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Heating of Rainfall Runoff on Residential and Commercial Roofs

by

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Abstract

A common assumption in stream water temperature modeling is that rooftops of all types contribute very little heat to runoff from rainfall. In this report we examine the accuracy of this assumption (a) by analyzing temperature data which we recorded on a residential rooftop, a commercial rooftop, and a concrete driveway, and (b) by simulating temperature profiles within rooftops and pavements, and estimating heat transfer from these surfaces to rainfall runoff.

Analysis of both wet- and dry-weather temperature data which we recorded over periods of several months allowed us to conclude that a driveway has a far greater capacity for heat storage and release than a rooftop, although the commercial rooftop was able to store and release more heat than the residential rooftop. On sunny days and prior to rainfall, rooftops can reach higher temperatures than paved surfaces, but not much heat is stored, and roof temperatures drop rapidly as cloud cover increases with an approaching storm. Interestingly, weather events leading to the highest dew point (rainfall) and surface temperatures often occurred during late night or early morning hours, contrary to the expectation that the worst-case runoff heating events would occur during daylight hours. The analysis conducted for three rainfall events showed that the heat export from the commercial rooftop was roughly three times that of the residential rooftop, but only 30%-90% of the heat export from the concrete driveway. Potential heat export was significantly higher for the driveway than for either rooftop.

In conclusion, the results of the data analysis and heat export simulations support the assumption that residential rooftops contribute very little heating to runoff from rainfall. Commercial rooftops may have a thermal impact on rainfall runoff because of their greater thermal storage capacity. An asphalt pavement, (road or driveway) is expected to have a greater thermal impact than a concrete pavement. Commercial rooftops in addition to asphalt and concrete pavements should be considered when the water temperatures of rainfall runoff from highly urbanized areas are estimated.

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1. INTRODUCTION

During the summer months, warm rainfall runoff from impervious urban areas can be a threat to coldwater (trout) streams. Although rooftops are impervious and cover a significant portion of urban areas, a common assumption is that they contribute a lot of water but little heat to urban surface runoff from rainfall. How much water is contributed by rooftops to runoff actually depends on stromwater best management practices (BMPs), which tend to route water from roofs to lawns, rain gardens, infiltration ponds or other places where infiltration into the soil is enhanced. This practice reduces surface runoff.

In the assessment or modeling of the temperature of urban storm water runoff, rooftops are usually ignored, because paved roads, parking lots and other impervious ground surfaces are expected to have much greater heat storage and release potential than roofs (Herb et al., 2007a, 2009). No validation of this assumption was found in the literature. The treatment of rooftop runoff is also not addressed in the literature of existing runoff temperature models: a model such as that by Van Buren et al. (2000) was developed for paved surfaces only and thus does not mention rooftop runoff; however, models such as TURM (Roa-Espinosa et al., 2003; Thompson et al., 2008), WEP (Jia et al., 2001), and MINUHET (Herb et al., 2009) were designed with the purpose of predicting runoff temperature and volume from partially-developed watersheds, and presumably treat rooftop runoff in some fashion even though it is not specifically mentioned in the literature. An experimental (field) and modeling study was therefore conducted to investigate the contribution of rooftops to the heating of rainfall runoff. Rooftop temperatures were collected and analyzed, and a previously-developed runoff model was applied to a typical residential (asphalt-shingled), a commercial (flat tar-and-gravel) and a "green" (vegetated) rooftop. The methodology, data and results of the analysis will be presented in order to support or refute the assumption that rooftops contribute little to the heating of rainfall runoff in urban areas.

2. ROOFTOP STRUCTURES

Three types of rooftops are investigated in this work: a residential rooftop, a commercial rooftop and a "green" roof. The residential rooftop is typically found on low-density single-family housing, and the commercial rooftop is typically a flat roof installed on shopping centers, warehouses, manufacturing and storage facilities, as well as public buildings. "Green" roofs are becoming increasingly popular, and are currently found on some public buildings, such as libraries, museums, schools, and government centers, and on commercial and residential buildings as well.

2.1 Residential Roof

The residential rooftop is generally constructed with a high slope to facilitate rapid runoff of rainfall from the rooftop to gutters. The roof structure normally consists of a rafter-supported thin (roughly ¾") wood decking on which is placed a vapor barrier or roofing felt to prevent moisture transfer (Figure 2.1a). Asphalt shingles are then placed on top of the felt in overlapping layers, which prevent runoff from seeping underneath the shingles and rotting the decking material. The roof is usually constructed over an uninhabited attic space; insulation is placed in the floor of the attic space and the temperature of the space is not controlled as in the rest of the house. The attic space is usually vented through air inlets in the eaves and turbines or air outlets near the top of the attic.

2.2. Commercial Roof

The second rooftop structure investigated is a built-up tar-and-gravel rooftop typical of commercial or industrial construction. The typical commercial roof is flat (on the order of 1% slope). The decking material is usually wood or metal, upon which is placed a layer of foam insulation (2-6" thick depending on climate) and a vapor barrier. The roof is then built up by alternating layers of an asphalt-based felt and a liquid hydrocarbon (tar) that fuses with the felt layer. Three to five layers are typical. For the top layer, a coarse gravel or stone is poured into the tar to cap the rooftop and provide resistance to abrasion by wind and rain (Figure 2.1b).

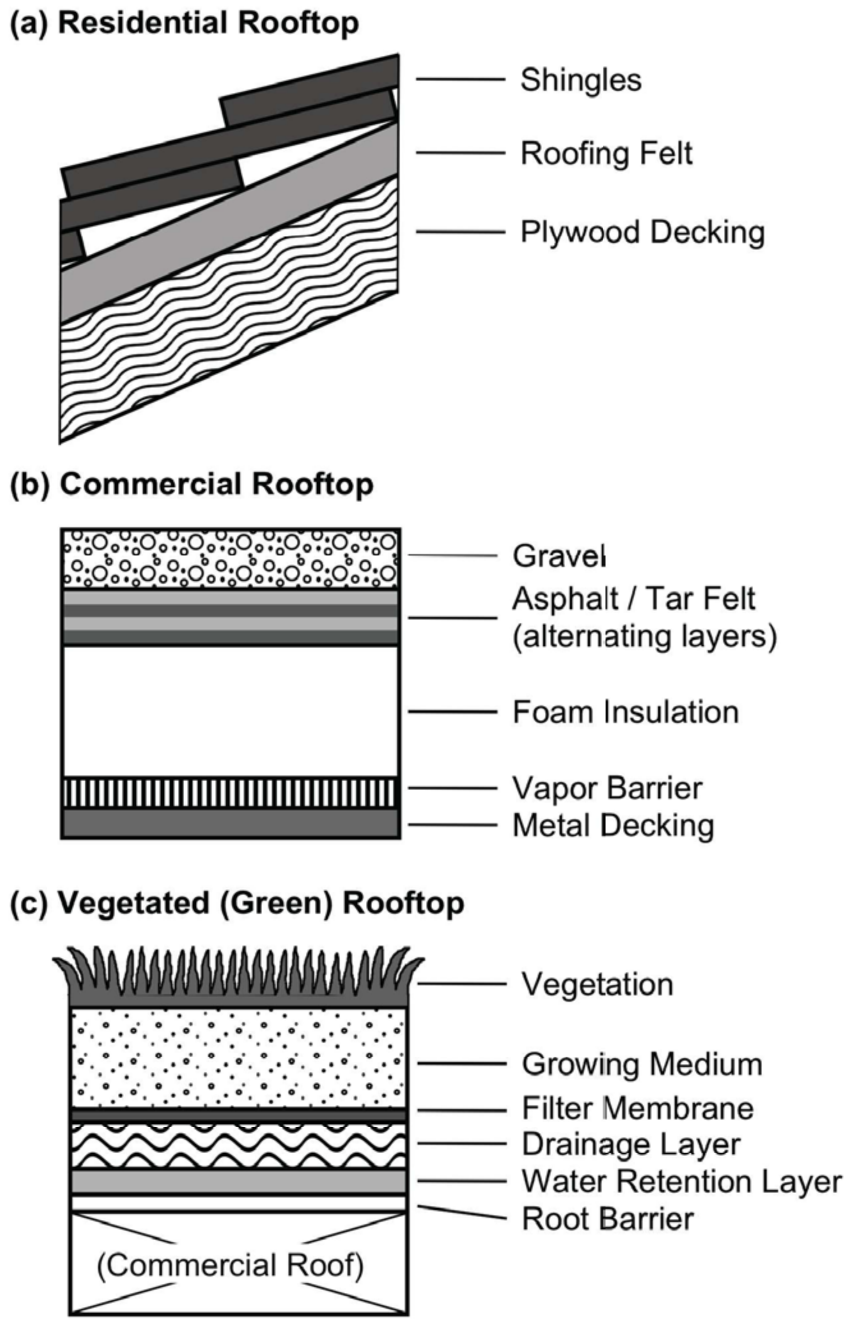

Figure 2.1. Typical structures of (a) a residential rooftop, (b) a commercial built-up roof, and (c) an 'extensive' green rooftop (not to scale).

2.3 "Green" Roof

A "green" (vegetated) rooftop, as it is used in the public sector, is usually constructed on top of a flat tar-and-gravel built-up roof such as the one shown in Figure 2.1b. However, instead of the gravel layer are several layers designed to support the growth of vegetation; these include a root barrier, water retention layer, drainage layer, filter fabric, growing media, and a plant layer. Growing media is usually very porous in order to facilitate the rapid infiltration of water, and consists of sand, crushed rock or gravel, and some organic material (Friedrich, unknown; Carter and Rasmussen, 2006). The depth of growing media is typically determined by the load capacity of the roof structure and the type of green roof being constructed. Two main types exist: intensive and extensive. An intensive green roof usually involves a variety of plants and even small trees, and will require regular irrigation, maintenance, and a greater media depth (10” or more). An extensive green roof, the more common of the two, is designed to be self-sustaining and to withstand the local climate, and normally consists of dense, drought-resistant mosses or succulents such as *Sedum*. Media depth in extensive green rooftops is usually 2-6”. A typical extensive green roof structure is shown in Figure 2.1c.

Additional background information on green roofs is given in Appendix B. Also included is a summary of a few field studies concerning storm water retention capability of green roofs and the reduction of roof surface temperature and heat flux that they provide.

3. DATA COLLECTION

3.1 Field Study Sites

The purpose of the field studies was to obtain temperature and runoff data along with on-site weather data. Roof temperature data were collected at two sites: a residential roof of a private residence in Shoreview, MN, and a commercial roof in Minneapolis, roughly 4 miles from the residential site. The latter was the roof of the wind tunnel enclosure at the St. Anthony Falls Laboratory (SAFL) of the University of Minnesota. An existing weather station at the SAFL site was used for weather data.

At the residential site, temperature was recorded at 1-minute intervals on north-facing and south-facing portions of the roof, on the concrete driveway, and on the lawn (grass) using thermistors. Rooftop thermistors were placed just under the first layer of shingles, the concrete thermistor was placed in a seam in the driveway and covered with a thin layer of light-colored caulk, and the lawn thermistor was installed such that it was approximately level with the dirt surface and shaded by the grass. Boxes were placed at the outlet of downspouts from the roof gutters to collect roof runoff. A V-notch weir was constructed at the end of each box and pressure transducers were placed in the bottom of the boxes to measure water level and temperature. Wind speed and precipitation were also recorded at the site. Data were collected from June through October, 2005. At the commercial site, thermistors were placed in the gravel layer of the roof at six locations, and roof temperatures were measured at 1-minute intervals. A weather station located at ground level within about 200 m of the roof site recorded solar radiation, air temperature, relative humidity, wind speed, and precipitation depth at 10-minute intervals. Data were collected from June to October 2005.

3.2 Samples of Temperature Records

Samples of data collected from both sites are shown in Figures 3.1 – 3.4. These plots are intended to show the temperature dynamics of the two roof types and the concrete driveway for both wet and dry weather. Solar radiation, air temperature, and rainfall are also shown in order to illustrate the influence of these parameters on surface temperatures. Because solar radiation and air temperature were not measured at the residential site, it is assumed that these two parameters are similar in terms of timing and value to the commercial site, especially for dry weather. For wet weather this assumption will likely not be as accurate due to the spatial variability in precipitation and air temperature patterns during rainfall events.

3.2.1. Dry Weather Surface Temperatures

Figure 3.1 shows measured surface temperatures at the residential site for a one-week period in July (July 9 – July 16, 2005) during which there was no rainfall and very little cloud cover. Temperatures shown include those measured at the north roof, south roof, lawn (grass), and driveway. Air temperature and solar radiation as measured at SAFL are shown for reference. Figure 3.2 shows measured roof temperatures at the commercial site (SAFL wind tunnel roof) for the same time period. Note that the 6 individual roof temperature measurements were averaged into one composite roof temperature since there was little variation (standard deviation around 1°C) between them. Also plotted are the driveway and south roof temperatures from the residential site, as well as air temperature and solar radiation. The south roof was chosen since it receives more direct solar radiation than the north roof, and therefore has higher peak temperatures. These plots are intended to show typical diurnal cycling of surface temperatures for dry, sunny, mid-summer weather.

