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Heat Export and Runoff Temperature Analysis for Rainfall Event Selection

by

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Abstract

Thermal pollution by surface runoff from urban areas can contribute to the degradation of coldwater ecosystems. The hydrothermal characteristics of surface runoff from rainfall are therefore of interest. Three hydrothermal parameters of surface runoff have been studied: runoff temperature (^oC), heat flux (W/m^2) and total heat export (J/m^2). Heat fluxes were defined above a reference temperature of 20^oC. The results can be used to identify storm events that have the potential for the largest heat export from a watershed and consequently the strongest thermal pollution of a receiving coldwater stream.

In this study, records of rainfall events and weather data are used to estimate the three hydrothermal parameters by model simulation. The model for predicting rainfall runoff temperatures and rates from an impervious surface (parking lot) has been described in Project Report No. 484 from the St. Anthony Falls Laboratory, University of Minnesota (Herb et al 2006). The weather data came from the MnROAD test site in Albertville, MN, and from the SAMSON data set. Runoff temperatures and heat export were calculated for a 100x100m paved surface using 6 years of 15 minute weather data or 30 years of 1-hour weather data. The 6-year data set contained 280 rainfall events from April through October.

The 280 values of the three hydrothermal parameters were related to basic rainfall event parameters such as total rainfall, duration, and rainfall temperature (dew point). Average runoff temperature was found to be well correlated to dew point temperature during the storm, and air temperature and solar radiation prior to the storm. 20 extreme values of the hydrothermal parameters were ranked and also related to basic rainfall parameters. Partial duration series of hydrothermal parameters were analyzed separately for frequency of occurrence (return periods).

Rainfall events with high heat export rate have several characteristics in common: They tend to occur mostly in the afternoon hours, have runoff temperatures significantly above 20^oC, and have relatively low total precipitation. The highest runoff temperatures also tend to occur with afternoon rainfall events of small total precipitation where the initial runoff from warm pavement surface is a significant fraction of the entire storm event.

The impact of the heat export from the paved 100mx100m paved lot on water temperatures in a specific stream was analyzed, to relate the hydrothermal parameters to changes in stream temperature. The heat export rate is directly related to the instantaneous change in stream temperature, while the total heat export of a runoff event relates to an integral temperature change in the receiving stream.

Finally, all the information generated was reviewed to recommend the characteristics of design storms to be used as input to models of surface runoff rates and temperatures from developed or undeveloped watersheds. These rainfall events typically have low total precipitation, occur on afternoons, and have return periods on the order of 1 to 5 years for maximum heat export rate or total heat export from a watershed. A methodology to create synthetic design storms with specific rainfall intensities, durations and return periods is also presented.

Table of Contents

NOTATIONS AND UNITS

ρ	water density [kg/m^3]
C_p	specific heat [J/kg·K]
g_{ro}	total heat export by rainfall/surface runoff event per unit area [kJ/m^2]
h_{ro}	runoff heat export rate per unit area [W/m^2]
H_{ro}	runoff heat export [W]
i	rainfall intensity [cm/h]
n	Manning’s roughness coefficient
q_{ro}	runoff flow rate per area [m/s]
Q_{ro}	volumetric runoff flow rate [m^3/s]
t_d	front delay time [h]
T_a	air temperature [°C]
T_{dp}	dew point temperature [°C]
T_{ref}	reference temperature for heat export calculation [ºC]
T_{ro}	runoff temperature [ºC]
T_s	stream temperature [ºC]

1. INTRODUCTION

Urbanization affects the temperature of cold water resources, streams and rivers in particular. Cold-water streams typically exist in well-shaded watersheds with large water inputs from groundwater. They are ecologically significant because they support coldwater fisheries and other wildlife that would be unable to survive in warmer streams. Of particular interest is the conversion of land from existing agricultural use or natural conditions. Urban expansion usually requires removing crops and trees and replacing them with parking lots, roads, lawns, and buildings. These changes affect shading, heat transfer, and hydrology within the watershed. Currently, there are few tools available to project to what extent stream temperatures are influenced by development in the watershed.

The main focus of this research is to create a model that would be useful for making decisions on land use and zoning in the watersheds of coldwater streams, to ensure that urbanization does not negatively impact the fragile nature of these ecosystems. Ease of use is essential if the model is to be used for planning and permit decisions. The ideal model would be able to accept standard climate data (solar radiation, air temperature, relative humidity, and wind speed) along with parameters concerning land usage to predict the changes in surface and subsurface runoff temperatures, and ultimately, stream temperature.

Perhaps the most important input to the model will be the rainfall event and the weather conditions during and before the rainfall. To specify one or several design storm event is no easy task. Rainfall and runoff frequency analysis is used to select design storms for storm sewer design and hydraulic structures. For example, a design storm of 1.25 inches of precipitation over 1 hour is used in the MPCA storm water manual to represent a storm event with a 10 year recurrence interval in Minneapolis. For the case of thermal loading, it is more difficult to specify a design storm event.

The thermal impact of surface runoff on receiving stream temperature depends on many factors, including land use, the characteristics of the precipitation event itself, and the associated climate conditions during and prior to the event. Prediction of the thermal impact of, for example, runoff from a housing development requires a complex model that includes runoff from a variety of surfaces, routing through storm sewers, and mitigation measures. To estimate the thermal impact of a variety of storm events without a specific watershed in mind and to select design storms for use in a more complex watershed model, it is useful to estimate runoff temperature, total heat export and heat flux using a relatively simple model.

This report has three parts: (1) a study of “heat export” from a small watershed using historical climate data and a simple model, (2) a brief study of how to measure “heat impact of a given “heat export” on a stream, and (3) an evaluation how the information from (1) and (2) can be used to select design storms from historical events. In essence this report describes work to characterize storms whose surface runoff has the potential to produce a large thermal impact on a stream.

In part (1) the thermal export is quantified by three parameters: runoff temperature (^oC), rate of heat export (W/m^2) during a rainfall runoff event, and the total amount of heat export by a rainfall/runoff event (kWh/m^2 or J/m^2). The study uses a relatively simple, one-dimensional model for the simulation of runoff temperatures during storm events for multiple years of measured climate data. Extreme values of heat export are ranked and subjected to a frequency analysis.

In part (2) a relatively simple mixing model is used to determine stream temperature rise for a given set of heat export parameters from part (1). Historical rainfall events have to be studied and ranked in terms of their potential hydrothermal impact on a stream. We will write the basic equations for stream temperature. Since the stream is yet unknown we will apply the extreme heat export values from historical rainfall events to a hypothetical stream. The results will provide some guidance to the selection of a design storm event.

In part (3) the information from (1) and (2) is reviewed to formulate recommendations for design storms to be used as input in the much more comprehensive model under development. After a review of the results of the study we propose several historical design storms. A methodology to create synthetic design storms with specific rainfall intensities, durations and return periods is also applied and results are presented.

2. DATA

Recorded weather data are the main input to the hydro-thermal analysis described in this report. Precipitation data are required to predict runoff hydrographs while air temperature, humidity, wind, and solar radiation data are required to predict land surface and runoff temperatures prior to and during precipitation events. Standard data sets give weather parameters at 3-hour intervals. This interval is too long to characterize the runoff flow and water temperature during a rainfall event. Therefore two climate data sets that provide weather data at shorter time intervals were examined for this study:

1) The SAMSON data set (Solar and Meteorological Surface Observation Network CDROM, available from the National Climatic Data Center). It compiles 30 years (1961-1990) of hourly weather data for 237 NWS weather stations across the US, including the Minneapolis/St. Paul airport.
2) The weather data from the MnROAD facility of the Minnesota Department of Transportation (MnDOT). In this study we used eight years of 15-minute MnROAD weather data from 1998 to 2005.

While the SAMSON data set is substantially longer than the MnROAD data set, it has two drawbacks: 1) the time interval is one hour, which is rather coarse for the analysis of a rainfall event on a small watershed such as individual parking lots, a residential development, etc. and 2) the data set uses solar radiation simulated from cloud cover. It was found that unrealistically high solar radiation during some precipitation events was reported in the SAMSON data set; as a result unrealistically high pavement and runoff temperatures were predicted. The bulk of the study was therefore conducted with the MnROAD climate data set, which includes air temperature, dew point, wind speed and direction, precipitation, and measured solar radiation at 15-minute time intervals.

3. METHODS OF ANALYSIS

For our simplified runoff study we used a 100m x 100m plot of asphalt pavement, with a slope of 2% and a Manning's roughness n= 0.01. We applied a total of 280 rainfall events to this plot. The climate data (1999 to 2005) came from the MnROAD test facility in Abertville, MN. Data from 2001 and 2002 was not used, because problems with the rainfall data were identified. An asphalt pavement was chosen as the watershed area for several reasons:

1) Asphalt pavement gives very high runoff rates and temperatures compared to any other land use; heat export values for an asphalt pavement therefore represent a quasi- upper bound for thermal impact of any land use with no mitigation.
2) The 0D models used were validated against measured temperature data (Herb et al. 2006a) from asphalt pavement sections at the MnROAD test facility and found to be very reliable for that type of surface.
3) Infiltration can be assumed to be negligible during a rainfall event, and therefore does not have to be estimated. The runoff temperature can be assumed to equal to the pavement surface temperature during the precipitation event.
4) We know from 2D runoff simulations for asphalt pavements (Janke et al. 2006) that surface temperature is fairly constant with distance on a 100 m asphalt paved lot.

The MnROAD climate data were used to simulate 15-minute pavement surface temperatures for all weather conditions from April through October, including surface temperatures prior to and during each storm event. Runoff temperature was simulated for each storm using a one-dimensional heat transfer model that simulates the pavement temperature, the soil temperature to a depth of 10 meters, and the runoff temperature during precipitation events. The heat transfer model was coupled to a 1D surface runoff model that simulates the runoff flow rate per unit width, based on a specified length. The models are described in detail in Project Report No. 478 (Herb et al. 2006a) and 484 (Herb et al. 2006b). A 2D runoff rate and temperature model could have been used as an alternative but the computational effort would have been considerably larger without much additional benefit. The analysis was performed in 15-minute time steps during dry weather periods and 1-minute time steps during runoff events, and in its present form, gives runoff temperature (^oC) and the runoff flow rate per unit width (m^2/s).

The computed runoff flow rates (q_{ro} m^2/s) and temperatures (T_{ro} ^oC) at 1-minute intervals were then used to calculate two other parameters: the maximum heat export rate during the rainfall event and the total heat export for each rainfall event. The export rate of heat (energy) per unit surface area (h_{ro} W/m^2) was calculated for each time step as follows:

$$(3.1)\ h_{ro} = (\rho C_p) q_{ro} (T_{ro} - \mathrm{Tref})$$

where q_{ro} and T_{ro} are the runoff flow rate and temperature at a specific time during the storm event, T_{ref} is a reference temperature. The reference temperature was chosen to be 20°C because coldwater streams can provide trout habitat up to approximately 20^{o}C. The flow rate per unit width (m^2/sec) obtained from the runoff model was divided by the specified length of the watershed (100 m) to give a runoff rate per unit area (m/sec); multiplied by the specific heat per unit volume of water (ρC_p=water density · specific heat) the rate of exported heat (energy) per unit area of pavement (h_{ro}) is obtained in units of W/m^2. Asphalt pavements give the highest runoff rates and temperatures of any land use; it is therefore expected that the heat export values obtained by the above procedure represent a quasi-upper bound for any parcel of land with no mitigation.

The total heat export for each storm (e.g J/m^2 or kWh/m^2) is the time integral of the heat export rate (h_{ro}) over the duration of the storm (Equation 2). Precipitation events with gaps of up to 1 hour were treated as a single event.

$$(3.2)\quad g_{ro} = \int h_{ro}\, dt$$

Lists of rainfall events were constructed from the data record with the corresponding climate data parameters, including total rainfall amount and duration, dew point temperature, pavement surface temperature, and maximum heat export rate and total heat export. The lists were then ranked, from highest to lowest, for a number of climate and runoff parameters, including total heat export, average heat export rate, and runoff temperature. The ranked lists were then used to construct partial duration series for frequency (return period) analysis of both rainfall parameters and runoff parameters. Hydrothermal runoff parameters such as total heat export were plotted against rainfall parameters such as rainfall duration, total rainfall amount, and dew point temperature, to test if relationships between heat export and rainfall event characteristics existed.

Frequency (return period) analysis was performed on both precipitation data (depth, intensity, and dew point temperature) and on simulated runoff data (heat export rate, runoff temperature). The return periods were analyzed as follows:

1. Two lists of storms were compiled which exceeded the threshold values for total heat export or maximum heat export rate, respectively.
2. The events were ranked from highest to lowest on each list.
3. If any two pairs of storms in the list were within 2 weeks of each other, the lower rank storm was eliminated to help ensure independent events, i.e. avoid serial correlation.
4. The return period for each ranked event was calculated as $R=(n+1)/m$, where $n=6$ is the number of years of record and m is the rank.
5. A semi-log plot was generated of total heat export or maximum heat export rate versus return period, and a best fit was made.
6. The rainfall parameters that led to the highest heat export and runoff temperatures were also subjected to a frequency analysis and plotted.

When surface runoff enters a stream, the change in stream temperature depends on the flow rate and temperature of the receiving stream and the flow rate and temperature of the runoff. Treating the runoff as a point source to the receiving stream, a simple heat balance may be formulated as follows:

$$(3.3)\quad \rho C_p\left(Q_s \cdot T_s + Q_{ro} \cdot T_{ro}\right) = \rho C_p\left(Q_s + Q_{ro}\right)T_m$$

where Q_T and T_T are the stream flow rate and temperature upstream of the inflow, and Q_{ro} and T_{ro} are the runoff flow rate and temperature, T_m is the temperature of the mixed stream downstream of the inflow, and $\rho C_p = 4.2\ \mathrm{MJ/m^3}$ is the product of density and specific heat of water. Equation 3.5 can be used to find the mixed stream temperature increase $\Delta T_m = T_m - T_s$, if the other quantities are known:

$$(3.4)\quad T_m = \frac{(Q_s \cdot T_s + Q_{ro} \cdot T_{ro})}{(Q_s + Q_{ro})}$$

$$(3.5)\quad \Delta T = T_m - T_s = (T_{ro} - T_s)\frac{Q_{ro}}{(Q_s + Q_{ro})}$$

Using Equation 3.5, characteristics of runoff from particular storm events can be related to changes in stream temperature.

4. RESULTS FOR HISTORICAL RAINFALL EVENTS

4.1 Storm Event Characteristics

The list of storm events was analyzed to determine the seasonal variation of and interrelationships between parameters such as duration, dew point temperature, runoff temperature, and total rainfall. All data presented (Table 4.1), except where noted, are based on six years of 15-minute climate data: 1998-2000 and 2003-2005. Some results from the Samson data set are also presented (Table 4.3).

Figure 4.1 gives plots of the seasonal distributions of maximum and mean event temperatures, rainfall event duration, and total precipitation. The plotted data are also given in Table 4.1. Mean event dew point temperature was calculated as an average over each rainfall event, weighted by the precipitation amount during each 15 minute measurement. The result represents a good approximation of rainfall temperature. Similarly, mean event runoff temperature was calculated as an average over each storm event, weighted by the runoff amount during each 15 minute measurement. The average event temperatures were highest in July, with the mean air (19.6 °C) and dew point temperatures (18.8 °C) approaching 20 °C, and the mean runoff temperature (22.3 °C) about 3.5 °C higher than mean dew point or rainfall temperature. The maximum event air and dew point temperatures were in July (24.6 °C) and June (21.6 °C), respectively, while the maximum runoff temperature had high maximum values in June, July, and August (30.9 to 32.2 °C). Rainfall events tended to be of shorter duration with greater total rainfall amounts in June, July, and August compared to spring and fall months.

Figure 4.2 gives the statistical distribution of dew point temperature, rainfall duration, and total precipitation for rainfall events compiled from the MnROAD data set. In the 6-year record, there were a total of 27 rainfall events with dew point temperature greater than 20°C: 6 in June, 13 in July, 2 in August, and 5 in September. The product of total precipitation and dew point temperature is strongly related to the total heat export, which is explored in a later section.

The inter-relationships between rainfall depth, duration, intensity and dew point temperature are explored in Figures 4.3 and 4.4. There is a general increase of rainfall depth with duration, but with substantial variability between and lower and upper bounds. The relationship between intensity and duration has some hint of an inverse function (Figure 4.3), but also with substantial scatter. The June 23, 2003 event appears quite clearly as an outlier, with 10 hour duration and 2 cm/hour average intensity. There is little correlation between rainfall depth and dew point temperature and between rainfall intensity and dew point temperatures, but there does appear to be a tendency for the higher rainfall depths and intensities to occur near a dew point temperature of 20 °C.

Results for frequency analysis of precipitation are given in Figures 4.5 and 4.6. The June 23, 2003 event, with 21 cm of precipitation over 10 hours, is clearly an outlier, as this rainfall total exceeds 12 hour, 100 year storm values given in previous studies (Table 4.2). This storm was removed from the frequency analysis. The precipitation frequency results obtained for this study can be compared to previous studies on precipitation frequency for the Minneapolis/St. Paul metropolitan area. Table 4.2 gives precipitation depth return periods for the present study, TP40 (Hershfield 1961), Huff and Angel (1992) and Skaggs (1998). For 1-year return periods, the precipitation depths obtained in the present study are quite similar to the other studies. For return periods of 2 to 10 years, precipitation depths obtained for the present study are higher than previous studies, e.g. about 20% higher than values given by Skaggs (1998). This is not surprising, since the data record used for the present study (6 years) is not long enough to confidently analyze return periods larger than 1 to 2 years.

Table 4.3 gives rainfall event statistics for 30 years of 1-hour data from the Minneapolis-St. Paul International Airport. The seasonal distributions of air and dew point temperatures during rainfall events are similar to those obtained from the 6-year 15-minute MnROAD data set (Table 4.1). The average and maximum event runoff temperatures are, however, about 2°C and 10°C higher than those obtained from the MnROAD data set, respectively. A likely cause of this discrepancy is that solar radiation in the SAMSON data set is simulated from cloud cover, resulting in higher solar radiation during periods of rainfall. Indeed, the SAMSON solar radiation given in Table 2 is about three times larger than the measured solar radiation from MnROAD given in Table 1..

Table 4.1. Rainfall event statistics derived from 15-minute climate data collected at the MnROAD site (Albertville, MN) over 6 years (1998-2000, 2003-2005).

Month	April	May	June	July	Aug	Sept	Oct	All
	Air and Dew PointTemperature							
Number of Events	32	58	54	40	30	36	30	280
Average Event Air Temp (°C)	6.9	12.8	17.3	19.6	18.4	16.9	12.1	15.0
Maximum Event Air Temp(°C)	19.7	20.5	23.6	24.6	23.6	21.9	17.5	24.6
Average Event Dew Point (°C)	6.1	12.0	16.2	18.8	17.5	16.2	11.6	14.2
Maximum Event Dew Point (°C)	16.1	18.0	23.9	21.6	21.4	21.4	16.8	23.9
	Event Duration and Precip							
Average Event Duration (°C)	4.1	4.1	2.8	2.4	2.5	3.7	3.1	3.3
Average Total Event Precip (cm)	0.84	1.18	1.45	1.24	1.19	1.69	0.97	1.24
	Event Solar Radiation							
Average Event Solar (W/m^2)	15.72	34.49	42.57	24.55	25.10	20.97	13.25	27.46
Maximum Event Solar (W/m^2)	109.61	258.83	243.53	148.38	164.78	166.26	54.80	258.83
	Runoff Temperature							
Average Event Runoff Temp (°C)	8.1	14.6	19.7	22.3	20.9	18.6	12.8	16.9
Maximum Event Runoff Temp (°C)	21.7	21.6	31.7	30.9	32.2	25.8	18.9	32.2
Average (Runoff - Dew Point) (°C)	2.0	2.6	3.5	3.5	3.4	2.4	1.2	2.7
Max (Runoff - Dew Point) (°C)	6.3	10.0	12.9	14.8	12.9	6.7	3.6	14.8
	Event Heat Export (20 C reference)							
Average Heat Export (KJ/m^2)	-421.7	-284.2	-19.8	86.8	-4.6	-83.2	-271.4	-138.8
Max Heat Export (KJ/m^2)	90.1	67.3	858.5	490.7	437.2	313.4	-10.5	858.5
Average Heat Export Rate(W/m^2)	-28.6	-16.7	0.4	12.7	6.8	-2.4	-22.4	-6.8
Max Heat Export Rate (W/m^2)	33.4	13.0	52.0	54.5	161.9	116.1	-3.9	161.9

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Table 4.2. Comparison of select precipitation return periods for the present study, Huff and Angel (1992), Skaggs (1998), and Hershfield (1961).

Event Duration (hours)	Return Period (years)	Precipitation Depth (cm)			
		Hershfield, 1961	Huff and Angel, 1992	Skaggs, 1998	Present Study
1	1	2.92	2.64		2.84
1	2	3.55	3.17	3.20	3.80
1	5	4.57	3.86	4.14	5.07
1	10	5.33	4.39	5.36	6.03
6	1	4.44	4.21		4.50
6	2	5.59	5.05	5.11	6.30
6	5	6.60	6.15	7.06	8.68
6	10	8.13	7.03	8.56	10.47
24	1	5.97	5.64		5.53
24	2	6.98	6.73	6.78	7.97
24	5	9.01	8.20	9.42	11.21
24	10	10.66	9.37	11.4	13.65

Table 4.3. Rainfall event statistics derived from 60-minute climate data (SAMSON data set) collected at the Minneapolis/St. Paul International Airport over 30 years (1961-1990).

Month	April	May	June	July	Aug	Sept	Oct	All
	Air and Dew Point Temperature							
Number of Events	190	253	258	184	208	208	144	1445
Average Event Air Temp (°C)	7.3	14.0	18.4	20.7	19.4	15.4	11.0	15.4
Maximum Event Air Temp (°C)	26.7	31.7	27.0	27.5	27.6	23.9	22.0	31.7
Average Event Dew Point (°C)	5.0	11.5	15.7	18.0	16.9	13.5	9.2	13.1
Maximum Event Dew Point (°C)	17.9	21.6	22.6	23.7	22.8	22.3	18.9	23.7
	Event Solar Radiation							
Average Event Solar (W/m^2)	82.4	101.7	125.1	102.9	85.8	62.9	54.2	90.9
Maximum Event Solar (W/m^2)	354.0	675.0	616.0	485.5	468.5	343.0	245.5	675.0
	Event Duration and Precip							
Average Event Duration (hours)	5.5	4.1	3.4	3.3	3.6	4.2	5.6	4.1
Aveage Total Evetn Precip (cm)	0.9	0.9	1.1	1.4	1.3	0.9	1.1	1.1
	Runoff Temperature							
Average Event (°C)	10.2	17.6	22.8	24.8	22.6	17.7	12.8	18.7
Maximum Event (°C)	36.1	43.2	43.9	42.5	40.4	37.6	24.3	43.9
	Event Heat Export (20 C reference)							
Average Heat Export (KJ/m^2)	-356.2	-92.5	94.7	244.3	106.3	-90.3	-351.3	-47.7
Max Heat Export (KJ/m^2)	1698.3	3289.1	1518.8	4535.5	1430.3	619.22	98.62	4535.5
Average Heat Export Rate (W/m^2)	-15.3	1.4	18.7	32.0	14.6	-3.9	-14.5	5.7
Max Heat Export Rate (W/m^2)	471.8	913.6	421.9	418.0	354.2	73.4	9.7	913.6

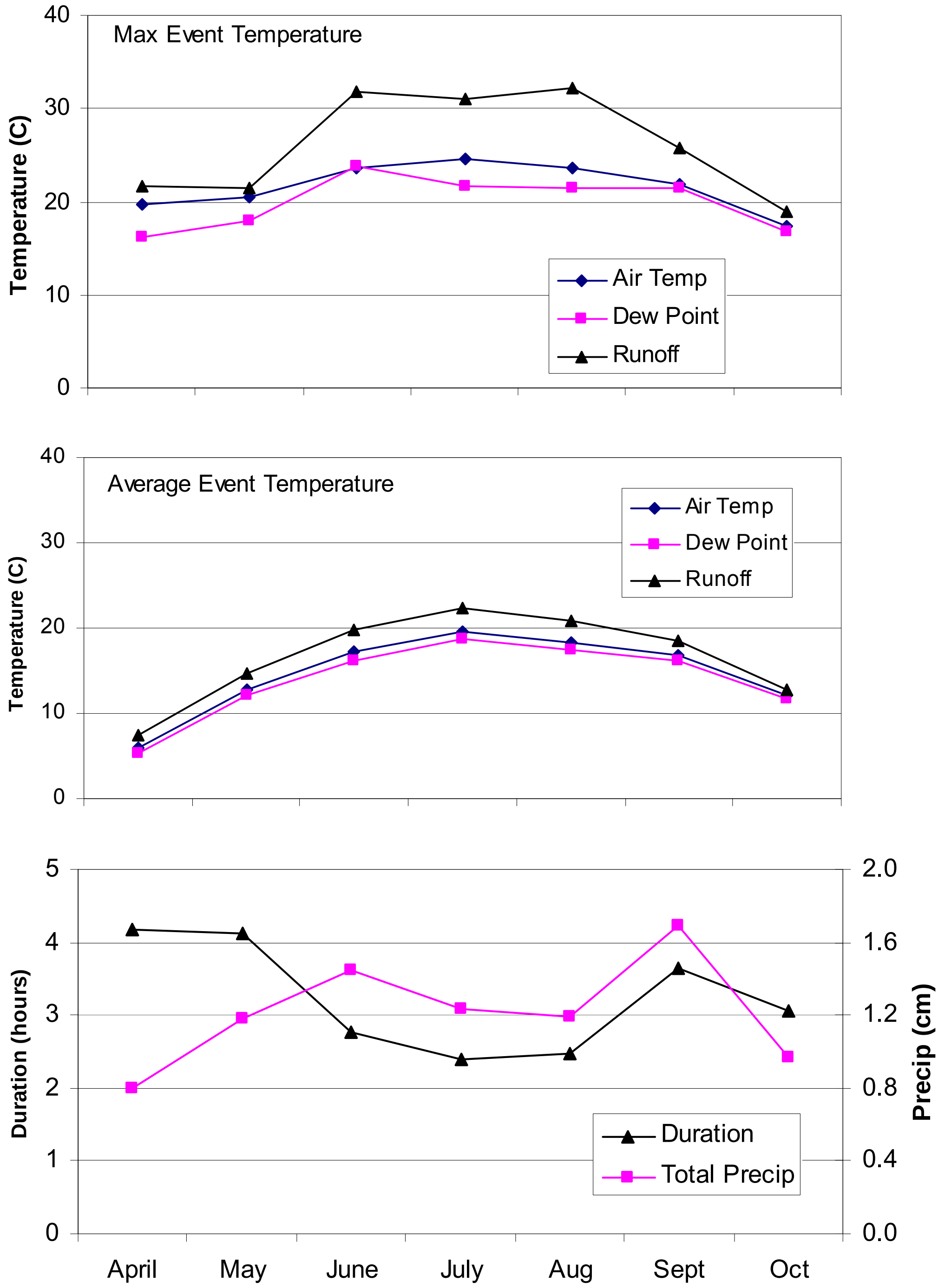


Figure 4.1. Monthly maximum event temperatures (top), average event temperatures (middle), average rainfall duration and average total precipitation (bottom) derived from 15-minute climate data collected at the MnROAD site (Albertville, MN) over 6 years (1998-2000, 2003-2005).

