Design, Implementation, and Monitoring of Purdue's First Green Roof

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ABSTRACT

To educate the Purdue community and general public about the environmental benefits of green roofs, the Boiler Green Initiative (BGI) installed Tippecanoe County's first green roof on Purdue's campus in May 2009. The extensive green roof is approximately 165 m^2 and consists of vegetation and pavers to make the space an aesthetically pleasing, usable environment. A monitoring system records surface temperature, soil moisture, rainfall, and stormwater runoff data. The environmental benefits of the roof were quantified by conducting water balances to determine the amount of rain prevented from becoming runoff and using surface temperature data to assess the green roof's ability to mitigate surface temperature fluctuations. BGI plans to use data collected from this monitoring system to promote the installation of green roofs on other existing and future buildings on Purdue's campus by demonstrating their ability to reduce energy consumption and stormwater runoff.

1. INTRODUCTION

Although green roofs have been implemented for environmental purposes in Germany since the 1970's (Oberndorfer *et al*., 2007), they now are becoming more widely accepted in the United States, particularly for their abilities to reduce the urban heat island (UHI) effect and to reduce stormwater runoff (Gaffin *et al*., 2009). In 2008, Purdue University's Boiler Green Initiative (BGI) received a grant from State Farm to install the county's first green roof on Schleman Hall of Student Services on Purdue's West Lafayette, IN campus. This student-led project was a successful collaboration among professors, undergraduate and graduate students, and physical facilities' staff. In addition to greening Purdue's campus, a major motivation in the installation of this green roof was to encourage collaboration between various disciplines. The disciplines included in this project were: landscape architecture, horticulture, civil and environmental engineering, entomology, and forestry and natural resources.

2. DESIGNING PURDUE'S FIRST GREEN ROOF

2.1 Retrofitted Design

Important criteria considered in selecting the location for the green roof included: (i) central campus location; (ii) ability to support the additional loading associated with a green roof; and (iii) accessibility to the public. Schleman Hall of Student Services is located in a busy area of campus and near a parking lot, making it easily accessible to both students and visitors. Prior to retrofitting, the original roof was publically accessible and consisted of picnic tables and benches. However, it was greatly underutilized because it was not aesthetically pleasing. After calculations conducted by Purdue's physical facilities engineers concluded that the roof could support the additional weight of a green roof, the idea generated excitement among employees in the building. By collaborating with physical facilities and architects, BGI obtained approval to implement the green roof on Schleman Hall. Prior to installation of the green roof, the roof was re-sealed to ensure its integrity. An extension was added to the surrounding railing to be incompliance with safety standards, as the installation of the green roof material raised the level of the roof. Figure 1 shows Schleman Hall before and after installation of the green roof, including the railing modifications.

Figure 1: Schleman Hall before and after green roof installation

The green roof was designed with the goal of educating its visitors. Highly reflective white pavers were included in the layout to allow visitors to walk on the roof and experience the green roof directly and to increase the roof's albedo. Green roofs typically are implemented in areas inaccessible to the general public, rendering tours impossible. The accessibility of Schleman Hall's roof therefore plays a vital role in educating visitors about green roofs and their environmental benefits. Although not yet completed, signs are currently being designed that will further educate visitors and foster self-guided tours of the roof. In addition, ramps were installed at each roof entrance to meet fire safety standards and make the roof handicapped-accessible.

2.2 Soil and Vegetation

The 165 m^2 green roof installed on Schleman Hall is an extensive, modular green roof system from LiveRoof, LLC. The "soil" is an engineered mixture of inorganic and organic materials designed to: (i) provide nutrients for the vegetation without additional fertilization; (ii) reduce shrinking and swelling; and (iii) have a low bulk density, reducing the load on the roof. The engineered soil is approximately 10 cm deep, and each green roof module is 155 cm^2. The modular system allows individual sections of the green roof to be removed easily for maintenance needs, and was therefore favored by Purdue's physical facilities staff. The vegetation consists of a variety of drought-tolerant plants including *Sedum*, *Allium*, *Sempervivum*, *Euphorbia*, and *Delosperma*. Due to spatial variability in sunlight, two different mixtures of plants were purchased, with the shade-tolerant mixture installed on the sides of the green roof closest to building walls. Over time, the variety of plants is expected to decrease, as the species best suited for the environment spread and out-compete others.

