Chapter 8

Thermal Enrichment of Stormwater by Urban Pavement

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Urbanization is known to increase the temperature of surface runoff during storm events and to increase the mean summer monthly temperature of receiving waters downstream (Galli, 1990; Pluhowski, 1970). It affects the temperature of streams as follows: urban construction, comprising roads, parking lots, roofs and sewers, reduces the original forest canopy, and increases impervious areas and, thus, surface runoff. Increased runoff in turn causes wider channels and more surface ponds, both of which lead to more exposure of stormwater to solar radiation, exacerbated by canopy loss. Increased imperviousness also leads to decreased infiltration and baseflow, which reduces the dilution of heated stormwater. Changes in the texture and color of the ground cover are also significant sources of thermal enrichment in an urban watershed. Elevated stream temperature is the inevitable result of these synergistic effects.

Several methods are available to control the thermal enrichment of stormwater - some infiltration approaches include: infiltration basins, infiltration trenches, seepage trenches, filter strips, grassed swales, and permeable pavement. While no single method may be sufficient, combinations of these methods may markedly reduce the impacts of urbanization on receiving waters (Marshall, Macklin, and Monaghan, 1991; Ahmed and James, 1995).

This study is part of our continuing research (Xie and James, 1994; Thompson and James, 1995; Kresin and James, 1996. See also the web: http://www.eos.uoguelph.ca/~james/research.html#porous); this chapter covers the

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thermal enrichment of surface runoff from impervious asphalt and porous concrete block pavement. Part of the research was conducted in a laboratory setting on pavement samples measuring about 1 x 1 x 0.5 m. Energy for heating the laboratory pavements was provided by either the sun or a 28000 Btu propane heater, and a rainfall simulator was used to generate thermally-enriched surface runoff. Experimental procedures are detailed in a dissertation (Verspagen, 1995) and will be published separately.

For this methodology a spatial resolution of about one hundred metres, approximately the size of a parking lot, is required. At this scale, the temporal resolution is of the order of one or two minutes. Such a resolution is considered to be very fine, even when compared to modern stormwater modeling practice.

We hope that this methodology will encourage designers, engineers, and planners of small urban areas, such as parking lots for shopping centers, to use alternative stormwater management practices, in particular pavement surfaces with environmentally-sensitive thermal characteristics.

8.1 Earlier Research

Related research has focused on long-term thermal enrichment as would result from reduced watershed infiltration, improper implementation of stormwater best management practices (BMPs) and removal of stream canopy (Galli, 1990; Pluhowski, 1970; Weatherbe, 1995). These three writers report significant impacts of thermal enrichment, including an alteration of the general thermal regime of receiving streams and rivers. However, increased temperature of urban stormwater resulting from rainfall on hot pavement has not received the same attention, and very little research has been conducted on the relevant component processes of heat transfer.

Xie and James (1994) evaluated the effectiveness of the Hydrological Simulation Program - FORTRAN (HSPF) for estimating expected thermal enrichment of stormwater runoff. They applied the model to the Speed River in Guelph, conducting additional field work to determine the required field parameters. Several conclusions were drawn:

1. runoff temperature is affected by the rainfall intensity and pavement temperature at the onset of storms;
2. air temperature is indirectly linked to pavement surface temperature;
3. a fine time resolution, of the order of minutes, is necessary when modeling expected stormwater runoff temperature, as storms may occur suddenly and last only a few minutes during hot weather; and
4. expected thermal enrichment in the Speed River receiving waters (early summer) was related to the percentage imperviousness:

$$Turb = 17.0 + 0.01 \times (\% imperviousness) \qquad (8.1)$$

where *Turb* is the expected or mean temperature of urban runoff (°C), and the constants 17.0 and 0.01 were determined by fitting against observed data.

Based on only three experiments using a rainfall simulator on an asphalt parking lot in medium-good condition (lot P10 at the University of Guelph), they tentatively proposed the following relationship between the temperature of the wet paving surface and the expected mean temperature of the surface runoff:

$$T_R = 3.26 + 0.828 \times T_{Pw} \qquad (8.2)$$

where:

T_R = the expected mean temperature of the surface runoff (°C),
T_{Pw} = the temperature of the pavement before wetting (°C).

8.2 Processes of Thermal Enrichment of Stormwater

To clarify our understanding of the underlying processes, a rather crude description is given here. Later, we state why we regard some of these processes as unimportant, in order to develop a simple empirical relation.

Clearly, pavement temperature fluctuates on a daily and seasonal basis. Seasonal cycles have been reported by Oke (1987). In areas such as southern Ontario, the subgrade experiences the warmest temperatures in July and the coldest temperatures in January. Diurnal fluctuations in Figure 8.1 were observed by the present authors in the subgrade of an instrumented asphalt pavement (described by Thompson and James, 1995) at 02:15 and 13:30 on August 23, 1995. This heating and cooling cycle is a commonly-observed, daily process.

Insolation (radiant energy from the sun) has a significant effect on the direction of the thermal gradient in the subgrade. Figure 8.1 is for a clear day where the temperature changes are relatively large. Late at night, heat energy accumulation from the previous day causes an gradient upward, because the pavement surface is cooler than the ground. During late afternoon, the thermal gradient is downward because the pavement surface is now warmer than the subgrade. A similar cycle might be observed in cloudy weather, although perhaps not as extreme.

Late afternoon, evening and early night rainfalls may advance the clear-weather day-night cycle: clouds reduce the amount of radiant energy reaching the pavement surface; relatively cold precipitation contacting the warm pavement surface creates a thermal gradient from the top of the pavement surface to the moving water film on the pavement surface, cooling the pavement surface and, subsequently, the subgrade.

