The Thermal Enrichment of Storm Runoff from Paved Areas - a Statistical Analysis

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The thermal behaviour of storm runoff from paved surfaces was studied at two different urban catchments in order to determine the reliability of some statistical modeling techniques. Three tasks formed the bulk of the statistical analysis: graphical observations of thermal trends, analysis of the event mean temperature (EMT), and analysis of thermal exponential decay theory. The thermal trends were explained by equilibrium of thermal influences, based on the physical interaction of runoff and paved surfaces. The EMT was found to be dependent only on the air temperature at the time of the event and the event duration. The decay theory showed good agreement with recorded temperature decrease during storm events, however closer analysis revealed that the decay parameters could not be expressed reliably as a function of the event variables. It was concluded that this modeling technique has serious limitations when daily mean, maximum and minimum air temperatures are used for determination of event air temperature.

The non-point nature of urban runoff necessitates the need for reliable modeling of pollution realized in urban areas. As a greater percentage of the urban landscape is covered with impermeable paving, the volume of storm runoff during and following rainfall events is greater than ever. Urban runoff is a wide-ranging pollution source; however this study is concerned only with the thermal characteristics of storm runoff.

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The increased volume of runoff has been shown to thermally enrich the receiving waters in a number of ways (James and Verspagen, 1996). Erosion of existing watercourses into wider and shallower pools, coupled with a reduction in the number of shade-providing trees, leads to a greater volume of water exposed to solar rays. The warmed volume is released in a rapid and potentially destructive pulse after a rainfall. However, the single greatest contributing factor is the ability of the asphalt surface to absorb atmospheric heat and solar radiation. Rain water falling on the surface is heated before it is drained away. It has been found that man-made modifications raised seasonal temperatures of an urban river by 3 to 5°C (Murakawa et al., 1991; James and Xie, 1998). This could have serious environmental impacts on certain aquatic species (for example cold water fish), and their ability to survive in the warmer conditions.

7.1 Data and Methods of Analysis

7.1.1 Available Data

Data was analyzed from two different urban areas: from Lund, Sweden, and Belgrade, Yugoslavia. The Lund catchment (Sponberg and Niemczynowicz, 1992, Sponberg and Niemczynowicz, 1993) was situated within a car-park and covered 270 m² of the asphalt surface. At this catchment, 68 events were recorded reliably from June to November, 1991. At the Miljakovac catchment (Deletic and Maksimovic, 1998) in Belgrade, which covered 211 m² of an asphalt street, 23 events were recorded reliably. The tarmac surfaces were in similarly good condition at both catchments. To allow for fair comparison of the results, similar recording instrumentation was employed at either site.

The recorded variables comprised rainfall data and runoff data. The rainfall data was collected by tipping bucket rain gages (0.2 mm/tip) which continuously recorded rainfall intensity. The runoff measurements included runoff rate and runoff temperature (besides other water quality characteristics) at 10 second intervals throughout the course of an event. The temperature probe was placed in a small container (of volume less than 400 ml) through which water ran continuously during a storm event. The recording process was initiated by the first tip of the rain gage and was discontinued if not followed by another tip within 20 minutes of the previous one. The detailed description of the experimental catchments, monitoring program, and data gathered are now available in the following publications: Deletic et al, 1997, Deletic and Maksimovic, 1998, and Deletic, 1998.

Air temperature was recorded by local meteorological stations in the form of daily mean, maximum and minimum, therefore the actual air temperature was unknown at the onset of rain. In order to be consistent in determining the event air temperature, T , the following guidelines were devised as shown in Table 7.1.

Table 7.1. Criteria for determining air temperature prior to storm event.

Event Start Time (hrs)	11.00 -17.00	23.00 - 05.00	Else
Temperature used in analysis	Daily maximum	Daily minimum	Daily mean

7.1.2 Trends and statistical methods

Graphical observations. Runoff temperature was plotted against runoff flow rate for the duration of each recorded event so that the main trends could be determined. Three main trends were evident, as shown in Figure 7.1 of Lund event 132, which is broadly representative of all events. The most immediate was that of an overall decrease in runoff temperature during the event duration (Trend 1). The trend was observed in 63 of the 68 Lund events and 18 of the 23 events recorded at Miljakovac, corresponding to 89% of all recorded events. The second trend was that the runoff temperature decreases most rapidly during runoff discharge peaks (Trend 2) and it was found to occur in all events. The third trend was a constant runoff temperature at the end of the event (Trend 3), suggesting that an equilibrium state had been reached. 67% of all recorded events showed this trend, with 25% experiencing a rising final temperature and the remaining 8% still experiencing a temperature decay. Figure 7.1 shows a constant ending runoff temperature.

Figure 7.1 Runoff temperature and discharge for Lund event 132.

