/sec)
 e = orbital eccentricity = 0.0167238
 θ_i = earth orbit position about the sun (radians)

- ϕ = site latitude for day i (radians)
 δ_i = sun declination for day i (radians)
 $h_{s,i}$ = sunrise/sunset hour angle for day i (radians)
 $H_{sx,i}$ = average daily extra-terrestrial solar radiation for day i (J/m²/sec)

The sunrise to sunset duration at a specific site is a function of latitude, time of year, and topographic features. It can be computed directly from the sunrise/sunset hour angle h_{si} . The average sunrise to sunset duration over the time period n to N is:

$$S_0 = (24/\pi)h_s$$

where:

- S_0 = average sunrise to sunset duration at the specific site over the time period n to N (hours)
 h_s = average sunrise/sunset hour angle over the time period n to N (radians)

The attenuation of solar radiation due to the atmosphere can be approximated by Beer's law:

$$H_{sa} = (e^{-\eta Z}) H_{sx}$$

where

- H_{sx} = average daily solar radiation (J/m²/sec)
 H_{sa} = average daily solar radiation corrected for atmosphere only (J/m²/sec)
 η = absorption coefficient (1/m)
 Z = path length (m)

The preferred measure of the effect of cloud cover is the "percent possible sunshine" recorded value (S/S_0), a direct measurement of solar radiation duration:

$$H_{sg} = [0.22 + 0.78 (S/S_0)^{2/3}] H_{sa}$$

where:

- H_{sg} = daily solar radiation at ground level (J/m²/sec)
 H_{sa} = solar radiation corrected for atmosphere only (J/m²/sec)
 S = actual sunshine duration on a cloudy day
 S_0 = sunrise to sunset duration at the specific site (unit for S/S_0 : decimal)

Solar or shortwave radiation can be reflected from a water surface. The relative amount of solar radiation reflected (R_t) is a function of the average solar angle (α) and the proportion of direct to diffused shortwave radiation. The percent possible sunshine S/S_0 indicates the direct-diffused proportions:

$$R_t = A(S/S_0)[\alpha (180/\pi)]^{B(S/S_0)} ; 0 \leq R_t \leq 0.99$$

where:

- R_t = solar-water reflectivity coefficient (decimal)
- α = average solar altitude (radians)
- $A(S/S_0)$ = coefficient as a function of S/S_0
- $B(S/S_0)$ = exponent as a function of S/S_0
- S/S_0 = percent possible sunshine (decimal)

Both $A(S/S_0)$ and $B(S/S_0)$ are based on values given by the Tennessee Valley Authority (1972).

13.4 Discussion

The City of Guelph has a population of about 95,000 (1991) and the area is 68.71 square kilometres. The population density is about 13 people/ha. From the City statistics, the population will increase to 112,000 (low growth) in 2006, and the imperviousness percentage in the city will increase too. Using the HSPF model, the relative water temperature changes are calculable, and the impacts of the heat from storm water or discharges of the city on water temperature confirmed, as will be shown in a later paper by the authors.

13.5 Conclusions

Since there are no algorithms in SWMM for computing (1) the heat gained by paving; (2) the washoff of heat by rainfall, we are currently developing appropriate codes.

The HSPF and SNTMP models allow continuous modelling of stormwater temperature due to solar radiation. Although a complete set of meteorological time series input data is sometimes not easy to obtain from measurements at a site, it should be relatively simple to obtain the data for calibration.

Note that HSPF assumes that the water body is isothermal (fully-mixed). This is often inaccurate for deep lakes or embayments, which are vertically thermally stratified, and for flowing streams, which exhibit longitudinally varying temperatures. The processes of diffusion and dispersion are not considered in HSPF, and the resulting bias is not known at this time.

Variables

HSPF	Hydrology Simulation Program - Fortran
SWMM	Stormwater Management Model
QSR	shortwave radiation in kcal/m ² .interval
CFSAXE	ratio of radiation incident to water surface to radiation incident to gage where data were collected. This factor also accounts for shading of the water body, eg. by trees
SOLARD	solar radiation in langleys/interval
QB	net transport of longwave radiation in kcal/m ² .interval
SIGMA	Stephan-Boltzman constant multiplied by 0.97 to account for emissivity of water
TWKELV	water temperature in degrees Kelvin
KATRAD	atmospheric longwave radiation coefficient with a typical value of 9.0
CLDFAC	$1.0 + (.0017 * C^{**2})$
TAKELV	air temperature in degrees Kelvin corrected for elevation difference
C	cloud cover, expressed as tenths (range 0 through 10)
DELT60	DELT(mins) divided by 60
QH	conductive-convective heat transport in kcal/m ² .interval
CFPRES	pressure correction factor dependent on elevation
KCOND	conductive-convective heat transport coefficient (typically in the range of 1 to 20)
WIND	windspeed in m/interval
TW	water temperature in degree C
AIRTMP	air temperature in degree C
q _s	solar constant = 1377 (J/m ² /sec)
e	orbital eccentricity = 0.0167238
θ _i	earth orbit position about the sun (radians)
φ	site latitude for day i (radians)
δ _i	sun declination for day i (radians)
h _{s,i}	sunrise/sunset hour angle for day i (radians)
H _{sx,i}	average daily extra-terrestrial solar radiation for day i (J/m ² /sec)
S ₀	average sunrise to sunset duration at the specific site over the time period n to N (hours)
h _s	average sunrise/sunset hour angle over the time period n to N (radians)
H _{sx}	average daily solar radiation (J/m ² /sec)
H _{sa}	average daily solar radiation corrected for atmosphere only (J/m ² /sec)
η	absorption coefficient (1/m)
Z	path length (m)

H_{sg}	daily solar radiation at ground level ($J/m^2/sec$)
H_{sa}	solar radiation corrected for atmosphere only ($J/m^2/sec$)
S	actual sunshine duration on a cloudy day
S_0	sunrise to sunset duration at the specific site (unit for s/s_0 : decimal)
R_t	solar-water reflectivity coefficient (decimal)
α	average solar altitude (radians)
$A(S/S_0)$	coefficient as a function of S/S_0
$B(S/S_0)$	exponent as a function of S/S_0
S/S_0	percent possible sunshine (decimal)

References

- Galli, John. 1990. Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices. Metropolitan Washington Council of Governments. pp:36.
- Gray, J.R.A. 1969. Effect of Woodland Clearance on Stream Temperature. J. Fish Res. Bd. Canada. 26:401.
- Johanson, R.C., Imhoff, J.C., Kittle, J.L. and A.S.Donigian. 1984. Hydrological Simulation Program - Fortran (HSPF): User Manual. U.S.EPA. EPA-600/9-80-015. pp:248-253.
- Klein, R.O. 1979. Urbanization and Stream Quality Impairment. Water Resources Bulletin, 15(4): pp:948-963.
- Pluhowski, E.J. 1970. Urbanization and Its Effect on the Temperature of the Streams on Long Island, New York. U.S. Geological Survey Professional Paper 627-D, pp:D1-D59.
- Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Prepared for the Washington Metropolitan Water Resources Planning Board. Publ. No. 87703. Washington, D.C.: Metropolitan Washington Council of Governments. pp:1-9.
- Theurer, F.D., Voos, K.A. and W.J. Miller. 1984. Instream Water Temperature Model. U.S. Fish and Wildlife Service. pp:II.5-II.86.
- Tennessee Valley Authority. 1972. Heat and Mass Transfer between A Water Surface and the Atmosphere. Water Resources Res. Lab. Rep.14. Norris, TN. 166pp.