3. REAL-TIME MONITORING

3.1 Sensor Network

To gather data to evaluate the green roof's performance, a real-time monitoring sensor network was designed and installed. The sensor network consists of four temperature sensors, two soil moisture sensors, two tipping-bucket rain gauges, and three pressure transducers. The sensors are connected to a data-logger, programmed in BASIC to scan the sensors every minute and output averages in table format every 15 minutes. The temperature sensors are located at the roof's surface under a reflective paver, in one of the stormwater drains (to monitor water temperature), and under vegetation at two locations. The soil moisture sensors are installed in the soil above the two temperature sensors that are under vegetation so that temporal and spatial relationships between soil moisture and surface temperature could be established. Because the green roof is on the first floor roof of a three-story building, the remaining stories influence the distribution of rainfall on the green roof's surface. To capture this spatial variability, two rain gauges were installed. Each of the roof's three stormwater drains was instrumented with a pressure transducer and a hydraulic control structure to quantify stormwater runoff.

3.2 Monitoring Stormwater Runoff

The ability to reduce stormwater runoff and delay hydrograph peaks are two of the major benefits of green roofs. To enable the real-time monitoring of stormwater runoff, a pressure transducer was used to measure water level in a V-notch weir box in each stormwater drain (Figure 2). A design requirement for the hydraulic control structure (i.e., V-notch weir box) was to prevent restriction of stormwater flow. Therefore, the cross sectional areas of the openings and outlets of the weir box needed to be equal to or greater than the cross sectional areas of the stormwater drain pipe. An additional consideration in designing the size of the weirs was minimizing stagnant water in the weir box while providing the minimum water level necessary for the pressure transducers to accurately measure the water level above the base of the weirs. The sensor on the pressure transducers (Keller America Acculevel) is located 2 cm from the bottom, and the water level must therefore be greater than this value for the pressure transducer to detect and measure it. Due to limitations on the pressure transducer's accuracy at very low water levels (i.e., on the order of mm), the dual weir design increases the water level above the weirs at low flowrates, thereby increasing the accuracy of the water level measured by the pressure transducer to ± 0.057 cm/mV. The base of the smaller, 15° V-notch weir is 2.5 cm above the bottom of the weir box to ensure that when water flows through the weir, the pressure transducer can accurately measure its level. The base of the second V-notch weir is 5 cm from the base of the weir box and has an opening of 60°. The top of the weir plate is 3.8 cm below the top of the weir box, providing a total cross sectional area of ~83 cm^2. This value is greater than the cross sectional area of the drainage pipe (81 cm^2) and meets the design criterion of preventing the restriction of stormwater flow. Although the weir boxes have been constructed, they are currently undergoing laboratory calibration to establish a rating curve and have not yet been installed in the roof's stormwater drains.

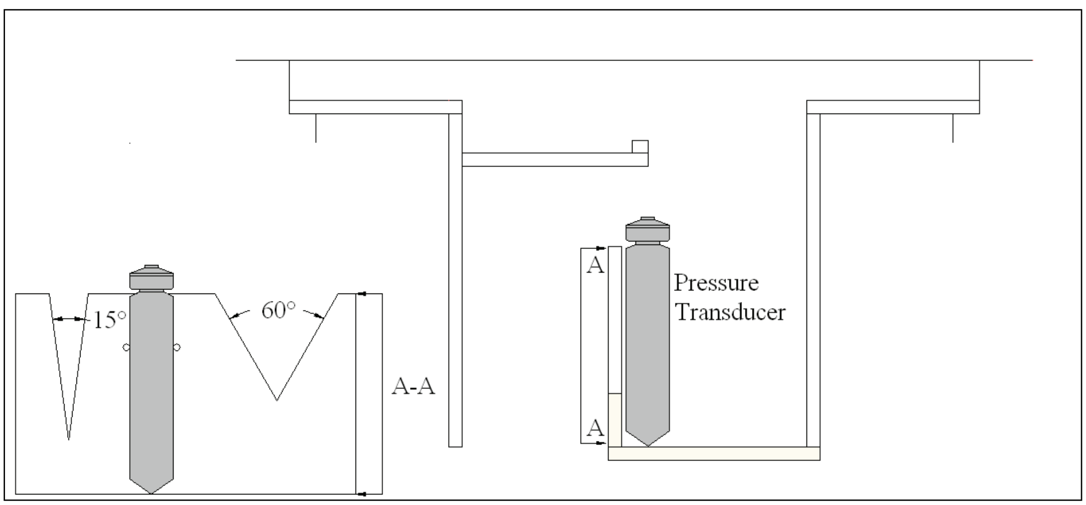

Figure 2: Design of V-notch weir box for monitoring stormwater runoff in roof drains