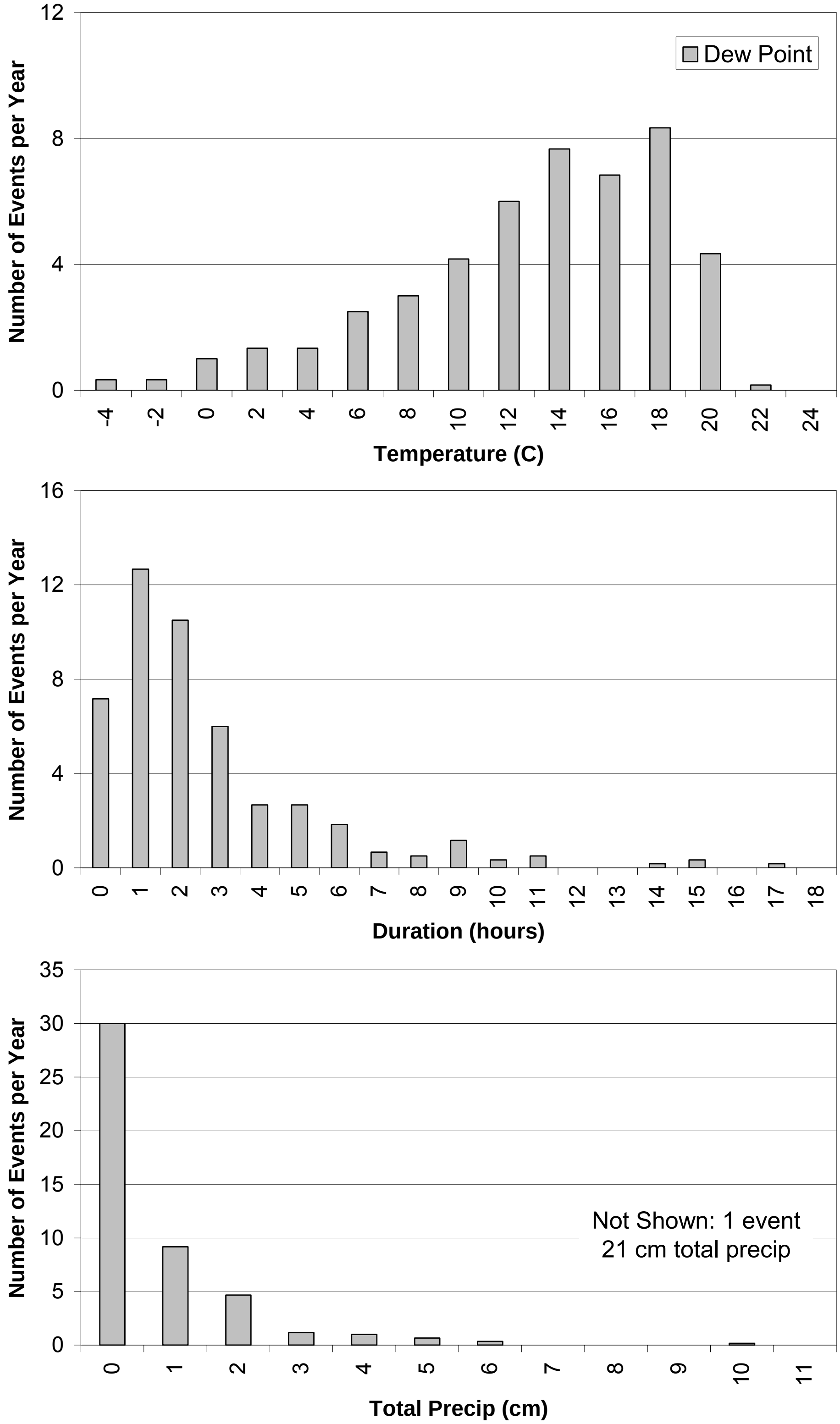


Figure 4.2. Distribution of average dew point temperature, rainfall duration and total precipitation per rainfall event at MnROAD, April-October. Labels give the lower end of each bin range.

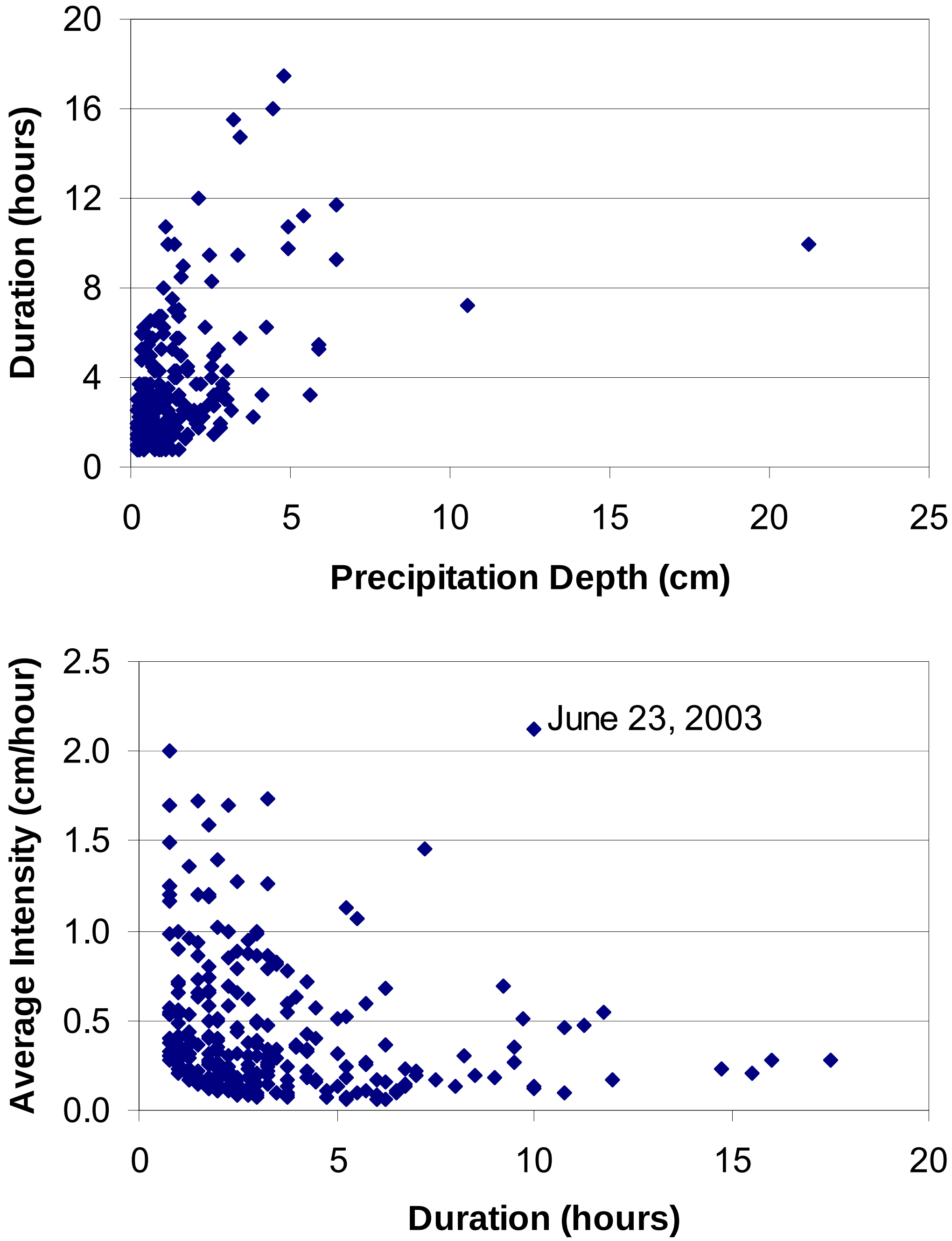


Figure 4.3. Storm duration vs. total precipitation depth (upper panel) and average intensity vs. duration (lower panel) for the 6 year MnROAD data set.

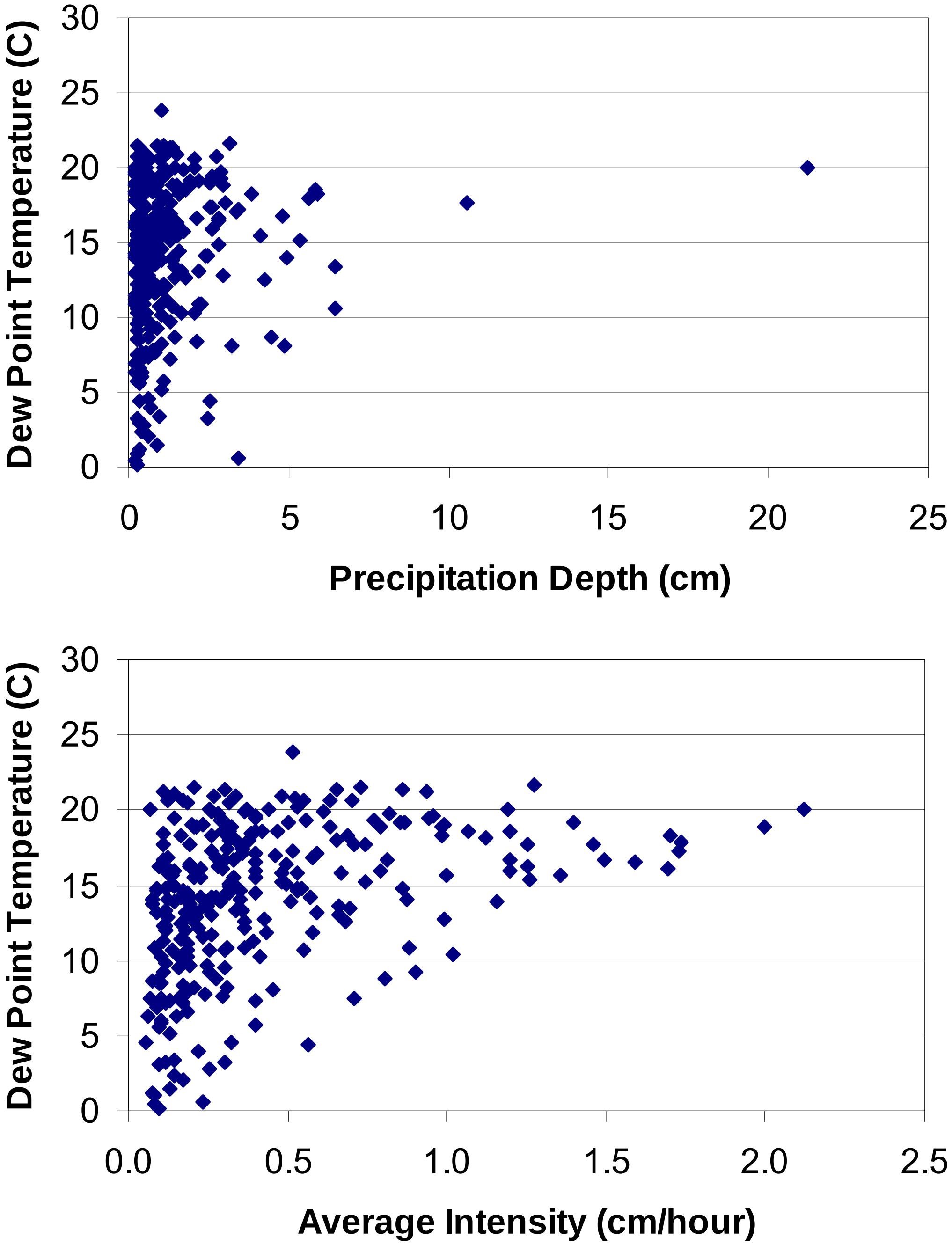
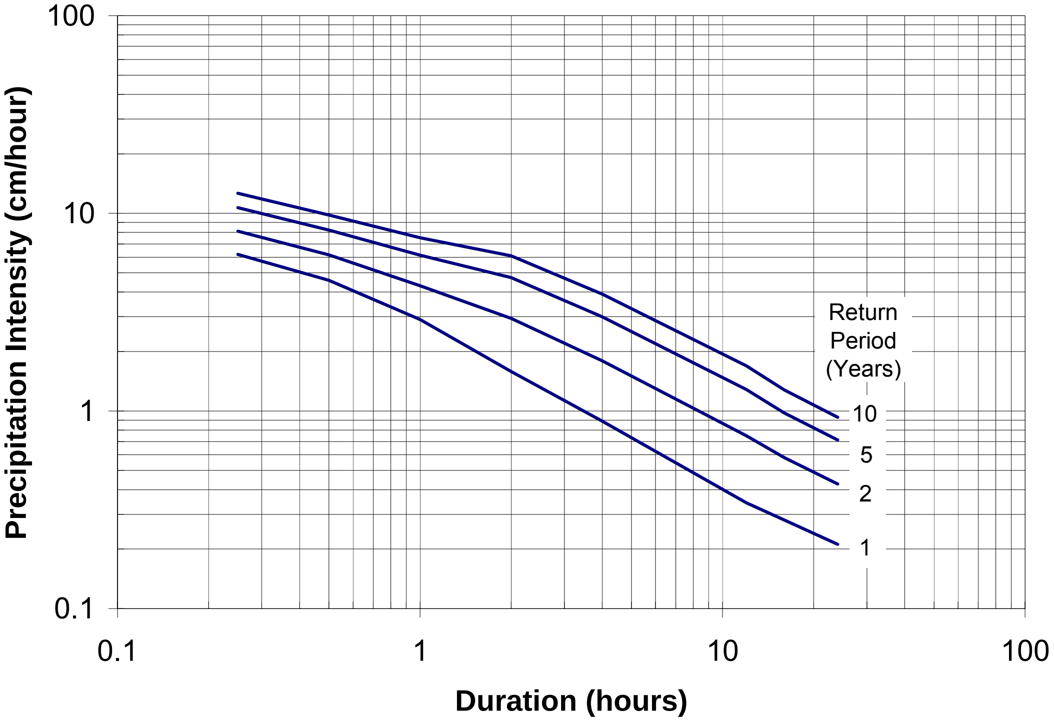


Figure 4.4. Average dew point temperature vs. average precipitation intensity for the 6 year MnROAD data set.



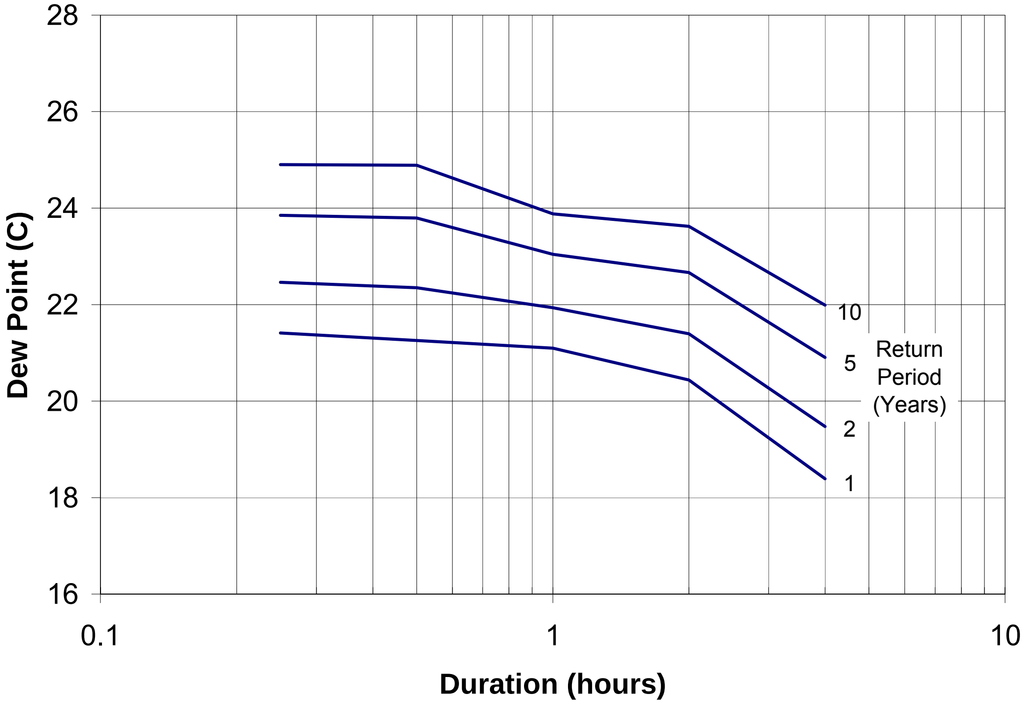


Figure 4.5. Precipitation intensity (upper panel) and dew point temperature (lower panel) versus duration and return period.

4.2 Runoff Temperature

The runoff temperature for each rainfall event in the 6-year MnROAD data set was simulated using a zero-dimensional (0D) runoff/heat transfer model, which is described in St. Anthony Falls Laboratory Project Report No. 484 (Herb et al. 2006b). The model gives time series of runoff temperature and runoff flow rate per unit width for a 100 m long asphalt surface at 1 minute time increments during runoff events. Runoff depth is not analyzed as a separate quantity.

Figure 4.6 gives the distribution of average dew point temperature, runoff temperature, and differential temperature (runoff temperature – dew point temperature) for the rainfall events recorded at MnROAD from April to October, 1998-2000 and 2003-2005. Runoff temperature exceeded 20°C for 91 rainfall events, including 1 in April, 6 in May, 23 in June, 32 in July, 15 in August, and 14 in September. Dew point temperature is considered to equal rainfall temperature. The differential temperature is therefore the temperature increase of the runoff due to heat conduction from the (usually) warmer ground (pavement) surface. The differential temperature was on average 2.7°C, and had a maximum of 14.8°C and a minimum of -2.7°C. Monthly differential temperature is given in Table 4.1.

The relationship between runoff temperature and dew point temperature is shown in Figure 4.7. The slope of the fitted line is approximately 1:1, and the offset is about 2°C. Also given in Figure 4.7 is the relationship between runoff temperature and average surface temperature during the hour preceding a rainfall event. The relationship appears to flatten out above 20 °C, i.e. runoff temperature increase less with surface temperature prior to the rainfall.

To better establish the driving parameters for runoff temperature, multi-variable linear regressions were performed using the regression analysis tool in Microsoft Excel. The regression results are summarized in Table 4.4.

1) 94% of the variation in runoff temperature was explained by variation in average dew point temperature during the storm and the surface temperature immediately prior to the storm, with the two parameters weighted almost equally.
2) 94% of the variation in surface temperature was explained by air temperature and solar radiation just prior to the storm.
3) Combining 1) and 2), 91% of the variation in runoff temperature is explained by variation in dew point temperature, air temperature, and solar radiation. However, dew point temperature during the storm is correlated to air temperature just prior to the storm ($r^2 = 0.82$). As a result, fitting runoff temperature to dew point temperature and solar radiation alone is almost as good ($r^2=0.89$) as fitting to dew point temperature, air temperature, and solar radiation ($r^2=0.91$).
4) Fitting runoff temperature to dew point temperature or solar radiation alone results in r^2 values of 0.79 and 0.19, respectively, suggesting that dew point temperature is the strongest driver of runoff temperature, even for runoff from asphalt.

Runoff temperature obtained from the two parameter regression (dew point and solar) is plotted against runoff temperature from the full hydrothermal model simulation in Figure 4.8. The overall root-mean-square error of the regression is 1.9 °C.

Figure 4.9 gives runoff temperature versus total precipitation and versus rainfall duration. In both cases, there is no empirical relationship, and highlights the need for a deterministic, numerical runoff temperature model. The data in Figure 4.9 indicate that rainfall events with low total precipitation amounts have the widest spread in runoff temperatures (1 to 33°C) while rainfall events with high total precipitation tend to produce intermediate runoff temperatures (10 to 20°C). According to Figure 4.9, rainfall duration has virtually no empirical relationship with runoff temperature.

The results of a return period analysis on runoff temperature are given in Figure 4.10. The variation in runoff temperature between 1 and 10 year return period storms, about 6 °C, is somewhat higher than the variation in dew point temperature (4 °C, Figure 4.5).

Table 4.4. Fit parameters for surface temperature and runoff temperature linear regression. Dew point temperature is a rainfall volume weighted average during each rainfall event, solar radiation is the mean solar radiation for one hour prior to the start of the event, and air temperature is the value immediately prior to the storm.

Dependent Parameter	Linear Fit Coefficients				R^2
	Surface Temperature	Dew Point Temperature	Air Temperature	1 hour Solar	
Runoff Temperature	0.41	0.55	-	-	0.94
Surface Temperature	-		1.02	0.033	0.94
Runoff Temperature	-	0.685	0.301	0.0149	0.91
Runoff Temperature	-	1.009	-	0.0173	0.89
Runoff Temperature		1.05			0.78
Runoff Temperature				0.022	0.19

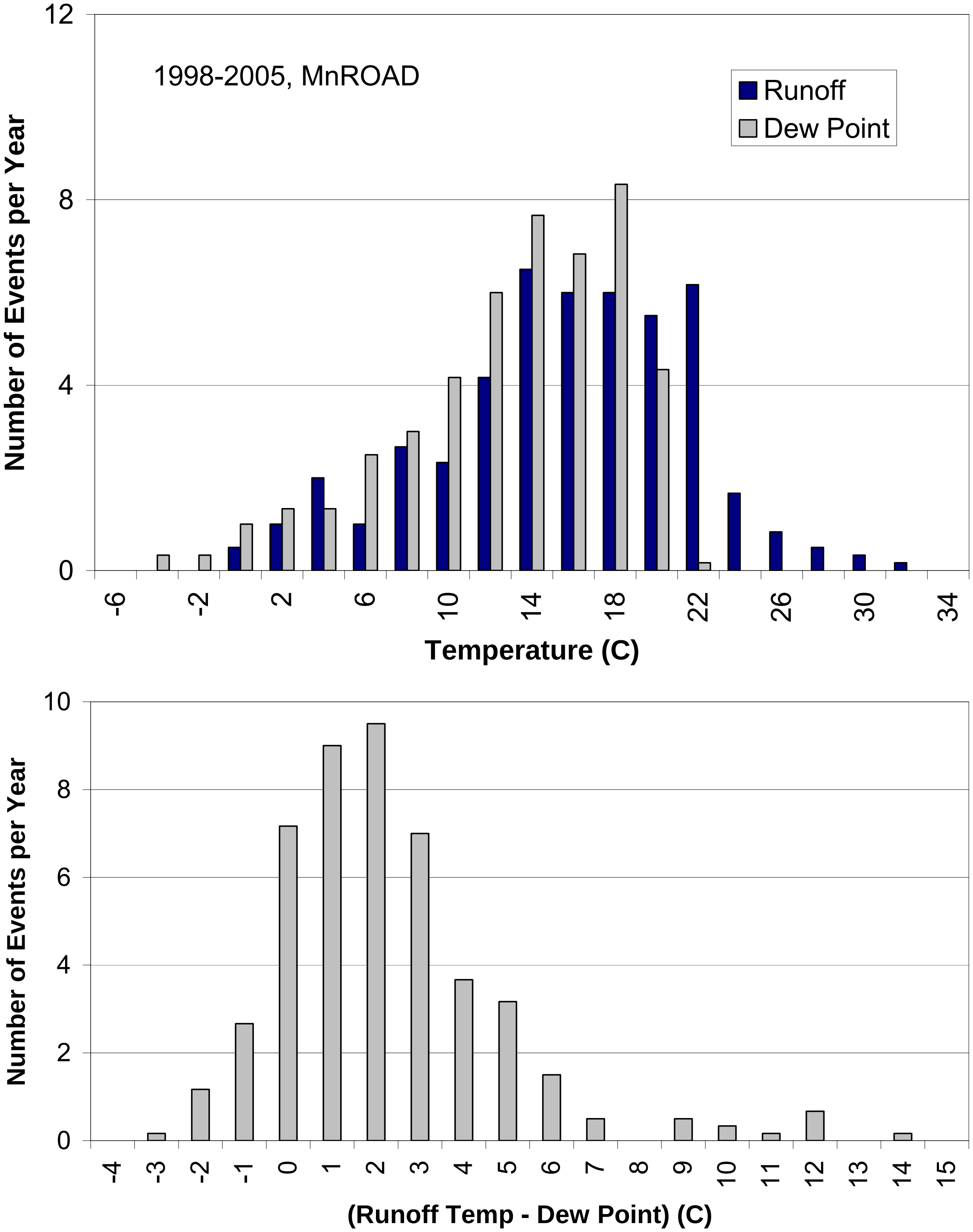


Figure 4.6. Distribution of average rainfall dew point temperature, runoff temperature and differential temperature for six years of rainfall events recorded at MnROAD, April - October. The x-axis labels give the lower end of each bin range.