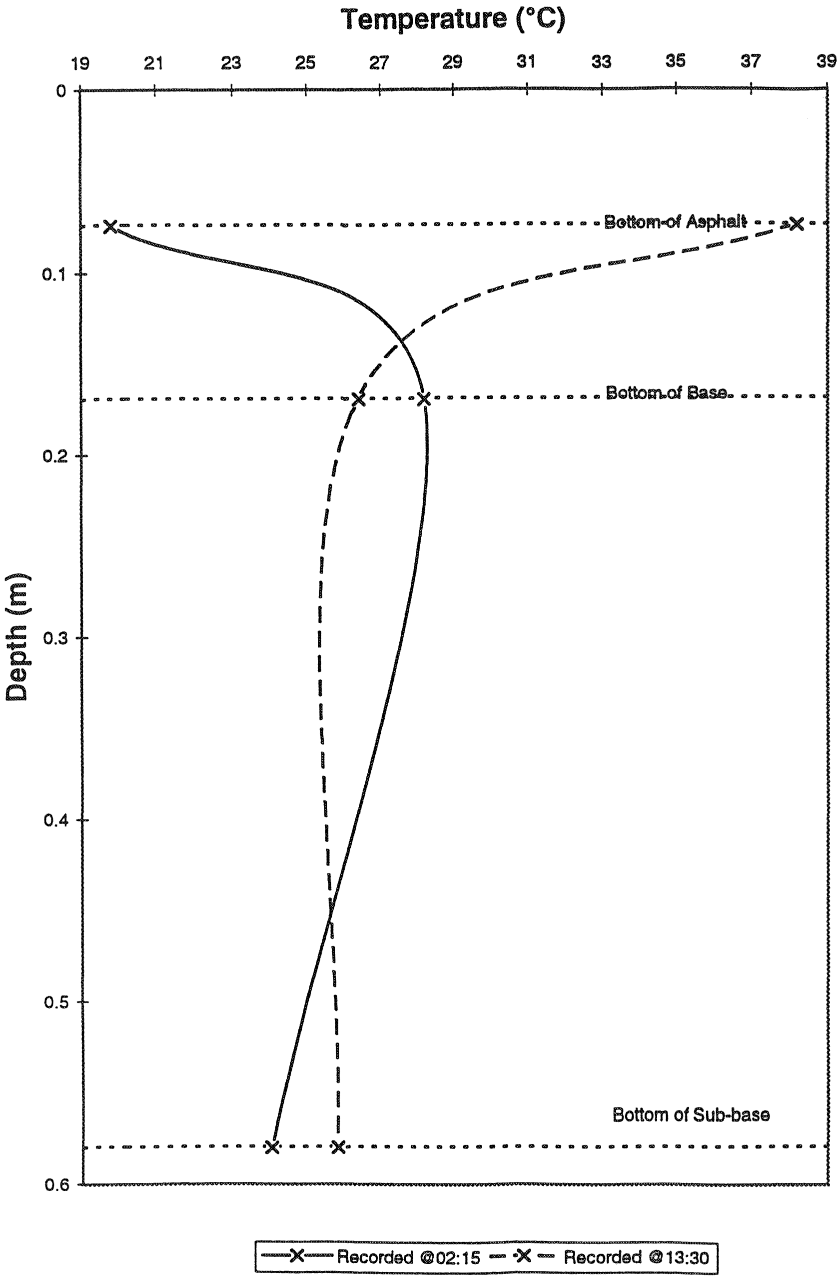

Figure 8.1 Diurnal temperature comparison - instrumented asphalt pavement, parking lot P10, August 23, 1995.

In this chapter we use the term *paving* to describe the hardened upper surface layer, e.g. four inches [10 cm] of asphalt or precast concrete block. *Subgrade* is placed below the paving. *Pavement* describes the entire construction (paving and subgrade) perhaps 3 ft [1 m] thick. *Surface* normally means a face having no thickness, usually the air/paving interface.

Cooling rates are influenced by many physical characteristics of the pavement, including the thermal and infiltration properties of the paving and subgrade. To consider the processes affecting temperature of surface runoff we follow hydrologic principles, expressing what thermodynamicists would consider an imprecise energy budget, for the combined, lumped paving-and-surface-water-film, whose temperature gradients across the paving and water film are not considered, as explained below:

$$\Delta H = (Q_n + Q_r - Q_e - Q_h - Q_g - Q_w) \times \Delta t \tag{8.3}$$

where:

ΔH = change in heat energy of the paving ($J \cdot m^{-2}$), averaged over the thickness of the paving, ignoring physical changes to the pavement material;

Q_n = net radiant heat flux at pavement surface ($W \cdot m^{-2}$) ignoring effects of the water film;

Q_r = heat transfer between raindrops and the paving surface ($W \cdot m^{-2}$), a likely process of pavement cooling;

Q_e = latent heat flux causing evaporation ($W \cdot m^{-2}$);

Q_h = convective heat flux, paving surface to air ($W \cdot m^{-2}$), conveniently ignoring the film which is considered to be discontinuous and intermittent;

Q_g = heat flux into or out of the ground ($W \cdot m^{-2}$);

Q_w = heat transfer between pavement surface and overlying water ($W \cdot m^{-2),}$ now admittedly inconsistently considered;

Δt = time interval over which change in stored heat energy is evaluated (s).

In reality the film of water on the pavement is ill-defined and likely to be thin compared to the large rugosity of urban paving, and it will be inherently difficult to identify its transient properties, as it drains across and through the paving. To avoid later difficulty in characterizing the film, our formulation does not separately consider heat flow through the water film to the paving surface. Nor does it allow temperature gradients to be identified within the subgrade, or within the water film. (No doubt this will raise concerns for thermodynamicists - our purpose here is only a consideration of the underlying mechanisms, in order to later derive a simple empirical relation, and not to derive a formal mathematical procedure!) By assuming that the water film is essentially intimately attached to the paving, the conceptual model favours situations where the depth-mean water-film temperature and the paving-mean temperature are similar. The model simply allows net energy in the paving to increase or decrease, depending on the conductivities, specific heats and thermal gradients between the subgrade and paving and between the pavement surface and the air above. It also allows paving to lose heat to the water film, but only paving-mean and water-film-mean (or depth-averaged) temperature is considered. Later we use this description to derive a very simple empirical relation.