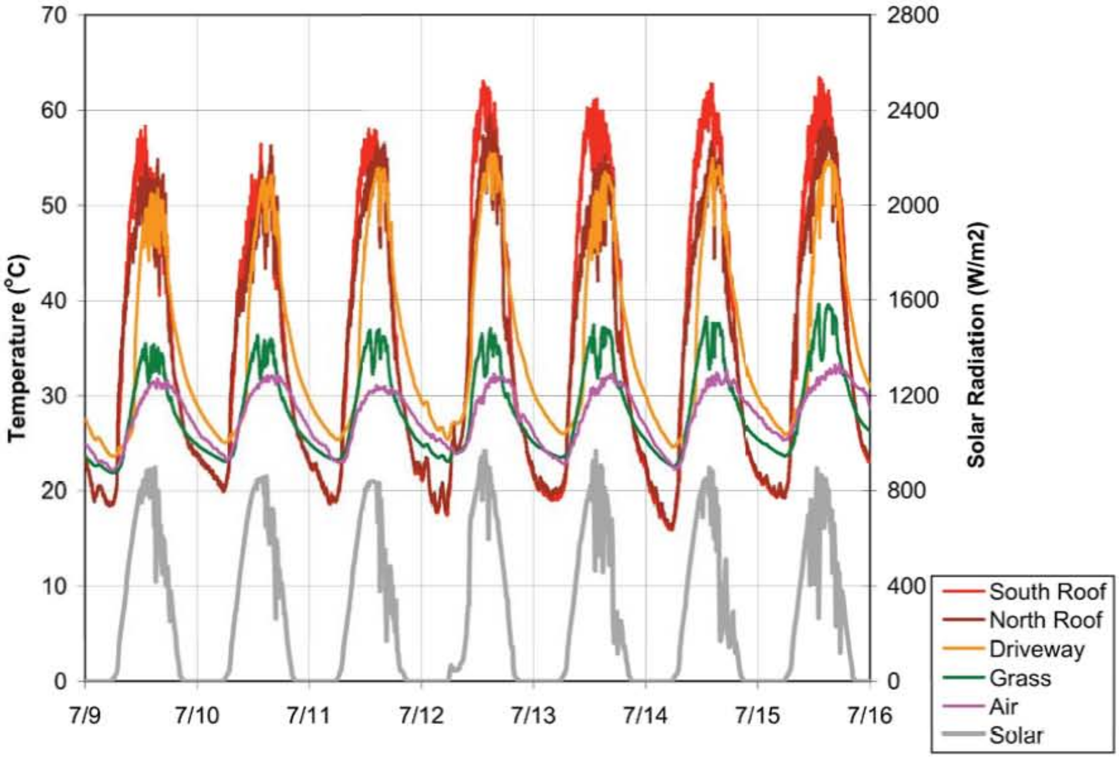

Figure 3.1. Dry-weather surface temperatures measured at the residential site, July 9 – July 16, 2005. Air temperature and solar radiation data are from the weather station at the commercial site (SAFL).

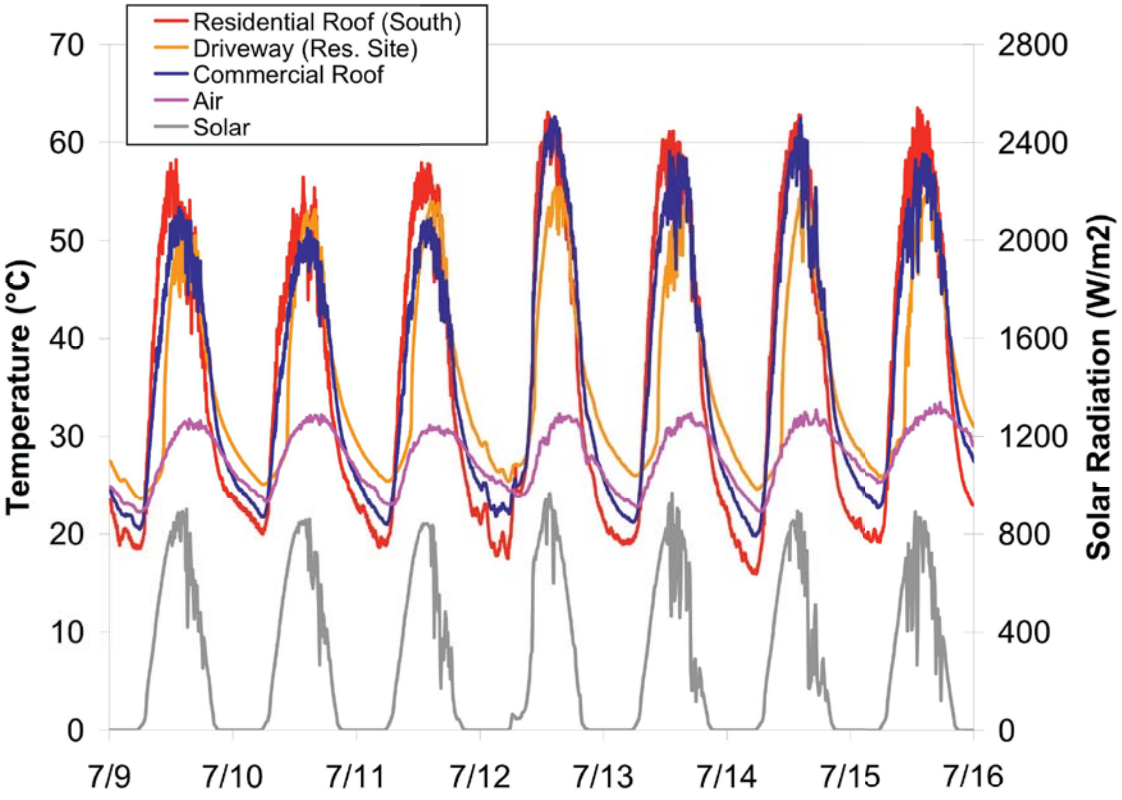

Figure 3.2. Dry-weather surface temperatures measured at the commercial site (SAFL wind tunnel roof), July 9 – July 16, 2005. Air temperature and solar radiation were recorded on-site. Also shown are the south roof and driveway temperatures from the residential site.

3.2.2. Detailed Surface Temperature Measurements for a Rainfall Event

Figures 3.3 and 3.4 show detailed surface temperature measurements for a rainfall event that occurred on June 20, 2005. The rainfall was relatively intense: 2.4 cm of rain fell in roughly 40 minutes beginning at 1:45 PM. Hot and sunny conditions were present prior to the onset of the storm. Figure 3.3 shows temperatures measured at the residential site, including the north roof, south roof, east downspout, and driveway. Air temperature from the SAFL weather station and precipitation from the residential site are also shown. Figure 3.4 shows surface temperatures at the commercial roof site for the same rainfall event. As before, south roof and driveway temperatures from the residential site are shown for comparison. Solar radiation, air temperature, and precipitation as measured at the SAFL weather station are also shown. Note that the precipitation data from the SAFL station was collected at 10-minute intervals, a coarser resolution than at the residential site, where precipitation was recorded at one-minute intervals.

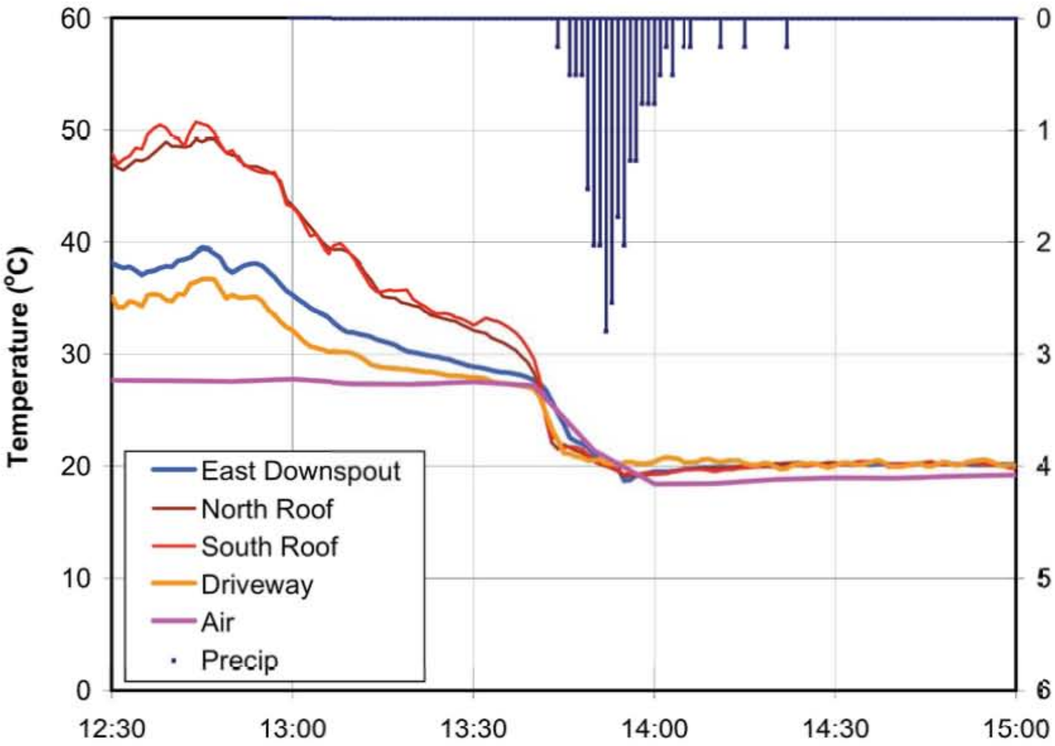

Figure 3.3. Surface temperatures measured at the residential site during a rainfall event on June 20, 2005. Total rainfall depth measured at the site was 2.4 cm. Air temperature was measured at the commercial site.

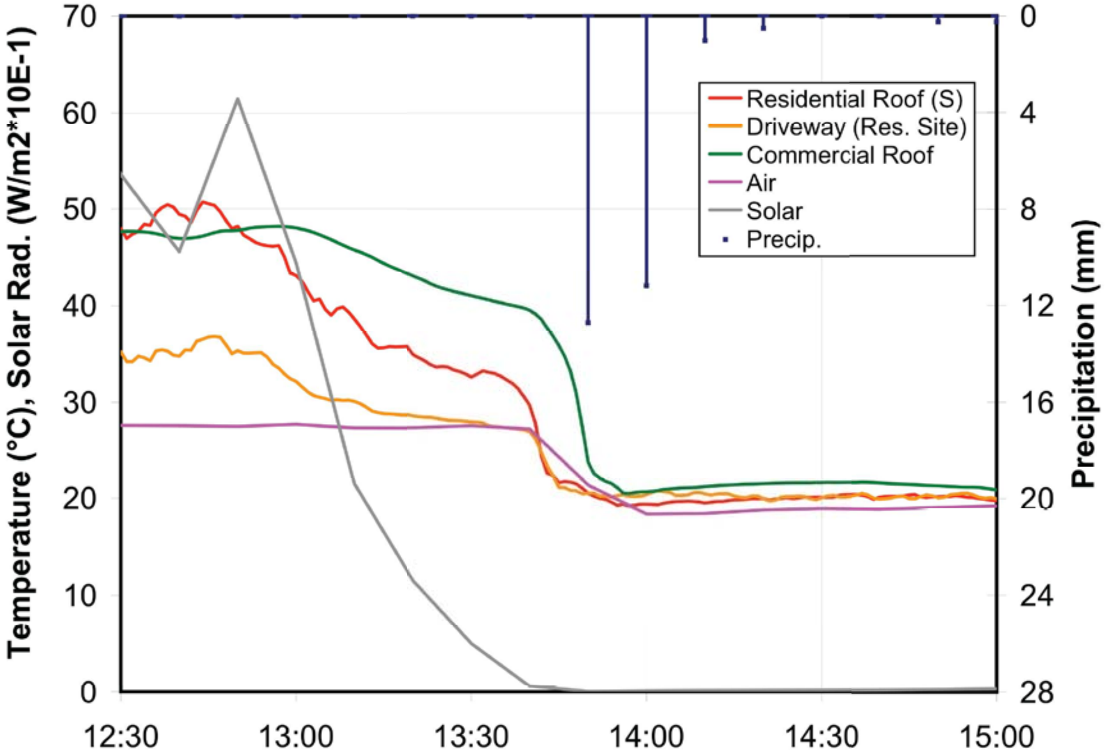

Figure 3.4. Surface temperatures measured at the commercial site during a rainfall event on June 20, 2005. Total rainfall depth measured at the site was 2.4 cm. Air temperature and solar radiation were measured at the commercial site. South roof and driveway temperatures are from the residential site.