The rating curve will be obtained by individually calibrating the 15° and 60° weirs. The calibration will be based on the theoretical equation for V-notch weirs given by eq. (1) (Sturm, 2001) where Q is the volumetric flow, H is the height above the weir, g is the local acceleration of gravity, θ is the notch angle, and Cd is the discharge correction coefficient.

$$Q = Cd\,\frac{8}{15}\tan\left(\frac{\theta}{2}\right)\sqrt{2g}H^{2.5} \qquad (1)$$

Since the weir box consists of two weirs, the flow equation is expected to take the form given by eq. (2)

$$Q = C_{sm} \cdot (H_{base} - H_{sm})^{2.5} + C_{\lg} \cdot (H_{base} - H_{\lg})^{2.5} \quad (2)$$

where C_{sm} and C_{lg} are the small and large weir correction coefficients, respectively, H_{sm} and H_{lg} are the heights from the bottom of the small and large weir to the base of the weir box, respectively, and H_{base} is the height of the water above the base of the weir box. Although the values of each weir's correction coefficient will be determined individually, it is likely that they will be co-dependent due to the close proximity of the two weirs. Differences between the measured flowrates and calculated flowrates will be minimized with the least squares method to determine the values of C_{sm} and C_{lg}. The equation will be programmed into the datalogger's BASIC code as a function of the H_{base}, measured by the pressure transducer.

4. RESULTS AND DISCUSSION

4.1 Reduction of Surface Temperature Fluctuations and Associated Energy Usage

The reduction of surface temperature fluctuations is known to extend the lifespan of a roof as much as three times (Wong *et al.,* 2003). Figure 3 shows the surface temperature fluctuations under the white reflective pavers and under the vegetation. In general, the surface temperature under the vegetation was cooler during the summer and warmer during the winter than the surface temperature under the pavers. The surface temperature reached maximums of 11°C cooler in late June 2009 and 13.5°C warmer in mid December 200 than the surface temperature underneath the pavers.