As shown in Figure 8.2, where the film is shown to be continuous and uniform, but would in reality forms puddles in depressions in the rough surface, three situations may be described:

1. late on a clear sunny day: the dry pavement surface is warmer than the air above and ground below: Q_n and Q_g are down, Q_h up;
2. night and cloudy days: Q_n is small, ground is warmer than the dry pavement which is warmer than the air above: Q_g is up; and
3. daytime rainfall: cloudy conditions prevail and Q_n may be assumed to be small.

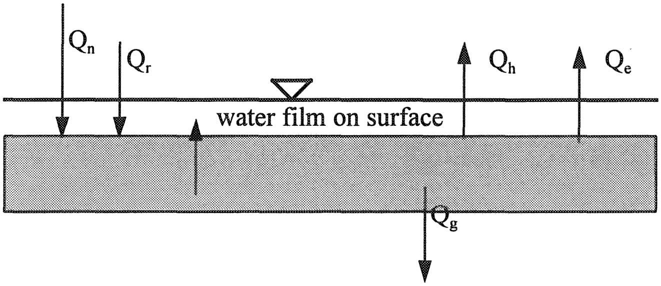

Figure 8.2 Wet pavement energy budget (note energy flux directly past water film, due to thin discontinuous and intermittent film and rough paving surface).

Infiltrating water will also convey heat to or from the paving and the subgrade. Partitioning of energy between overland surface runoff and infiltrating water is given approximately by the ratio of infiltrating water to surface runoff.

Because, during rainfall, the air and surface water temperatures are similar, and the humidity is high, the convective heat loss (Q_h) and the latent heat loss (Q_e) are small. (In reality this may not be true after cessation of rain and during drying of the paving surface; it is common for most of the residual water to gradually evaporate, perhaps within an hour or so in hot weather). If the pavement surface is warmer than the surface water, the heat energy loss to the surface water (Q_w)

will be significant. Energy is supplied from ΔH. If it is assumed that no thermal gradient exists between the bottom of the paving and the top of the subgrade, or if the energy budget is considered over a sufficiently short period of time so that conductive heat transfer from the bottom surface to the top surface of the paving is not significant, $Q_w \times \Delta t$ may be considered to be equal to ΔH.

8.2.1 Paving Energy Components

Net radiation absorbed by a pavement surface, Q_n, may be calculated using the following equation (Oke, 1987):

$$Q_n = K_n + L_n. \qquad (8.4)$$

where K_n = net short wave radiation (W·m^{-2}).

K_n represents the difference between the short wave radiation energy transmitted by the atmosphere and the short wave radiation energy reflected by the pavement surface:

$$K_n = (1-\alpha)K\downarrow \qquad (8.5)$$

where:

α = albedo or reflectivity of the receiving pavement surface,
K = total short wave radiation in direction indicated (W·m^{-2}).

L_n represents the net longwave radiation (W·m^{-2}), i.e. the difference between the longwave radiation energy emitted by the atmosphere and the longwave radiation emitted by the pavement surface:

$$L_n = \varepsilon_o \varepsilon_a \sigma (T_a + 273)^4 - \varepsilon_o \sigma (T + 273)^4 \qquad (8.6)$$

where:

ε_o = emissivity of the pavement surface (dimensionless);
T_o = temperature of the pavement surface (°C);
σ = Stefan-Boltzman constant (5.67×10^{-8} W·°K^{-1}·m^{-2});
T_a = air temperature (°C); and
ε_a = atmospheric emissivity (dimensionless):

$$\varepsilon_a = (0.72 + 0.005T_a)(1 + an_c^{\,2}) \qquad (8.7)$$

where:

n_c = fraction of cloud cover (n_c=1 is overcast), and
a = cloud constant (under cloudy conditions, a=0.20).

For the purposes of this study, primarily warm-weather rainfall, raindrops are normally cooler than the pavement surface. The temperature of the film of water on the pavement is used to estimate the heat transfer from/to the paving.

Thus, ignoring heat transfer to/from the paving, and assuming complete mixing (overlooking the effect of raindrop splash redistribution), water-film mean temperature may be determined using a heat balance:

$$T'_{sr} = \frac{q_r T_r + q_{sr} T_{sr}}{q_r + q_{sr}} \tag{8.8}$$

where:

T'_{sr} = mean temperature of the film of water on the pavement surface evaluated for the current time step (°C);
q_r = rainfall flow rate ($L \cdot t^{-1}$);
T_r = temperature of the rainfall (°C);
q_{sr} = surface runoff flow rate ($L \cdot t^{-1}$); and
T_{sr} = mean temperature of the surface runoff from the previous time step (°C).

The latent heat flux is:

$$Q_e = L_v \times E \tag{8.9}$$

where:

L_v = latent heat of vaporisation ($J \cdot kg^{-1}{}_{water}$) approx. 2.5×10^6, varies with temperature, and
E = mass flux of water removed through evaporation per unit time ($kg \cdot m^{-2} \cdot s^{-1}$).

Evaporation rates are dependent on the humidity of a relatively thin layer of air above and near the pavement surface. If this layer is very dry (and windy), the evaporation rate will be significant. Wind near the pavement surface promotes mixing of the upper and lower layers of the air above. Traffic also affects local air turbulence. When upper layers of relatively unsaturated air are mixed with lower, saturated, layers, greater evaporation rates result. E can be estimated from mass balances of long-term simulations, when it is likely to be significant.