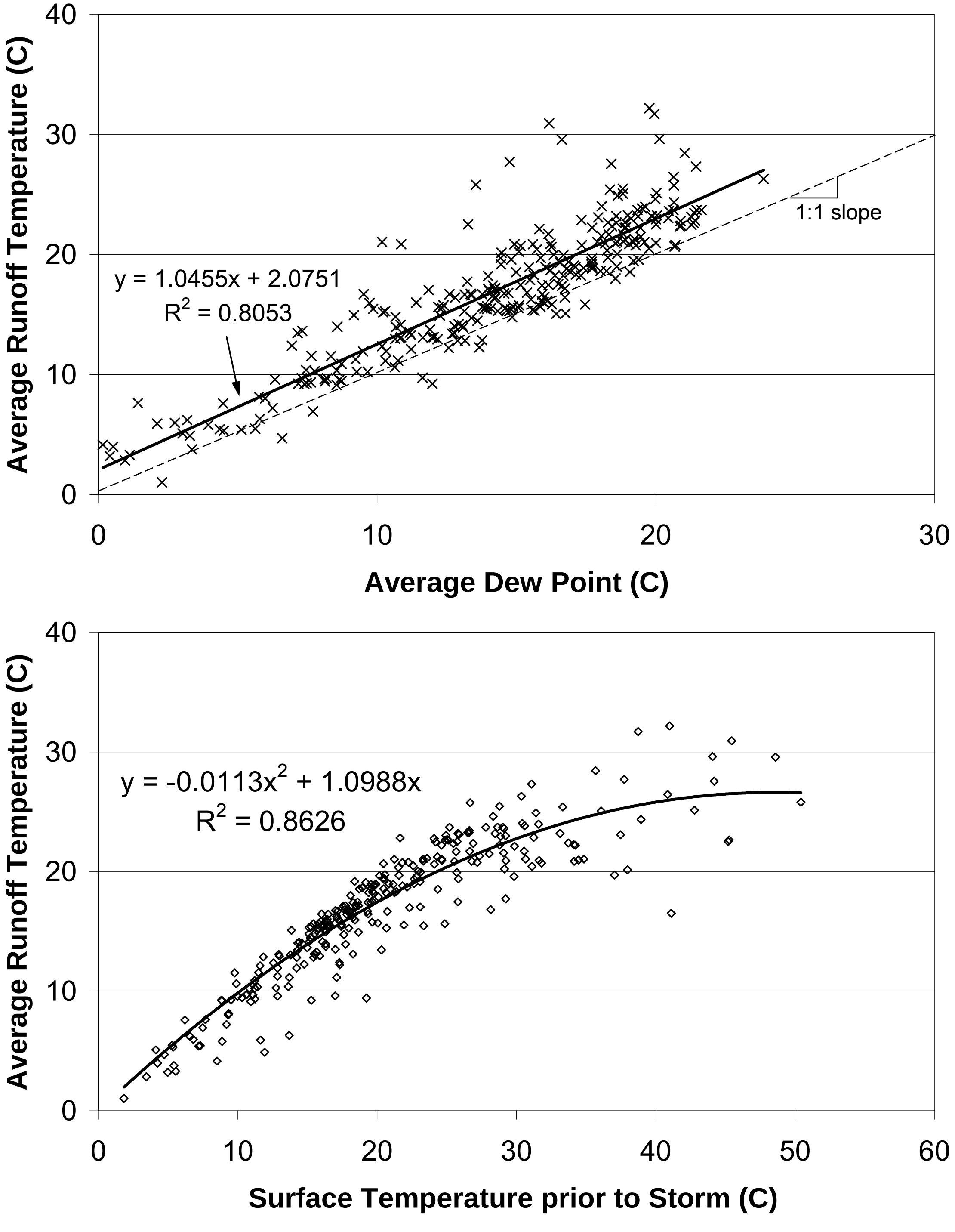


Figure 4.7. Average runoff temperature versus average dew point temperature during a rainfall event (upper panel) and versus surface temperature prior to rainfall event (lower panel) for 284 rainfall events, April – October, 1998-2006. Prior surface temperature is the average of simulated pavement temperatures for a one hour period prior to the onset of each rainfall event.

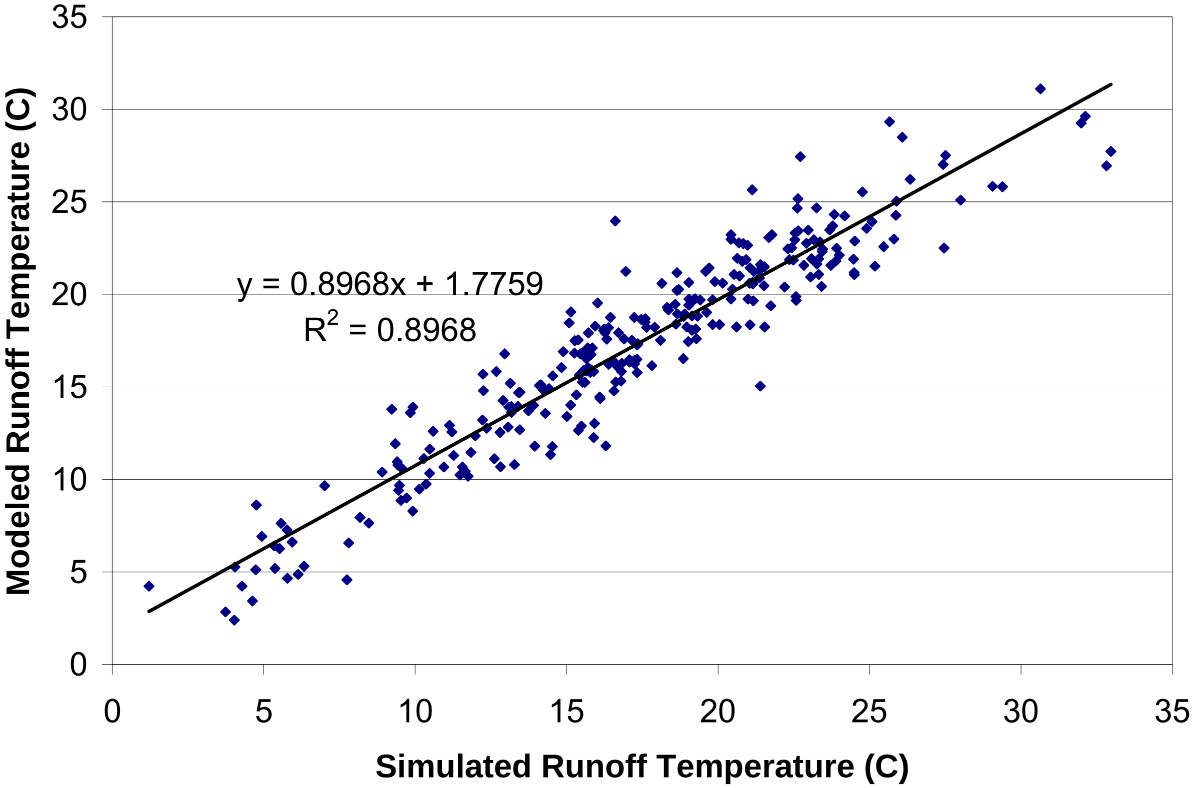


Figure 4.8. Modeled runoff temperature versus simulated runoff temperature for 280 rainfall events, April – October, 1998-2006. Modeled runoff temperature is based on a two parameter regression of simulated runoff temperature against dew point temperature and solar radiation (Table 4.4).

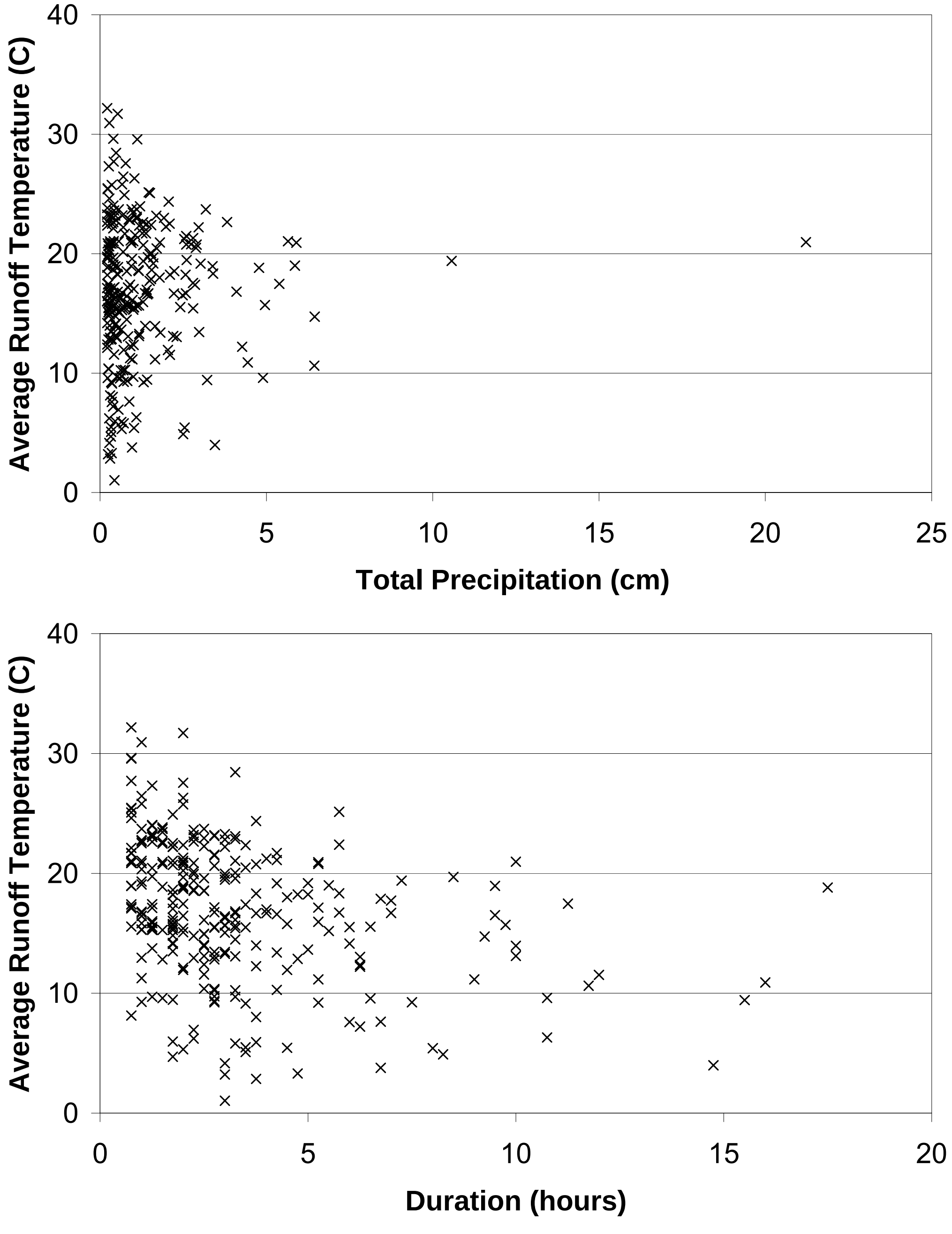


Figure 4.9. Average runoff temperature versus total precipitation (upper panel) and storm duration (lower panel).

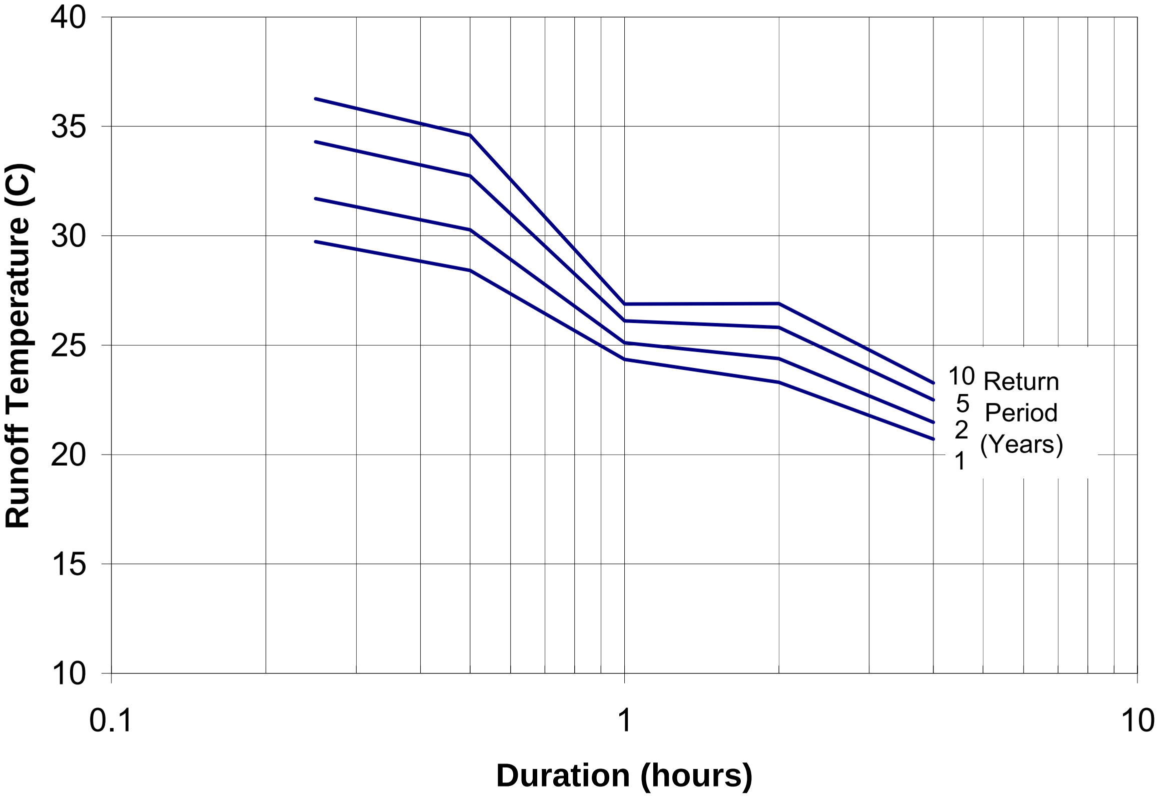


Figure 4.10. Asphalt runoff temperature versus duration and return period.

4.3 Total heat export and heat export rates per rainfall event

The storm runoff temperatures for six years of MnROAD climate data were processed to calculate the total heat export (Equation 3.2) and the average and maximum heat export rate (Equation 3.1) for monthly windows of rainfall events, using 20°C as the reference temperature. The results are tabulated in Table 4.1 and plotted in Figure 4.11. The distribution of the total heat export and heat export rate for the entire 6-year data set is given in Figure 4.12. To recall, total heat export is the amount of energy contained in the runoff above 20^{o}C, and heat export rate is the total heat export divided by rainfall duration. The distributions reach a peak at slightly negative values. 75% of the rainfall events having a total heat export between -200 and 200 kJ/m^2. Only rainfall events in July have positive heat export on average, but all months from April through September had at least one rainfall event with positive heat export over the six years (Table 4.1). June, July, August and September have rainfall events with maximum heat export values exceeding 300 kJ/m^2.

Figure 4.13 gives relationships between total heat export, runoff depth, and runoff temperature, while Figure 4.14 gives relationships between runoff flow rate, runoff temperature, and heat export rate. It is apparent that heat export depends strongly on both runoff rate and runoff temperature, but neither parameter is a good predictor of heat export or heat export rate by itself.

Figure 4.15 shows heat export rate versus total heat export. While the relationship passes through the origin, as it should, the relationship is fairly weak ($r^2 < 0.50$), i.e. rainfall events with high total heat export do not necessarily have the highest heat export rate. In other words, rainfall duration has a significant effect on heat export rates.

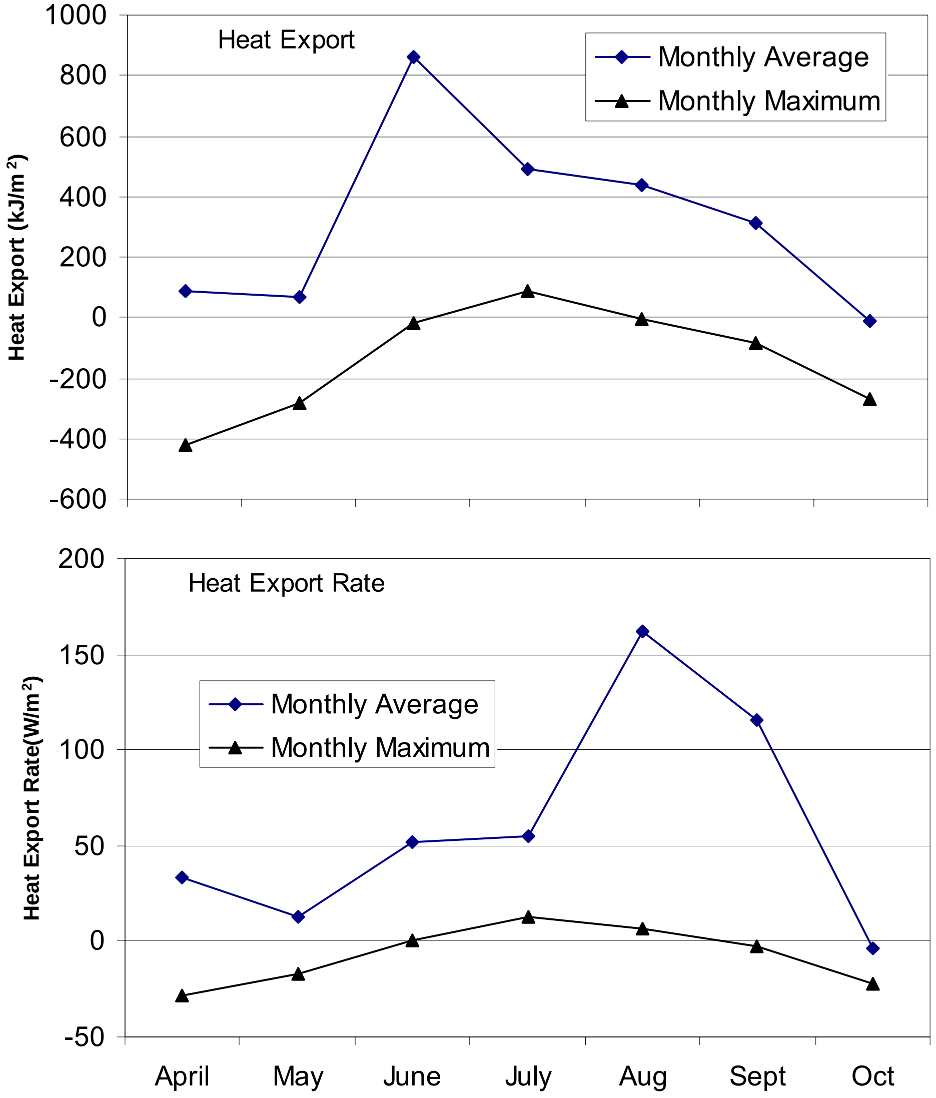


Figure 4.11. Average and maximum total heat export (kJ/m^2) and heat export rate (W/m^2) per rainfall event in a month.

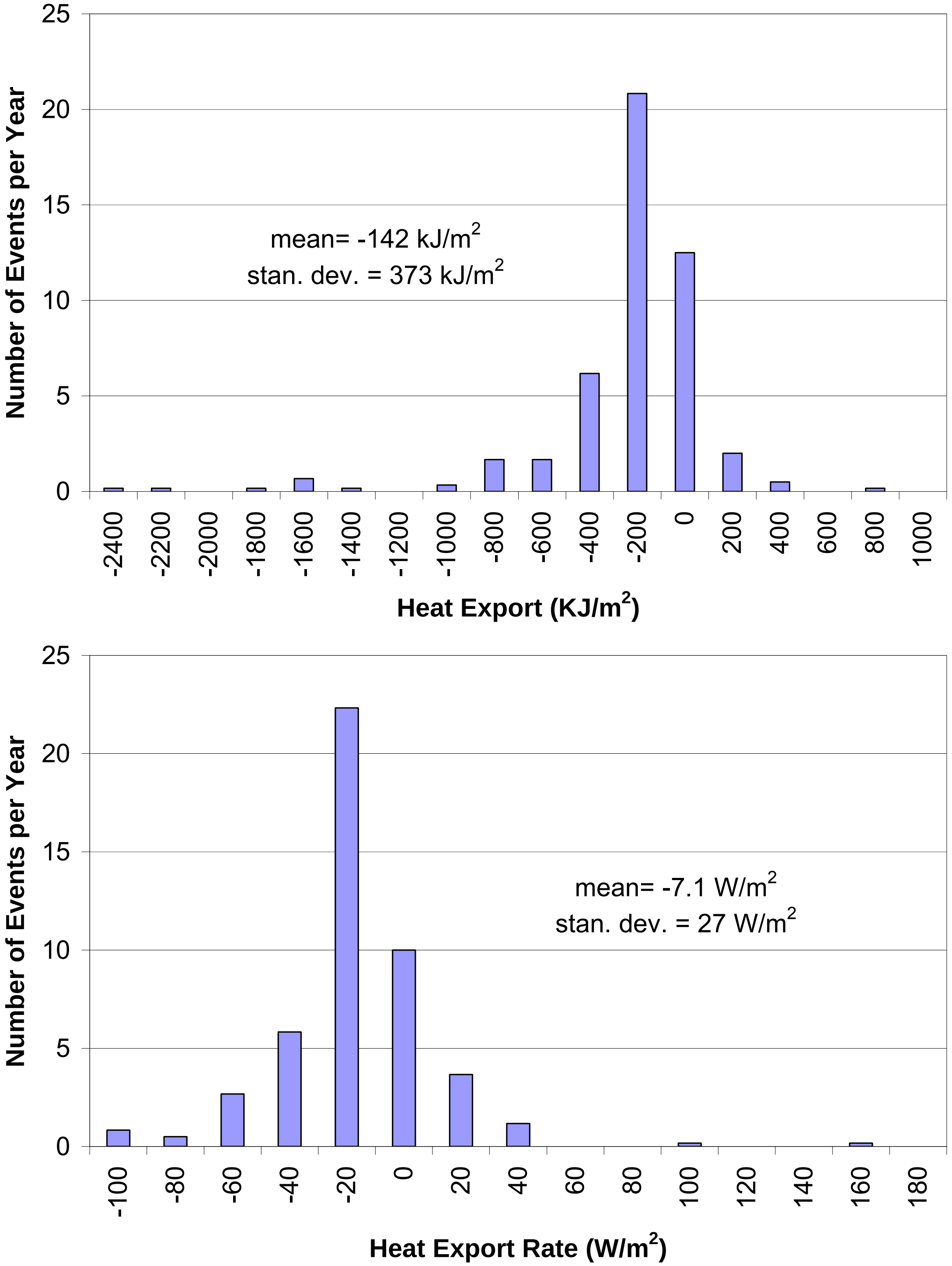


Figure 4.12. Distribution of total heat export (upper panel) and average heat export rate (lower panel) per rainfall event for 6 years of storm events, April through October. The x-axis labels give the lower end of each bin range.

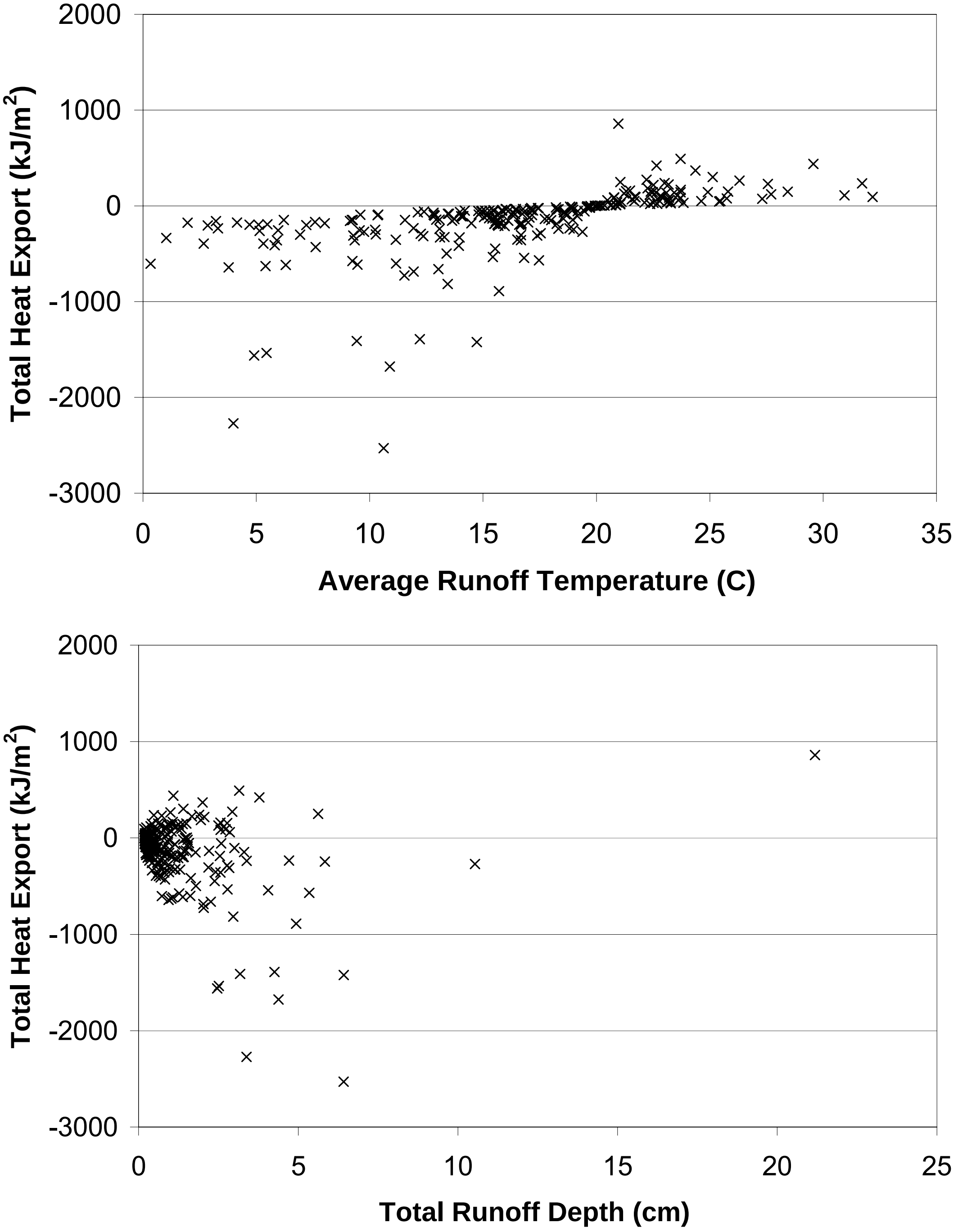


Figure 4.13. Total heat export versus average runoff temperature (upper panel) and runoff depth (lower panel).