3.3. Interpretations of Sample Records

The surface temperature data reveal that for dry, sunny conditions, the rooftop and driveway surfaces undergo expected temperature dynamics (Figures 3.1 and 3.2). For example, the residential rooftop experiences the highest peak temperatures and largest diurnal amplitudes: the south rooftop often exceeds 60 ˚C in mid-day and drops to below 20 ˚C at night. The temperature peaks on the residential rooftop generally occur at the same time as the maximum daily solar radiation, while the peak temperatures of the driveway, grass, commercial rooftop, and to a lesser extent the north residential roof, lag behind the peak solar radiation and occur closer to the peaks in air temperature. This behavior is due to the smaller heat storage capacity of the residential roof relative to the driveway and commercial roof, which both have greater mass. Due to the pitch of the residential roof and the orientation of the house, the south roof receives more direct solar radiation than the north roof and therefore reaches slightly higher peak temperatures; at night the two temperature records are essentially the same. The grass surface experienced the lowest peak temperatures and smallest diurnal amplitudes, and was very similar to air temperature except during the middle of the day when solar radiation was greatest.

At night, when back-radiation to the atmosphere is the dominant heat flux, the effect of thermal storage is even more apparent: the residential rooftop rapidly radiates away any heat stored during the day and becomes much cooler than air temperature, while the driveway slowly releases stored heat and decreases to a much higher minimum temperature than either rooftop, and at a later point in time. The commercial rooftop reaches its minimum temperature slightly later than the residential rooftop and does not become quite as cool, though it drops below air temperature. The driveway temperature always exceeds that of air. Potential correlation of surface temperatures to solar radiation and/or air temperature will be explored in the next section.

The plots of surface temperatures for the June 20 rainfall event (Figures 3.3 and 3.4) reveal that temperatures become very similar for all surfaces after the onset of rainfall. This might not be true for smaller rainfall events, but for this event the temperatures measured on the north roof, south roof, driveway, and downspout at the residential site all decrease rapidly in the first 5-10 minutes of the rainfall event. The temperatures eventually level out around 20 °C, which is just slightly higher than the measured air temperature for the event. This suggests that the surface temperatures are near or slightly above rainfall temperature, which is often approximated by dew point temperature. Air temperature and dew point temperature are approximately equal when relative humidity is near 100%, as is usually true during rainfall events. A similar trend in temperature occurs for the commercial rooftop, which drops rapidly with the onset of rainfall and levels off around 20 °C. Commercial rooftop temperatures are plotted with the residential south roof and driveway temperatures as a reference in Figure 3.4. Temperatures of the commercial rooftop appear to lag slightly behind those of the residential rooftop surfaces, but this lag could be accounted for by the fact that rainfall for this storm occurred slightly later at the commercial site than at the residential site.

Major decreases in observed temperatures just prior to the onset of rainfall are present for all surfaces. The drop in temperatures begins with increased cloud cover as the storm front moves into the area, which coincides with the decrease in solar radiation roughly one hour prior to the first detected rainfall (see Figure 3.4). The residential roof, which at ~50 °C was the hottest surface prior to rainfall, experienced the greatest cooling, reaching 33 °C just before the onset of rainfall. The commercial rooftop, which was nearly as warm (~48 °C), did not cool off as quickly as the residential rooftop, and the driveway experienced the smallest temperature drop in the hour prior to rainfall, though initially it was not nearly as hot as the other two surfaces. Little difference existed between the north and south roof temperatures at the residential site. An analysis of surface temperatures before, during, and after rainfall events is presented in the next section.

4. DATA ANALYSIS / DYNAMICS OF ROOF AND PAVEMENT TEMPERATURES

4.1 Objectives

In addition to the weather record, the data from both sites give a time series of rooftop temperatures before, during and after a rainfall event. Similar time series data from the residential driveway (pavement) and grass (lawn) were also available.

The first objective of the data analysis was to better understand and quantify the temperature dynamics of the two roofs compared to the pavement, and by inference rank the heat release (export) from all three for multiple rainfall events. A second objective was to relate the roof and pavement temperature records to the weather record, e.g. investigating the correlation of solar radiation and surface temperature for dry weather, or of dew point (rainfall) temperature and surface temperature for wet weather.

For the purposes of data analysis, a rainfall event was defined as all rainfall occurring with a gap of an hour or less between subsequent measurements of rainfall. Thus it is possible to have multiple events in a single day, or for a single event to begin in one day and end in the next. Some days, particularly in the fall, have sporadic, light rainfall; these days are labeled "intermittent" and are not included in the final analysis. Any other rainfall event is considered "significant." There were 17 "significant" rainfall events in the record from June to October 2005 at the residential site, and 15 at the commercial site. This discrepancy in the number of significant events is due to the 4-mile (6.4 km) distance between the two sites and the often spatially variable nature of rainfall, particularly in autumn.

4.2 Data Extraction

The first step to meet the above objectives was to assemble specific data. For each of the rainfall events the following information was extracted from the record:

From the weather station record:

(1) onset, end, and duration of rainfall,

(2) solar radiation one hour prior to rainfall, at the onset, the end, and mean during rainfall,

(3) dew point temperature one hour prior to rainfall, at the onset, the end, and mean during rainfall.

From the surface temperature records:

(1) rooftop and pavement temperature one hour prior to rainfall,

(2) rooftop and pavement temperature at the onset, the end and during rainfall (mean),

(3) rooftop and pavement temperature change within the hour before rainfall,

(4) rooftop and pavement temperature change during a rainfall event.

Data from the boxes below the downspouts were not included in the analysis because they were inconsistent. Sometimes water was standing in the box from previous rainfall, at other times the box was dry before the onset of rain (as was likely the case for the June 20 event in Figure 3.3). Since wet weather data were of primary concern, the north and south residential roof temperatures were averaged into a single characteristic roof temperature since they were nearly identical for wet weather (see Figure 3.3).

To relate the 1-minute rooftop temperatures to the rainfall and solar irradiance characteristics we extracted dew point and solar radiation data from the 10-minute weather station record. Because rainfall temperature is not measured at weather stations, an assumption was necessary; we assumed that the rainfall temperature would be the dew point temperature, although that is not always case, e.g. during hailstorms or other events when raindrops do not have the time to fully respond to ambient air conditions while they fall. It is fair to expect that rainfall can be colder than dew point temperature, but rarely warmer.

Solar radiation is the main source of heat stored in a rooftop. There is generally little solar radiation during a rainfall event, but solar radiation and cloudiness prior to a rainfall event are crucial. We therefore extracted solar radiation one hour prior to rainfall, and mean solar radiation over the duration of the rainfall event. This information will be more important in analysis of daytime rainfall events than those occurring at night or in the early morning, when solar radiation is nonexistent or negligible.

Solar radiation and rooftop temperature prior to rainfall give the initial conditions, and dew point temperature is an estimate of rainfall temperature. The changes in temperature of the rooftop before and during the rainfall are important characteristics of the event. The difference between the dew point temperature (rainfall temperature) and the roof temperature can give an idea of how much heat has been extracted by the rainfall runoff. Separate analysis of daytime events can provide insight into expected "worst-case" scenarios of maximum heating of runoff, although some of the highest temperatures been associated with evening and early morning rainfall events.

Also worth noting is that for the residential site solar radiation and dew point temperature data from the SAFL weather station were applied because these weather parameters were not measured at the residential site.

4.3 Results

The rainfall events for the residential site and for the commercial site are characterized in Appendix A (Tables A.1 and A.2, respectively.) Timing, duration, and depth of rainfall events as well as dew point and solar radiation characteristics are shown. All dew point and solar radiation data were recorded at SAFL. Rainfall events are flagged if they occur during daytime or are intermittent throughout an entire day. In this case, daytime was defined as any event for which non-zero solar radiation was observed one hour prior to the onset of rainfall. The motivation for analyzing daytime events separately is to investigate presumed worst-case scenarios: rainfall events occurring when rooftop and driveway surfaces have had sufficient time to heat up over the course of the day. Intermittent events are included in overall statistics but not in the "daytime" statistics.

The total precipitation from June 1 to September 30, 2005 was 16.5 inches (419 mm), as measured at SAFL. Comparison to a long-term average (1891 to 2008) of 14.2 inches recorded at the Minneapolis-St. Paul Airport indicates that the 2005 data were collected in a relatively wet year. However, a more recent average precipitation total (1975 to 2008) of 15.7 inches suggests that 2005 is closer to normal. Events prior to June 18, 2005 are not included in the analysis because thermistors were not installed until this date at the commercial site.

Temperature observations for all surfaces are summarized in Figure 4.1 for daytime rainfall events, and in Figure 4.2 for all rainfall events. Mean and one standard deviation about the mean of wet-weather temperatures are shown for the grass surface, driveway, residential roof, and commercial roof. Dew point is shown as a reference for rainfall temperature. These results are also summarized in Table 4.1 along with values for solar radiation.

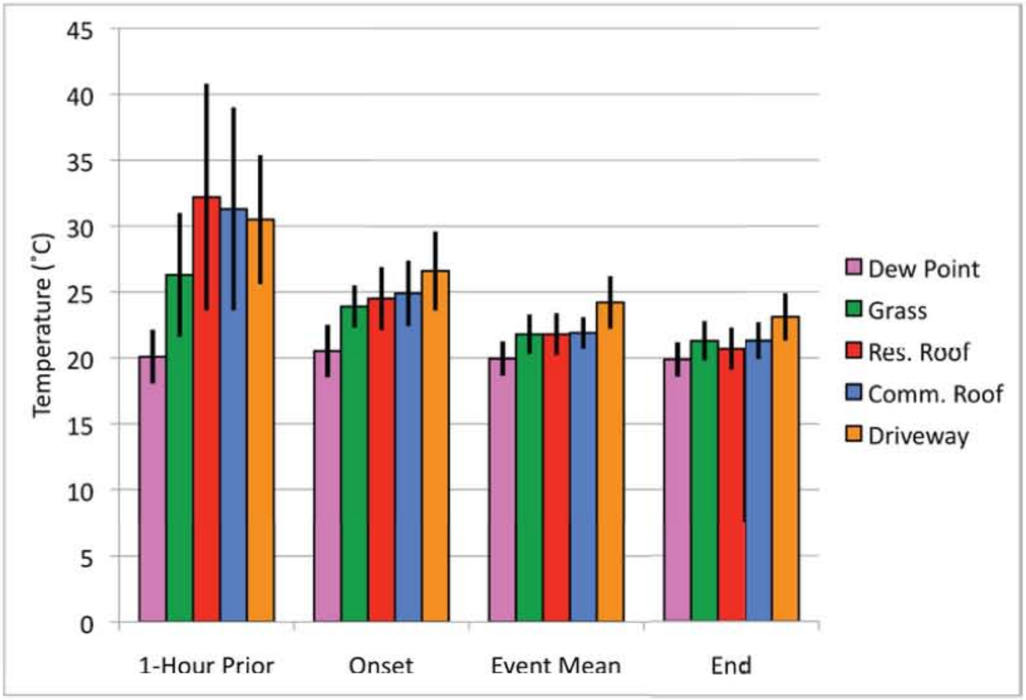

Figure 4.1. Summary of daytime, wet-weather surface temperature observations at both the residential and commercial sites, June-September 2005. Mean and one standard deviation about the mean for all daytime rainfall events in the record are shown. Dew point (rainfall) temperature was measured at SAFL.

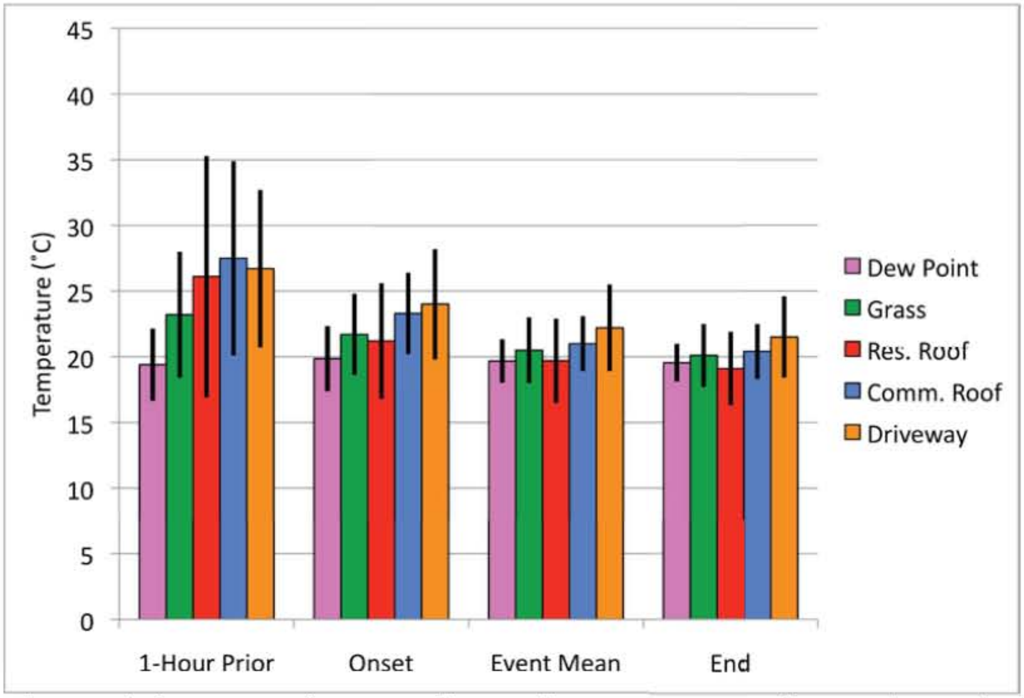

Figure 4.2. Summary of wet-weather surface temperature observations at both the residential and commercial sites for all significant rainfall events in the record from June-September 2005. Mean and one standard deviation about the mean are shown. Dew point (rainfall) temperature was measured at SAFL.