Convective heat flux, Q_h, may be calculated using:

$$Q_h = C_a \frac{(T_o - T_a)}{r_H} \tag{8.10}$$

where:

C_a = volumetric heat capacity of air ($J \cdot m^{-3} \cdot K^{-1}$) (commonly assumed to be 1200 $J \cdot m^{-3} \cdot K^{-1}$, Oke, 1987);
T_0 = temperature of the pavement surface (°C);
T_a = temperature of the air (°C); and
r_H = aerodynamic resistance (s/m) - for more details see Oke (1987).

In calm conditions, the air above forms an insulating barrier due to its low heat capacity. But wind increases convective heat flux: the temperature gradient between the pavement surface and air above is steeper in windy conditions because the insulating barrier is removed and air from upper layers is mixed with air at the surface.

The subsurface heat flux, Q_g, may be first-order estimated using Fourier's law:

$$Q_g = k_s \left. \frac{dT_s}{dz} \right]_{z=o} \approx k_s \frac{T_1 - T_2}{z} \qquad (8.11)$$

where:

k_s = thermal conductivity of the paving ($W \cdot m^{-1} \cdot K^{-1}$);
T_1 = temperature at a predetermined depth in the subgrade (°C); and
T_2 = temperature at a small depth z (m) below T_1 (°C) (where Q_g has not changed significantly from its value immediately below the pavement surface).

Change in heat storage ΔH is:

$$\Delta H = C_s \times \frac{\Delta T}{\Delta t} \times \Delta z \qquad (8.12)$$

where:

C_s = heat capacity of the paving ($J \cdot m^{-3} \cdot K^{-1}$);
ΔT = mean temperature change (°C) over time;
Δt = change in time (sec); and
Δz = thickness of the layer under consideration (m).

8.2.2 Heat Transfer from Paving to the Overlying, Moving Water Film

Conductive heat transfer is dependent on the medium's mass density, specific heat, heat capacity, thermal conductivity, thickness, and thermal gradient (Arya, 1988). (Convective heat transfer to the fluid moving *around* the paving, e.g. down into the subgrade, is ignored here.) Specific heat is defined as the amount of heat absorbed or released in raising or lowering the temperature of a unit mass of the material by 1 °C. The product of mass density and specific heat is called the heat capacity per unit volume. The thermal conductivity of a material is a proportionality constant relating the rate of heat flux or heat transfer in a direction along the temperature gradient. The ratio of thermal conductivity to heat capacity is called the thermal diffusivity ($m^2 \cdot sec^{-1}$). Thermal diffusivity is considered to be the most appropriate measure of how rapidly temperature changes are transmitted to other layers in a medium (Arya, 1988).

It is useful to note that air has the lowest heat capacity and thermal conductivity of all natural materials. On the other hand, the thermal diffusivity of air is very large because of its low density. Conversely, water has the highest heat capacity of known natural materials. Addition of water to an initially dry soil will significantly increase its heat capacity and thermal conductivity, because the water replaces air in the pore spaces of the soil matrix. Heat capacity and thermal conductivity have been found to be monotonically increasing functions of soil moisture content (Arya, 1988).

Somewhat different from heat transfer between soil media, heat transfer from a plane surface to a liquid under turbulent conditions has been given by Holman (1990):

$$Q_w = \bar{h} \times (T_o - T_\infty) \tag{8.13}$$

where:

Q_w = amount of heat transfer from plate to the liquid (W·m^{-2});
T_0 = temperature of the pavement surface (°C);
T_∞ = temperature of overlying fluid under free stream conditions (°C) (free stream conditions occur at the point in the fluid where the thermal gradient is no longer influenced by the warm pavement surface over which it flows);
$\bar{h}$ = average heat transfer coefficient (W·m^{-2}·°C^{-1}) calculated using the Nusselt number:

$$\bar{h} = \overline{Nu_L} \times \frac{k}{L} \tag{8.14}$$

where:

k = thermal conductivity of the overlying fluid (W·m^{-1}·°C^{-1});
L = length of fluid flow over the pavement surface (m); and
$\overline{Nu_L}$ = average Nusselt number (dimensionless).

The Nusselt number provides a basis for comparing rates of convective heat loss from similar bodies but at different scales (Monteith and Unsworth 1990). Under turbulent conditions, which is what we experience at the paving surface during rainfall, it may be calculated using the following equation (Holman, 1990):

$$\overline{Nu_L} = Pr^{1/3} \times (0.037 \times Re_L^{\,0.8} - 871) \tag{8.15}$$

where Pr is the Prandtl number (dimensionless) whose value for water may be obtained from tables or by:

$$Pr = \frac{c_p \times \mu}{k} \tag{8.16}$$

where:

c_p = specific heat capacity of the paving ($\mathrm{kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}}$);
μ = dynamic viscosity of the fluid ($\mathrm{kg \cdot s^{-1} \cdot m^{-1}}$); and
k = thermal conductivity of the fluid ($\mathrm{kW \cdot m^{-1} \cdot {}^\circ C^{-1}}$).

Re_L is the Reynolds number (dimensionless) describing the fluid flow over the pavement surface:

$$Re_L = \frac{\rho \times u_\infty \times L}{\mu} \tag{8.17}$$

where:

ρ = density of the fluid ($\mathrm{kg \cdot m^{-3}}$);
u_∞ = velocity of the fluid under free stream conditions ($\mathrm{m \cdot s^{-1}}$);
L = length that the fluid flows over the pavement surface (m); and
μ = dynamic viscosity of the fluid ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$).

Together, these equations permit the net energy flux, its direction, and the periods of warming and cooling of the paving to be estimated. Warming of the surface water can be computed from the energy flux into surface runoff during rainfall if all the variables are known.