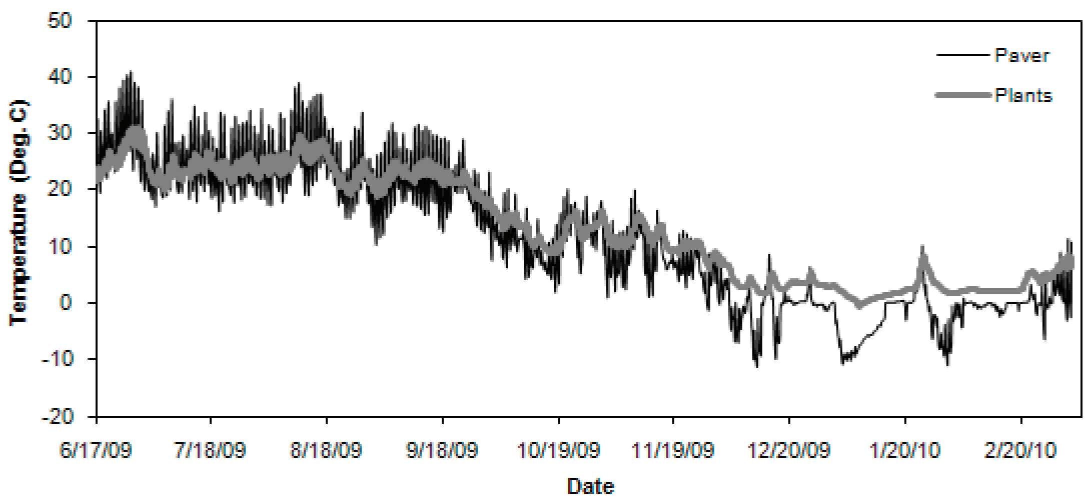

Figure 3: Surface temperature underneath reflective pavers and vegetation

To determine the ability of the pavers and plants to mitigate the effects of temperature extremes, 15-minute air temperature data was obtained from a Purdue weather station (WS) located approximately 1 mile from the Schleman Hall green roof. On the coldest day to date (January 2, 2010), the average, maximum, and minimum temperatures on that day were -13.99°C, -10.59°C, and -17.97°C, respectively. The average, maximum, and minimum temperatures on the warmest day (June 24, 2009) were 27.97°C, 34.37°C, and 22.18°C, respectively. Figure 4 shows the temperature variations in the air measured at the WS and under the pavers and vegetation on the green roof during these two days, and Table 1 provides a summary of these temperature differences. These data suggest that the vegetation is significantly more effective at reducing temperature fluctuations than the pavers.

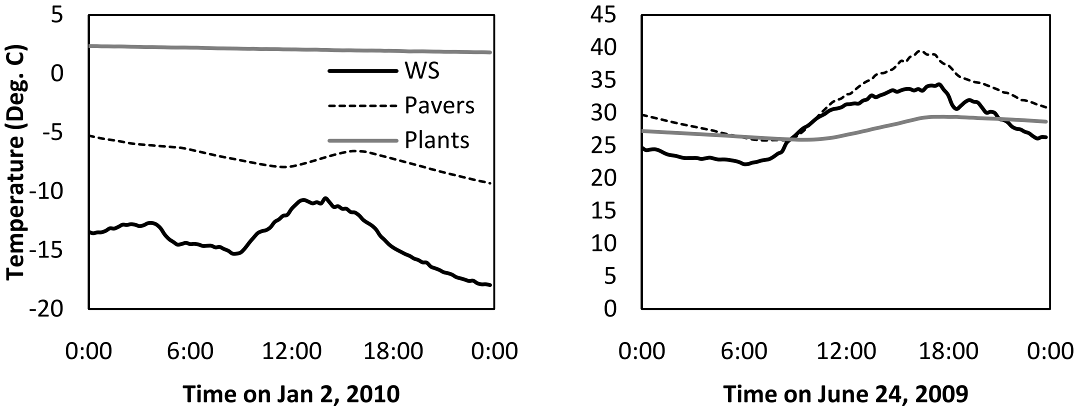

Figure 4: Diurnal temperature fluctuations on the coldest and hottest day at the WS, and roof surface temperature underneath the pavers and plants

Table 1: Temperature differences between WS and roof surface temperature underneath the pavers and plants

	WS (°C)	Pavers (°C)	Plants (°C)	WS (°C)	Pavers (°C)	Plants (°C)
	January 2, 2010			*June 24, 2009*		
Average	-13.99	-7.14	2.08	27.97	31.50	27.54
Maximum	-10.59	-5.27	2.36	34.37	39.39	29.41
Minimum	-17.97	-9.31	1.82	22.18	25.80	25.88

4.2 Reduction of Stormwater Runoff

To determine the ability of the green roof to reduce stormwater runoff, water balances were estimated for 36 rain events between September 2009 and February 2010 using rainfall and soil moisture content, as data on water flow through the drains was not yet being measured. The roof was divided into two sections to account for spatial variability in rainfall, and the amount of rainwater held on the roof was calculated as the difference between the antecedent and post-event moisture contents of the soil in each section of the green roof. Figure 5 shows the percent runoff reduced as a function of total rainfall and maximum rainfall intensity. In general, the amount of rainfall retained on the roof decreased with increasing total rainfall amounts and intensities. Variability in these trends is affected by antecedent moisture conditions. Similar trends in runoff reduction were observed by Bliss *et al*. (2009); however, data were collected from fewer events and therefore contained less variability. Reductions in runoff are comparable to other studies, with up to 70% and 83% reductions observed by Bliss *et al*. (2009) and VonWoert *et al*. (2005), respectively.