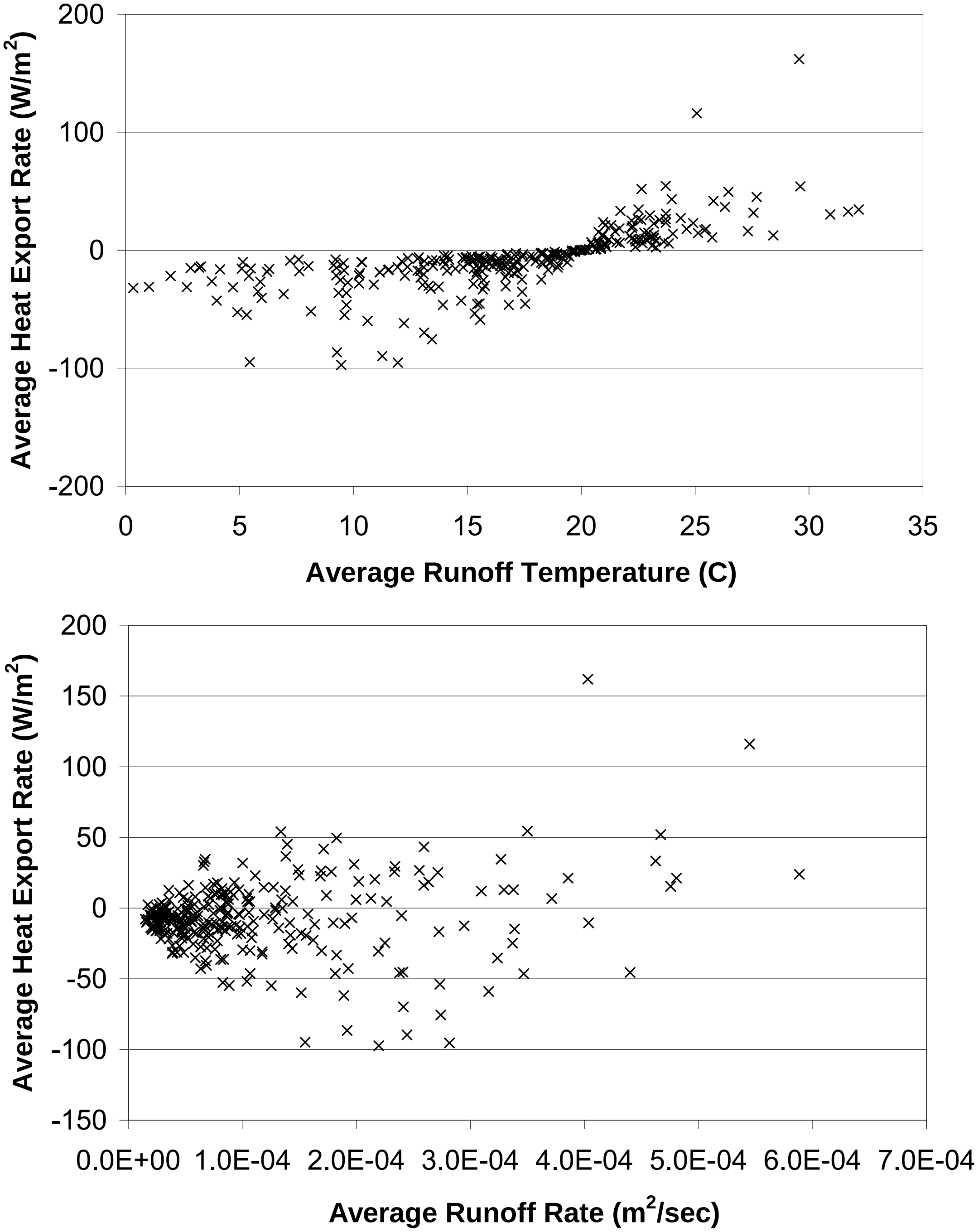


Figure 4.14. Average event heat export rate versus average runoff temperature (upper panel) and average runoff rate (lower panel).

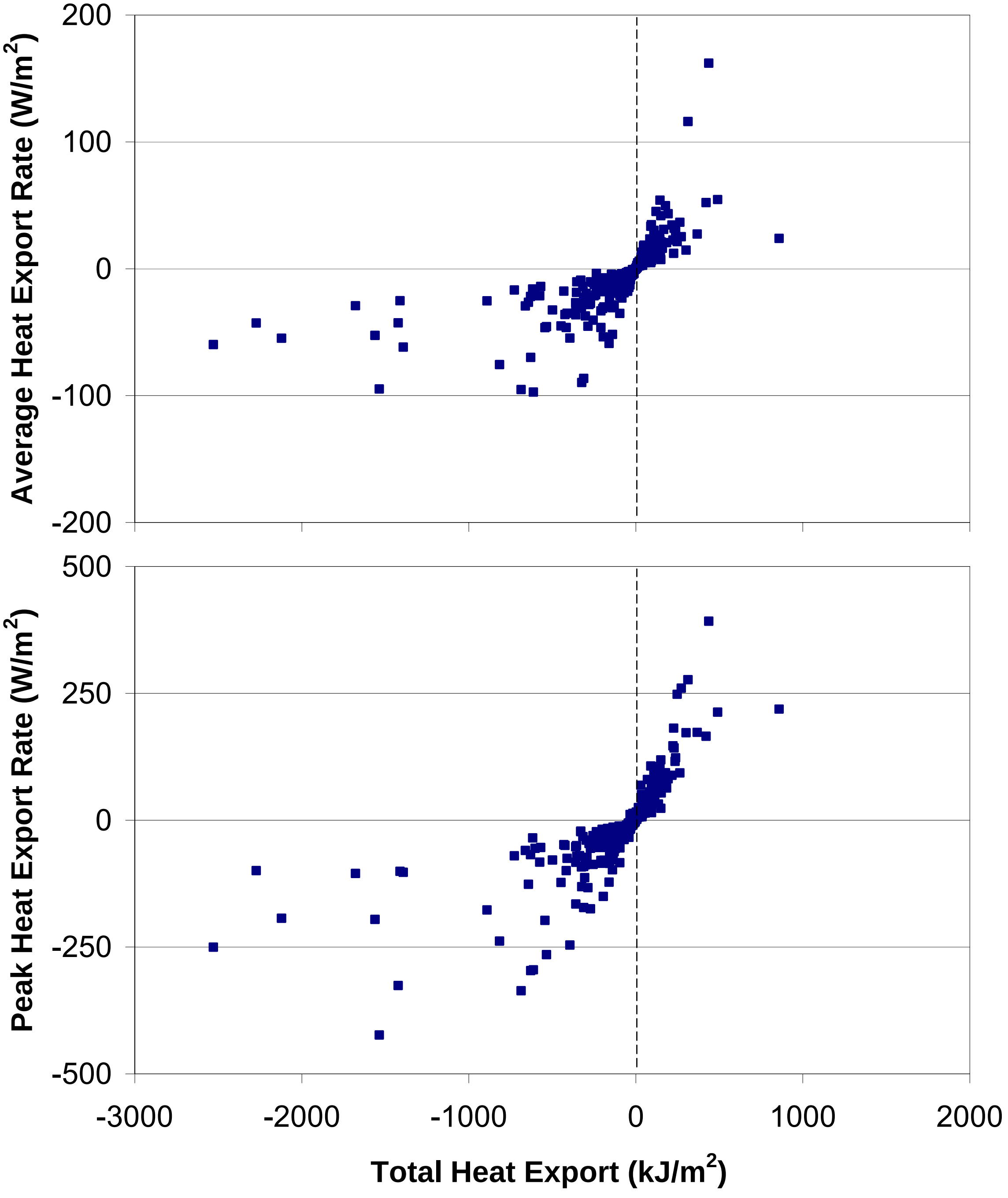


Figure 4.15. Average event heat export rate (upper panel) and peak heat export rate (lower panel) versus total heat export for 284 rainfall events, April-October, 1998-2000, 2003-2005.

4.4 Ranking of extreme values of heat export, heat export rate and runoff temperature

The twenty rainfall events with the highest values of total heat export, heat export rate, and runoff temperature, respectively, are listed and ranked in Tables 4.5, 4.6, and 4.7. These events may have occurred at any hour of the day from May through September. The associated total precipitation and average runoff temperature are also given in Tables 4.5 to 4.7. The heat export of runoff from a rainfall event is due to the combination of the heat energy in the rainfall itself plus the heat energy gained or lost as it runs off the land surface. If a rainfall event has an average rainfall temperature (dew point) higher than 20 °C, the rainfall event will create a runoff event with positive heat export, even if no heat is added from the land surface. Figure 4.16 gives the partitioning of heat energy contribution between the rainfall and the land surface (pavement) for the 20 storms with the highest heat export. In most cases, the heat content of the rainfall itself is relatively low or even negative, so that the heat energy from the pavement is the dominant contributor to the total heat export of the runoff event. In a few cases, e.g. the July 25, 1999 event, the heat energy contributions from the rainfall and pavement are similar in magnitude.

Characteristics of the rainfall events with the highest total heat export are presented graphically in Figure 4.17, with the bottom panel shows the decreasing total heat export rates for the 20 rainfall events. Heat export rates do not vary systematically with total heat export. Neither the rainfall (dew point) nor the runoff temperature seems to vary systematically with the total heat export of the 20 events (top panel of Figure 4.17). Total precipitation or duration of the 20 rainfall events also do not vary systematically with the total heat export rate (middle panel of Figure 4.17).

According to Figures 4.16 and 4.17 and Tables 4.5 and 4.6, rainfall events with high heat export rate have several characteristics in common: They tend to occur mostly in the afternoon hours, have runoff temperatures significantly above 20^{o}C, and have relatively low total precipitation. 13 of the 20 highest ranked rainfall events appear in both Table 4.5 and Table 4.6. The highest runoff temperatures (Table 4.7, Figure 4.18) also tend to occur with afternoon rainfall events of small total precipitation where the initial runoff from warm pavement surface is a significant fraction of the entire storm event. Several rainfall events in Table 4.7 appear also in Tables 4.5 and 4.6. Eight storms appear in both Table 4.5 and Table 4.7, and 12 storms appear in both Table 4.6 and Table 4.7.

Table 4.5. Rainfall events ranked by total event heat export (kJ/m^2) above a 20°C reference temperature.

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
163	1	6/24/03 18:45	858.5	23.8	218.8	10.0	21.2	21.2	20.0	21.0	29.9	9.57
83	2	7/25/99 21:29	490.7	54.5	212.8	2.5	3.2	3.2	21.6	23.7	24.7	10.80
265	3	8/16/05 16:30	437.2	161.9	391.9	0.8	1.1	1.1	16.6	29.6	30.7	8.71
256	4	6/20/05 11:30	421.1	52.0	165.4	2.3	3.8	3.8	18.3	22.7	32.3	3.20
85	5	7/30/99 15:45	368.5	27.3	173.1	3.8	2.1	2.0	20.7	24.4	31.7	9.14
24	6	7/14/98 19:59	351.1	17.7	269.8	5.5	5.6	5.6	18.4	21.5	29.3	18.25
77	7	6/22/99 15:14	301.5	14.6	172.2	5.8	1.5	1.4	20.0	25.1	30.0	4.11
215	8	8/25/04 16:44	272.3	25.2	260.1	3.0	3.0	2.9	18.9	22.2	26.3	9.78
254	9	6/11/05 12:29	263.9	36.7	93.0	2.0	1.0	1.0	23.9	26.3	30.9	3.83
276	10	9/21/05 17:30	248.5	21.2	248.0	3.3	5.7	5.6	17.9	21.1	25.5	10.76
34	11	9/19/98 15:45	242.1	67.2	216.7	1.0	1.5	1.4	16.4	24.0	32.2	11.13
262	12	7/23/05 9:00	239.2	29.5	122.8	2.3	1.9	1.9	19.1	23.0	25.3	5.48
255	13	6/13/05 17:15	235.7	32.7	115.6	2.0	0.5	0.5	19.9	31.7	35.0	2.27
175	14	7/31/03 15:45	229.6	31.9	142.3	2.0	0.8	0.7	18.4	27.6	32.9	5.03
209	15	7/28/04 18:29	222.9	22.5	146.5	2.8	1.7	1.7	19.9	23.2	24.7	7.48
13	16	6/18/98 13:15	221.3	49.2	105.9	1.3	1.2	1.1	20.1	24.6	28.2	5.15
170	17	7/14/03 12:29	217.3	34.5	88.3	1.8	2.1	2.1	20.0	22.5	26.4	10.28
17	18	6/26/98 16:30	206.4	57.3	105.7	1.0	0.7	0.7	20.2	27.1	33.2	4.12
259	19	6/27/05 16:44	184.6	20.5	63.5	2.5	2.0	1.9	18.9	22.3	26.7	5.75
171	20	7/14/03 16:59	167.1	31.0	91.1	1.5	1.1	1.1	21.5	23.7	25.0	6.11
		Average	309.0	40.6	170.2	2.8	3.1	3.0	19.5	24.4	29.0	7.5
		Standard Deviation	156.8	32.0	81.0	2.1	4.5	4.5	1.7	2.8	3.3	3.8

Table 4.6. Rainfall events ranked by event heat export rate (W/m^2) above a 20°C reference temperature.

Event Number	Rank	Start Day/Time	Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (cm^2/sec)
265	1	8/16/05 16:30	437.2	161.9	391.9	0.8	1.1	1.1	16.6	29.6	30.7	8.71
34	2	9/19/98 15:45	242.1	67.2	216.7	1.0	1.5	1.4	16.4	24.0	32.2	11.13
17	3	6/26/98 16:30	206.4	57.3	105.7	1.0	0.7	0.7	20.2	27.1	33.2	4.12
83	4	7/25/99 21:29	490.7	54.5	212.8	2.5	3.2	3.2	21.6	23.7	24.7	10.80
256	5	6/20/05 11:30	421.1	52.0	165.4	2.3	3.8	3.8	18.3	22.7	32.3	3.20
13	6	6/18/98 13:15	221.3	49.2	105.9	1.3	1.2	1.1	20.1	24.6	28.2	5.15
121	7	6/20/00 17:15	121.8	45.1	87.7	0.8	0.4	0.4	14.8	27.7	28.5	2.45
165	8	6/28/03 14:30	150.4	41.8	118.7	1.0	0.7	0.6	13.5	25.8	36.5	4.90
254	9	6/11/05 12:29	263.9	36.7	93.0	2.0	1.0	1.0	23.9	26.3	30.9	3.83
264	10	8/9/05 12:45	93.3	34.6	66.3	0.8	0.2	0.2	19.8	32.2	33.8	1.14
170	11	7/14/03 12:29	217.3	34.5	88.3	1.8	2.1	2.1	20.0	22.5	26.4	10.28
183	12	4/18/04 16:44	90.1	33.4	106.7	0.8	1.3	1.2	16.1	21.7	22.3	10.98
255	13	6/13/05 17:15	235.7	32.7	115.6	2.0	0.5	0.5	19.9	31.7	35.0	2.27
175	14	7/31/03 15:45	229.6	31.9	142.3	2.0	0.8	0.7	18.4	27.6	32.9	5.03
171	15	7/14/03 16:59	167.1	31.0	91.1	1.5	1.1	1.1	21.5	23.7	25.0	6.11
168	16	7/11/03 13:15	109.0	30.3	95.2	1.0	0.3	0.2	16.2	30.9	33.7	1.65
262	17	7/23/05 9:00	239.2	29.5	122.8	2.3	1.9	1.9	19.1	23.0	25.3	5.48
29	18	8/7/98 15:14	79.3	29.4	65.3	0.8	0.2	0.2	20.2	29.8	34.3	1.53
23	19	7/7/98 16:59	104.8	29.1	83.4	1.0	0.3	0.3	20.2	29.1	40.3	2.15
85	20	7/30/99 15:45	368.5	27.3	173.1	3.8	2.1	2.0	20.7	24.4	31.7	9.14
		Average	224.4	45.5	132.4	1.5	1.2	1.2	18.9	26.4	30.9	5.5
		Standard Deviation	121.7	29.6	74.8	0.8	1.0	1.0	2.6	3.3	4.5	3.5

Table 4.7. Rainfall events ranked by average event runoff temperature (^{o}C)

Event Number	Rank	Start Day/Time	Total Heat Export (KJ/m^2)	Average Heat Export Rate (W/m^2)	Peak Heat Export Rate (W/m^2)	Duration (hours)	Total Rain (cm)	Total Runoff (cm)	Average Dew Point Temp (C)	Average Runoff Temp (C)	Peak Runoff Temp (C)	Peak Flow (m^2/sec)
264	1	8/9/05 12:45	93.3	34.6	66.3	0.8	0.2	0.2	19.8	32.2	33.8	1.14
255	2	6/13/05 17:15	235.7	32.7	115.6	2.0	0.5	0.5	19.9	31.7	35.0	2.27
168	3	7/11/03 13:15	109.0	30.3	95.2	1.0	0.3	0.2	16.2	30.9	33.7	1.65
29	4	8/7/98 15:14	79.3	29.4	65.3	0.8	0.2	0.2	20.2	29.8	34.3	1.53
265	5	8/16/05 16:30	437.2	161.9	391.9	0.8	1.1	1.1	16.6	29.6	30.7	8.71
23	6	7/7/98 16:59	104.8	29.1	83.4	1.0	0.3	0.3	20.2	29.1	40.3	2.15
164	7	6/25/03 12:45	147.6	12.6	72.1	3.3	0.5	0.4	21.0	28.4	30.8	1.59
121	8	6/20/00 17:15	121.8	45.1	87.7	0.8	0.4	0.4	14.8	27.7	28.5	2.45
175	9	7/31/03 15:45	229.6	31.9	142.3	2.0	0.8	0.7	18.4	27.6	32.9	5.03
133	10	8/12/00 8:30	73.1	16.2	33.6	1.3	0.3	0.2	21.4	27.3	28.6	0.93
17	11	6/26/98 16:30	206.4	57.3	105.7	1.0	0.7	0.7	20.2	27.1	33.2	4.12
254	12	6/11/05 12:29	263.9	36.7	93.0	2.0	1.0	1.0	23.9	26.3	30.9	3.83
165	13	6/28/03 14:30	150.4	41.8	118.7	1.0	0.7	0.6	13.5	25.8	36.5	4.90
273	14	9/12/05 12:45	78.3	10.9	14.9	2.0	0.4	0.3	20.6	25.8	30.0	0.69
221	15	9/14/04 16:00	48.5	18.0	31.7	0.8	0.2	0.2	18.8	25.5	26.4	1.19
91	16	8/23/99 16:59	46.0	17.0	26.4	0.8	0.2	0.2	18.4	25.4	28.3	1.31
77	17	6/22/99 15:14	301.5	14.6	172.2	5.8	1.5	1.4	20.0	25.1	30.0	4.11
208	18	7/28/04 12:14	144.7	23.0	71.7	1.8	0.7	0.7	18.6	24.9	26.8	2.51
13	19	6/18/98 13:15	221.3	49.2	105.9	1.3	1.2	1.1	20.1	24.6	28.2	5.15
84	20	7/28/99 23:45	48.8	18.1	42.2	0.8	0.3	0.3	20.0	24.6	27.5	2.03
		Average	157.1	35.5	96.8	1.5	0.6	0.5	19.1	27.5	31.3	3.57
		Standard Deviation	101.2	32.4	80.2	1.2	0.4	0.4	2.4	2.4	3.6	2.94

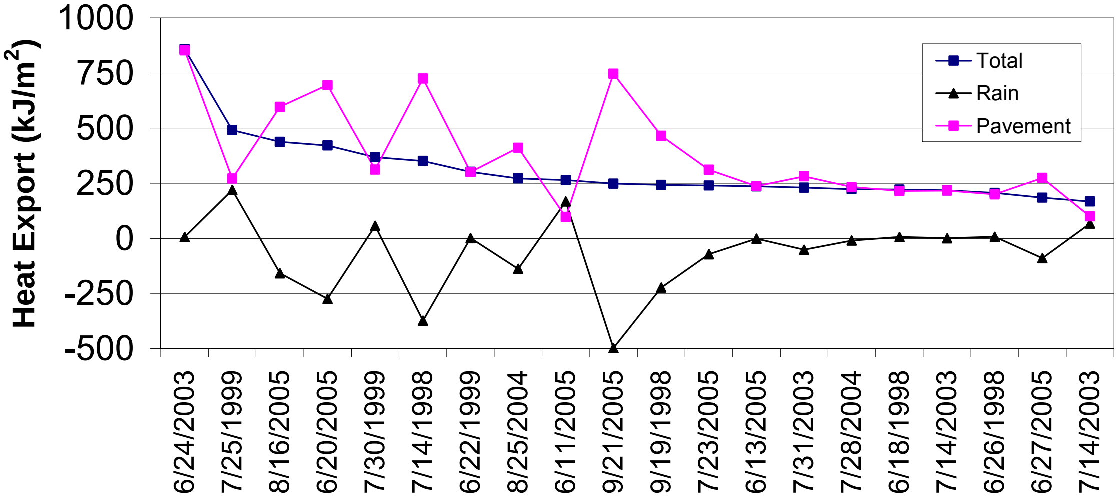


Figure 4.16. Partitioning of heat energy contribution between rainfall and pavement (lower panel) for 20 rainfall events with the highest total heat export in the years 1998-2000 and 2003-2005.

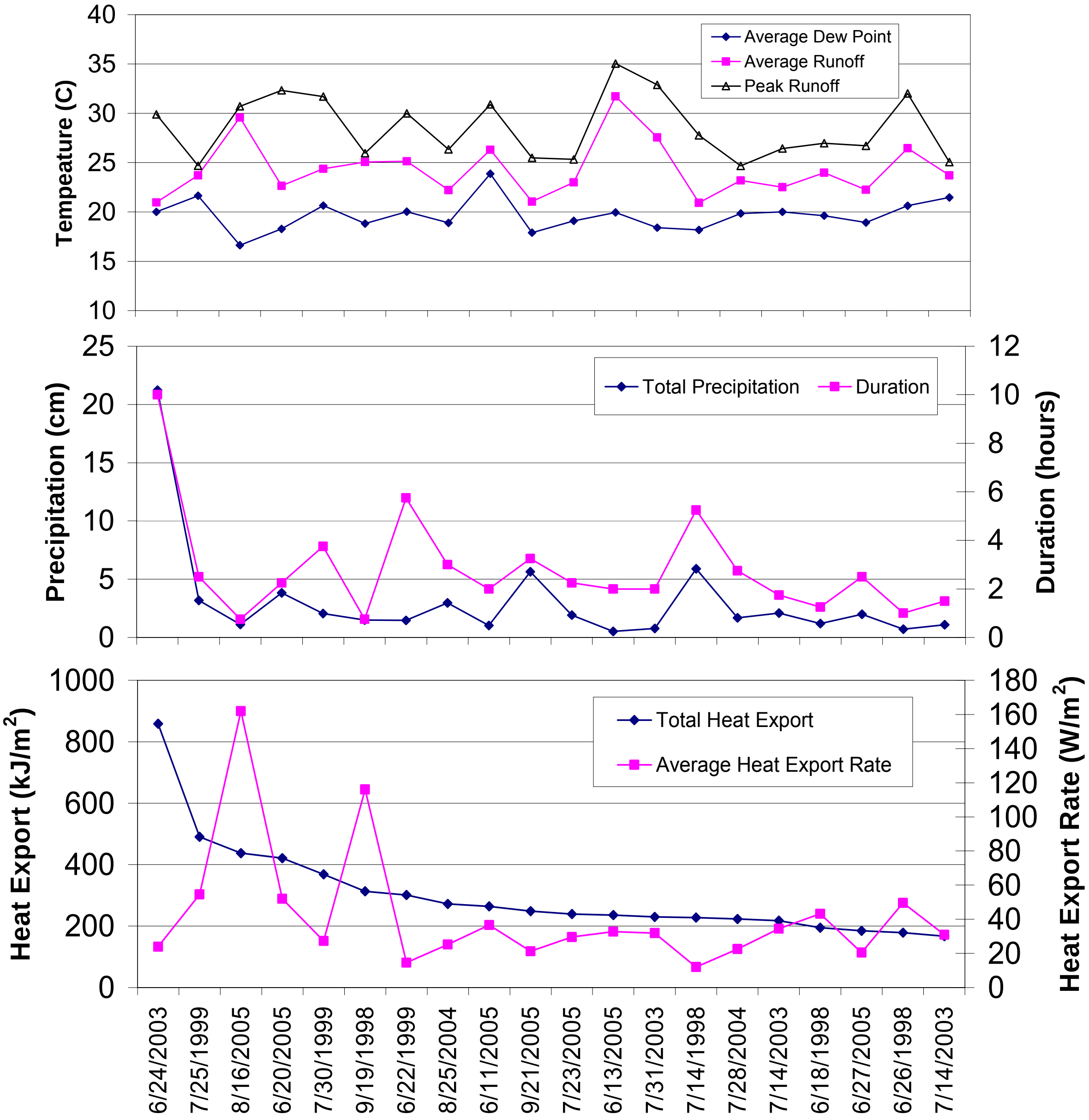


Figure 4.17. Characteristics of 20 rainfall events with the highest total heat export in the years 1998-2000 and 2003-2005, based on simulated runoff from an asphalt surface using climate data from the MnROAD site (Albertville, MN). Lines connect ordered events and do not represent time series.