The heat capacity of water, i.e. the amount of energy necessary to warm 1 kg of water by 1°C, is approximately 4.2 $\mathrm{kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}}$. Noting that 1 joule is 1 W·s and that 1 L of water may be assumed to have the same mass as 1 kg of water, the change in temperature is:

$$\Delta T_{sr} = \frac{Q_w}{4200 \times q} \tag{8.18}$$

where:

ΔT_{sr} = change in temperature of the surface water (°C);
Q_w = total energy transferred from the pavement surface to the overlying water (kW);
4200 = heat capacity of water ($\mathrm{W \cdot s \cdot kg^{-1} \cdot {}^\circ C^{-1}}$) between 10 and 80°C; and
q = flow rate of water ($\mathrm{kg \cdot s^{-1}}$).

8.3 Development of a Design Methodology

Collectively the above expressions form a mathematical model for estimating the temperature of surface runoff, but such a model requires a significant quantity of physical information in the form of input parameters describing the pavement surface, and time series describing rainfall. The following outline suggests how the model could be used.

1. Assume that net radiant heat flux (Q_n) is negligible during rainfall (net longwave back radiation is balanced by weak shortwave influx). Similarly, assume that upward heat flux from the ground does not influence the paving temperature during rainfall (conductive heat process is slow, considering the thickness of the pavement and typical short duration of summer thunderstorms). Thus assume that all energy flux to the water film is the result of thermal energy stored in the paving (ΔH) or thermal energy in the raindrops (Q_r).
2. Measure or otherwise determine the initial pavement surface temperature.
3. Assume that on the pavement surface a film of water exists that does not disappear during rainfall. Further, assume that the temperature of this water is the same as that of the pavement surface.
4. Determine the temperature of the surface water using Equation 8.8 where the rain temperature is known and the surface runoff flow rate equals the rainfall rate from the previous time step. The runoff flow rate here represents both the surface water that has run off from the pavement surface and water that has infiltrated the pavement surface, and may be partitioned to reflect the respective proportions. Thus, a control volume is established for each time step.
5. Using the temperature of the surface water calculated in (4), determine the heat transferred to the surface water from the pavement from Equation 8.19 and Equation 8.13. The temperature of the pavement surface and other parameters such as the Reynolds' number must be known to complete this step.
6. Calculate the runoff temperature by summing T'_{sr} and ΔT_{sr}.
7. Substitute the calculated surface water temperature from (6) into the mass balance in (4).
8. Iterate steps (4) to (7) for the duration of rainfall re-evaluating the rainfall temperature and intensity at each time step.

8.3.1 Sensitivity Analysis

For modeling purposes using varying rainfall intensities as input time series, it would clearly be advantageous to simplify the method, perhaps by eliminating component processes that are less important than others, using environmental parameters to describe pavement materials, and using a reasonable range of paving temperatures as initial or start-up conditions.

Significant parameters may be found by sensitivity analysis:

1. assuming that $\frac{\Delta H}{\Delta t} = Q_w$,

2. substituting the energy budget and the heat transfer relationship (Q_w) into the equation converting input heat energy to a change in temperature,
3. examining the sensitivity of the heat storage expression $\left(\frac{\Delta H}{\Delta t}\right)$, and
4. determining the change in pavement surface temperature runoff (ΔT_{sr}) in both situations.

Parameters that would be appropriate when considering an asphalt pavement surface at 35°C were perturbed by adding 10%. The marginal sensitivity coefficient was then determined using the following equation:

$$S_c = \frac{\partial \phi}{\partial \alpha_i} \tag{8.19}$$

where:

S_c = the marginal sensitivity coefficient of the equation;
$\partial \phi$ = the change in the calculated objective function (i.e. the solution obtained using all base parameters minus the solution obtained using base plus the perturbed parameter); and
$\partial \alpha_i$ = the change in the *i*th parameter.

A spreadsheet used to calculate the sensitivity of the input parameters in the energy budget and heat transfer equations is presented elsewhere (Verspagen, 1995). Table 8.1 presents in rank order the seven most sensitive input parameters.

Table 8.1 Parameter ranking for heat transfer equations.

Rank	Input Parameter
1	T_{sr} surface runoff temperature
2	T_0 pavement surface temperature
3	μ dynamic viscosity of fluid (Reynolds equation)
4	Re_L Reynolds number ρ fluid density u_∞ free stream velocity L flow length (Reynolds number equation)

Thus, from the rather long discussion on processes, we conclude that the dominant processes are associated with the following parameters: *paving temperature*, the *initial water temperature*, the *surface runoff temperature*, the *heat* *capacity* of the paving, and the *surface runoff flow rate*. Since it is designed to have a high infiltration rate, some difficulty should be anticipated in obtaining the *surface runoff flow rate* for the permeable pavings, and for this reason *rainfall intensity* is used instead. For impervious paving, the surface runoff flow rate is nearly the same as the rainfall rate. Bearing in mind the uncertainty of estimates of flow lengths for the permeable pavers, and of scale-up errors to larger areas with non-planar surfaces, we stress that these parameters merely form the basis of a simplified surface runoff thermal enrichment relationship, one that should be calibrated for local surfaces and conditions. Indeed we recommend that this problem be given further attention.

Moreover, at this point we make a further gross simplification since the *heat capacities* of the pavement materials are not well known parameters, whereas *thermal conductivities* are available (Holman, 1990; Omega, 1992). *Thermal conductivity* provides a measure of the energy transferred per unit thickness per °C gradient, while *heat capacity* provides a measure of the work necessary per kg mass of material per °C. The correlation between *thermal conductivity* and *heat capacity* is expected to be high for paving materials since the materials have similar densities: i.e. as *thermal conductivity* increases, *heat capacity* will also increase. Therefore, for our simplified thermal enrichment model, *thermal conductivity* of the pavement surface is used instead of the little-known *heat capacity*.