Table 4.1. Summary of wet-weather surface temperature, dew point temperature, and solar radiation observations for periods of interest, June-September 2005. Mean, standard deviation, and maximum value are shown. Dew point (rainfall) temperature and solar radiation were measured at SAFL.

Period	**Parameter**	**Mean**		**St Dev**		**Largest Value**
		All Events	*Daytime*	*All Events*	*Daytime*	
One hour prior to event	Solar (W/m^2)	91.6	150.9	157.0	187.4	615.0
	Dew Point (°C)	19.4	20.1	2.7	2.1	23.6
	Res. Roof (°C)	26.1	32.2	9.2	8.6	50.0
	Comm. Roof (°C)	27.5	31.3	7.4	7.7	47.8
	Driveway (°C)	26.7	30.5	6.0	4.9	39.2
	Grass (°C)	23.2	26.3	4.8	4.7	36.1
At onset of rain	Solar (W/m^2)	14.4	25.8	29.6	38.5	99.0
	Dew Point (°C)	19.9	20.5	2.5	2	23.7
	Res. Roof (°C)	21.2	24.5	4.4	2.4	28.6
	Comm. Roof (°C)	23.3	24.9	3.1	2.5	29
	Driveway (°C)	24.0	26.6	4.2	3.0	31.9
	Grass (°C)	21.7	23.9	3.1	1.6	26.9
Event mean values	Solar (W/m^2)	14.8	27.8	31.7	41.8	107.0
	Dew Point (°C)	19.7	20	1.7	1.3	23.2
	Res. Roof (°C)	19.7	21.8	3.2	1.6	24.9
	Comm. Roof (°C)	21.0	21.9	2.1	1.2	24.7
	Driveway (°C)	22.2	24.2	3.3	2.0	26.7
	Grass (°C)	20.5	21.8	2.5	1.5	24.5
At end of event	Solar (W/m^2)	28.0	52.7	50.0	62.6	144.0
	Dew Point (°C)	19.6	19.9	1.4	1.3	22.4
	Res. Roof (°C)	19.1	20.7	2.8	1.6	22.6
	Comm. Roof (°C)	20.4	21.3	2.1	1.4	23.7
	Driveway (°C)	21.5	23.1	3.1	1.8	26.0
	Grass (°C)	20.1	21.3	2.4	1.5	24.1

4.3.1. Roof and pavement temperatures prior to rainfall

For all events (Figure 4.2), the mean temperatures of the driveway and both rooftops are very similar one hour prior to the onset of the rainfall (within 1 °C), while the lawn surface, as expected, is cooler (by about 4 °C). For daytime rainfall events (Figure 4.1) the residential roof is slightly warmer than the other impervious surfaces: on average 1.7 ˚C hotter than the driveway and roughly 1˚C hotter than the commercial roof one hour before rainfall begins. However, this is a far smaller difference in temperature than can be present between the two surfaces on a typical sunny mid-summer day. For example, during the dry, sunny period of July 9 – 15, the mean difference between the residential roof and driveway was approximately 8 ˚C during the daytime hours 8:00 – 16:00, with differences as high as 22 ˚C.

Table 4.2. Mean changes in dew point and observed surface temperatures at both sites in the hour prior to onset of rainfall and over the duration of rainfall for events during June – September, 2005.

Period	**Parameter**	**Mean**		**Largest Value**
		All Events	*Daytime*	
During hour before onset	Dew Point (°C)	0.5	0.4	1.8
	Res. Roof (°C)	-4.9	-7.7	-28.0
	Comm. Roof (°C)	-4.2	-6.4	-24.0
	Driveway (°C)	-2.7	-3.9	-14.1
	Grass (°C)	-1.5	-2.4	-12.7
Over duration of event	Dew Point (°C)	-0.3	-0.6	-4.7
	Res. Roof (°C)	-2.1	-3.8	-10.9
	Comm. Roof (°C)	-2.9	-3.6	-8.3
	Driveway (°C)	-2.5	-3.5	-8.1
	Grass (°C)	-1.6	-2.6	-7.5

Changes in surface temperatures both before and over the duration of events are shown in Table 4.2. Roof and driveway temperatures decrease rapidly before many rainfall events due to increased cloud cover that significantly reduces solar radiation, especially for rainfall events that occur during the day. The average drop in residential roof temperature during the hour prior to the onset of daytime rainfall events was 7.7 ˚C, compared to 6.4 ˚C for the commercial rooftop and 3.9 ˚C for the driveway. Temperature changes were slightly less overall when considering all rainfall events in the record. That temperature drops were larger for the rooftop surfaces than for the driveway and lawn is the result of the greater mass below the latter two surfaces, which store more heat and release it more slowly than either of the rooftops.

Standard deviations of surface temperatures were much higher in the hour before rainfall than during the rainfall event. This is true for all events and for daytime events only, because events start at different times of day. It is an indication of the considerable variation in antecedent conditions for summer rainfall events.

4.3.2. Roof and pavement temperatures during rainfall events

For daytime rainfall events, the mean event surface temperature of the two rooftops and the lawn are nearly identical, while the driveway is roughly 2.3 ˚C warmer than these other surfaces in spite of starting at a lower temperature than either of the rooftops. This is attributed to the greater heat storage capacity of the pavement; it also supports the idea that pavement runoff is likely to have a greater thermal impact than runoff from a rooftop. When considering all rainfall events, the mean event temperatures for all surfaces are similar, with the driveway temperature again slightly higher than the others, and the residential rooftop slightly lower (nearly the same as dew point temperature).

Standard deviations of surface temperatures during rainfall events are both similar and relatively low for the various surfaces. This might suggest that heat transfer is not as dynamic during wet weather as during dry, sunny weather, particularly beyond the first few minutes of rainfall.

The change in surface temperature over the course of a rainfall event might be expected to provide an idea of the relative amount of heat storage below the various surfaces. However, the drop in temperature of the impervious surfaces over the duration of daytime rainfall events was essentially the same: 3.8 ˚C, 3.6 ˚C, and 3.5˚C for the residential roof, commercial roof, and driveway, respectively. Given the difference in heat storage capacity below the three surfaces, this implies that a different amount of heat is being extracted from each surface, and that perhaps atmospheric heat transfer or runoff velocity (residence time) is playing a role in the temperature changes experienced by the surfaces.

4.3.3. Comparison of surface and dew point (rainfall) temperatures

The difference between dew point (rainfall) temperature and surface temperature drives the heat flux across the surface that is heating the runoff; if this number is zero, no heating of the runoff occurs. Similarly, this quantity can be a measure of potential thermal impact if it is calculated with temperatures at the onset of rainfall. The higher the difference in surface temperature and rainfall temperature, the greater the initial heat extraction rate will be. It is important to bear in mind that the event mean of this parameter will be more useful for estimating total or prolonged heat impact, and that actual heat extraction rates are dependent upon the thermal properties of the surface involved (see Section 5). Differences between surface temperature and dew point temperature are summarized in Table 4.3. Note that all dew point temperatures were measured at the commercial site, which is located roughly 4 miles (6.4 km) from the residential site. This distance likely contributes some uncertainty to the quantities calculated for the surfaces at the residential site (grass, driveway, residential roof).

In general, the results support the expectation that the surfaces with the least heat storage capacity (rooftops) exhibit the smallest difference with dew point (rainfall) temperature, while the surface with the greatest heat capacity (driveway) maintained a significant difference with dew point temperature. Mean values of the difference between surface temperature and dew point temperature for daytime events were nearly identical for the two rooftops and the grass surface (1.8 °C), but very different for the driveway (4.2 °C). When considering individual rainfall events the residential roof is at the dew point temperature on average. This suggests that heat contribution from rooftops, and especially the residential rooftop, may be very small.

Table 4.3. Mean difference between surface temperature and dew point (rainfall) temperature for rainfall events occurring during the period June – Sep, 2005. DP = dew point temperature.

Period	**Parameter**	**Mean**		**Largest Value**
		All Events	*Daytime*	
One hour prior to event	Res. Roof - DP (°C)	6.7	12.1	30.9
	Comm. Roof - DP (°C)	8.1	11.2	28.4
	Driveway - DP (°C)	7.3	10.4	18.3
	Grass - DP (°C)	3.8	6.2	17.0
At onset of rain	Res. Roof - DP (°C)	1.3	4	7.9
	Comm. Roof - DP (°C)	3.4	4.4	10.3
	Driveway - DP (°C)	4.1	6.1	10.9
	Grass - DP (°C)	1.8	3.4	5.5
Event mean values	Res. Roof - DP (°C)	0.0	1.8	5.2
	Comm. Roof - DP (°C)	1.3	1.9	4.3
	Driveway - DP (°C)	2.5	4.2	7.6
	Grass - DP (°C)	0.8	1.8	5.2
At end of event	Res. Roof - DP (°C)	-0.5	0.8	4.1
	Comm. Roof - DP (°C)	0.8	1.4	3.5
	Driveway - DP (°C)	1.9	3.2	6.6
	Grass - DP (°C)	0.5	1.4	5.8

The potential thermal impact of the driveway is higher than that of the two rooftops; while the surface minus dew point temperature difference is slightly higher for the rooftops an hour before rainfall for daytime events, by the time rainfall starts the rooftops have cooled enough that the driveway is once again at a higher relative temperature (6.1 °C versus 4.4 °C and 4.0 °C for the commercial and residential rooftops, respectively). This also illustrates the greater capacity of the driveway for heat storage and release relative to the two rooftops.

4.3.4. Solar radiation

Solar radiation is a major heat source that has sometimes been neglected in runoff temperature models. In this study it was recorded at the commercial site (SAFL). Mean observed solar radiation one hour prior to the daytime rainfall events at the commercial site was 157 W/m^2, with a standard deviation of 187 W/m^2 and a maximum value of 615 W/m^2 (see Table 4.1). This suggests that considerable variability exists in antecedent conditions. However, by the onset of rainfall solar radiation was considerably smaller (mean = 26 W/m^2) and less variable (standard deviation = 39 W/m^2), and over the duration of daytime rainfall events the mean solar radiation remained low at 28 W/m^2. This is a small but potentially significant contribution of heat, and mean event values as high as 107 W/m^2 were observed during daytime rainfall events. It appears that the assumption of zero solar radiation during rainfall events is erroneous.

4.3.5. Worst-case scenarios (extreme events)

While the primary objective of observing surface temperatures was to investigate the contribution of rooftops to heating of rainfall runoff relative to a paved surface, the timing of maximum dew point (rainfall) temperature was found to be contrary to the expectation that the worst-case events (i.e. those with the greatest potential for heating of runoff) occur during late afternoon or early evening, when antecedent solar radiation and surface temperatures have been highest. The four events with the highest mean event temperature (by surface) are shown in Table 4.4. For this data set, the highest mean event dew point temperature (23.6 ˚C) occurred for a rainfall event that began just after midnight on Aug 4. The 3rd highest mean event dew point occurred for an event beginning at 6:40 on June 27, and the 4th highest for an event beginning at 21:20 on Sep 3 (well after sunset). What makes these events particularly interesting is that they all occurred during times of the day with presumably low risk for high heat export because solar radiation was absent and surface temperatures were low. However, surface temperatures alone do not control the heat content of the runoff. A relatively high rainfall (dew point) temperature (above 21 ˚C in the three cases above) by itself leads to a high heat content of the runoff. Given that solar radiation and other atmospheric heat fluxes are much reduced during rainfall events, dew point temperature becomes the primary influence on total event heat export (Janke et al., 2006). In terms of event parameters, these late night / early morning storms represent the worst-case scenarios in this particular data set, a result contrary to initial expectations.