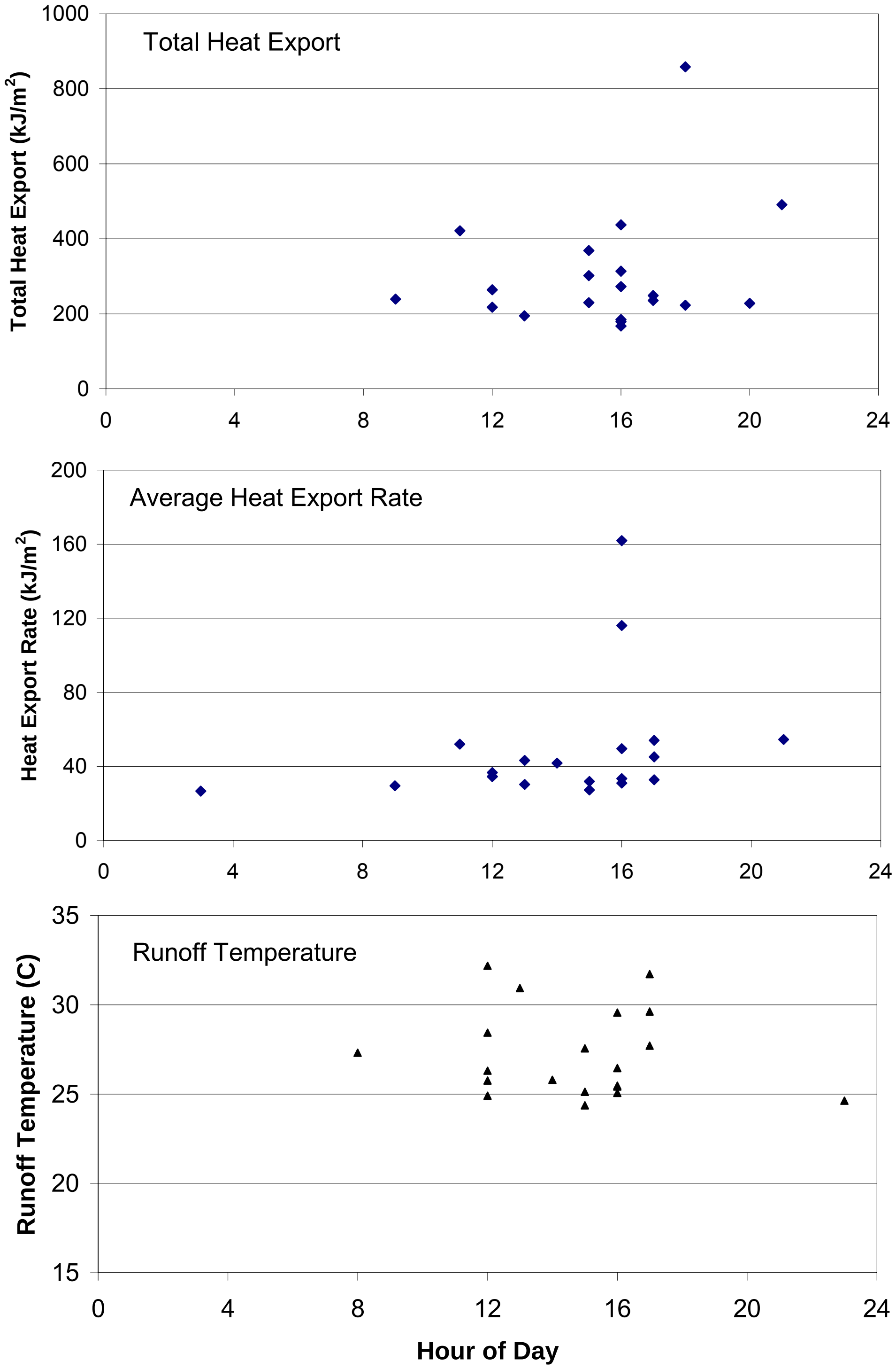


Figure 4.18. Total heat export, average heat export rate, and runoff temperature versus hour of day for the events listed in Tables 4.5, 4.6, and 4.7, respectively.

4.5 Frequency analysis of heat export values

Rainfall and runoff frequency analysis is used to select design storms for storm sewer design and hydraulic structures. For example, the U.S. Weather bureau TP40 paper (Hershfield 1961) gives a design storm of 5.3 cm (2.1 inches) of precipitation to represent a 1 hour duration storm event with a 10 year recurrence interval in Minneapolis. For the case of thermal loading, it is more difficult to analyze storm recurrence intervals, because each storm event in a watershed has a unique combination of runoff flow, runoff temperature, and weather conditions that all influence the thermal export from the watershed and the thermal impact on a stream.

A reasonable approach, however, is to perform recurrence analysis on the total heat export and the heat export rate individually, and then examine the results. For the 6-year record of storm events from MnROAD, it is appropriate to perform an analysis for 1- to 6-year recurrence intervals, and to extrapolate to 10-year recurrence intervals. The return period analysis was performed on the following partial duration series:

1) The total heat export of complete rainfall events of any duration for runoff from asphalt.
2) The average heat export rate of complete rainfall events of any duration for runoff from asphalt.
3) The average heat export rate of partial or complete rainfall events with fixed duration of 15 minutes to 24 hours for runoff from asphalt.
4) The average heat export rate of partial or complete rainfall events with fixed duration of 15 minutes to 24 hours for runoff from a roof, i.e. runoff at dew point temperature.

The results of the frequency (return period) analysis for complete rainfall events are shown in Figures 4.19 and 4.20. The results for total heat export are given in Figure 4.19; the results change if the extreme rainfall event of June 24, 2003 (21.2cm total precipitation) is included or not. As noted earlier, his storm has most likely a return period of greater than 6 years. For the maximum heat export rate frequency analysis, including or excluding the June 24 event changed the results only slightly, because this storm has only moderate maximum heat export rate. The results in Figure 4.19 suggest that there is a 1 year return period on rainfall events with a total heat export of about 300 kJ/m^2, and a 1 year return period on storms with a heat export rate of about 200 W/m^2. The storm on June 22, 1999 is close to being a 1 year storm for both total heat export and maximum heat export rate.

For the more extreme values of heat export, storms with the highest values of total heat export did not have the highest values of heat export rate, and vice-versa. Figure 4.20 gives the return period of total heat export versus the return period of heat export rate for the 13 storms with the highest total heat export. The points follow two distinct lines, with the upper line corresponding to high export rate events in August and September and the lower line corresponding to events with high total heat export. The data set is probably not large enough to establish the physical significance, if any, of these data patterns. It is evident, however, that storms with extreme values of total heat export, e.g. a 10 year storm, would not also have an extreme value of maximum heat export rate.

Figure 4.21 gives the return period results for rainfall events of fixed duration, from 15 minutes to 24 hours. These charts mimic the precipitation intensity – duration – return frequency (IDF) charts commonly used in the design of storm water management systems. As with rainfall intensity, heat export rate decreases markedly for longer duration events, with the average heat export rate for a 24 hour event about 100 times lower than the rate for a 5 minute event. The curves shift down for runoff from a roof compared to runoff from asphalt, since little or no heat is added to the runoff from a roof. The curves given for asphalt and rooftop runoff give approximate upper and lower bounds to runoff from all surfaces.

Figure 4.22 gives average dew point temperature versus precipitation intensity for measured 1 hour duration events from the 6 year database, along with lines representing combinations of dew point temperature and precipitation intensity producing heat export rate values corresponding to 1, 2 , 5, and 10 year return periods. The upper bounds of the measured events show an inverse relationship between precipitation intensity and dew point temperature, so that events with high heat export have either 1) extreme values of precipitation intensity, 2) extreme values of dew point temperature, or 3) moderate values of both. One point with a 10 year recurrence heat export is towards the right on the figure (June 24, 2003), corresponding to a very high precipitation intensity with a dew point temperature only slightly above 20 °C.

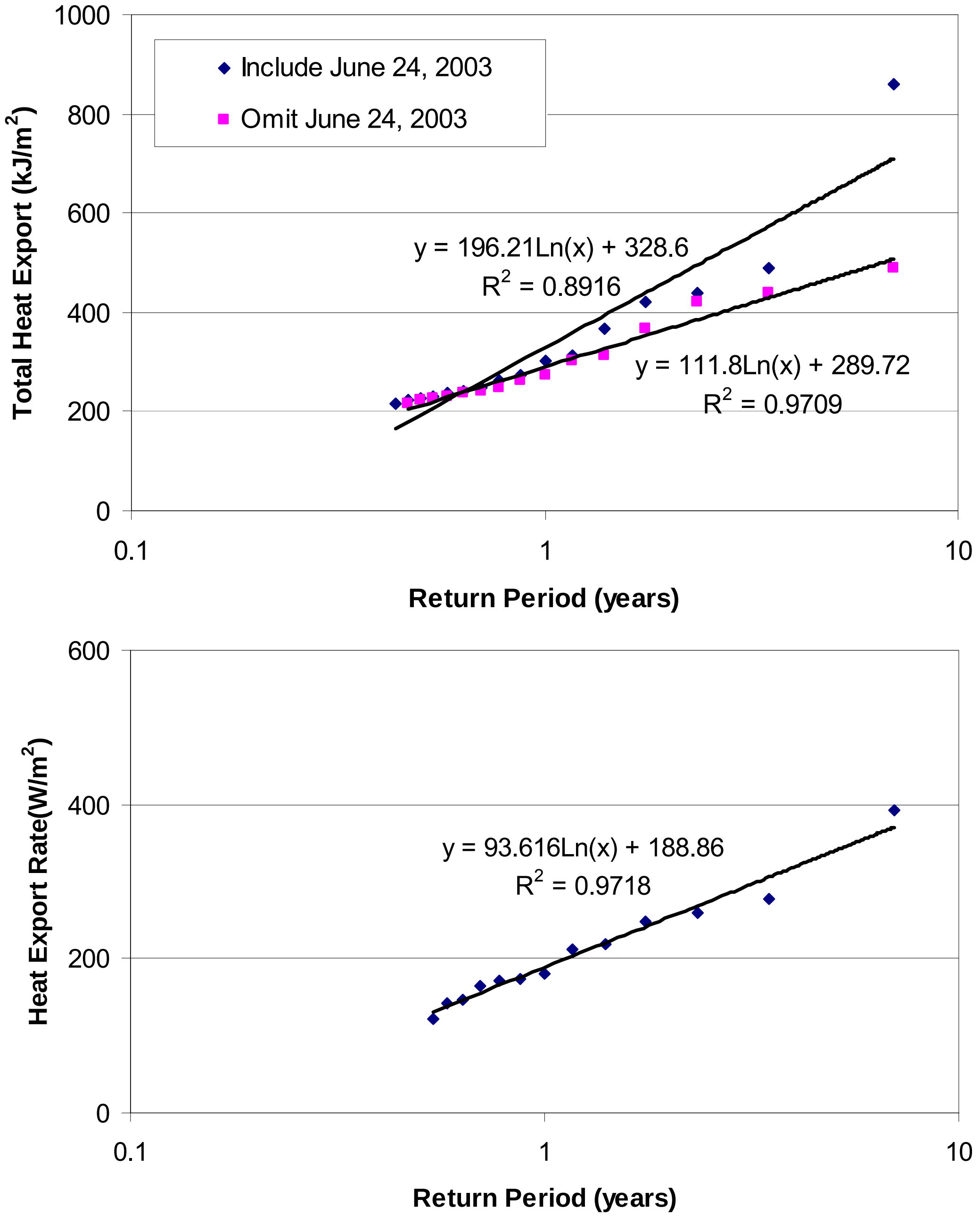


Figure 4.19. Return periods of total event heat export (upper panel) and maximum event heat export rate (lower panel) based on partial duration series from 6 years of simulated runoff data.

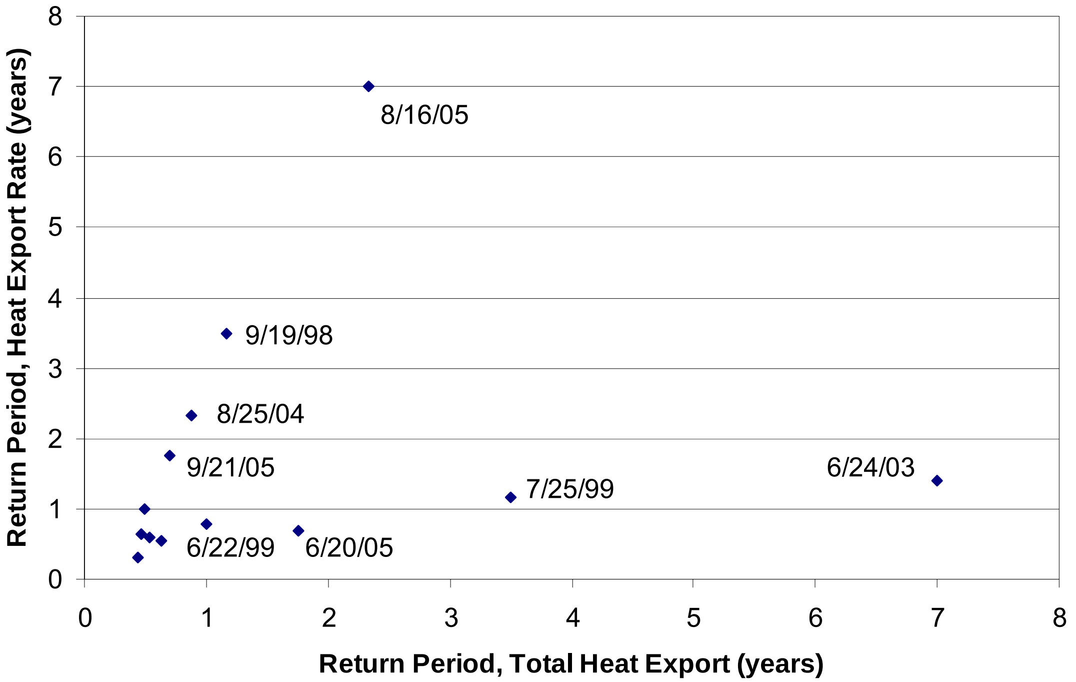


Figure 4.20. Return period of heat export rate versus return period of total heat export for 13 rainfall events with the highest rankings from 6 years of simulated runoff data.

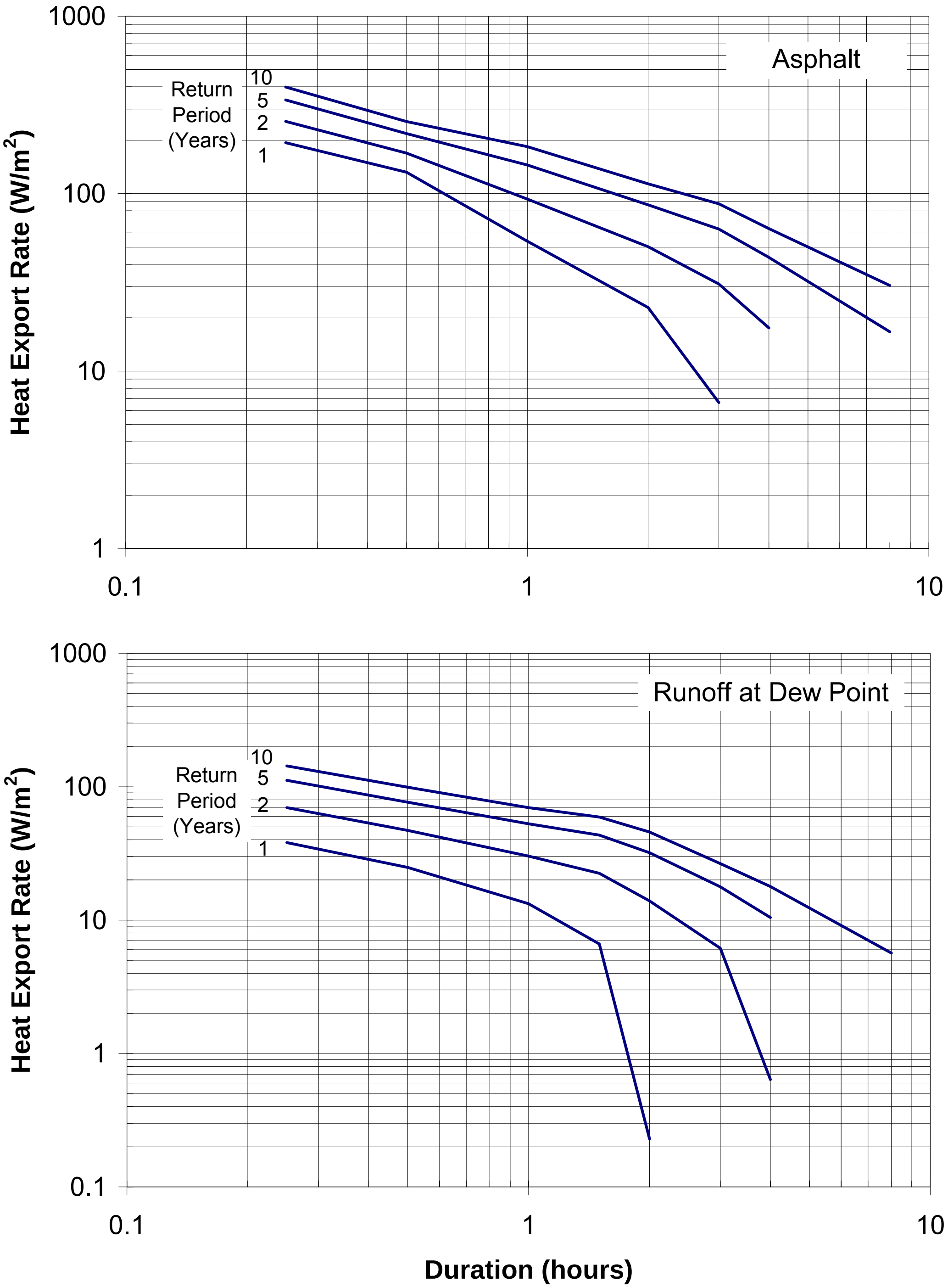


Figure 4.21. Heat export rate versus duration and return period for runoff from asphalt and runoff at dew point temperature, based on simulated runoff data using 6 years of MnROAD climate data.

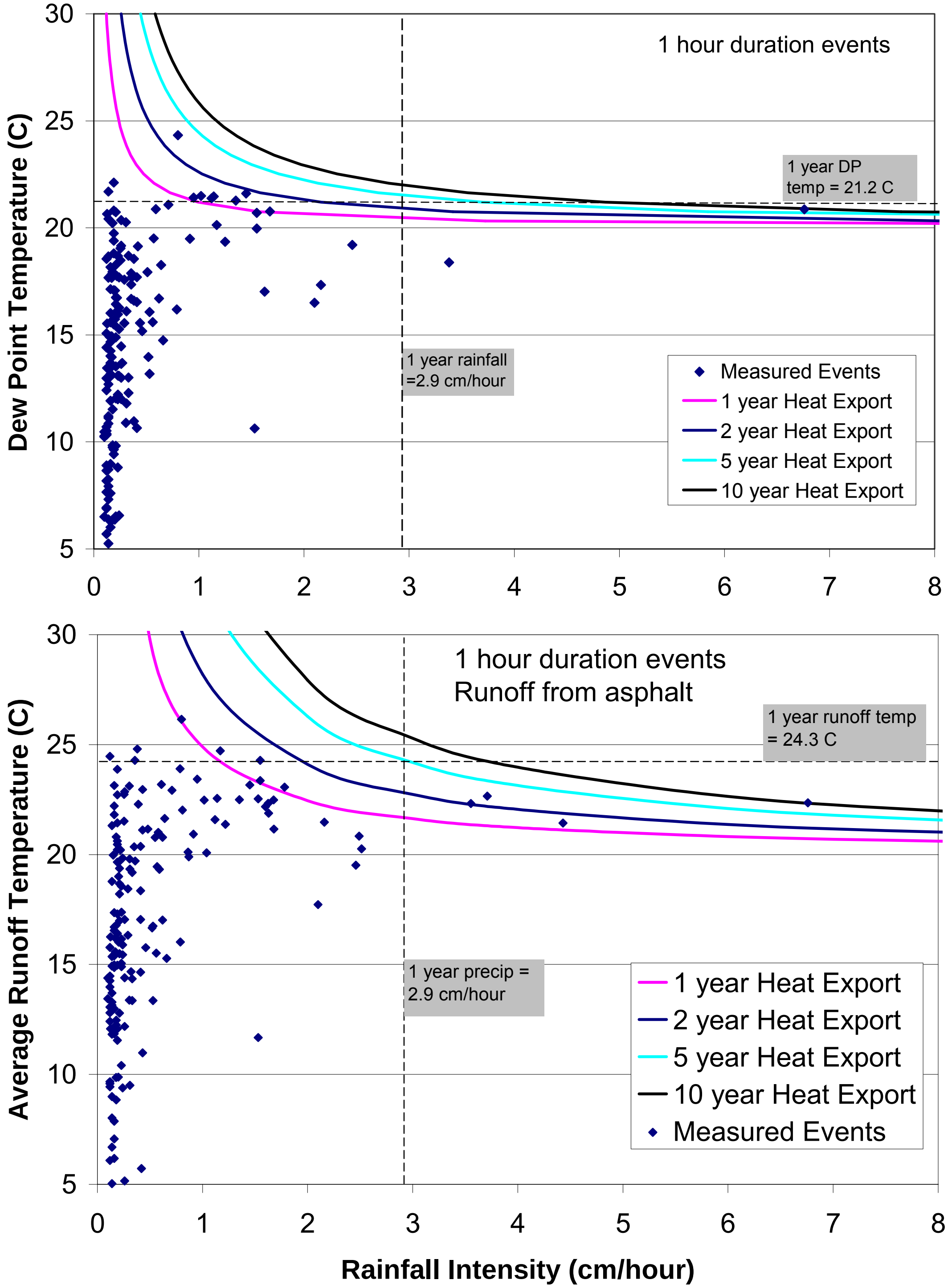


Figure 4.22. Average dew point temperature versus precipitation intensity (upper panel) and average asphalt runoff temperature versus precipitation intensity for 178 1 hour duration events. Also shown are lines representing combinations of dew point or runoff temperature and precipitation intensity producing heat export rate values corresponding to 1, 2 , 5, and 10 year return periods .

5. IMPACT ON STREAM TEMPERATURE

The hydrothermal export parameters used in the previous sections are very useful to compare rainfall events with each other, but they do not give the impact of each rainfall event on a specific stream. In this section the relationship between heat export parameters and temperatures of a receiving stream will be examined using a simple mixing mode. This analysis is general in nature, but uses as an example the simulated runoff from a 100 x 100 m paved (asphalt) area discharging directly to a stream. Using Equation 3.5, characteristics of runoff from particular storm events can be related to changes in stream temperature. The following example was chosen:

Q_s= 2 to 20 cfs
T_s = 20 °C
Runoff area = 100m x 100m, asphalt pavement

The flow range of 2 to 20 cfs approximates July stream flow rates for the main stem of the Vermillion River near Farmington, MN, i.e. from Hamburg Avenue (3.3 cfs) to Chippendale Avenue (25.1 cfs), based on 2005 flow measurements provided by the Dakota County Soil and Water Conservation District.

Using these parameters, and the runoff temperature and runoff flow rate per unit area for 280 rainfall events from 1998 to 2005 (see previous sections), the change in stream temperature was calculated for average or peak values of heat export during a rainfall event. The change in stream temperature at some time during a rainfall event is strongly related to the instantaneous rate of heat export, $H_{ro} = \rho C_p Q_{ro} T_{ro}$, as well as the stream flow, as shown in Figure 5.1. For a given heat export rate, runoff flows with higher runoff temperature and lower flows will produce more change in stream temperature. This effect produces the scatter in the relationships between heat export rate and change in stream temperature evident in Figure 5.1.

For low stream flow, the maximum possible increase in stream temperature is bounded by the runoff temperature, so that the relationship loses linearity at high values of heat export rate (Figure 5.1). The average change in stream temperature over the storm event is also strongly related to the average rate of heat input, but the average temperature change is typically half the peak change. Values of heat export, stream temperature change, and duration are given in Table 5.1 for the 20 storms producing the highest change in stream temperature for a 10 cfs stream flow rate. Note that the ranking by change in stream temperature at 2 cfs stream flow would be slightly different from the ranking for 10 cfs.

Based on the relationships given in this section and the results given in Section 4 for heat export rate versus durations, rainfall/runoff event of longer duration can be expected to give a smaller average stream temperature change. Figure 5.2 gives rainfall/runoff duration versus average change in stream temperature. It shows that the longest duration storms give the smallest average change in stream temperature, as expected. The largest stream temperature changes are produced by rainfall/runoff events of short duration, e.g. 2 hours or less. The results are very similar for 2 and 10 cfs, except that the range of stream temperature change is larger for lower stream flow.

Table 5.1. Rainfall events ranked by average change in stream temperature (^{o}C) at 10 cfs stream flow.