In fact, determination of the thermal conductivity of some pavements requires additional research. When dry, the permeable paver consists of very dense concrete interspersed with open drainage cells filled with permeable material. Warming of the pavement surface and heat transfer to the subgrade is affected by the degree of saturation. As the material becomes wetted during rainfall, the thermal properties of the pavement surface change sharply, depending on the rainfall hyetograph and how the infiltration properties of the open drainage cell material have changed with age of the pavement and adjacent land-use. Over months or years, organic matter and dust forms a covering skin in the open drainage cells and significantly changes the infiltration properties from the original design conditions. Qualitative estimates of clogging are difficult to obtain.

8.3.2 Simplified Relations

Heat transfer between paving and the overlying liquid may be described in two ways (joules per second, T_s is a representative temperature of the surface paving material):

either: $\frac{\Delta H}{\Delta t} = C_s \times \frac{\Delta T_s}{\Delta t} \times \Delta z$ (8.20) or: $Q_w = \bar{h} \times (T_s - T_\infty)$ (8.21)

Change in temperature of the surface water is based on the known quantity of input energy:

$$\Delta T_{sr} = \frac{Q_w (or \frac{\Delta H}{\Delta t})}{4.2 \times q} \tag{8.22}$$

To describe the temperature trend, these equations should be solved stepwise in time. However, the expression for thermal enrichment during rainfall is expected to be an exponential decay from a high initial starting temperature and slope at the onset of rain. Since cloudy conditions predominate during rain, Q_n may be assumed to be negligible. Because temperature gradients between the paving and the surface water are initially large, the quantity of energy initially transferred from paving to surface runoff will also be large. As the paving temperature decreases, the thermal gradient driving the heat transfer diminishes proportionately. Thus, the paving and the surface runoff temperature drops during the rain. In sufficiently long rains, it would continue to do so until no temperature difference exists between the pavement surface and the runoff, and the paving and surface water runoff temperature will both approach the temperature of the rain. The exponential decay relationship is:

$$T_{sr} = A \ln(t) + B \tag{8.23}$$

where:

T_{sr} = the temperature of the surface runoff;
t = the time following the start of the rainfall (minutes); and
A and B = fitting parameters with units of (°C·time^{-1}) and (°C) respectively; they are functions of the rainfall temperature, pavement surface temperature, heat capacity of the paving, and runoff flow rate.

8.4 The Laboratory and Test Pavements

A central purpose of this study is a comparison of the thermal characteristics of: (a) impervious asphalt and (b) Uni-ecostone (the registered name is given in the acknowledgements at the end) with the 4 inch [10 cm] layer of mixed sand and washed stone. A detailed description of the construction of the test pavements is presented by Thompson and James (1995). Thermocouples were placed at several locations in the subsurface of the lab pavements, which were carefully insulated, as described elsewhere (Verspagen, 1995). Both pavement samples were stored in the laboratory; on sunny days when the samples were to be tested, they were moved outside early in the morning, and remained in the sun until approximately 13:30. Tests rarely continued for longer than 2 hours and the second sample was often brought into the laboratory by 15:30. On average, the samples were exposed to 5 hours of daytime sun.

A propane heater consisting of two 14,000 Btu radiant elements was constructed for use on cloudy or rainy days. The heater was capable of warming the upper layers of the pavement samples to extremely high temperatures in less than two hours. Longer durations were required to heat the full depth of the sample subgrade.

Data was also collected from the external instrumented parking lot pavements, and they showed differences from the lab pavements, as is to be expected. The surface temperature of the lab asphalt pavement was typically 2.3 °C warmer than the surface temperature of the instrumented parking lot asphalt, probably the result of ageing of the parking lot, which had been exposed to weathering since November, 1994. The colour has worn from black to grey by traffic eroding the bituminous coating on the upper surface of the surface aggregate. The laboratory sample is the same age and material, but had been protected and remained dark black. The darker colour of the lab pavement is considered to be the primary factor causing the surface of the test sample to absorb thermal energy more quickly and to reach greater temperatures than the parking lot pavement. Relationships have been developed for the change in emissivity of asphalt as it ages and are available from various asphalt research agencies, such as the asphalt industry and the American Association of State Highway and Transportation Officials (AASHTO).

Comparison of the temperatures immediately below the pavement indicated that the lab pavement was much cooler than the parking lot pavement. This is attributed to the difference in exposure time to direct sunlight. Had this study included another type of subgrade, the thermal conductivity of the subgrade would have had to be included in the analysis, because the thermal conductivity of the subgrade influences the surface temperature.

Surface temperatures for both permeable instrumented pavements were less than that of either asphalt surface.

8.5 Results for Various Rain Intensities

Detailed temperature plots from each experiment for the asphalt and paving stone test samples are presented in Verspagen (1995), and are only briefly summarized here. The plots indicate that the asphalt surface reaches greater surface temperatures than the paving stone surface. The rate of cooling of the asphalt surface runoff is observed to be consistently greater than that observed in the paving stone sample. Both surfaces exhibit similar properties in that the temperature of the surface runoff drops to a relatively constant level before the temperature immediately below the surface equals the temperature at the sub-base/base interface. This indicates that the heat flow to this point remains in the downward direction. A warmer temperature at the sub-base/base interface than immediately below the surface would indicate an upward thermal gradient from the subgrade, contributing to warming of the surface and the surface runoff. Therefore, these results confirm that warming of surface runoff results from release of heat energy solely from the pavement surface. The type of base does not directly influence the cooling portion of the experiment and thus inclusion of the heat capacity of the base is not necessary when developing an expression for thermal enrichment of surface runoff. The *type* of surface medium is less significant under high surface runoff flow rates conditions: the rate of cooling for both samples was observed to be significantly faster for higher than lower intensity tests.