Table 4.4. The four highest dew point and mean event surface temperatures for the residential rooftop, commercial rooftop, and driveway out of all rainfall events from June – September, 2005.

Parameter	**Temperature** °C	**Day**	**Time**
Dew Point Temperature	23.2	4-Aug	0:30
	21.6	12-Sep	14:30
	21.5	27-Jun	6:40
	21.3	12-Sep	21:20
Residential Roof Temperature	24.8	27-Jun	6:38
	23.1	4-Aug	0:39
	22.9	11-Aug	12:37
	22.7	25-Jul	16:44
Commercial Roof Temperature	24.7	4-Aug	0:30
	23.8	12-Sep	14:30
	23.3	27-Jun	6:40
	22.6	16-Aug	21:50
Driveway Surface Temperature	26.7	4-Aug	0:39
	26.7	25-Jul	16:44
	26.5	27-Jun	6:38
	25.3	11-Aug	12:37

A similar pattern was observed in the extreme values of roof and driveway temperatures (Table 4.4). The highest observed mean event temperatures for both the commercial rooftop (24.7 ˚C) and the driveway (26.7 ˚C) occurred on Aug 4. For the commercial rooftop, the 2nd highest mean event temperature was observed for a mid-day event, but the 3rd and 4th-highest values occurred for the early-morning event on June 27 and a late-evening event on Aug 16, respectively.

For the residential rooftop the two highest mean event surface temperatures occurred on June 27 and Aug 4, and for the driveway two of the four highest values were observed on the same two dates. This pattern suggests that because of the lag associated with heat storage and release, the rainfall events with the greatest potential for heat export may not always occur during daylight hours; rainfall events occurring after sunset and during early morning can be worse than mid-afternoon events. This is especially true of surfaces with greater storage capacity, such as the driveway and commercial roof. The timing of dew point (rainfall) temperature also appears to play a significant role in determining the worst-case scenarios.

4.4 Dry Weather Surface Temperature Dynamics

The dry weather temperature dynamics of the two rooftops and the driveway were investigated to better understand the heat storage and release characteristics of these surfaces. The analysis consisted of two parts: (1) a simple linear regression analysis relating solar radiation and air temperature (separately) to rooftop temperature, and (2) a multiple linear regression analysis attempting to correlate both observed solar radiation and air temperature with observed rooftop temperature. The least squares approach was used to fit the linear models to the data.

For this analysis, a two-week period was selected from a portion of the record in which no rainfall occurred (July 4 – 17, 2005). Only the daytime observations were used (i.e. solar radiation > 0) since at night solar radiation is not present and temperature dynamics are driven instead by air temperature and long-wave radiation. The coefficient of determination (R^2) was used to establish the strength of the relationship. The observed surface temperatures were allowed to lag the observations of solar radiation and air temperature by a variable amount of time required by the roofs or the driveway to store and release heat. The lag time was adjusted until a maximum R^2 was obtained; the lag time can be considered a measure of the relative thermal inertia or mass to store heat (i.e. a greater lag time would be associated with greater storage capacity). Complete results are summarized in Table 4.5.

Table 4.5. Summary of surface temperature regression analysis: coefficient of determination (R^2) and Lag obtained by (a) linear regression with solar radiation, (b) linear regression with air temperature, (c) multiple linear regression with air temperature and solar radiation. Daytime data for the dry weather period July 4 – 17, 2005.

Regression Analysis	**Surface**	**R^2**	**Lag** *minutes*
Solar Radiation Only	Res. Roof	0.78	15
	Comm. Roof	0.76	50
	Conc. Driveway	0.73	120
Air Temperature Only	Res. Roof	0.34	0
	Comm. Roof	0.49	0
	Conc. Driveway	0.58	0
Solar Radiation and Air Temperature	Res. Roof	0.85	0
	Comm. Roof	0.88	5
	Conc. Driveway	0.85	90

To illustrate the relationships, plots of surface temperature vs. solar radiation are shown in Figure 4.3 for the residential roof, commercial roof, and concrete driveway for the dry weather period (July 4-17, 2005). All three plots show a positive relationship between surface temperature and solar radiation, and have similar R^2 values: 0.78, 0.76, and 0.73 for the south residential roof, commercial roof, and driveway, respectively. The slope of the linear fit represents the increase in observed surface temperature for a unit increase in solar radiation (˚C per W/m^2); not surprisingly, the residential roof had the highest value (0.038 ˚C per W/m^2), the driveway had the lowest (0.027 ˚C per W/m^2), and the commercial roof was in between (0.032˚C per W/m^2). These trends indicate that the rooftops, in particular the residential rooftop, are more readily influenced by solar radiation than the driveway. This behavior is directly related to the thermal capacities of the surfaces.

Air temperature alone was not a good determinant of surface temperature; R^2 values were 0.34, 0.49, and 0.58 for the south residential roof, commercial roof, and driveway, respectively. Interestingly, the driveway (greatest thermal storage capacity) had the lowest R^2 with solar radiation, but the highest R^2 with air temperature. Likewise, the residential roof (lowest thermal storage capacity) had the highest R^2 with solar radiation and the lowest R^2 with air temperature. This suggests that solar radiation is the primary factor in determining dry-weather surface temperatures, particular for low-mass surfaces such as the residential roof.

A multiple linear regression analysis of surface temperatures with both air temperature and solar radiation improved R^2 values for all three surfaces ($R^2 = 0.85$ to 0.88). The improvement in fit means that both solar radiation and air temperature have a significant influence on surface temperature dynamics, and the relatively high R^2 values suggest that these parameters are the primary determinants of surface temperature. It should also be noted that the time lag values decreased significantly in the multiple linear regression analysis.

Overall, lag values were considerably higher for the driveway than the two rooftops (Table 4.5), especially in the multiple linear regression analysis. The commercial rooftop temperature had a greater lag time than the residential rooftop. These are logical results considering that more heat is required to change the temperature of the driveway than either of the two rooftops (owing to its greater heat storage capacity), so surface temperature will be expected to lag significantly behind changes in heat input.

While not immediately relevant to rainfall runoff temperature and heat export analysis, dry weather temperature analysis provides a useful illustration of the relative heat storage capability of the three urban surfaces of primary interest in this study: commercial roof, residential roof, and concrete driveway. The results of this exercise show that the concrete driveway has a far greater capacity for heat storage and release than either of the rooftops; and the commercial roof has the ability to store appreciably more heat than the residential roof. It can also be concluded that solar radiation and air temperature are the primary forcing functions of dry weather surface temperature dynamics.

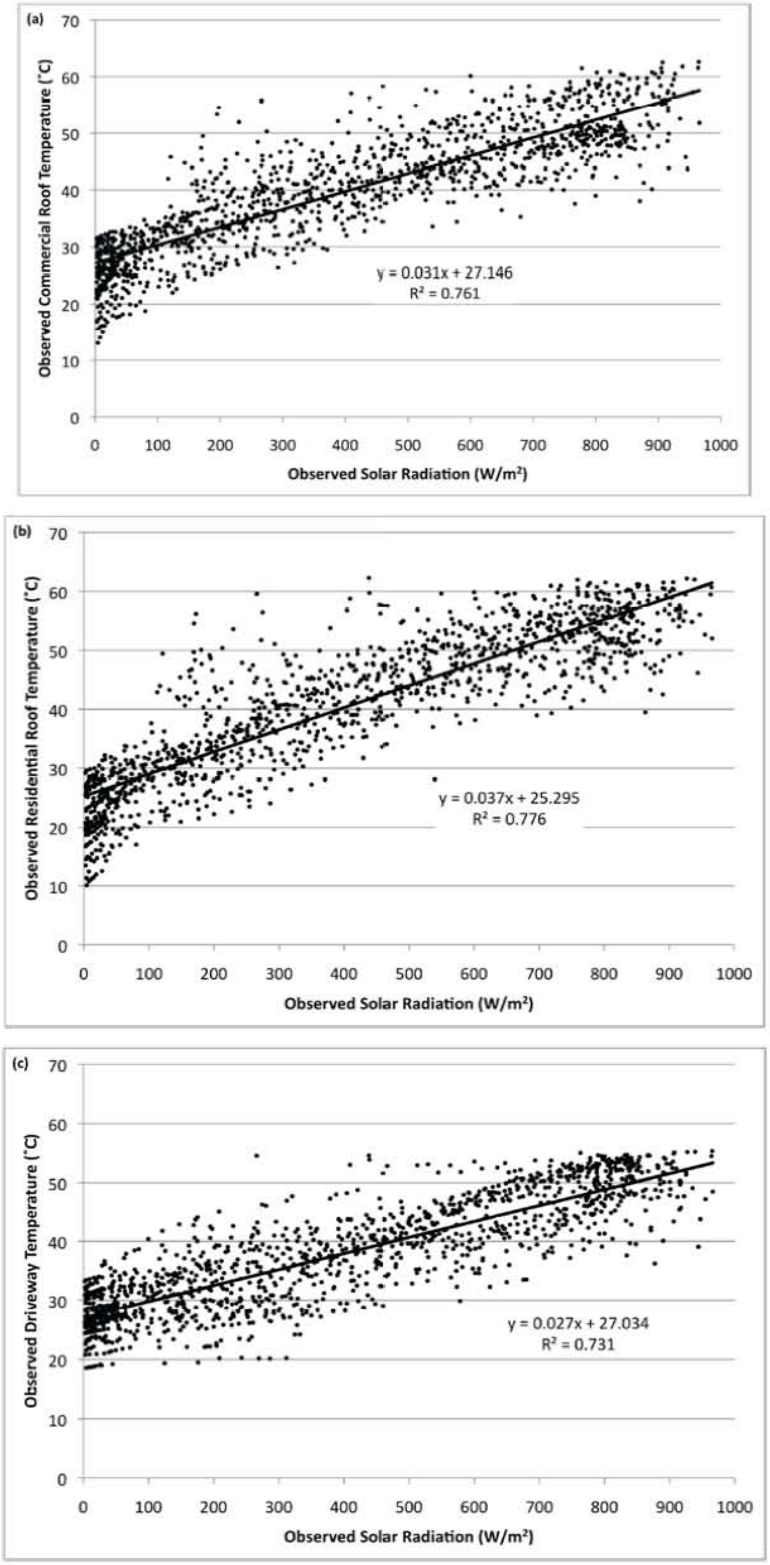

Figure 4.3. Plots of daytime surface temperature versus solar radiation for (a) commercial roof, (b) residential roof, and (c) concrete driveway at the residential site for the dry weather period of July 4 – 17, 2005. Linear fit is by least squares method. Solar radiation was measured at the commercial site.

5. MODELING OF ROOF TEMPERATURES / HEAT STORAGE AND RELEASE

5.1. Heat Release (Export) From Roof to Runoff

Heat export is defined here as an amount of heat (Joules) in a volume of runoff water. The runoff volume is in response to a rainfall event. Since runoff data were not collected at the field study sites, the calculation of heat export as a function of runoff flow rate and runoff temperature (Janke et al., 2006; Herb et al., 2007b) cannot be employed here. Instead, heat export can be estimated by modeling temperature profiles within the roof material. The total heat extracted from a roof by a rainfall-runoff event can be estimated by comparing the roof temperature profile at the beginning of rainfall with that at the end of the rainfall event. The amount of heat extracted from the roof is calculated layer by layer, and the sum is the total heat export (J/m^2). The calculation can be made using equation (5.1).

$$HE = \sum_{i=1}^{n} \rho_i C_{p,i} z_i \left(T_{0,i} - T_{f,i} \right) \qquad (5.1)$$

where i is the roof layer, ρC_{pi} is the heat capacity of the layer (J/m^3 °C), z_i is the thickness of the layer (m), $T_{0,i}$ is the initial temperature of the layer (°C), and $T_{f,i}$ is the final temperature of the layer (°C). Calculation of heat export requires knowledge of the thermal properties (Table 5.1) of the roof layers (Figures 2.1 and 2.2). The analysis can also be applied to a concrete or asphalt pavement if its structure and properties are known (Table 5.2).

Table 5.1. Thermal properties of residential and commercial rooftop components.

Material	**Density** *kg/m3*	**Specific Heat** *J/kg*k*	**Thermal Cond.** *W/m*K*	**Reference**
Residential Roof				
Plywood	545	1215	0.12	Incropera and DeWitt (2002)
Roofing Felt	1700	*1000*	0.5	ESRU (2002)
Asphalt Shingles	1100	1260	0.080	McQuiston et al (2000)
Commercial Roof				
Foam Insulation	55	1210	0.027	Incropera andDeWitt (2002)
Tar/Felt Layers	1120	1464	0.16	ASHRAE (2003)
Gravel	1840	840	0.36	ESRU (2002)

Table 5.2. Thermal properties of concrete driveway components.