Rank	Event Number	Start Day/Time	Duration (hours)	Total Rain (cm)	Average Flow (cfs)	Heat Export KJ/m^2	Heat Export Rate, Average (W/m^2)	Stream Flow			
								2 cfs	5 cfs	10 cfs	20 cfs
								Average ◊T (°C)			
1	262	8/16/05 16:30	0.75	1.12	1.42	437.23	161.94	3.979	2.121	1.193	0.636
2	31	9/19/98 16:15	0.75	1.5	1.93	313.39	116.07	2.488	1.410	0.819	0.445
3	20	7/7/98 17:30	0.75	0.4	0.47	146.06	54.10	1.840	0.832	0.435	0.222
4	76	7/25/99 21:29	2.5	3.18	1.24	490.75	54.53	1.417	0.736	0.408	0.216
5	14	6/26/98 16:44	1	0.7	0.65	178.51	49.58	1.577	0.739	0.392	0.202
6	253	6/20/05 11:30	2.25	3.82	1.65	421.12	51.99	1.198	0.658	0.375	0.202
7	118	6/20/00 17:15	0.75	0.41	0.49	121.79	45.11	1.523	0.691	0.362	0.185
8	11	6/18/98 13:30	1.25	1.2	0.92	194.54	43.23	1.247	0.615	0.333	0.174
9	162	6/28/03 14:30	1	0.66	0.61	150.38	41.77	1.349	0.627	0.331	0.171
10	251	6/11/05 12:29	2	1.03	0.49	263.94	36.66	1.239	0.562	0.294	0.151
11	261	8/9/05 12:45	0.75	0.21	0.24	93.32	34.56	1.299	0.555	0.284	0.144
12	252	6/13/05 17:15	2	0.53	0.24	235.66	32.73	1.232	0.526	0.269	0.136
13	167	7/14/03 12:29	1.75	2.09	1.15	217.34	34.50	0.920	0.472	0.260	0.137
14	172	7/31/03 15:45	2	0.77	0.35	229.63	31.89	1.139	0.501	0.259	0.132
15	165	7/11/03 13:15	1	0.28	0.23	108.97	30.27	1.141	0.487	0.249	0.126
16	168	7/14/03 16:59	1.5	1.1	0.70	167.13	30.95	0.964	0.457	0.243	0.126
17	180	4/18/04 16:44	0.75	1.27	1.63	90.10	33.37	0.773	0.423	0.241	0.130
18	259	7/23/05 9:00	2.25	1.92	0.83	239.24	29.54	0.879	0.426	0.230	0.119
19	78	7/30/99 15:45	3.75	2.06	0.53	368.45	27.29	0.909	0.416	0.218	0.112
20	114	6/13/00 15:29	1.5	0.95	0.60	142.12	26.32	0.853	0.396	0.209	0.108

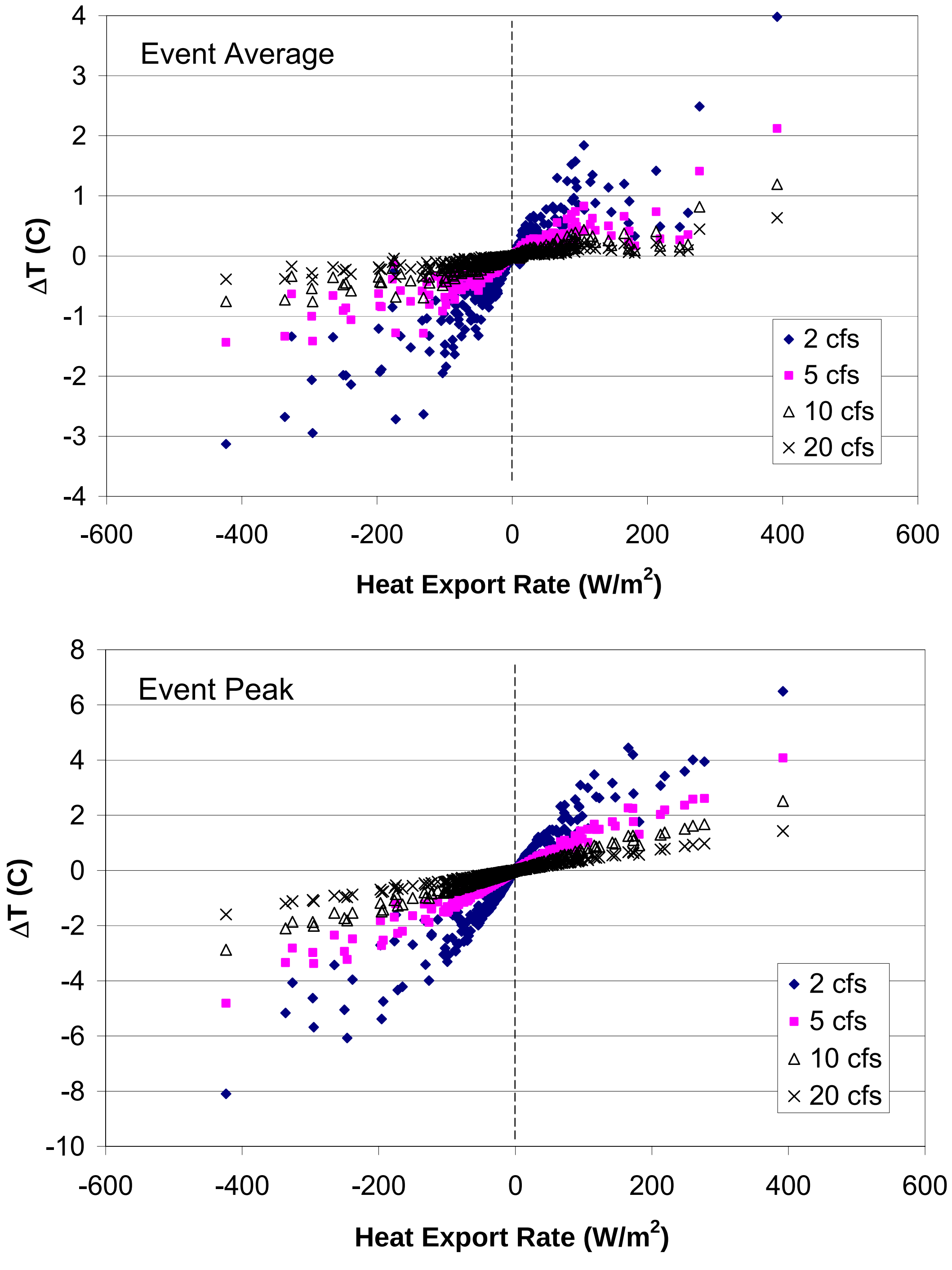


Figure 5.1. Change in stream temperature versus heat export rate for 280 rainfall events, using simulated runoff temperature and flow rate. Average change in stream temperature versus average heat export rate for each rainfall event (upper panel), maximum change in stream temperature versus maximum heat export rate during each rainfall event (lower panel). Results are given for receiving stream flow rates of 2, 5, 10 and 20 cfs.

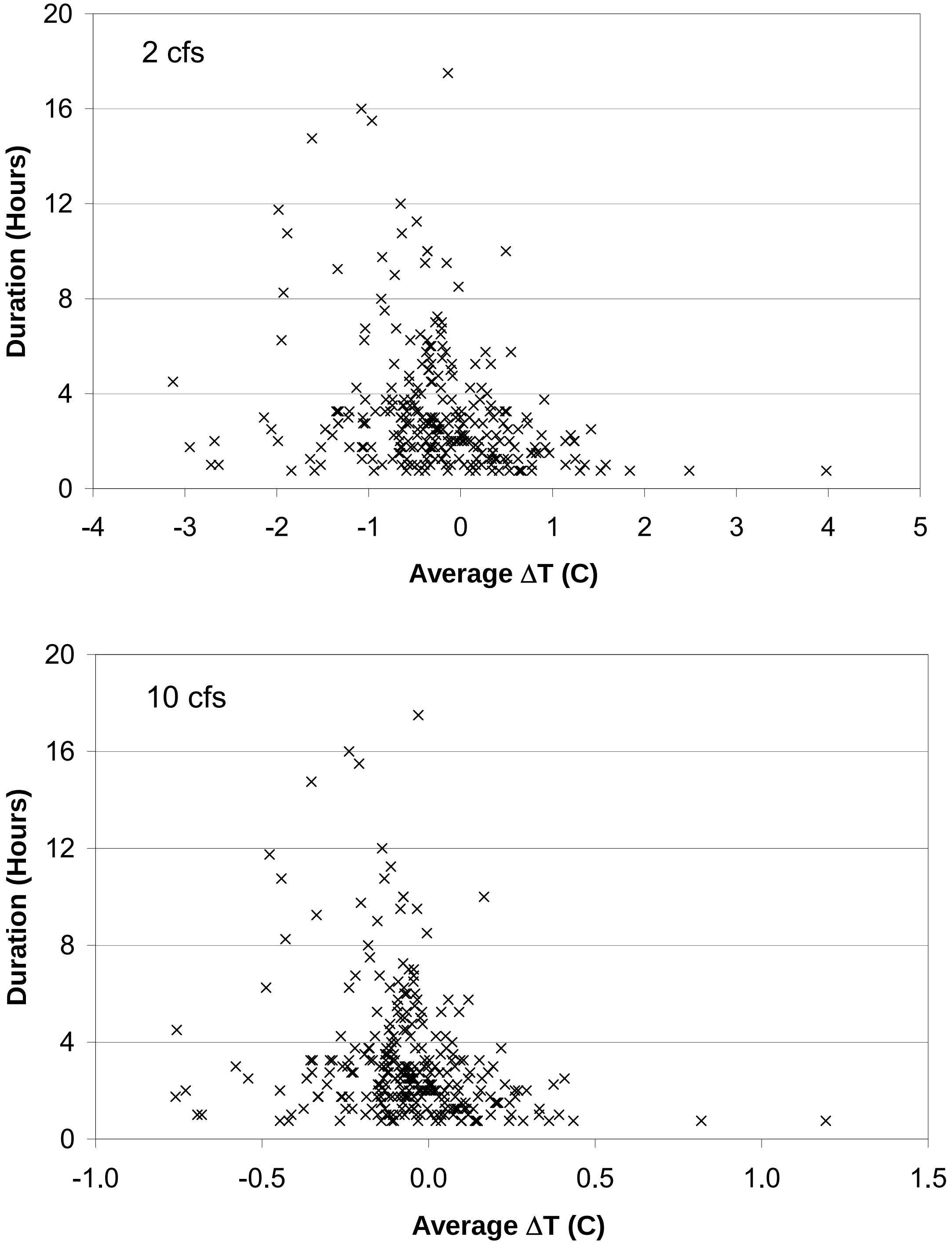


Figure 5.2. Runoff event duration versus average change in stream temperature for 2 cfs (upper panel) and 10 cfs (lower panel) stream flow rate.

6. DESIGN STORM EVENT SELECTION

6.1 Recorded Design Storm Events

Surface runoff from urban areas can contribute to the thermal degradation of coldwater streams. A hydrothermal simulation tool is currently being developed that will simulate runoff rate and runoff temperature from a watershed under commercial or residential development. While many of the runoff temperature results presented in this report were generated using continuous simulations, the general application of the simulation is more practical for event based analysis, i.e. simulating select, individual rainfall events. This requires the specification of one or several rainfall events as the model input. Rainfall/runoff events that produce a major temperature change in the receiving coldwater streams are of particular interest. It is necessary to identify design storm events that have the potential for the largest heat export from a watershed and consequently the potential for the strongest thermal pollution of a receiving coldwater stream.

In the preceding sections of this report three hydrothermal parameters of surface runoff have been identified to guide a design storm event selection: runoff temperature (^{o}C), heat export rate (W/m^{2}) and total heat export (J/m^{2}). The highest 20 of the 284 values for the three hydrothermal parameters were ranked and also related rainfall event parameters such as total rainfall amount, rainfall event duration, and average rainfall temperature (dew point). Partial duration series of extreme hydrothermal parameters were analyzed for frequency of occurrence (return periods). From the results given in Section 4, the following recommendations are derived for design storm events which are characterized by one or all three of the following: high runoff temperature, high total heat export rate, high total heat export.

1. There should be more than one design storm event, since no single storm has both high total heat export and heat export rate.
2. The design storm events occur typically on days with high dew point temperature.
3. The design storm events with high heat export rate typically have low total precipitation. The highest total precipitation for the events listed in Table 4.6 was 3.8 cm.
4. The design storm events occur on days with high solar irradiance, i.e. clear days before the rainfall event.
5. The design storm events occur predominantly on days with high air temperature, i.e typically in June, July and August.
6. The design storm events occur predominantly in the afternoon, i.e. between noon and midnight (Tables 4.5 – 4.7).

From the list of events in Tables 4.5 – 4.7, and using Table 4.6 as the principal guide, rainfall events that are possible candidates for design storm events have been summarized in Table 6.1. Storms M1 through M2 have relatively high runoff temperature, while M3 and M4 have relatively high rainfall volume. The M5 storm is a reasonable representation of an event with 1 year return period for both total heat export and heat export rate.

Table 6.1. Candidates for observed design storm events, taken from the 6 year MnROAD data base.

ID	Date	Start Time	Dew Point (°C)	Total Precip (cm)	Duration (hours)	Runoff Temp. (°C)
M1	8/16/05	16:30	16.6	1.1	0.8	29.6
M2	9/19/98	16:15	18.8	1.5	0.8	25.1
M3	7/25/99	21:29	21.6	3.2	2.5	23.7
M4	6/20/05	11:30	18.3	3.8	2.3	22.7
M5	6/22/99	15:15	18.1	1.5	5.75	25.1

ID	Avg. Heat Export Rate (W/m^2)	Return Period of Heat Export Rate (years)	Total Heat Export (kJ/m^2)	Return Period of Total Heat Export (years)
M1	162	7.8	437	3.7
M2	116	4.0	313	1.1
M3	54	1.6	491	6.0
M4	52	1.5	421	3.2
M5	14.6	0.9	301	1.0

6.2 Synthetic Design Storm Events

Analysis of measured rainfall events provides valuable information on the relationships between storm characteristics and thermal loading to receiving streams. Statistical analysis of recorded storms gives some idea of the return period of rainfall events that have different levels of thermal impact (see e.g. Figure 4.22). However, it is difficult to select a recorded event with a specified return period. e.g. 10 years, since no storm has been recorded with the predicted magnitude of heat export for a 10 year return period event. In addition, it may be desirable to create a storm event with specific characteristics, such as a particular duration or rainfall intensity. For these reasons, it is useful to examine processes for creating synthetic design storms for heat export analysis. In some ways this is similar to creating synthetic hydrographs for hydraulic design.

In Section 4, the thermal impact of observed storm events was analyzed in terms of 1) the heat export of the rainfall itself and 2) the heat export due to heat addition from pavement. In Section 6.2.1, synthetic storms are designed to mimic observed events in terms of the rainfall heat characterisitcs. In Section 6.2.2, these synthetic storms are further specified so that they mimic the heat export of observed rainfall events for runoff from pavement.

6.2.1 Design of Synthetic Storms based on Rainfall Heat Energy

Ignoring the interaction of rainfall with pavement heating for the moment, the heat export of a rainfall event is determined by the precipitation intensity, the dew point temperature (a surrogate for rainfall temperature), and the duration of the rainfall event. The process of creating a synthetic design storm can be started by selecting a desired event duration and return period. For this study, the focus will be on shorter duration storms (1 hour), because short duration storms tend to give the highest average runoff temperature. Note that for storms with fixed duration, total heat export and average heat export rate are directly coupled, so that it is not necessary to consider each separately. There are several approaches for selecting a rainfall intensity and dew point temperature for the event, using the observed storm statistics given in Section 4.1:

1) For a chosen storm duration and return period, e.g.1 hour and 1 year, respectively, select a dew point temperature (T_{dp}) and precipitation intensity (i) based on Figure 4.5. For this example, T_{dp}=21.2 °C and i=2.9 cm/hour for a 1 hour duration, 1 year return period storm. With no additional heat input from a pavement surface, the runoff from this event would create a heat export h*=40 W/m^2, based on a reference temperature of 20 °C, using Equation 3.1. Based on Figure 4.22, this heat export rate for a one hour duration rainfall corresponds to a return period between 2 and 5 years.

2) For a chosen storm duration and return period, select a dew point temperature (T_{dp}) based on Figure 4.5 and a target heat export rate (h) based on Figure 4.22. For this example, T_{dp}=21.2 °C and h=14 W/m^2 for a 1 hour duration, 1 year return period storm. Assuming no additional heat input, the required rainfall intensity to obtain h=14 W/m^2 is i*=1.0 cm/hour, using Equation 3.1.

3) For a chosen storm duration and return period, select a rainfall intensity based on Figure 4.5 and a target heat export rate (h) based on Figure 4.22. For this example, i =2.9 cm/hour and h=14 W/m^2 for a 1 hour duration, 1 year return period rainfall. Assuming no additional heat input, the required dew point temperature to obtain h=14 W/m^2 is T_{dp}*=20.4 °C, using Equation 3.1. As an alternative to Figure 4.5, previously published Intensity/Duration/Frequency (IDF) diagrams can also be used to specify rainfall intensity based on duration and return period. For example, city engineering departments and the Minnesota Department of Transportation (MNDOT) have developed IDF diagrams of rainfall events for storm sewer and culvert design (Figure 6.1). These diagrams are available for different regions of the state, but may not include the effects of recent changes in precipitation patterns.

The results of using these three methods to choose design storm parameters are summarized in Table 6.2, for return periods of 1, 2, 5 and 10 years and storm durations of 1, 2 and 4 hours. Columns 2-4 of Table 6.2 summarize values of heat export (h), dew point temperature (T_{dp}), and precipitation intensity (i), based on observed storm statistics. The heat export value (h*) given in Column 5 gives the value of heat export that would result from an event having, e.g., the observed 1 year precipitation intensity combined with the observed 1 year dew point temperature. Note that the h* values are 3 to 4 time higher than the observed heat export for each return period, suggesting that real storms do not possess both extreme precipitation intensity and extreme dew point temperature. Column 6 of Table 6.2 gives the precipitation intensity (i*) that gives 1 year observed heat export (h) when combined with 1 year dew point (T_{dp}). Similarly, column 7 gives the dew point temperature (T_{dp}*) that gives 1 year observed heat export (h) when combined with 1 year rainfall intensity (i). Note that T_{dp}* changes only slightly for 1 to 10 year return period events.

1 and 10 year return period events from Table 6.2 are plotted in Figure 6.2. For a given return period, the combinations (i, T_{dp}*) and (i*, T_{dp}) both result in heat export with the same return period, while the combination (i, T_{dp}) results in a storm with a higher return period for heat export.

Table 6.2. Heat export, dew point temperature, and precipitation intensity versus return period for 1, 2 and 4 hour duration events. Heat export (h), dew point (T_{dp}), and rainfall intensity (i) are taken from Figures 4.22 and 4.5, while h*, i*, and T_{dp}* are calculated, as described in the text.

1 Hour Duration Events						
Return Period (years)	h (W/m^2)	T_{dp} (°C)	i (cm/hr)	h* (W/m^2)	i* (cm/hr)	T_{dp}* (°C)
1	13.9	21.09	2.9	36.8	0.99	20.41
2	30.3	21.93	4.3	97	1.23	20.61
5	51.8	23.04	6.1	217	1.38	20.72
10	68.1	23.88	7.5	341	1.45	20.78
2 Hour Duration Events						
Return Period (years)	h (W/m^2)	T_{dp} (°C)	i (cm/hr)	h* (W/m^2)	i* (cm/hr)	T_{dp}* (°C)
1	0.2	20.4	1.4	7.0	0.04	20.01
2	13.9	21.4	2.8	46.1	0.85	20.42
5	32.0	22.7	4.8	148.1	1.03	20.58
10	45.7	23.6	6.2	263	1.08	20.63
4 Hour Duration Events						
Return Period (years)	h (W/m^2)	T_{dp} (°C)	i (cm/hr)	h* (W/m^2)	i* (cm/hr)	T_{dp}* (°C)
1	-6.8	18.4	0.6	-10.8	0.36	18.99
2	0.6	19.5	1.6	-9.9	N/A	20.03
5	10.4	20.9	3.0	31.5	0.99	20.30
10	17.9	22.0	4.0	93.3	0.77	20.38

6.2.2 Design of Synthetic Storms based on Runoff from Pavement

The information given in Table 6.2 demonstrates that a synthetic storm can be made to mimic the rainfall heat content of observed storms for a particular duration and return period. The next question to consider is: Can such a synthetic storm also mimic observed storms for runoff from pavement? The return period of runoff temperature and heat export for runoff from asphalt was analyzed in Section 4 for observed storm data. Using this data, Table 6.3 was constructed. In Table 6.3 runoff temperatures from asphalt, rainfall intensity\ies, and heat export rates for storms of varying duration and return period are compared. The parameters listed in Table 6.3 are analogous to those in Table 6.2: h, T_{ro} and i are the heat export rate, runoff temperature, and rainfall intensity, respectively, based on observed storms. h* is the heat export rate that would result from the combination of T_{ro} and i. T_{ro}^* is the average runoff temperature required to, e.g. produce the 1 year observed heat export rate (h) for a storm with the 1 year rainfall intensity (i). i* is average rainfall intensity required to produce, e.g. the 1 year heat export rate for a storm with the 1 year average dew point (T_{dp}).

Values in Table 6.3 make it evident that extreme values of runoff temperature do not coincide with extreme values of rainfall intensity, since, e.g., the combination of 1 year dew point with 1 year rainfall intensity produces a storm with heat export about 3 times higher than the 1 year value. T_{ro}* is nearly constant for each storm duration and return period. For the chosen value of reference temperature (20 °C), the 1 year return period heat export rate for a 4 hour storm is slightly negative, so that a value of i* does not exist for this case.

Table 6.3 gives values of runoff temperature for particular storm durations and return periods, but gives no information on the weather conditions that are required to produce this runoff temperature. To examine this issue, antecedent weather conditions must be considered along with the basic storm parameters of rainfall intensity and dew point temperature. Thus, a method for specifying antecedent conditions is required, and a model to simulate the effect of antecedent conditions on runoff temperature is required. For this study, the following procedure was used to specify antecedent conditions:

1) Changes in air temperature, dew point temperature, and solar radiation preceding a rainfall event were determined based on typical weather conditions for the calendar days of the rainfall event. Average weather parameters (air and dew point temperature, solar radiation, and wind speed) were calculated at 15 minute time intervals using 8 years of climate data from MnROAD.

2) A period of 100% cloud cover prior to the storm (front delay) is specified. Over this period, e.g. 1 or 2 hours, solar radiation is decreased to a fixed, low value for full cloud cover, and air temperature and dew point temperature are ramped towards the specified dew point temperature. This chosen method for varying the weather parameters immediately prior to the storm by no means produces the observed variations for all cases, but it establishes a reasonable approach with a single parameter, the front delay time (t_d), to examine sensitivity.

Figure 6.3 illustrates a synthetic storm event with the antecedent conditions and with a triangular rainfall hyetograph for a 1 hour duration storm. To evaluate the synthetic design storm events, the hydrothermal runoff model (Herb et al. 2006b) was used to simulate the runoff temperature and heat export of the synthetic storms for an asphalt surface. The resulting runoff temperature and heat export of the synthetic storms can be compared to the runoff temperature and heat export of the observed storms.

Figure 6.4 gives results of the hydro-thermal runoff simulation for a 1 hour duration storm with T_{dp} = 20.4 °C and rainfall intensity of 2.9 cm/hour. Table 6.2 indicates that these storm parameters give a rainfall heat energy (13.9 W/m^2) corresponding to a 1 year return period. The storm was analyzed assuming that it occurred on July 9, using the antecedent conditions as shown in Figure 6.3. The front delay time was varied from 1 to 8 hours, resulting in a substantial variation in the initial surface temperature of the asphalt, the average runoff temperature, and the average heat export rate of the runoff (Figure 6.4). For a high intensity, low dew point storm (i=2.9 cm/hour, T_{dp} = 20.4 °C), the sensitivity to front delay was relatively high (Figure 6.4, upper panel), and a front delay time of between 7 and 8 hours was required to produce 1 year return period runoff temperature (21.7 °C) and heat export rate (57.1 W/m^2). For a low intensity, high dew point storm (i=1.13 cm/hour, T_{dp} = 21.2 °C), the sensitivity to front delay was relatively low (Figure 6.4, lower panel). A front delay time of between 3 and 4 hours was required to produce 1 year return period runoff temperature (24.3 °C) and heat export rate (57.1 W/m^2) for i=1.13 cm/hour.

Tables 6.4 and 6.5 list a number of 1 hour duration synthetic storm events for heat export return periods of 1, 2, 5 and 10 years. The storms given in Table 6.4 all use the same rainfall intensity (2.9 cm/hour) and dew point temperature (18.8 °C), where 18.8 °C is the average dew point temperature during rainfall events for the month of July (Table 4.1). The heat export for each storm was varied via the front delay parameter from 1.8 to 4 hours, further demonstrating the importance of this parameter. The synthetic storms given in Table 6.5 all use the same rainfall intensity (2.9 cm/hour) and front delay (2 hours), while the dew point temperature was used to vary heat export to values appropriate for each return period.