All trends can be explained by considering the thermal exchange processes between the paved surface and the rainfall water. Immediately before the first rain drops reach the surface there exists a large temperature difference between the warm surface and the cooler rain water. When contact occurs the rain water acts to cool the surface which simultaneously heats the runoff. The influence one exerts on the other is dependent on the volume of runoff and the magnitude of the temperature difference. Therefore, Trend 1 is a result of the net cooling effect of the rain. Trend 2 highlights the point in the event where the cooling effect is at a maximum. This corresponds to a large volume of cooling rain water hitting the surface, i.e. a runoff peak. The final trend, that of a constant runoff temperature, indicates that surface and runoff have equal temperature, and have reached an equilibrium of thermal influence. Events showing a rising final runoff temperature have surpassed this state, and the surface re-absorbs the lost heat and thus warms the last trickle of runoff. Events experiencing a falling final runoff temperature have not yet reached the thermal equilibrium state.

7.1.3 Event Mean Temperature (EMT)

The EMT was evaluated numerically for each reliably recorded event, using the following equation:

$$EMT = \frac{\sum_{i=1}^D (Q \text{ Temp } dt)}{\sum_{i=1}^D (Q dt)} \quad (7.1)$$

where:

- Q = the runoff discharge [l/s],
- Temp = the runoff temperature [°C],
- dt = the time increment of 10 seconds, and
- D = the event duration [sec].

The objective was to determine which of the event variables the EMT was dependent on, and to what extent. It was hypothesized that EMT depends on a single or a group of the following event variables: event air temperature, T [°C]; event aggregate runoff volume per unit area, V_{agg} [l/m²]; event aggregate rainfall depth, P [mm]; event duration, D [mins]; event mean runoff discharge per unit area, Q_{mean} [l/sm²]; event maximum runoff discharge per unit area, Q_{max} [l/sm²]; and event maximum rainfall intensity, I_{max} [mm/min].

Since it was expected that air temperature would have the most dominant influence on the EMT, a similar analysis was carried out on a normalized event mean temperature (EMT*). Absolute temperature scale (°K) was used for calculating normalized EMT*, as shown in Equation 7.2.

$$EMT^* = \frac{EMT + 273}{T + 273} \quad (7.2)$$

where EMT and T are in °C.

Statistical methods. Various statistical techniques were used to test the hypotheses listed above. The linear cross-correlation coefficients R were calculated, as well as their corresponding p, from the Student's t-test (the significance levels of calculated R values were determined using a standard Student's t-test). As a measure of non-linear association, the rank correlation coefficients, R_r , were also calculated for each pair. This is a standard statistical procedure to examine a possibility of a non-linear correlation between two variables. The significance of the rank correlation coefficients, p_r , were also calculated (p-value from Student's t-test). It was assumed that a relationship exists between two variables if the calculated p-value (p for linear or p_r for non-linear relationship) is less than 5%.

Correlation analysis offers no information about the nature of variable relationships, so regression analysis, including multiple regression analysis, was used from which significance tests were carried out and standard errors were determined.

7.1.4 Exponential decay of storm runoff water temperature

Thermal decay theory is an attempt to mathematically describe observed overall temperature decrease during one storm event by means of an exponential function. This simplified model was proposed by James and Verspagen, (1996) in the form of the function shown below.

$$\text{Temp} = A \ln(t) + B \quad (7.3)$$

where:

Temp = runoff temperature [°C],
 t = time after start of event [mins], and
 A and B = fitting parameters with units of [°C mins⁻¹] and [°C]
 respectively.

Decay parameters A and B were determined for each individual event by performing regression analysis on the runoff temperature data recording during that event, as well as the coefficient of determination between the exponential function and the actual temperature decay. When all the values had been calculated, the reliability of the method, and the existence of any relationships between decay parameters and event variables were investigated. The statistical methods used were similar to those described earlier.

7.2 Results and Discussion

7.2.1 Event mean temperature (EMT)

The linear correlation coefficients, R and their corresponding p , between EMT and event variables are given in Table 7.2 along with the rank correlation coefficients, R_r and their corresponding p_r . Also included are standard errors of linear regression, Stand. Err., and the mean event variable values, MEV, to offer an indication of the main differences between the catchment areas.

Air temperature during the event, T , is the most important variable in determining EMT, as Table 7.2 shows. This can be explained easily by the fact that the rain and surface temperatures throughout the course of an event are heavily dependent on the air temperature. The scatter charts of T variable versus the event EMT value are shown in Figure 7.2 for both catchments. The Lund relationship is more certain than at Miljakovac, but both appear to indicate a linear interdependency between the recorded event air temperature, T , and the EMT ($p=2.2\%$ for Miljakovac and $p=0.0\%$ for Lund).