Material	**Density** *kg/m3*	**Specific Heat** *J/kg*k*	**Thermal Cond.** *W/m*K*	**Reference**
Concrete	545	1215	0.12	Incropera and DeWitt (2002)
Soil	1700	1000	0.5	Incropera and DeWitt (2002)

5.2. Simulation of Roof Temperature Profiles – Boundary Conditions

Heat transfer within the roof structure is by conduction. The temperature profile within the roof can therefore be found by numerically solving the unsteady 1-D heat diffusion equation for the roof. The spatial coordinate is perpendicular to the roof surface, and the solution of the 1-D equation is very similar to the solution for a pavement surface (Janke et al., 2006). As the upper boundary condition for the roof surface we will use the observed rooftop temperature time series. Equations for atmospheric heat exchange at the roof surface will be therefore unnecessary. The lower boundary condition for the roof will be a specified temperature, i.e. an attic temperature or an indoor air temperature. It is acknowledged that these boundary conditions applied to Equation 5.1 will result in a slight over-estimation of the amount of heat transferred to the runoff volume on top of the roof because a small amount of heat will flow through the bottom boundary of the rooftop. The use of an adiabatic bottom boundary condition would prevent this effect, but it is not a realistic condition for the underside of either a residential or commercial rooftop.

The underside of a commercial rooftop is typically located in a climate-controlled space. A fixed temperature of 25 ˚C was used as the bottom boundary condition. For the residential rooftop, the bottom boundary condition is more difficult to determine given that the attic space is not climate-controlled. While outdoor air temperature might be a good estimate of attic temperature at night or during cloudy days, attic temperature can be considerably higher than air temperature on sunny days, even with moderate solar radiation (Winandy and Beaumont, 1995; Winandy et al, 2000). The temperature at the underside of the wood decking, which would be the bottom boundary of the modeled rooftop, is often higher than attic temperature during the day (Winandy and Beaumont, 1995; Winandy et al, 2000). Based on visual inspection of data from the Forest Products Laboratory Reports (see Figure 5.1), the bottom boundary temperature is assumed to be roughly 7°C higher than outdoor air temperature. Since daytime rainfall events are of primary interest the effect of any error during nighttime periods in continuous simulations will be small, given the low thermal mass of the residential rooftop.

For the simulation of the concrete pavement, the bottom boundary condition used is a constant temperature at a depth of 0.6 m. At the model time scale of a day the soil temperature at this depth can be considered as constant. The value used (20.8 °C for June, 27.3 °C for July) was determined from data collected at the Minnesota DOT's MNRoad pavement research site in Albertville, MN.

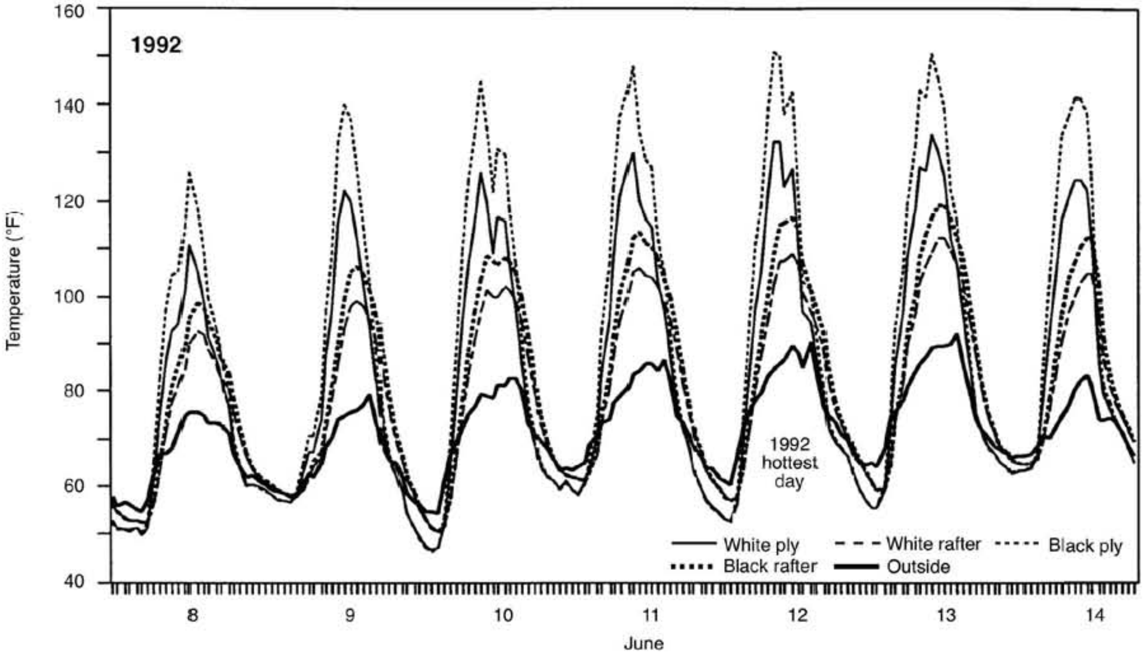

Figure 5.1. Temperatures measured on black- and white-shingled roofs at a Forest Products Laboratory research site in Madison, WI in 1992. 'Ply' refers to the top side of the plywood sheathing upon which the shingles are attached. From Winandy and Beaumont (1995).

5.3. Potential Maximum Heat Export from Roof

Maximum (or potential) heat export is the maximum amount of heat that can be extracted from a surface by a given rainfall-runoff event for given initial conditions. This parameter is useful for the comparison of potential heating of runoff by different surfaces. A comparison of potential heat export from rooftops and from pavements can validate the assumption that rooftops make a negligible contribution of heat to rainfall runoff because of their low thermal storage capability.

Three methods were considered for estimation of maximum heat export. The first assumes that the entire rooftop or pavement volume reaches a temperature equal to the dew point temperature at the end of the rainfall event; after this point no more heat can possibly be extracted from the roof or pavement. While not a realistic scenario, it would provide an upper bound for the potential heat export. The second method allows the roof or pavement to reach a steady-state linear temperature profile by holding constant its upper and lower boundary conditions at the end of the rainfall event. This approach would provide a more reasonable value of maximum heat export, but the time scale of reaching 'steady-state' conditions would not be realistic. The third method is based on the expectation that the rate of heat extraction is greatest at the beginning of the rainfall and decreases as the difference between rooftop and rainfall temperature decreases; given enough time, the rate of heat export becomes negligible. Temperature profiles in the roof or pavement at intermediate times during the rainfall event can be used to compute a time series of instantaneous heat export rates. A curve fit to these heat export rates can be used to find additional heat extraction beyond the end of the event to any point in time. The third method was chosen, and to provide a conservative analysis, the heat export over the duration of the rainfall event plus six additional hours was calculated.

5.4. Selection of Rainfall Events for Analysis

Three rainfall events were selected for the application of the model; these occurred on June 20, July 23, and July 25, 2005. Depth and duration of observed rainfall varied slightly between the two sites for all three events (Table 5.3). The three events were chosen because of their large potential for thermal impact. All three events had a relatively large amount of total rainfall (greater than 20 mm), a duration of 3 hours or less, occurred in the earlier part of the summer during daylight hours with significant solar radiation 1 hour prior to the onset of rainfall. By these criteria, the three events can be considered 'worst-case scenarios' in the 2005 data set. However, it is acknowledged that these might not correspond to the actual worst-case events in the record, as dew point temperature (a major determinant of heat export) was not considered. See Section 4.3.5 for more details.

Table 5.3. Depth, duration, and start time for the three rainfall events chosen for analysis of temperature profiles in the residential and commercial roofs.

	Residential Site			**Commercial Site**		
Date	**Rainfall depth** *(cm)*	**Rainfall duration** *(h)*	**Rainfall start time (h:min)**	**Rainfall depth** *(cm)*	**Rainfall duration** *(h)*	**Rainfall start time (h:min)**
20 Jun 2005	2.4	0.63	13:44	2.6	1.2	13:50
23 Jul 2005	2.18	0.87	10:41	1.9	2	10:40
25 Jul 2005	2.9	3	16:44	3.5	3	16:50

Note: 1 in = 2.54 cm

5.5. Sample Computation: Determining Heat Export from a Commercial Rooftop

An example is presented here to illustrate the calculation of actual and maximum heat export. Consider the commercial rooftop (Figure 2.2) and the rainfall event that occurred on July 23, 2005 (Table 5.3). As the lower boundary condition an indoor air temperature of 25°C is used; the upper boundary condition is specified as the time series of observed roof surface temperatures. Simulations are started two days prior to the rainfall event (July 21) with a linear initial roof temperature profile. During the simulation roof temperatures recorded from July 21 to July 24, including the day of the rainfall event (July 23), are applied in 10-minute increments as the upper boundary condition. The rainfall hyetograph and three simulated temperature profiles are shown in Figures 5.2(a) and (b), respectively. The rainfall lasted from about 10:40 to 12:40. The significant loss of heat during the hour prior to the onset of rainfall is noteworthy.

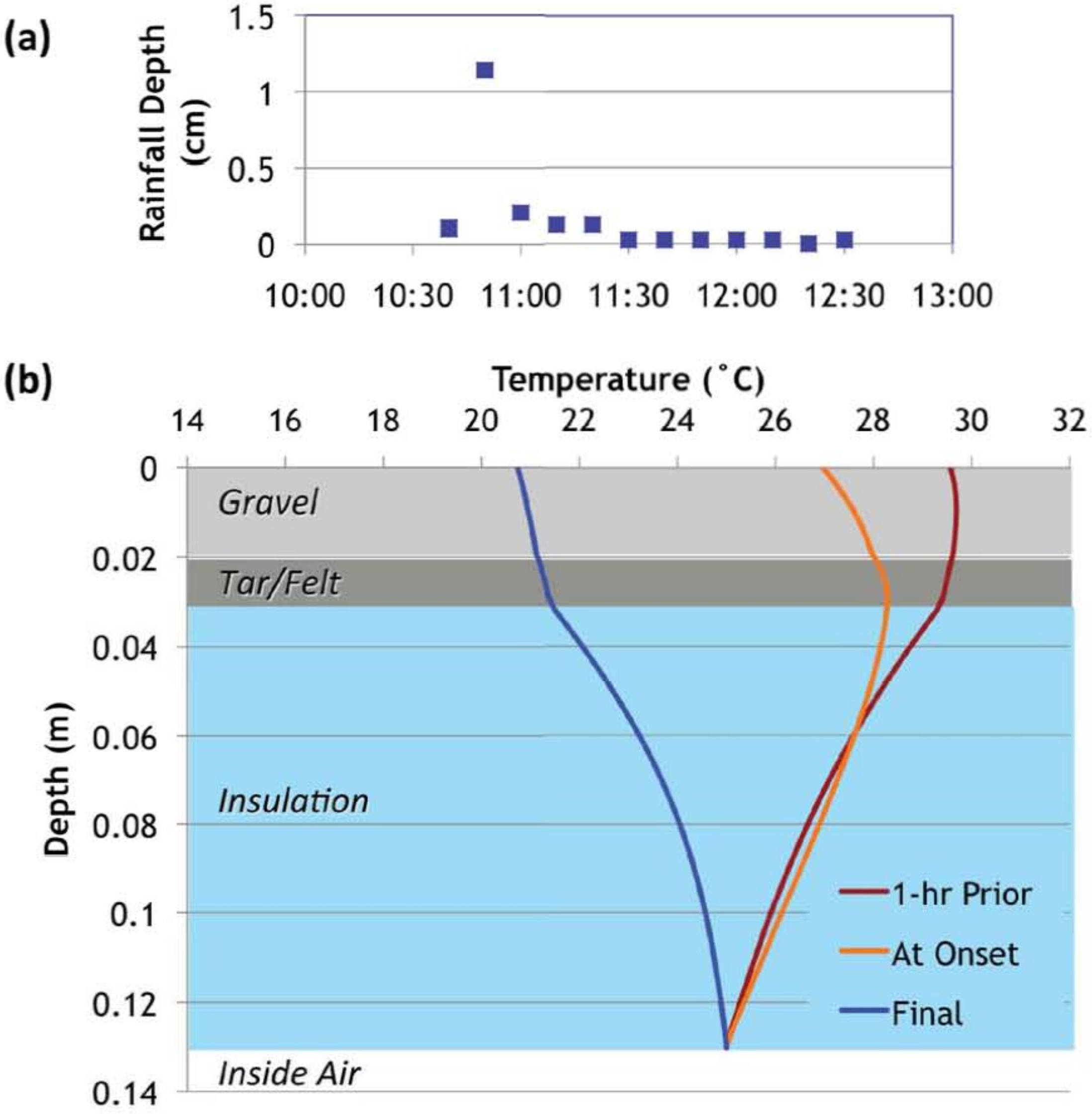

Figure 5.2. (a) Rainfall hyetograph for a 1.9-cm rainfall observed at the St. Anthony Falls Laboratory (SAFL) on July 23, 2005. (b) Simulated temperature profiles in the SAFL (commercial) rooftop for this rainfall event.