8.5.1 Regression Analysis

The variation of the surface runoff temperature time series was regressed using a logarithmic regression function in Microsoft Excel for each experiment. The regressed equations are of the form:

$$T_{sr} = A \ln(t) + B \tag{8.24}$$

where:

A = decay of the temperature;
B = y intercept (a starting temperature);
t = time (minutes); and
T_{sr} = surface runoff temperature (°C).

Correlation coefficients were calculated to determine the relationship between the fitting parameters A and B and the independent variables: *rainfall intensity*, *thermal conductivity* of the paving, *initial paving surface temperature*, and *initial rainfall temperature*. Initial surface runoff temperature was found to be strongly related to A. Rainfall intensity and initial rainfall temperature were found to have an approximately equal correlation to A and thermal conductivity was found to have the weakest correlation to A. Initial surface temperature was also found to have a strong relationship to the B parameter. Rainfall intensity and initial rainfall temperature parameters were determined to have a smaller correlation to B. Thermal conductivity of the surface was calculated to have a weak relationship to B. Calculated correlation coefficients for the independent parameters and the parameters A and B are presented in Verspagen (1995).

Multiple variable regression analyses were then performed using the dependent parameters A and B and the independent parameters: rainfall intensity, paving thermal conductivity, initial surface temperature, and initial rainfall temperature. The regression was performed using all parameters from 22 of the 31 experiments. Data from the remaining nine experiments were used to verify the accuracy of the regressed expressions. Linear relationships for *A* and *B* were then developed:

$$A = 0.0047 \times i - 5.18 \times k_s - 0.13 \times T_{is} + 0.15 \times T_{ir} - 1.55$$

$$B = -0.0294 \times i - 2.26 \times k_s + 0.52 \times T_{is} + 0.07 \times T_{ir} - 14.62$$

where:

A and B = the fitting parameters for the general equation ;
i = the rainfall intensity ($\mathrm{mm \cdot hr^{-1}}$);
k_s = the thermal conductivity of the surface ($\mathrm{kW \cdot m^{-1} \cdot {}^\circ C}$);
T_{is} = the initial surface runoff temperature (°C); and
T_{ir} = the initial rainfall temperature (°C).

The regression analysis indicated that these expressions had R^2 values of 0.88 and 0.79 (F-test: $P<<0.001$) respectively.

Values of *A* and *B* calculated using the above expressions can be substituted into the general equation (Equation 8.24), to determine the temperature of the surface runoff at any time *t* (minutes) following the start of the rainfall event.

8.5.2 Accuracy of the Proposed Equations

In total 31 experiments were conducted. Of these experiments, 22 were used to perform a regression analysis to determine linear expressions for the parameters *A* and *B*. Data from the remaining 9 experiments were used as an independent data set to validate the accuracy of the proposed equations.

A spreadsheet was written that included the recorded surface runoff temperatures from all experiments. The average absolute error of the estimate was then calculated for each experiment. The average absolute error for all regressed data was determined to be 1.6°C.

The surface runoff temperatures recorded for the data not used in the regression were then compared to the surface temperatures calculated using the regressed expressions for *A* and *B* and the general equation. The average absolute error of the estimate was then calculated for each experiment, and the average absolute error for the independent data set was determined to be 1.4 °C.

Average absolute error was plotted against the difference between the initial surface runoff temperature and the initial rainfall temperature, and it indicated that the error for the independent data set is similar to that of the regressed data. The high absolute average error for large differences between the initial surface runoff temperature and the initial rainfall temperature indicates that the regressed expressions should not be used for extreme conditions such as were obtained on days that the propane heater was used and the pavement surface was able to attain very warm temperatures. The rainfall temperature on these days is not considered to be properly representative of an actual day. The error obtained on those days where the pavement samples were warmed naturally, however, generally appears to be within the range of the regressed data.

The error in the estimate of the surface runoff temperature was also plotted for the first hour of those experiments not used in the regression analysis, and it indicated that the surface runoff temperatures in eight of the experiments were initially underestimated. The error in the first 10 minutes is less than 4°C. After ten minutes, the error is generally less than 2°C.

The error analysis indicates that the equations may be used to determine the temperature of the surface runoff to an accuracy of ± 1.5°C. Over the first ten minutes, however, the accuracy is somewhat less and an error margin of ± 4.0°C should be expected.

8.5.3 Sensitivity Analysis of the Proposed Relations

A sensitivity analysis of the regressed equations and the general expression was performed. The results indicate that the initial surface runoff temperature is the most important parameter and must be the most accurately predicted. The initial rainfall temperature and the rainfall intensity are also influential and should be estimated with care. The thermal conductivity is of less importance but indicates that a difference in the temperature of the surface runoff exists between the asphalt and permeable paving.

8.6 Asphalt and Permeable Concrete Pavers Compared

The results of the experiments indicate that the asphalt paving generally reaches greater temperatures than the permeable paving. The regressed expressions were used to compare the asphalt and permeable pavings. Surface temperature data for the instrumented pavements were used. On August 23, 1995 at 13:29 hours, the observed surface temperature of the permeable paving was 36.9 °C and the observed temperature of the asphalt paving was 40.0 °C. These temperatures are considered to be typical of those seen in the summer months of 1995. The expressions developed from the regression analysis were applied using an initial rainfall temperature of 23.0 °C and a rainfall intensity of 115 mm/hr. These initial conditions are very close to the initial conditions used for the experiments run on that day. The initial surface runoff temperature recorded in the laboratory for those experiments were 35.1 and 36.0 °C for the permeable paving and asphalt paving respectively. The applied rainfall temperatures were 22.7 and 23.0 °C. These conditions are considered to be sufficiently similar for an unbiased comparison of the two surfaces.

The calculations were performed using a spreadsheet which is presented in Verspagen (1995). It was apparent that the calculated temperature of asphalt paving is warmer than the calculated temperature of permeable paving throughout the duration of the experiment. These results are consistent with those observed in the experiments conducted on August 23, 1995. The calculated difference is initially 1.9°C and gradually increases through the remainder of the simulation duration. The difference in calculated surface runoff temperatures, however, is within the error margins.