Table 7.2 Correlation coefficients and standard errors between *EMT* and event variables.

Catchment	Event Variable	MEV	R	p [%]	Stand. Err.	R_r	p_r [%]
Miljakovac	V_{avg} [l/m ²]	2.88	-0.27	20.8	3.54	-0.24	27.6
	T [°C]	18.9	0.47	2.2	3.49	0.49	1.8
	P [mm]	3.6	-0.32	13.5	4.26	-0.38	7.3
	D [mins]	122	-0.39	7.3	148.13	-0.56	0.5
	Q_{max} [l/sm ²]	0.67	0.23	29.5	0.73	0.15	48.3
	Q_{mean} [l/sm ²]	0.0006	0.23	29.4	0.0008	0.18	41.2
	I_{max} [mm/min]	0.36	0.20	35.7	0.36	0.20	36.4
Lund	V_{avg} [l/m ²]	1.95	-0.06	61.2	4.54	-0.16	20
	T [°C]	12.5	0.92	0.0	1.75	0.93	0.0
	P [mm]	3.1	-0.08	50.0	4.54	-0.16	19.3
	D [mins]	115	-0.22	6.6	99.96	-0.40	0.1
	Q_{max} [l/sm ²]	0.37	0.30	1.4	0.49	0.14	27.2
	Q_{mean} [l/sm ²]	0.0003	0.30	1.4	0.0003	0.08	50.5
	I_{max} [mm/min]	0.3	0.23	5.6	0.37	0.11	36.2
	Q_{mean} [l/sm ²]	0.0003	0.30	1.4	0.0003	0.08	50.5

The definition of EMT (Equation 7.1) shows that it is a function of runoff discharge and rain duration. As expected, EMT was found to have a good correlation with event duration, D , and this is a negative and non-linear relationship as shown in Figure 7.3, and in Table 7.2 ($p_r=0.5\%$ for Miljakovac and

Figure 7.2 Scatter charts of EMT vs event air temperature, T, for both catchments.

Figure 7.3 Scatter charts of EMT vs event duration, D, for both catchments.

$p_r=0.1\%$ for Lund). In this analysis the discharge was represented only by the event variables Q_{mean} and Q_{max} . This simplification of an often rapidly changing runoff property is seriously misleading and as a result, neither correlated well with EMT.

A series of multiple regressions showed that T and D were sufficient for the prediction of EMT using this standard statistical method. When only these two independent variables were included, the following linear multiple regressions were found:

$$\text{Miljakovac: } \text{EMT} = 8.6 \times 10^{-5}D + 0.026T - 1.022 \quad (7.4)$$

$$\text{Lund: } \text{EMT} = 0.0028D + 0.0788T - 1.836 \quad (7.5)$$

where the multiple regression coefficients were 0.63 for Miljakovac and 0.93 and Lund. The multiple coefficients for long transformed linear regressions were slightly smaller than these figures for both catchments. It should be noted that for the Lund catchment only T could be used for reliable prediction of EMT (see Table 7.2).

The normalized event mean temperature, EMT* did not correlate with any of the event variables listed above.

The biggest question raised by the analysis was the greatly differing influence of T between catchments, as shown by the respective scatter charts. It was noted that the temperature probe at Miljakovac was less sensitive than at Lund, but the difference is too great to be entirely due to a slight disparity between the equipment. The suitability of the air temperature guidelines are suspect, as the climates may show significantly contrasting temperature patterns. However, even if the guidelines were appropriate, the Belgrade values of T are still more prone to error due to a greater daily temperature range. To improve this method further, the hourly temperature should be used for the determination of T.

7.2.2 Exponential decay equation

Lund Event 60, shown in Figure 7.4, is an example of reliable modeling of runoff temperature using the decay theory. Parameters A and B, and regression coefficient, R^2 , of the decay relationship (Equation 7.3), were calculated for each recorded event, for which statistics are given in Table 7.3. The mean R^2 values at both catchments suggest that the decay function is useful in estimating the actual runoff temperature. However, it was found that 11% of all events did not feature an overall temperature decay, therefore a method had to be derived to determine the conditions for which the decay equation is applicable. All events which did not correlate well with the exponential function, i.e. $R^2 \leq 0.25$, were analyzed and classified as exceptions to reliable correlation. It was noticed that the events with long periods of low rainfall intensity usually belong to this group.

It is speculated that, during the periods of low rainfall intensity, the asphalt surface had been re-heated due to low runoff rates, which resulted in an increase of the runoff water temperature.

Figure 7.4 Runoff plot of Lund event 60 showing the exponential modeling.

Table 7.3 Mean, standard deviations and range of decay statistics.