Applying Equation 5.1 gives a total heat export of 357 kJ/m^2 for the rainfall event. This maximum heat export is calculated using Method 3, which utilizes a time series of instantaneous heat export rates calculated from intermediate roof temperature profiles and the runoff rate, which is set equal to the rainfall rate because of the short lag between rainfall and runoff from the roof. These values are plotted in Figure 5.3 along with an exponential curve fit ($R^2 = 0.96$). The plot shows, as expected, that considerably more heat is extracted from the rooftop at the beginning of the event than at the end of the event. Extrapolating this curve beyond the end of the rainfall at about 12:40 shows that an additional 16 kJ/m^2 (4% of the actual heat export) would be extracted within 3 hours after the rainfall. This results in a maximum heat export of 373 kJ/m^2, and suggests that at least in the case of this particular rooftop and rainfall event, most of the available heat has been extracted by the end of the rainfall.

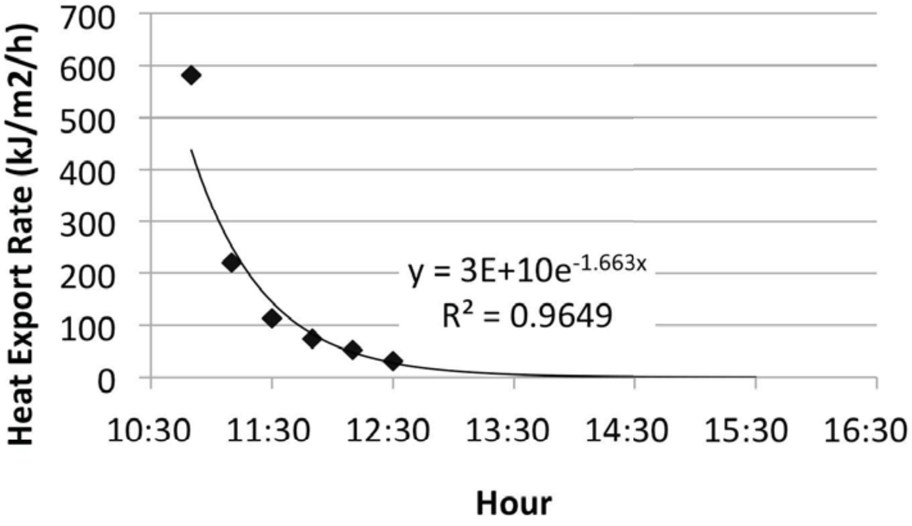

Figure 5.3. Exponential curve fit to time series of instantaneous heat export rates (kJ/m^2*h) determined from simulated roof temperature profiles and measured rainfall for the commercial rooftop. Rainfall event occurred from 10:40 to 12:40 on July 23, 2005.

5.6. Results: Heat Export from Residential and Commercial Rooftops and a Pavement

The above analysis was completed for a residential roof (Figure 2.1), a commercial roof (Figure 2.2) and a concrete pavement (driveway) for the three rainfall events in Table 5.3. Results are summarized in Table 5.4. In general, the heat export values in Table 5.4 support the conclusions of the roof temperature data analysis in Section 4. The residential rooftop contributes little heat to the rainfall runoff; in the case study, the heat export from the residential rooftop did not, on average, exceed 20% of the estimated actual heat export (or 14% of the potential heat export) from the concrete driveway. For the commercial roof, the estimated heat export was on average 3 times that of the residential rooftop, and on average 59% of the estimated actual heat export (47% of the potential heat export) from the concrete driveway.

Both this heat export analysis and the temperature analysis in Section 4 justify the assumption that the heat export from the residential rooftops is negligible compared to other impervious surfaces. Heating of runoff on commercial rooftops is relatively significant, and should not be ignored.

Table 5.4. Estimated actual and potential maximum heat export from a residential roof, a commercial roof, and a pavement during three rainfall events (Table 5.3), in kJ/m^2 and as a percentage of the heat export from a concrete pavement.

Surface	**6/20/05**		**7/23/05**		**7/25/05**		**Average**	
	Est HE	Pot HE	Est HE	Pot HE	Est HE	Pot HE	Est HE	Pot HE
Heat Export in kJ/m^2								
Residential Roof	247	251	115	117	245	257	202	208
Commercial Roof	793	990	357	373	560	610	570	658
Concrete Driveway	876	1288	648	882	1885	2709	1136	1626
As Percent of Heat Export from Concrete Driveway:								
Residential Roof	28%	19%	18%	13%	13%	9%	20%	14%
Commercial Roof	91%	77%	55%	42%	30%	23%	58%	47%

Also noteworthy is that for both rooftops the estimated actual heat export was lower than the potential (maximum) heat export, but not by much. The difference was on average 3% for the residential rooftop, 13% for the commercial roof, and 30% for the driveway. The nearly complete extraction of potential heat from the residential rooftop and the lower extraction rates for the commercial roof and the driveway are clearly related to the heat storage capacity (mass) below these surfaces, which is considerably smaller for the rooftops than for the driveway.

Rainfall duration plays a logical role in heat export. Roof surfaces reach their potential maximum heat export (i.e. estimated heat export is approximately equal to maximum heat export) in longer rainfall events, such as the ones occurring on July 23 and July 25. The absolute value of potential heat export for all surfaces appears to be directly proportional to total rainfall depth.

6. SUMMARY AND CONCLUSIONS

A common assumption in runoff temperature modeling is that rooftops of all types contribute very little heat to rainfall runoff. We examined the accuracy of this assumption (a) by analyzing temperature data which we collected on a residential rooftop, a commercial rooftop, and a concrete driveway, and (b) by simulating temperature profiles and surface heat transfer for these same three urban surfaces.

Roof temperature data were collected at two sites in Minneapolis, MN, from June to September, 2005: a residential rooftop of a single family home, and a commercial-style building roof. Temperature at both sites was recorded at 1-minute intervals. On the commercial roof, temperature was recorded at 6 locations within the gravel layer of the rooftop, whereas on the residence temperature was recorded at single locations on the north- and south- facing roof portions. Temperature was also recorded at single points on the surface of the concrete driveway and the lawn (grass) at the residential site.

The surface temperature data were analyzed for all rainfall events in the record; results are shown in Tables 4.1 - 4.4. The results indicate that the residential and the commercial rooftops store less heat than a concrete driveway. All three surfaces cooled significantly in the hour prior to the rainfall events. The associated temperature drop for all surfaces was on average 5.1 ˚C for daytime events (ranging from 2.4 ˚C for the lawn to 7.7 ˚C for the residential roof). Both rooftops had slightly higher temperatures than the concrete driveway one hour prior to the onset of rainfall (1-2 °C on average), but had lower mean temperatures during the duration of daytime rainfall events (21.8°C and 21.9°C for the residential and commercial rooftops, respectively, versus 24.2°C for the driveway). This suggests that on sunny days and prior to rainfall rooftops can reach higher temperatures than paved surfaces, but rooftops do not store much heat and drop rapidly in temperature as cloud cover increases with an approaching storm. Antecedent weather conditions might therefore be more important for surfaces with large heat storage capacity (e.g. driveways or lawns) than for those with small storage capacity (e.g. rooftops).

The difference in rainfall (dew point) temperature and surface temperature over the duration of rainfall provides an estimate of how much heat is being extracted by the runoff; if this difference is small then very little heat is being exchanged. For both roofs, the mean elevation of roof temperature above dew point was very similar when averaged over all daytime rainfall events (1.8 °C; see Table 4.5); the mean difference between driveway and dew point temperatures was more than twice that value (4.2 °C). At the end of rainfall events the residential roof had the smallest difference between surface temperature and dew point temperature (0.8 °C for daytime events); it tended towards rainfall temperature faster than the other surfaces. This behavior can be attributed to differences in thermal storage capacity. The least amount of heat was being extracted by rainfall runoff from the residential roof, more from the commercial roof and the most from the paved surface.

It was expected that daytime rainfall events--in particular those occurring in late afternoon or early evening of hot, sunny days--would have the greatest potential for thermal impact. Instead, it was discovered that the rainfall events with the highest dew point and surface temperatures often occurred late at night or in the early morning (Table 4.4). The highest mean event dew point temperature (23.2 °C), commercial roof temperature (24.7 °C), and driveway temperature (26.7 °C) all occurred for an event beginning at 12:30 AM on Aug 4, 2005. An early morning storm on June 27 also appeared to be a worst-case event based on criteria of highest dew point and surface temperatures. This is contrary to the expectation that worst-case scenarios occur during daylight hours, but is logical considering that atmospheric heat fluxes, including solar radiation, are significantly reduced during rainfall events, and that heat export by rainfall runoff is often driven primarily by antecedent surface temperatures and rainfall (dew point) temperature.

Actual and potential maximum heat export amounts (J/m^2) were estimated for three selected daytime rainfall events using a 1-D roof temperature model. The three rainfall events were chosen because they were among the largest daytime rainfall events on the record, and not on the basis of maximum observed surface or dew point temperatures. An unsteady heat diffusion equation was solved using the observed surface temperature time series as an upper boundary condition and a specified temperature as a bottom boundary condition to estimate temperature profiles in the roof material during each rainfall event. Actual heat export was estimated from the temperature profiles at the beginning and end of the rainfall event (Equation 5.1). Maximum (potential) heat export was estimated by fitting an exponential curve to a time series of heat export rates and extrapolating beyond the end of the event (Figure 5.3).

The results of this heat export analysis for three rainfall events showed that the residential roof contributed, on average, less than 20% of the amount of heat release from a paved surface (driveway) under the same weather conditions, and that nearly all available heat was being extracted from the roof, i.e. actual heat export ≈ potential maximum heat export (see Table 5.4). For the commercial rooftop the fraction was on the order of 50%. Potential heat export was significantly higher for the driveway than for either rooftop.

In conclusion, the results of the temperature data analysis and the heat export simulations support the assumption that residential rooftops contribute little heating to rainfall runoff, particularly for large and/or long-duration rainfall events. However, the same assumption does not appear justified for commercial roofs, which can have a significant thermal impact on rainfall runoff due to their greater thermal storage capacity. How significant this impact might be is not clear, as the estimated heat export for the commercial rooftop was from 30% to 90% of that estimated for a concrete driveway. This contribution might be smaller relative to an asphalt surface, which would be expected to have a greater thermal impact than a concrete driveway. Nevertheless, the commercial rooftops should be considered when rainfall runoff is simulated by hydrothermal runoff models, especially in urban areas where significant commercial buildings are present. This statement gains additional weight if it is considered that the drainage systems of commercial buildings have been traditionally connected to storm sewer systems, whereas residential roof tops and their downspouts often discharge onto lawn areas where infiltration is significant. Modern commercial buildings use "green roofs" which have a much smaller impact on runoff heating, as discussed in Appendix B of this report.

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APPENDIX A. SUMMARY OF RAINFALL DATA

A summary of all significant rainfall events as measured at both the residential and commercial sites is presented here. Rainfall depth, rainfall duration, and timing are included, as well as dew point temperature and solar radiation measured one hour before rainfall onset, at the moment rainfall begins, at the end of the event, and as the mean over the duration of the event. Mean and standard deviations for all events and for daytime events are also shown. The results from the residential site are presented in Table A.1 and those from the commercial site are shown in Table A.2.

Table A.1. Summary of rainfall event data at the residential site including rainfall depth, rainfall duration, and timing. Dew point temperature (˚C) and solar radiation (W/m²) at selected points in time and measured at the commercial site. D = daytime event, I = intermittent.