Table 6.3. Heat export and runoff temperature for asphalt, and precipitation intensity versus return period for 1, 2 and 4 hour duration events. Heat export (h), dew point (T_{ro}), and rainfall intensity (i) are taken from Figures 4.22 and 4.5, while h*, i*, and T_{ro}* are calculated, as described in the text

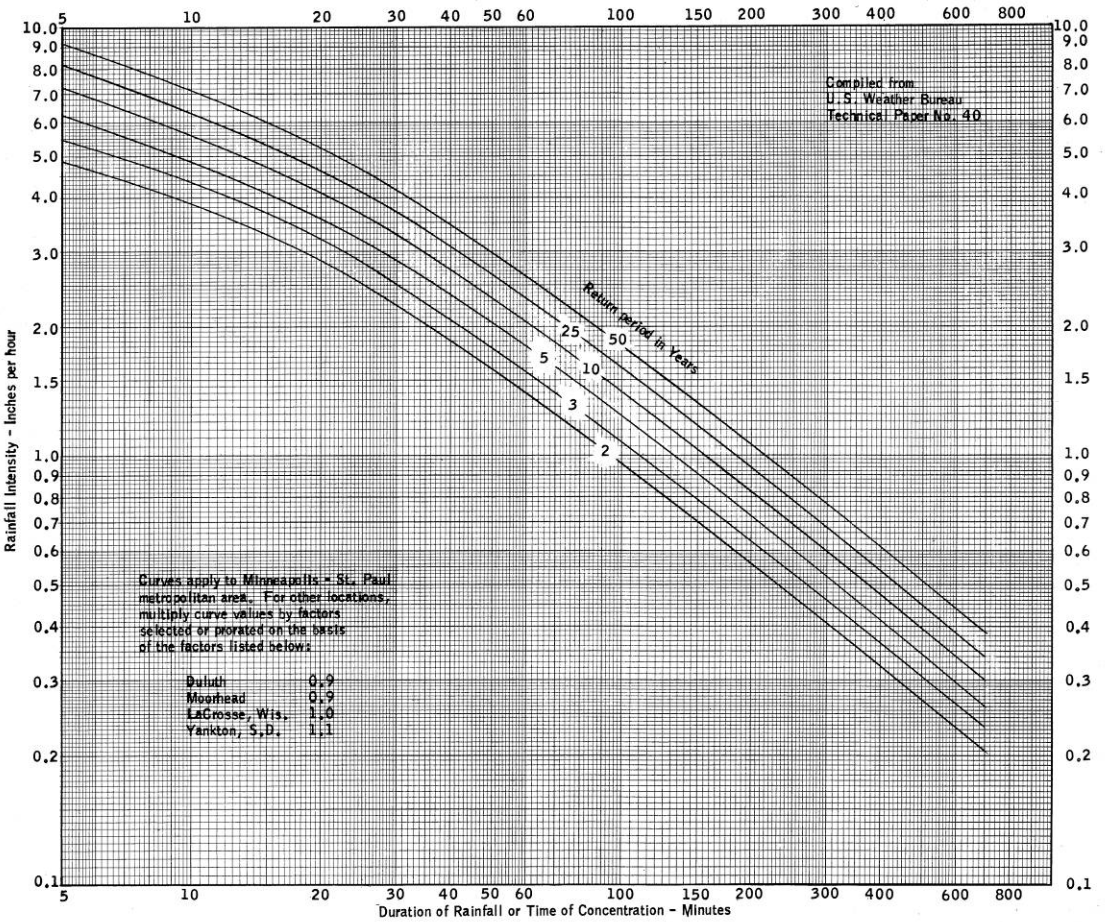
<table>
<tr><th colspan="7">1 Hour Duration Events</th></tr>
<tr><th>Return Period (years)</th><th>h (W/m^2)</th><th>T_{ro} (°C)</th><th>i (cm/hr)</th><th>h* (W/m^2)</th><th>i* (cm/hr)</th><th>T_{ro}* (°C)</th></tr>
<tr><td>1</td><td>57.1</td><td>24.3</td><td>2.9</td><td>146</td><td>1.13</td><td>21.70</td></tr>
<tr><td>2</td><td>95.6</td><td>25.1</td><td>4.3</td><td>255</td><td>1.61</td><td>21.92</td></tr>
<tr><td>5</td><td>146.5</td><td>26.1</td><td>6.1</td><td>437</td><td>2.05</td><td>22.05</td></tr>
<tr><td>10</td><td>185.1</td><td>26.9</td><td>7.5</td><td>603</td><td>2.31</td><td>22.11</td></tr>
<tr><th colspan="7">2 Hour Duration Events</th></tr>
<tr><th>Return Period (years)</th><th>h (W/m^2)</th><th>T_{ro} (°C)</th><th>i (cm/hr)</th><th>h* (W/m^2)</th><th>i* (cm/hr)</th><th>T_{ro}* (°C)</th></tr>
<tr><td>1</td><td>23.3</td><td>23.3</td><td>1.4</td><td>52.7</td><td>0.61</td><td>21.46</td></tr>
<tr><td>2</td><td>51.1</td><td>24.4</td><td>2.8</td><td>145</td><td>1.00</td><td>21.55</td></tr>
<tr><td>5</td><td>87.8</td><td>25.8</td><td>4.8</td><td>323</td><td>1.29</td><td>21.58</td></tr>
<tr><td>10</td><td>115.6</td><td>26.9</td><td>6.2</td><td>502</td><td>1.44</td><td>21.59</td></tr>
<tr><th colspan="7">4 Hour Duration Events</th></tr>
<tr><th>Return Period (years)</th><th>h (W/m^2)</th><th>T_{ro} (°C)</th><th>i (cm/hr)</th><th>h* (W/m^2)</th><th>i* (cm/hr)</th><th>T_{ro}* (°C)</th></tr>
<tr><td>1</td><td>-2.3</td><td>20.7</td><td>0.6</td><td>4.7</td><td>N/A</td><td>19.66</td></tr>
<tr><td>2</td><td>17.5</td><td>21.5</td><td>1.6</td><td>28</td><td>1.02</td><td>20.93</td></tr>
<tr><td>5</td><td>43.7</td><td>22.5</td><td>3.0</td><td>87</td><td>1.50</td><td>21.26</td></tr>
<tr><td>10</td><td>63.5</td><td>23.3</td><td>4.0</td><td>153</td><td>1.66</td><td>21.35</td></tr>
</table>

Table 6.4. 1 hour duration synthetic design storms for 1, 2, 5, and 10 year return periods, using the observed precipitation intensity, the average dew point temperature during rain events for July (18.8 °C), and the appropriate front delay time required to produce the observed heat export rate for each return period.

Return Period (years)	i (cm/hr)	T_{dp} (°C)	t_d (hours)	T_{ro} (°C)	h_{ro} (W/m^2)	g_{ro} (kJ/m^2)
1	2.9	18.8	4	21.8	57.4	206.6
2	4.3	18.8	3	22.0	96.1	346.0
5	6.1	18.8	2	22.2	151.7	546.3
10	7.5	18.8	1.75	22.1	179.5	646.0

Table 6.5. 1 hour duration synthetic design storms for 1, 2, 5, and 10 year return periods, using the observed precipitation intensity, a 2 hour front delay, and the appropriate dew point temperature required to produce the observed heat export rate for each return period.

Return Period (years)	i (cm/hr)	T_{dp} (°C)	t_d (hours)	T_{ro} (°C)	h_{ro} (W/m^2)	g_{ro} (kJ/m^2)
1	2.9	16.9	2	21.8	57.2	206.1
2	4.3	17.9	2	21.9	95.4	343.6
5	6.1	18.7	2	22.1	146.1	525.9
10	7.5	19.1	2	22.2	186.7	672.3



Compiled from
U.S. Weather Bureau
Technical Paper No. 40

Curves apply to Minneapolis - St. Paul metropolitan area. For other locations, multiply curve values by factors selected or prorated on the basis of the factors listed below:

Duluth	0.9
Moorhead	0.9
LaCrosse, Wis.	1.0
Yankton, S.D.	1.1

Figure 6.1. Rainfall Intensity-Duration-Frequency (IDF) diagram for the Twin Cities (MNDOT 1969).

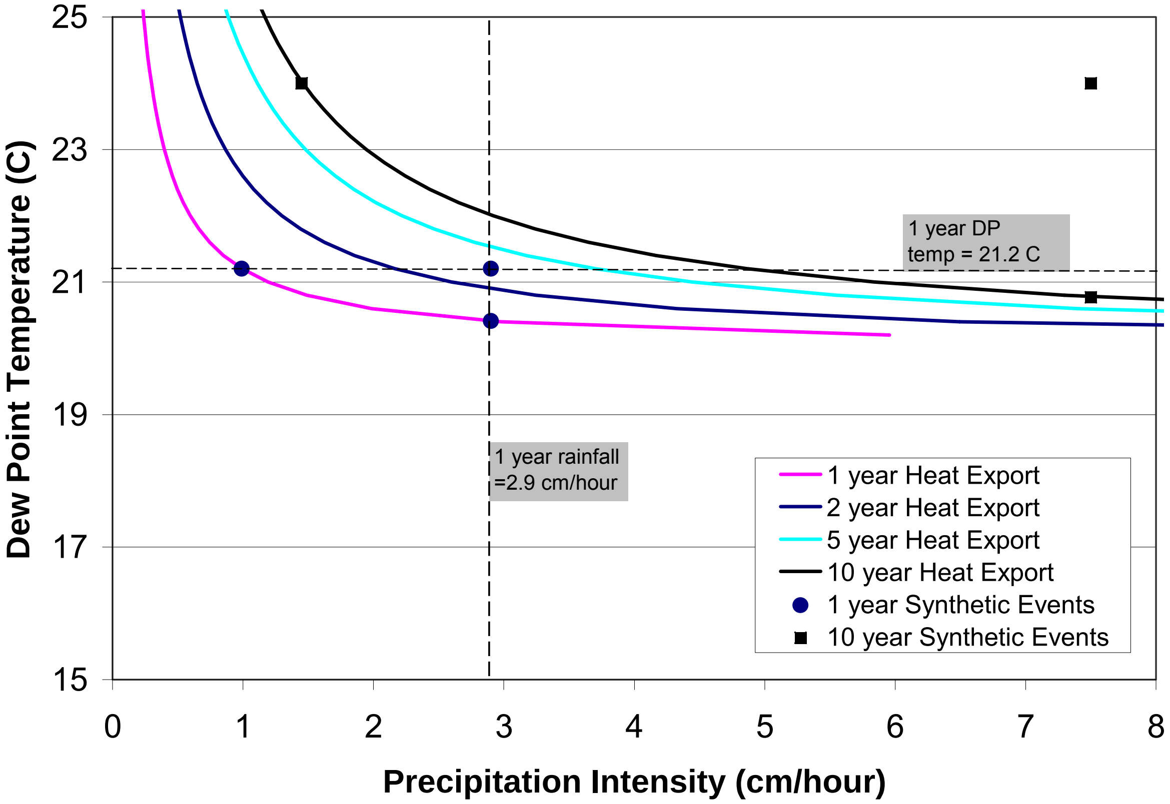


Figure 6.2. Dew point temperature versus precipitation intensity for synthetic storm events of 1 year and 10 year return period.

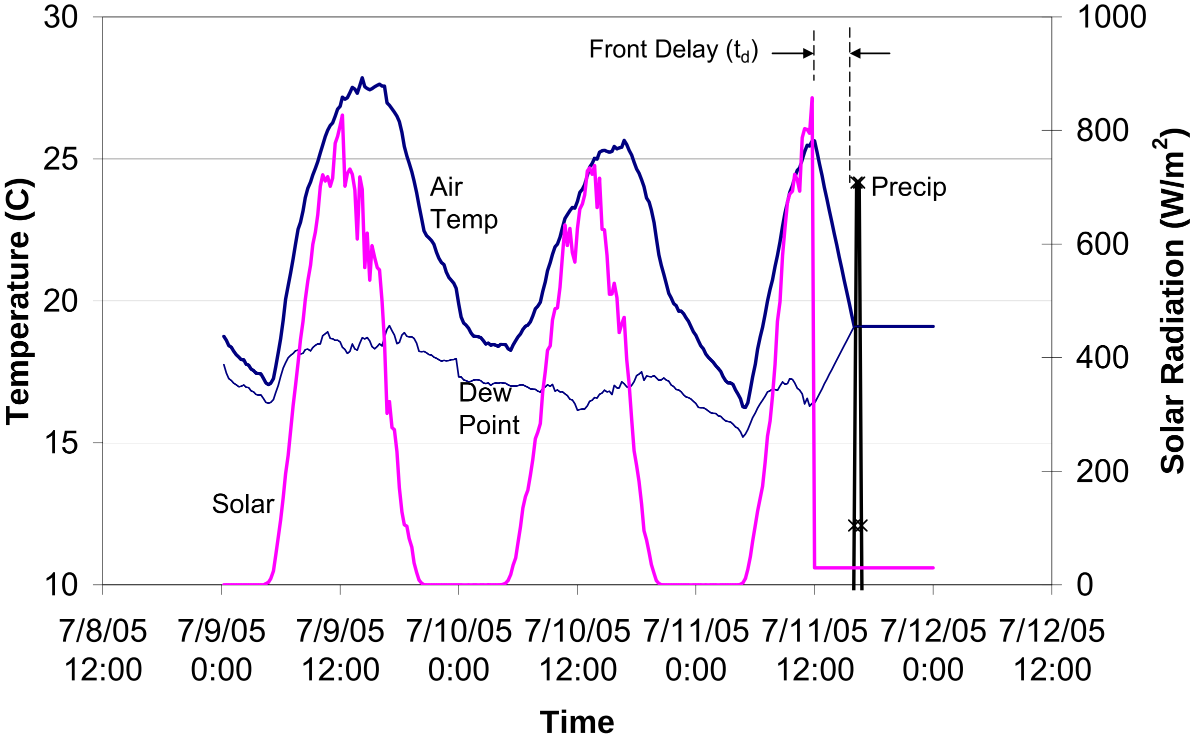


Figure 6.3. Example of synthetic design storm in July, with a 1 hour precipitation duration and a 4 hour front delay. The antecedent conditions prior to the front delay are from recorded weather data for July, 2005 from the MnROAD weather station.

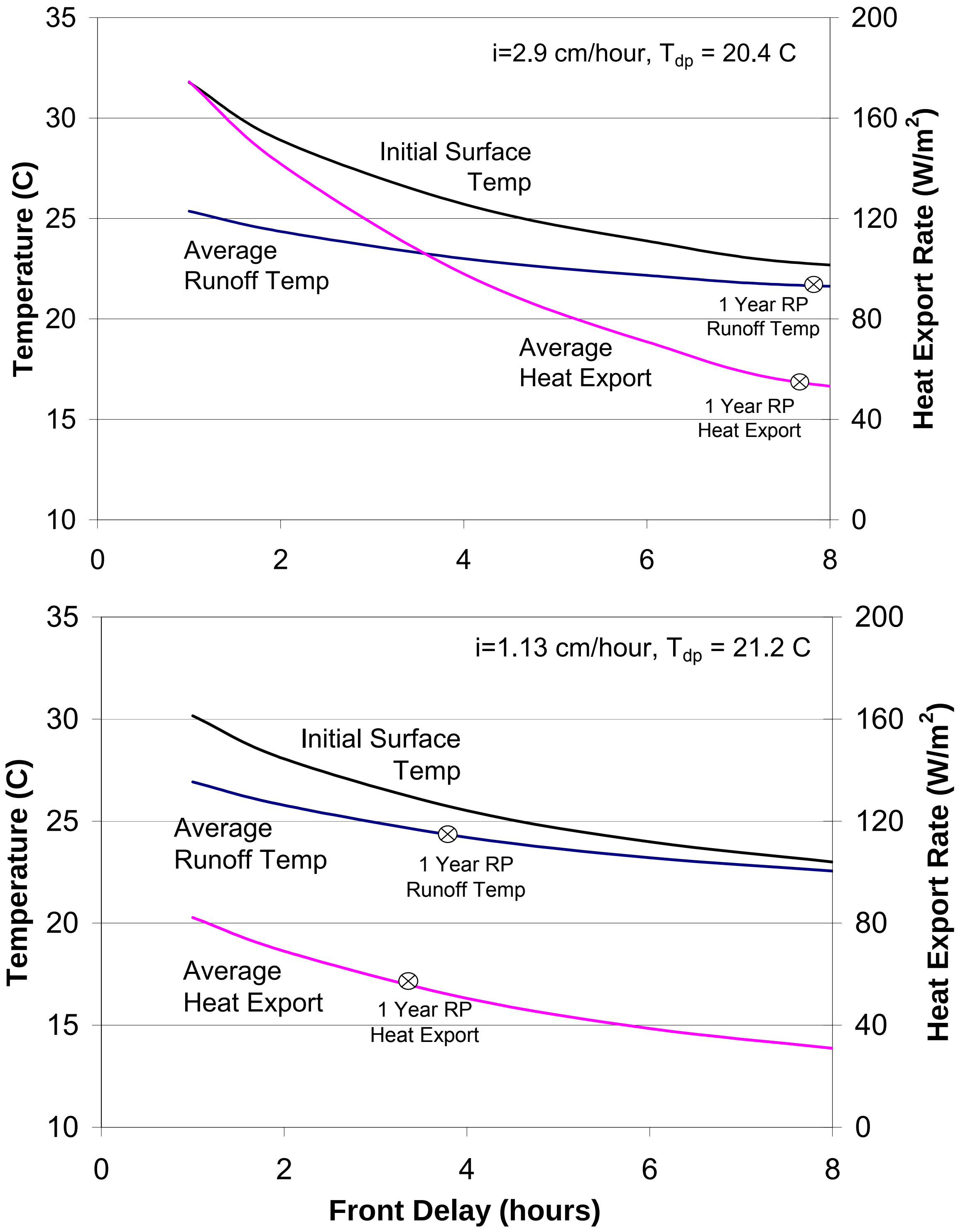


Figure 6.4. Initial surface temperature, average runoff temperature, and average heat export rate versus front delay time, for a 1 hour duration, 2.9 cm/hour storm with 20.4 °C dew point temperature.

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7. CONCLUSIONS

Rainfall/runoff events have been characterized in terms of runoff temperature (^oC), total heat export (J/m^2) and heat export rate (W/m^2) to rank their potential impact on the thermal pollution of coldwater streams, based on a reference temperature (stream temperature) of 20^oC.
In this study, records of rainfall events and weather data are used to estimate the three hydrothermal parameters by model simulation. The model for predicting rainfall runoff temperatures and rates from an impervious surface (parking lot) has been described in Project Report No. 484 from the St. Anthony Falls Laboratory, University of Minnesota (Herb et al 2006). The weather data came from the MnROAD test site in Albertville, MN, and from the SAMSON data set. Runoff temperatures and heat export were calculated for a 100x100m paved surface using 6 years of 15 minute weather data or 30 years of 1-hour weather data. The 6-year data set contained 280 rainfall events from April through October.

The 280 values of the three hydrothermal parameters were related to basic rainfall event parameters such as total rainfall, duration, and rainfall temperature (dew point). Average runoff temperature was found to be well correlated to dew point temperature during the storm, and air temperature and solar radiation prior to the storm. 20 extreme values of the hydrothermal parameters were ranked and also related to basic rainfall parameters. Partial duration series of hydrothermal parameters were analyzed separately for frequency of occurrence (return periods).

Rainfall events with high heat export rate have several characteristics in common: They tend to occur mostly in the afternoon hours, have runoff temperatures significantly above 20^oC, and have relatively low total precipitation. The highest runoff temperatures also tend to occur with afternoon rainfall events of small total precipitation where the initial runoff from warm pavement surface is a significant fraction of the entire storm event.

Although average runoff temperatures are the highest in July, storm events with high heat export can occur from May through September. Storms with extreme values of total heat export tend to have moderate values of heat export rate, and vice-versa. It may be desirable to consider multiple design storms, so that storms with extreme values of both total heat export and heat export rate may be included. It is possible to choose design storms from observed data sets, or to create synthetic design storms based on the statistics of observed storms. To better characterize extreme rainfall events it would be desirable to analyze longer data sets, and data sets from different regions of the state.

The results presented in this report can be used to establish criteria for choosing design storm events. The total heat export (J/m^2) multiplied by the total watershed area is a measure of the total heat energy input from a rainfall event to a stream. The instantaneous heat export rate is a measure of the rate at which heat energy is delivered to a receiving stream from a rainfall event at any given time, and is strongly related to the instantaneous change in stream temperature. Both parameters depend on both the rainfall weather characteristics and the watershed surface characteristics.

The impact of rainfall/surface runoff on stream temperatures was explored in general terms, but introduces additional variables, such as stream flow rate, that cannot be included in the selection of a design storm event. In addition, mitigation measures such as storm water detention ponds, heat transfer and time delays during routing in storm sewers, and the mixing of runoff from different land uses, as well as mitigation measures such as rain gardens, infiltration ponds etc. cannot be considered in the selection of a design storm event.

For illustration, the impact of the heat export from a paved 100mx100m paved lot on water temperatures in a specific stream was analyzed, to relate the hydrothermal parameters to changes in stream temperature. The heat export rate is directly related to the instantaneous change in stream temperature, while the total heat export of a runoff event relates to an integral temperature change in the receiving stream.

Finally, all the information generated was reviewed to recommend the characteristics of design storms to be used as input to models of surface runoff rates and temperatures from developed or undeveloped watersheds. These rainfall events typically have low total precipitation, occur on afternoons, and have return periods on the order of 1 to 5 years for maximum heat export rate or total heat export from a watershed.

A methodology to create synthetic design storms with specific rainfall intensities, durations and return periods was also presented.

ACKNOWLEDGEMENTS

This study was conducted with support from the Minnesota Pollution Control Agency, St. Paul, Minnesota, with Bruce Wilson as the project officer. We would like to acknowledge Ben Worel and Tim Clyne of MnDOT for proving climate and pavement temperature data used in this study.