From this example, it may be concluded that surface runoff from the asphalt paving is slightly warmer than surface runoff from the permeable paving. This is consistent with the observed results.

A dominant factor that has not been stressed is infiltration of precipitation into the permeable paving. The temperature of surface runoff from the permeable paving is between 2°C and 4°C cooler than that of the surface runoff from the asphalt paving and itself a noteworthy environmental benefit, but the environmental advantage of the porous pavement is its ability to allow rainfall to infiltrate the surface. Thus, the total thermal loading on receiving waters is reduced.

An example of this can be considered using the data from August 23, 1995. Assuming two parking lots, 70 m on a side (4900 m^2), are equal in all respects except for their pavings. One parking lot has an impervious asphalt paving and the other a permeable paving. Using conservative numbers, a 20% infiltration rate may be assumed for the asphalt and an 80% infiltration rate may be assumed for the porous concrete. Also assume that the parking lots are directly connected to a receiving river flowing at 8.5 m^3/min (5 cfs, approximately that of the Speed River in Guelph) and at a temperature of 20 °C. This parking lot represents a typical parking lot found in many grocery stores or strip malls. Assuming a brief 15 minute storm event occurs in this catchment, the asphalt parking lot would produce 7.5 m^3/min of surface runoff while the porous paving parking lot would produce 1.9 m^3/min of surface runoff.

The impact on the river by the surface runoff from the asphalt, aside from the obvious increase in flow volume, is that the temperature of the water in the river is increased to 26°C for the first two minutes and drops to 23°C after 9 minutes. The impact on the river temperature receiving surface runoff from the permeable paving is that the temperature increases to 22°C and drops to 21°C after 3 minutes. While both surfaces increase the temperature of the surface runoff, the permeable paving is estimated to have a less severe thermal impact on the receiving waters. The stress resulting from a short term, instantaneous, temperature change as estimated for permeable paving is more likely to be within an acceptable tolerance level of aquatic biota. The calculations for this example are presented in Verspagen (1995). Instantaneous changes in temperature such as this are stressors to aquatic life and have an impact on the health of the aquatic ecosystem. The total thermal loading on the receiving water may be considered as the product of the temperature and the surface runoff flow rate: the resulting total thermal loading from the asphalt surface is significantly greater than that of the paving stone surface.

While the thermal impact presented in this example may seem small and to occur over a sufficiently small period of time as to be insignificant, the accumulated impact of many warm, impervious surfaces in a city may be significant.

The aspect of clogging of the porous paving stone surface is often noted. The above example considers the permeable paver to be four times more permeable than the asphalt. Studies regarding the infiltration capacity of aged porous paving stone surfaces are ongoing (Kresin, James and Elrick, 1996).

It is important to note that the relationship in this study was developed for a 1 m by 1 m lab pavement. Full scale testing should be completed to determine the true applicability of this relationship. For example, if a catchment 30 m by 30 m with one central catch basin is considered, this relationship would apply to the outer 1 m perimeter of the catchment. The inner catchment area would receive surface runoff from the outer catchment area. Thus the surface runoff flow rate towards the centre of the catchment could be significantly greater than the outer perimeter. The type of surface and micro-topography of the catchment should be considered. The surface runoff may flow along a narrow strip of the catchment and the relationship would give an accurate estimate of the surface runoff temperature. This is likely to be the case with the permeable paving since the bevelled edges of the individual paving stones encourage flow along the joints rather than the raised surface.

8.7 Conclusions and Recommendations

Further research is required, but the relationship proposed in this study represents a cautious estimate (from an environmental perspective) of the thermal enrichment of surface runoff from the asphalt and paving stone surfaces described in this study. Thermal enrichment of urban stormwater runoff should be considered when new developments are proposed, and thermally-sensitive pavement materials should be used more extensively than is the case now. Specific findings from this study include the following.

- Very little surface water runs off permeable paving in the laboratory.
- Both pavings in this study caused increases in the temperature of the surface runoff, asphalt more than permeable concrete.
- These results confirm that warming of surface runoff results from release of heat energy solely from the pavement surface.
- The rainfall intensity, thermal conductivity of the pavement, initial surface runoff temperature, and initial rainfall temperature are dominant parameters in surface runoff thermal enrichment.

- The expression $\Delta T_{sr} = A\ln(t) + B$ may be used to determine the thermal enrichment of surface runoff from either impervious asphalt or permeable paving stones, where:

$$A = 0.0047 \times i - 5.18 \times k_s - 0.13 \times T_{is} + 0.15 \times T_{ir} - 1.55$$

$$B = -0.0294 \times i - 2.26 \times k_s + 0.52 \times T_{is} + 0.07 \times T_{ir} - 14.62$$

The accuracy of the relationship is ± 4.0 °C in the first 10 minutes after rainfall begins and ± 1.5 °C when averaged over the entire duration of the rainfall event.

Empirical coefficients *A* and *B* were regressed for specific conditions, and therefore the results of this study are limited to pavements, climatological and instrumentation conditions encountered in this study. Extrapolation of the results beyond these will require verification. If the initial pavement surface temperatures are extremely warm and the difference in temperature between the rainfall and the pavement surface is large, the evaporative heat component may not be negligible and the relationship developed in this study may not be applicable. Similar limitations apply to continuous modeling methodologies. Research should continue to improve the accuracy of the relationship and further validate the relationship over a range of rainfall intensities.

Application of this or a similar relationship will lead to a better understanding of the thermal impact of new and existing developments. Approval agencies, engineers, and planners may make better informed decisions and choose a more thermally sensitive pavement surface or implement appropriate best management practices to minimize any negative thermal impacts.

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