					Dew Point (˚C)				Solar Radiation (W/m^2)				
Event	Depth, cm	Start	End	Duration h	1-hr Prior	At Onset	Event Mean	At End	1-hr Prior	At Onset	Event Mean	At End	Flag
20-Jun	2.4	13:44	14:21	0.63	19.1	19.1	19.3	19.3	456	6	2.3	1.8	D
27-Jun	0.99	6:38	7:56	1.3	20.5	21	21.5	21.8	5	21.7	9.4	9.5	D
27-Jun	0.15	9:42	9:48	0.1	22.1	21.7	21.7	21.9	76	40.6	42.4	44.2	D
27-Jun	2.54	17:20	20:39	3.33	21.1	22.8	20.1	18	646	32	23.7	3.5	D
3-Jul	0.66	6:13	6:41	0.48	17.9	17.6	18.5	18.8	0	0	0.0	0	
20-Jul	1.57	5:42	6:46	1.07	17.3	18.7	19.8	20.2	0	0	1.5	7.8	
23-Jul	2.18	10:41	11:33	0.87	22	22.4	20.4	20	129	5.2	4.6	2.8	D
25-Jul	2.9	16:44	19:44	3	20.9	21.8	21.2	19	133	7.3	17.7	51.3	D
4-Aug	0.36	0:39	1:22	0.72	23.6	23.5	23.2	22.4	0	0	0.0	0	
8-Aug	0.56	7:37	8:32	0.93	20.9	21	21.0	21.1	50.9	24.5	7.7	5.3	D
11-Aug	0.13	12:37	13:29	0.88	15.7	17.5	17.7	18.5	174	86.3	106.9	168	D
16-Aug	0.43	21:50	22:14	0.4	18.5	18.9	19.4	19.8	0	0	0.0	0	
19-Aug	0.33	10:46	10:59	0.22	18.8	19.3	19.1	19.1	196	3.4	87.8	143.6	D
26-Aug	4.5	5:35	8:30	2.93	20.8	21	19.4	19.4	0	0	2.6	7.3	
3-Sep	0.91	13:38	19:21	5.72	12.2	13.9	15.6	16.7	290.3	30.3	11.1	3.6	D,I
4-Sep	0.64	2:30	3:04	0.58	16.6	16.4	16.4	16.5	0	0	0.0	0	
4-Sep	2.91	5:02	7:57	2.93	16.3	16.4	17.0	17	0	0	0.0	0	
12-Sep	1.4	21:12	3:55	6.72	22	22	19.6	18.5	0	0	0.0	0	I
21-Sep	5.69	19:15	23:25	4.18	20	18.1	19.5	19.3	18.2	0	0.0	0	D
24-Sep	2	22:55	7:44	8.82	17.7	17.8	17.9	18.1	0	0	0.0	0	I
28-Sep	0.61	7:10	11:19	4.15	11.4	11	10.2	9.1	0	0	22.0	69.3	I
Mean (all)	1.61	11:18	13:41	2.38	18.8	19.1	19.0	18.8	103.5	12.3	16.2	24.7	
Mean (day)	1.79	12:30	14:03	1.54	20.1	20.5	20.2	19.8	188.4	22.7	30.3	43.0	
StDv (all)	1.48	6:33	8:08	2.41	3.16	3.10	2.72	2.74	172.6	21.3	29.2	47.8	
StDv (day)	1.74	4:13	5:26	1.42	1.89	1.85	1.26	1.36	206.0	26.2	37.8	62.4	

Table A.2. Summary of rainfall event data at the commercial site, including rainfall depth, rainfall duration, and timing. Dew point temperature (°C) and solar radiation (W/m²) at selected points in time were measured on-site. D = daytime event, I = intermittent.

					Dew Point (°C)				**Solar Radiation (W/m²)**				
Event	**Depth cm**	**Start**	**End**	**Duration h**	**1-hr Prior**	**At Onset**	**Event Mean**	**At End**	**1-hr Prior**	**At Onset**	**Event Mean**	**At End**	**Flag**
20-Jun	2.6	13:50	14:30	0.67	19.4	19.1	19.2	19.3	615	0.3	1.8	3.5	D
27-Jun	0.6	6:40	7:50	1.17	20.5	21	21.5	21.8	5	21.7	9.4	5.3	D
27-Jun	2.3	18:20	21:10	2.84	22.8	23.5	19.2	18.8	32	10.7	7.5	1.1	D
3-Jul	0.7	6:10	7:59	1.83	17.9	17.6	18.5	18.6	0	0.1	1.8	9.8	
20-Jul	1	5:40	6:50	1.17	17.3	18.7	19.8	20.2	0	0	1.5	7.8	
23-Jul	1.9	10:40	12:40	2	22	22.4	20.4	20.6	129	5.1	4.5	13.7	D
25-Jul	3.5	16:50	19:50	3	20.9	22	21.2	18.9	133	6	7.6	51.3	D
4-Aug	0.3	0:30	1:20	0.84	23.6	23.7	23.2	22.4	0	0	0.0	0	
11-Aug	0.2	12:30	13:19	0.83	15.7	17.5	17.7	18.5	174	86.3	107.0	136	D
16-Aug	0.5	21:50	22:30	0.67	18.5	18.9	19.4	19.8	0	0	0.0	0	
19-Aug	0.6	10:50	11:10	0.34	18.8	19.2	19.2	19.2	196	3.4	17.6	143.6	D
26-Aug	4.5	5:30	8:40	3.17	20.8	21	19.4	19.5	0	0	2.6	11.6	
3-Sep	1.8	13:30	0:00	10.5	12.2	13.9	16.2	16.9	290	27.5	11.1	0	D,I
12-Sep	0.2	14:30	15:19	0.83	20.7	21.3	21.6	22	56	98.9	94.6	119.6	D
12-Sep	0.6	21:20	23:20	2	22	22.1	21.3	18.7	0	0	0.0	0	
13-Sep	0.4	1:40	3:50	2.17	18.2	18.9	18.9	18.9	0	0	0.0	0	
21-Sep	2.2	19:20	20:20	1	20	18.7	19.6	19.9	18	0	0.0	0	D
24-Sep	1.5	22:45	5:10	6.42	17.8	17.8	17.9	17.9	0	0	0.0	0	I
Mean (all)	1.41	12:21	14:39	2.30	19.4	19.9	19.7	19.6	91.6	14.4	14.8	28.0	
Mean (day)	1.57	13:43	15:07	1.41	20.1	20.5	20.0	19.9	150.9	25.8	27.8	52.7	
StDev (all)	1.23	6:55	7:48	2.50	2.74	2.48	1.66	1.43	157.0	29.6	31.7	50.0	
StDev (day)	1.20	4:03	4:31	0.97	2.05	1.99	1.31	1.30	187.4	38.5	41.8	62.6	

APPENDIX B. GREEN ROOFS

Design

City planners, developers and architects are increasingly turning to vegetated rooftops (also known as "green" roofs) to help reduce the volume and frequency of urban storm water runoff. These rooftops also provide additional benefits by reducing heat flow through the roof (therefore reducing building heating and cooling loads), decreasing daily maximum temperature and the amplitude of temperature fluctuations experienced by roofing materials, and preventing damage to roofing membranes from exposure to UV radiation and abrasion by wind and rain (Liu and Minor, 2005; VanWoert et al., 2005; Carter and Rasmussen, 2006; Deutsch et al., 2007; Oberndorfer et al., 2007). In dense urban areas, rooftops can make up a significant portion of total impervious surface cover, and the use of green rooftops in both new and existing construction is a logical way to add storm water BMPs to areas that do not have the land area available for more traditional types of BMPs such as detention ponds or infiltration structures (Moran et al., 2004).

From a thermal pollution perspective, rooftops do not contribute as much heat to runoff as paved (concrete or asphalt) surfaces. Commercial roofs have a greater thermal storage capacity than residential rooftops and heat export from commercial rooftops can be comparable to that of a concrete driveway (see Table 8). Green roofs are often constructed on top of commercial buildings, and among other benefits, can provide mitigation of potential thermal impact.

A green rooftop is usually constructed on top of a tar-and-gravel built-up roof, with a structure similar to that shown in Figure 2.2. Instead of the gravel layer are several layers designed to support the growth of vegetation; these include a root barrier, water retention layer, drainage layer, filter fabric, growing media, and a plant layer. Growing media is usually very porous in order to facilitate the rapid infiltration of water, and consists of sand, rock/gravel, and some organic material (Friedrich, unknown; Carter and Rasmussen, 2006). The depth of growing media is typically determined by the load capacity of the roof structure and the type of green roof. Two main types exist: intensive and extensive. An intensive green roof usually uses a variety of plants and even small trees, and will require regular irrigation, maintenance, and a greater media depth (10" or more). An extensive green roof, the more common of the two, is designed to be self-sustaining and withstand the local climate, and normally consists of dense, drought-resistant mosses or succulents such as *Sedum*. Media depth in extensive green rooftops is usually 2-6" (5-15cm).

Previous Studies

Most research on storm water retention capacity of green roofs has been conducted on the extensive type of roof. The results of a few studies are summarized here. The list is not exhaustive, but provides background on extensive roof types likely to be constructed in the north-central part of the country. In these studies it was generally found that green roofs store between 25% and 100% of incident rainfall, and total annual retention of 60%or higher is fairly common (Oberndorfer et al., 2007). Retention amounts depended primarily on media conditions (total depth and antecedent moisture content) and on rainfall characteristics (intensity and depth). Green roofs also tend to increase time to peak and reduce the magnitude of peak runoff.

1. VanWoert et al. (2006) investigated the impact of media depth and roof slope on the retention abilities of three types of roof: vegetated (*Sedum*), un-vegetated (i.e. media-only), and gravel-covered (commercial) rooftop. The study site was in Lansing, Michigan and runoff volume data were collected for 430 days. Very little direct runoff occurred on the vegetated rooftop with 2.5cm of media, and 98%, 86%, and 65% of total rainfall volume was retained for small (< 0.2cm), medium (0.2-0.6cm), and large (> 0.6cm) rainfall events, respectively. Increasing media depth from 2.5cm to 4cm resulted in slightly greater retention by the vegetated rooftop (71% of overall volume, versus 61% for the 2.5cm depth). Media depth had no effect once the media was saturated, as rainfall had to depart the green rooftop as

direct runoff, much as it does for the gravel rooftop. Little difference in retention was observed between the vegetated and media-only rooftops except for heavy rainfall events with 52% of total rainfall volume retained by the vegetated green rooftop versus 39% for the media-only rooftop. This is perhaps due to the ability of the vegetation to restrict some direct runoff during the heaviest rainfall events.

2. A study by Carpenter and Kaluvakolanu (2009) showed similar results. A black rooftop, a gravel rooftop, and a green rooftop were instrumented in Southfield, Michigan during April – September, 2008. The green roof utilized *Sedum*-type vegetation and had a media depth of 4in. Roughly 68% of the total storm water volume was retained by the green roof, relative to 49% for the gravel roof and 10% for the asphalt roof. Again, the effect of total rainfall depth was apparent: 96% retention by volume was achieved for small (< 0.5in = 1.2cm) rainfall events, 87% for medium (0.5-1.0in) events, and 45% for large (> 1.0in = 2.5cm) events. These retention percentages were considerably higher than those observed by VanWoert et al. (2006) for comparable intensities.
3. In a third study Carter and Rasmussen (2006) investigated the retention capability of a *Sedum*-type green roof in Athens, Georgia. Media depth was 3 in, and runoff data was collected from Nov 2003 to Nov 2004. Rainfall is considerably more intense in this part of the country than in Michigan, yet the results showed a greater retention by the monitored green roof than in either of the other two studies. The Athens green roof retained roughly 88% of total runoff volume for "small" events (< 2.5 cm), 54% of "medium" events (2.5 - 7.6 cm), and 48% of "large" events (> 7.6 cm). Greater than 90% of total storm water volume was retained for events of less than 1.2 cm depth, which is similar to the retention found by Carpenter and Kaluvakolanu (2009). The authors also noted a reduction in peak flow and time-to-peak for the green roof relative to a gravel ballast roof, and concluded, similarly to VanWoert et al. (2005), that the green roof tended to serve as a volume abstraction rather than a slowing mechanism. In other words, once the roof reaches its holding

capacity of water, the rest tends to run off directly; very little seeps out of the drainage layer.

4. In a fourth study, Moran et al. (2003) instrumented a pair of green rooftops in North Carolina, and found total volume retention of 63% and 55% at the two sites. Runoff was delayed relative to an asphalt rooftop in 90% of events, and the green rooftops retained the first 1.5 cm of rainfall, on average.

5. Liu and Minor (2005) monitored two green roofs and a gravel roof in Toronto. Total runoff volume retention of 57% was observed for the two green roofs, as well as a 10-30% reduction in peak flow relative to the gravel roof. Events with 1.5cm rainfall depth or less were completely retained when no rainfall had occurred within the previous 6 days. The authors also observed a 70-90% reduction in heat flow through the green roofs relative to the gravel roof during summer periods, and a 10-30% reduction during winter. Green roofs reduced maximum roof membrane temperature by 20˚C or more during summer, with a reduction of 30˚C in amplitude of daily membrane temperature fluctuations.

Conclusions

The results of these studies suggest that for a majority of rainfall events, very little runoff occurs from green roofs, relative to commercial (gravel) or residential roofs. The exception is heavy rainfall and/or events in which antecedent conditions are relatively wet. It is concluded that no modeling of runoff temperature from green roofs is necessary, because any runoff that does occur will happen later in the event when roof temperature approaches that of the rainfall, and heat export will be small due to lower temperatures and reduced volume. Furthermore, any drainage that occurs through the roof media should be considerably cooler than direct surface runoff. Therefore, from a heat export perspective, the replacement of any type of rooftop with a green rooftop will have a positive effect. Potential negative effects of green roofs include loss of water by evapotranspiration (water that would otherwise have infiltrated or reached a surface water body, regardless of temperature), and leaching of nitrates from periodic fertilizer applications.