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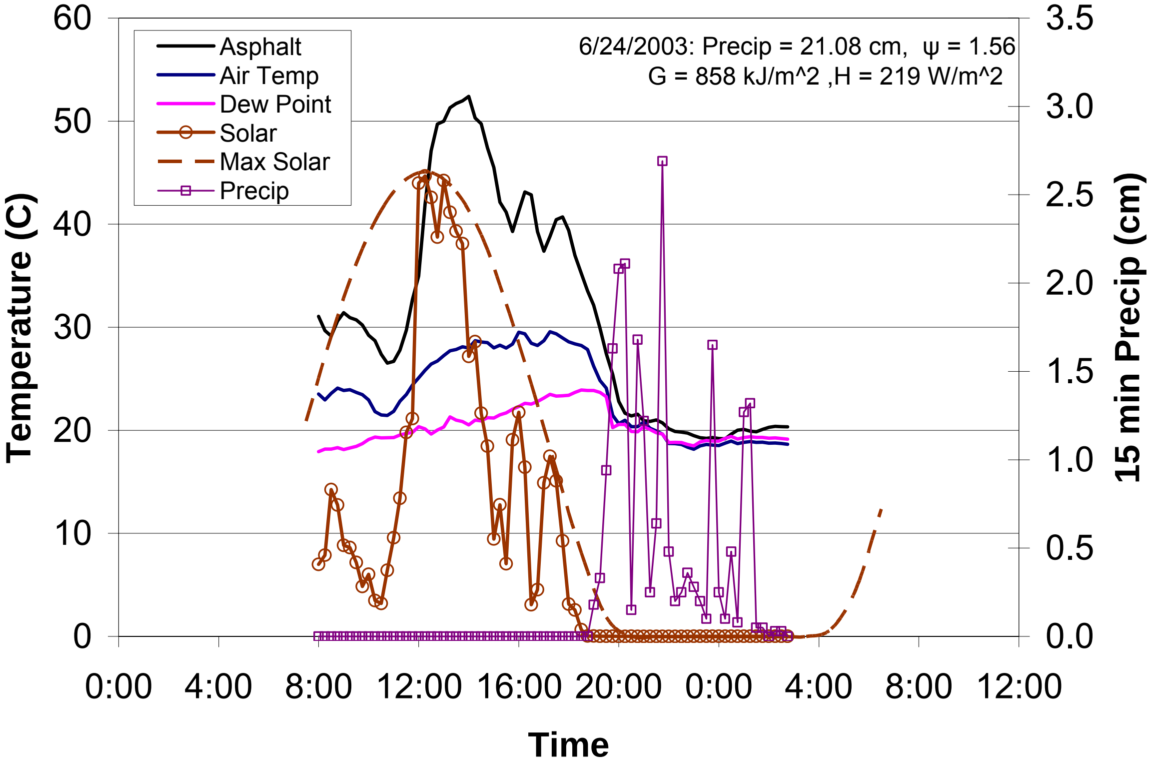
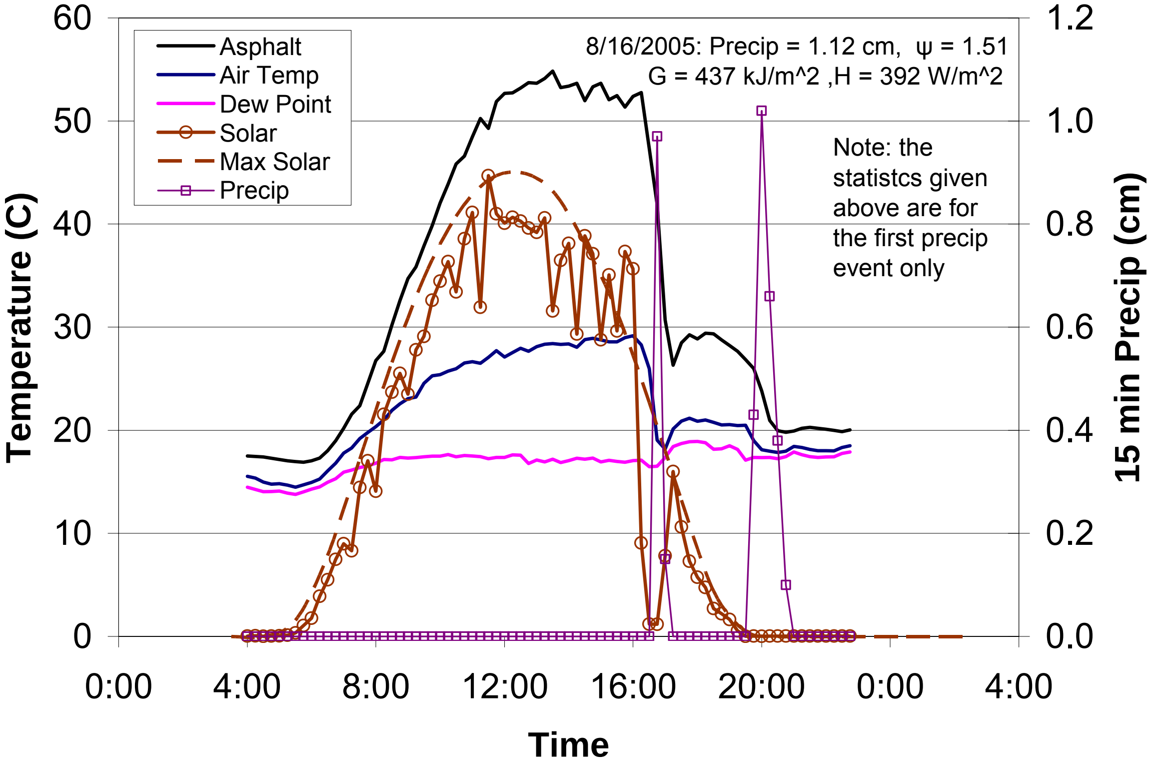
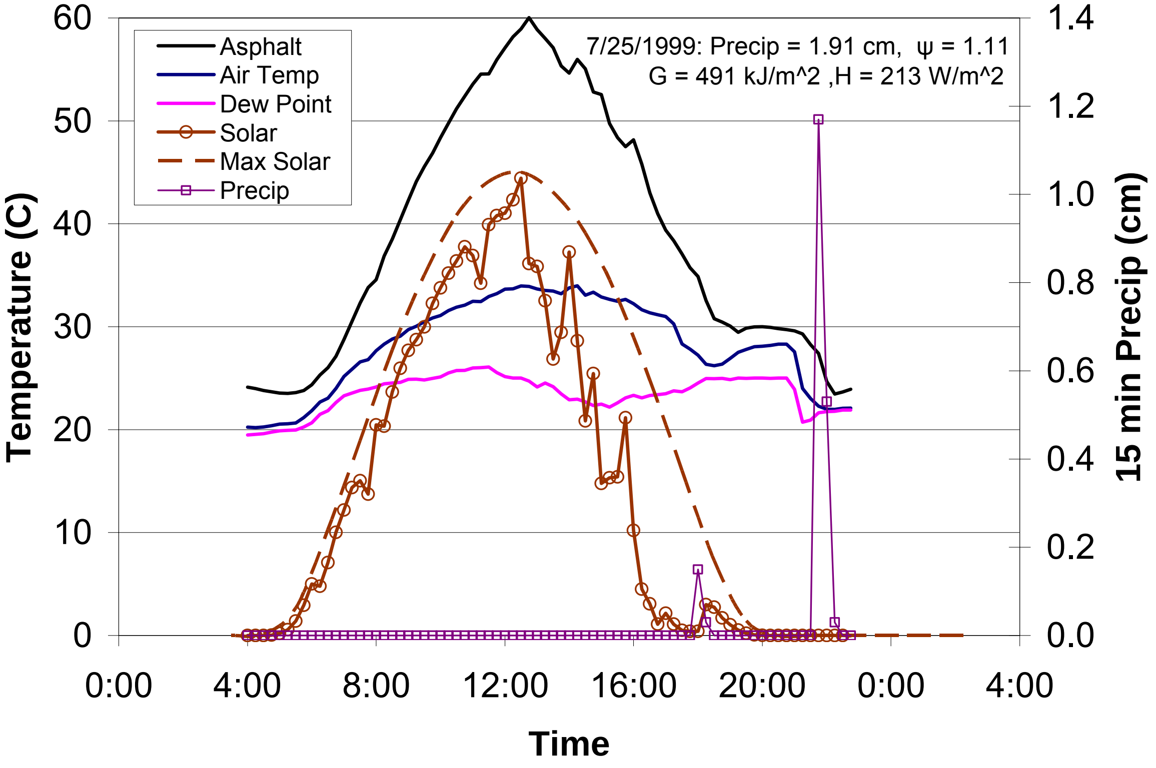
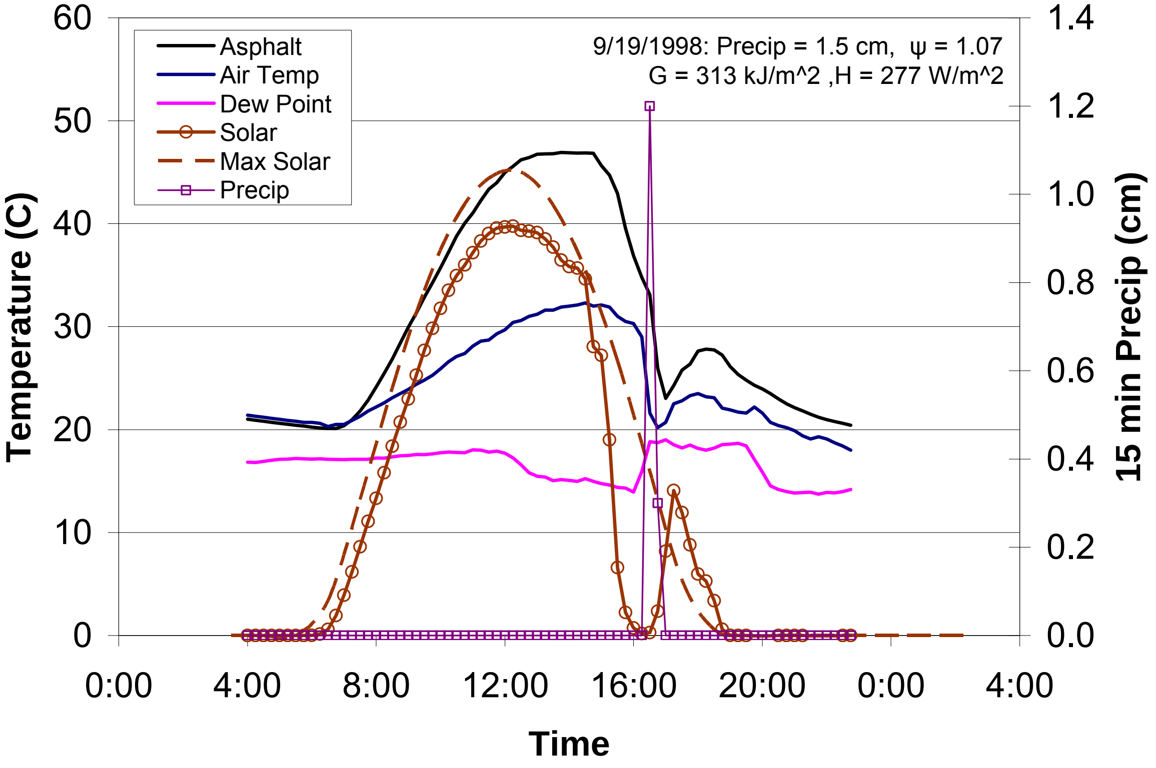
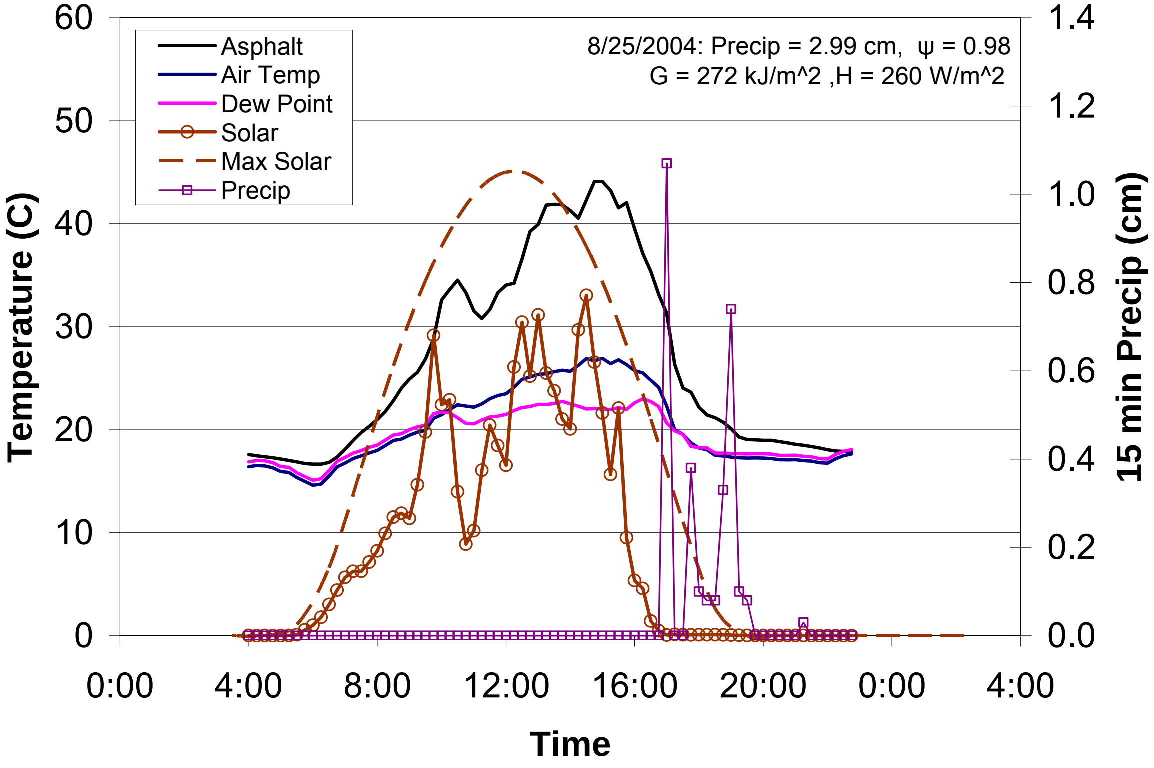
APPENDIX. TIME SERIES OF CLIMATE PARAMETERS FOR RAINFALL EVENTS THAT PRODUCE THE HIGHEST HEAT EXPORT



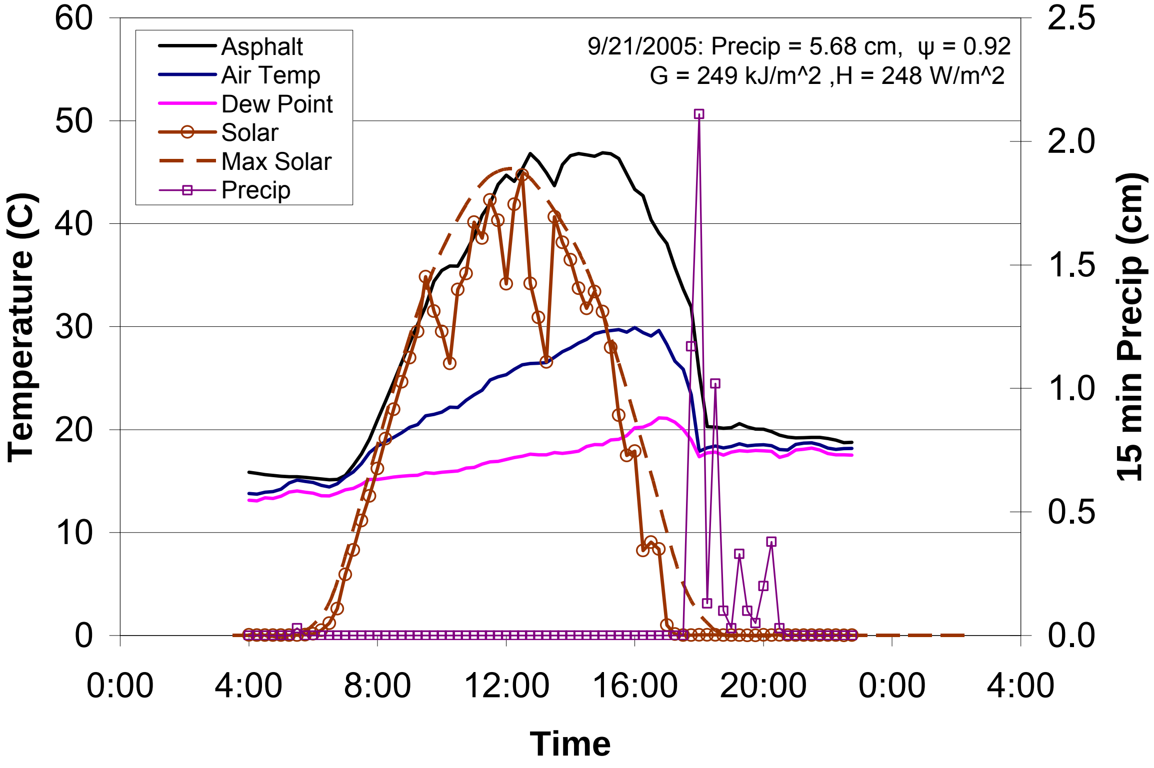



Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
7/25/1999: Precip = 1.91 cm, ψ = 1.11
G = 491 kJ/m^2 ,H = 213 W/m^2
Temperature (C)
15 min Precip (cm)
Time
60
50
40
30
20
10
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00

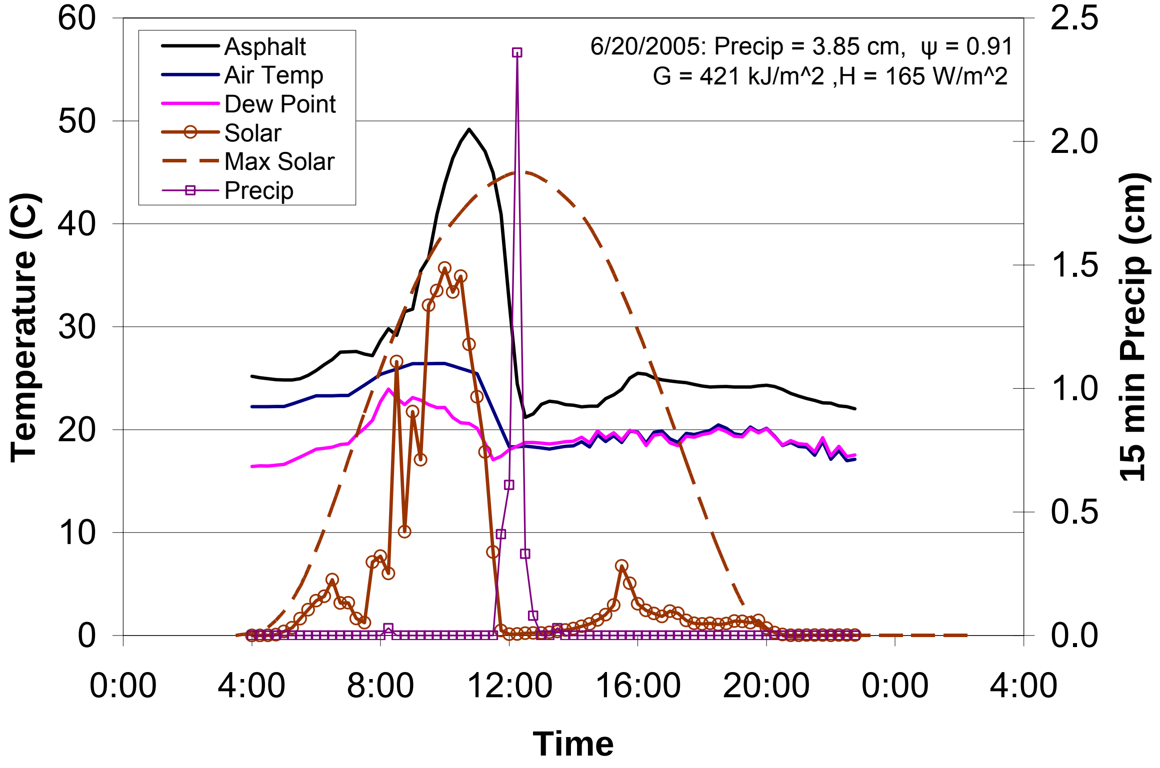

Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
9/19/1998: Precip = 1.5 cm, ψ = 1.07
G = 313 kJ/m^2 ,H = 277 W/m^2
Temperature (C)
15 min Precip (cm)
Time
60
50
40
30
20
10
0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00

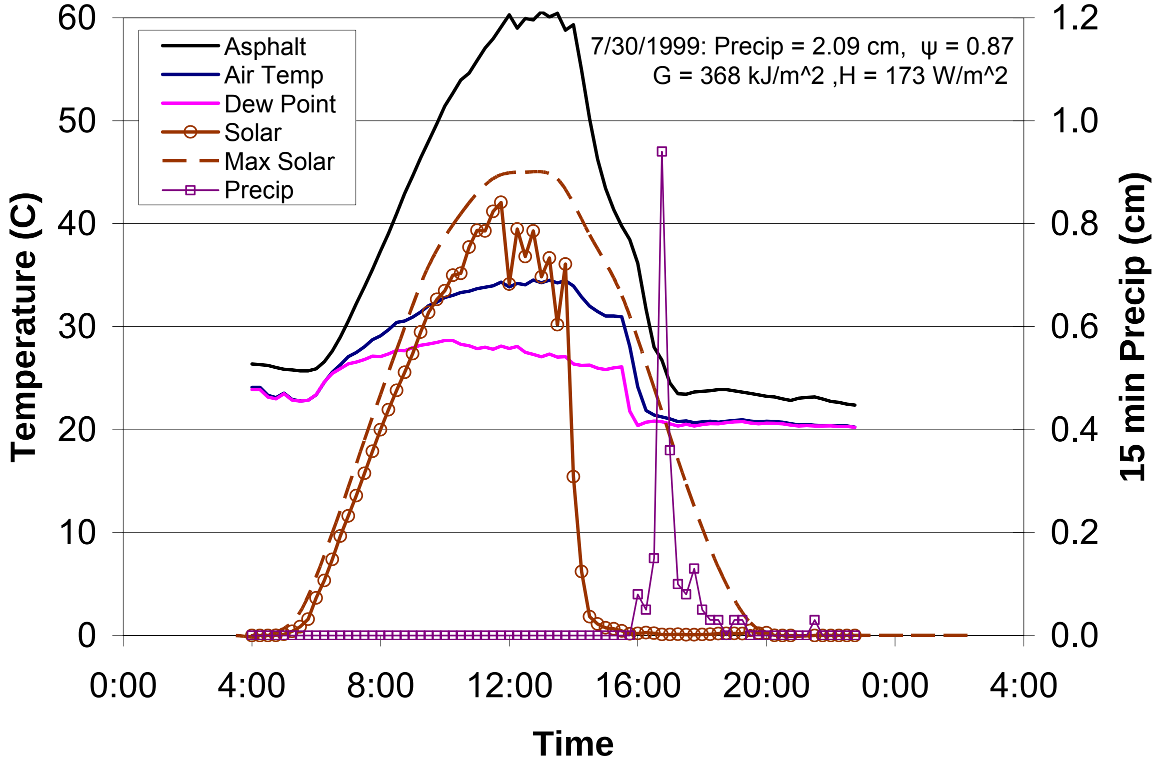


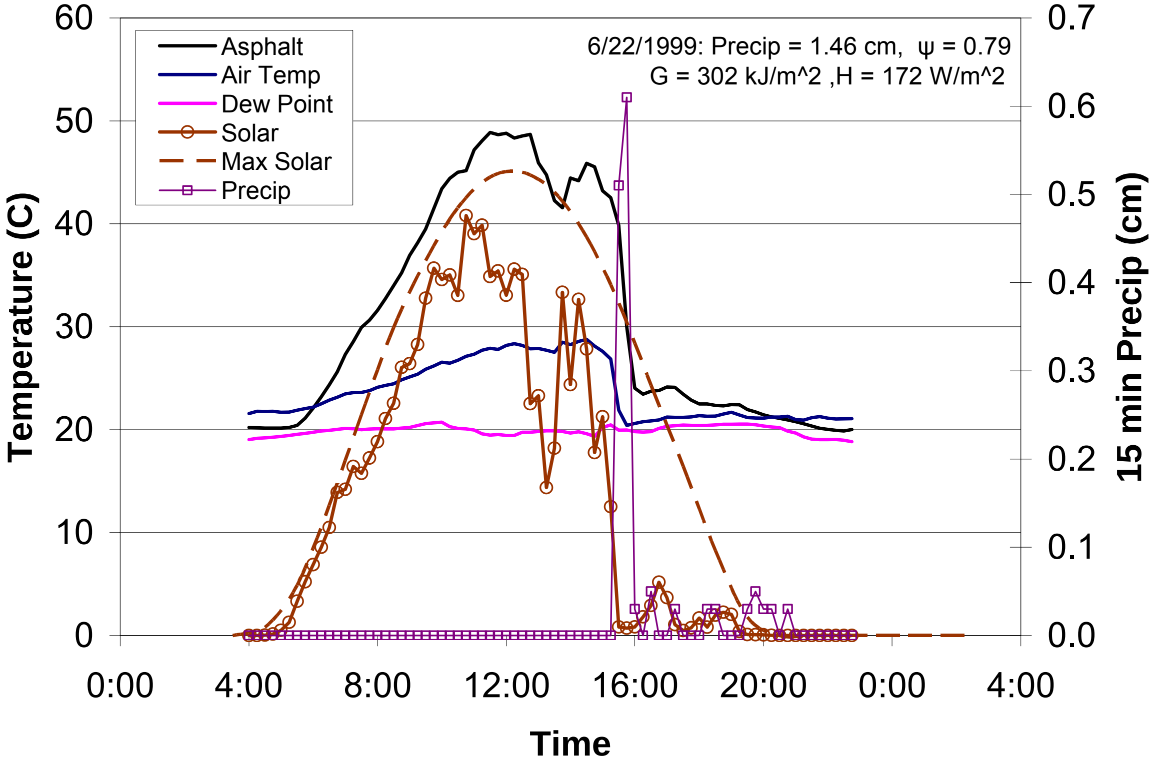
60
50
40
30
20
10
0
Temperature (C)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
15 min Precip (cm)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time
Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
8/25/2004: Precip = 2.99 cm, ψ = 0.98
G = 272 kJ/m^2 ,H = 260 W/m^2



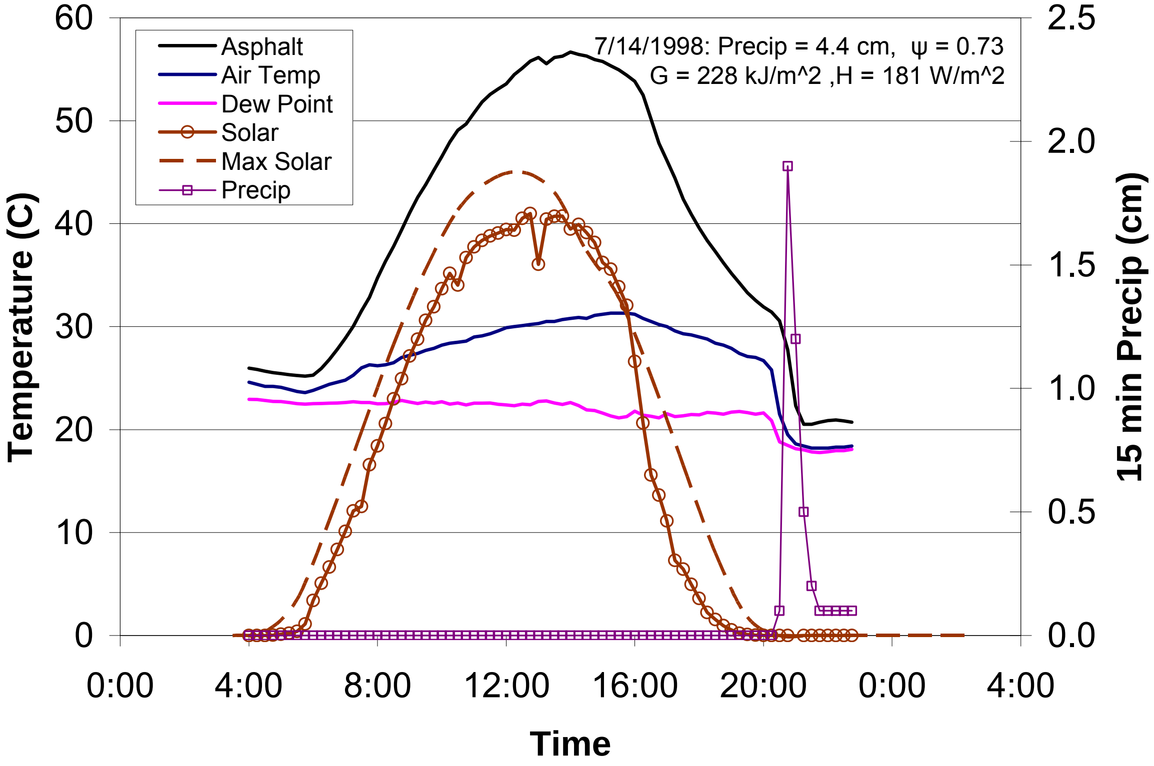
60
50
40
30
20
10
0
Temperature (C)
2.5
2.0
1.5
1.0
0.5
0.0
15 min Precip (cm)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time
Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
9/21/2005: Precip = 5.68 cm, ψ = 0.92
G = 249 kJ/m^2 ,H = 248 W/m^2


Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
6/20/2005: Precip = 3.85 cm, ψ = 0.91
G = 421 kJ/m^2 ,H = 165 W/m^2
Temperature (C)
15 min Precip (cm)
Time
0
10
20
30
40
50
60
0.0
0.5
1.0
1.5
2.0
2.5
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00


Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
7/30/1999: Precip = 2.09 cm, ψ = 0.87
G = 368 kJ/m^2 ,H = 173 W/m^2
Temperature (C)
15 min Precip (cm)
Time
0
10
20
30
40
50
60
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00



Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
6/22/1999: Precip = 1.46 cm, ψ = 0.79
G = 302 kJ/m^2 ,H = 172 W/m^2
Temperature (C)
15 min Precip (cm)
Time
0
10
20
30
40
50
60
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00



Asphalt
Air Temp
Dew Point
Solar
Max Solar
Precip
7/14/1998: Precip = 4.4 cm, ψ = 0.73
G = 228 kJ/m^2 ,H = 181 W/m^2
Temperature (C)
15 min Precip (cm)
Time
0
10
20
30
40
50
60
0.0
0.5
1.0
1.5
2.0
2.5
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00