Catchment	Lund			Miljakovac		
Decay Statistics	A	B	R ²	A	B	R ²
Mean	-0.584	15.69	0.62	-0.592	21.30	0.75
Maximum	0.239	23.97	0.93	2.180	26.40	0.97
Minimum	-2.093	5.63	0.00	-2.433	15.89	0.44
Standard deviation, σ	0.489	4.53	0.22	0.905	2.50	0.14

The method was developed in the form of the following conditions which an event must satisfy if it is to be modeled reliably using the decay theory:

1. The event total rainfall, P , must be over 0.6 mm. Initial losses depend on antecedent conditions, and therefore the modeling of small rainfalls is not reliable unless these conditions are considered (which is not the case in the model applied here). However, the environmental significance of such events is low as a result of the small volume of runoff, therefore their modeling is of no importance.
2. The events longer than 120 minutes, which exhibit runoff rate per unit catchment area less then $Q_{low} = 2 \cdot 10^{-4} \text{ l/sm}^2$ continuously over a period longer then 25 minutes, should be split into two events: (i)

the first which ends when this period of low flow begins and (ii) the second which starts when this period is over. Event (i) could be modeled as an individual event, while event (ii) could be modeled only if the duration of the period of low flow is not longer than 50 minutes. This condition is introduced in order to define the duration of each single event for the purpose of the temperature modeling by the exponential decay equation. However, it has been recognized that it is always difficult to set correct rules for the start and finish of an event for any purpose.

These conditions were developed entirely on the Lund data and then tested successfully for the Miljakovac catchment. Implementation of the conditions to both catchments led to the elimination of 18 of the original 91 events, accounting for approximately 10% of total recorded rainfall depth. Only three events with low R^2 were not excluded in this way and were used in further analysis (they were regarded as exceptions to the developed rules). The decay parameters A and B, were then studied in detail to see if they could be expressed in terms of the observed event variables. The linear cross-correlation coefficients from this analysis are shown in Table 7.4. The rank correlation coefficients had very similar values to these, therefore they are not presented here.

Table 7.4 Linear correlation coefficients between decay parameters and event variables

Event Variable	Correlation coefficients - Lund		Correlation Coefficients - Miljakovac	
	A	B	A	B
A	1		1	
B	-0.03	1	-0.80	1
P (mm)	-0.08	0.02	-0.14	0.07
D (mins)	-0.04	-0.14	-0.40	0.40
Q (l/s.m ²)	0.00	0.38	0.10	0.02
T _{max} (°C)	0.25	0.84	0.46	-0.08
Q _{min} (l/s.m ²)	0.17	0.22	0.32	-0.24
I _{min} (mm/min)	-0.01	0.26	0.09	0.00
V _{avg} (l/m ²)	-0.09	0.07	-0.03	-0.06

A strong relationship has been expected between T and B because of the physical influence of air temperature on pavement temperature. The Lund catchment showed this to be the case, but contrasting correlation at Miljakovac casts further doubt over the air temperature values. The multiple regression analysis was also carried out and it was found that decay parameter A could not be expressed as a function of any of the studied groups of event variables at Lund. The Miljakovac data revealed that A and B were strongly interdependent, however the same was not found at the other catchment. Finally, it was concluded

that no universal set of variables could be used for prediction of the decay parameters for both catchments. This could be explained by the different climates of the studied cities, but also by low accuracy in event air temperature recording.

7.3 Conclusion

Runoff temperature is expected to decrease throughout the course of an event and the sharpest decrease will be initiated by discharge peaks. The temperature reaches an equilibrium after some time, although different thermal trends could occur towards the end of the event as cloud conditions, time of event and climate will all affect the runoff temperature to some degree.

The event mean temperature, EMT, is dependent on the air temperature at the time of the event and rainfall duration. Other event variables are not useful in determining EMT as shown by the analysis of the normalized EMT. The daily mean, maximum and minimum temperatures could be used for determination of event air temperature, however this could lead to certain errors especially in the climates with big daily fluctuations of temperature. Better indication of the exact EMT dependency of event air temperature should be detected using the hourly recorded air temperatures.

The exponential decay theory explains well a decreasing logarithmic trend of runoff temperature throughout the course of an event. As expected, decay parameter B is highly dependent on air temperature at the Lund catchment, but this was not the case at Miljakovac. There was no solid indication that parameter A is dependent on any combination of the recorded event variables at Lund. Because the decay parameters A and B cannot be expressed as functions of a universal group of event variables for both catchments, it was finally concluded that this theory is very difficult for practical implementation. However, this conclusion is valid only when event air temperatures are determined from daily mean and extremes temperatures (as it was done in this study), and only further analysis with hourly recorded air temperatures will lead to the final evaluation of the proposed method.

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