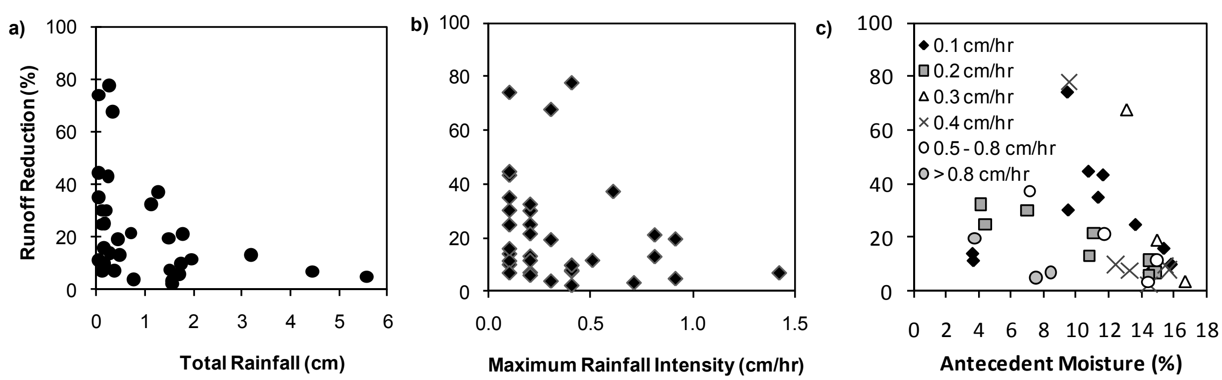

Figure 5: Runoff reduction as a function of a) total rainfall, b) maximum rainfall intensity, and c) antecedent moisture

In addition to reducing the volume of stormwater runoff, green roofs also are known to delay and dampen hydrograph peaks, further helping to mitigate the negative impacts of storm events in areas with large amounts of impervious surfaces. Although volumetric runoff data for this roof has not yet been collected, it is likely that the hydrograph peaks will not be as reduced and delayed as other researchers have reported since 42% of the roof consists of impervious pavers. However, soil moisture data suggests that runoff generated by the soil and vegetation potentially can be delayed by up to 13 hours after the beginning of a rain event. The soil moisture responses to several rain events are shown in Figure 6.

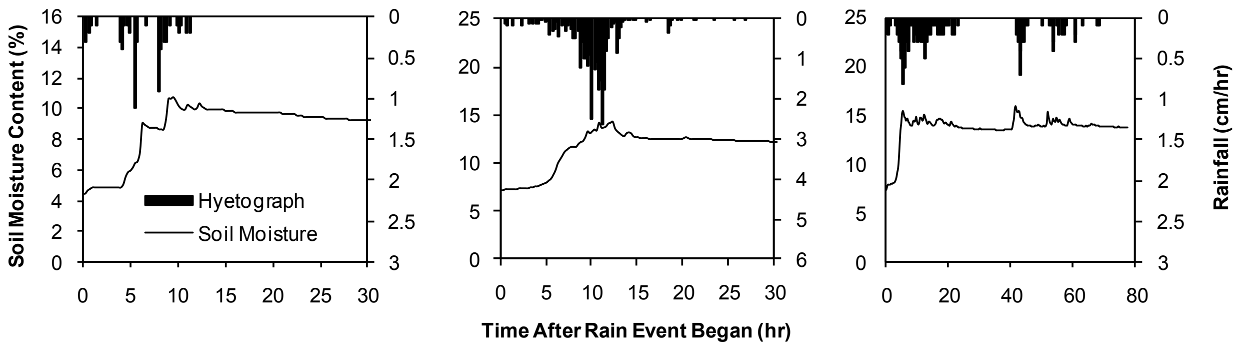

Figure 6: Soil moisture content response to several rain events

5. CONCLUSIONS

In addition to achieving the goal of using the Schleman Hall green roof for educational purposes, the green roof also has demonstrated environmental benefits. Analysis of nine months of surface temperature data suggests that the vegetated areas of the roof were able to significantly reduce diurnal temperature fluctuations, as well as keep the rooftop cooler during the summer and warmer during the winter, thereby reducing the amount of energy required to heat and cool the building. Specifically, on the hottest day, the ratio of the temperature increase between the pavers and vegetated area was 3.85:1.

The green roof also was able to reduce the amount of surface water runoff generated by the roof. Water balance calculations suggest that during storm events, as much as 80% of rainfall was retained on the roof's surface; however, the green roof is 58% vegetation. Therefore, it is likely that the soil moisture sensors do not accurately represent the spatial variation in soil moisture and are leading to an overestimation of surface water runoff reductions. Installation of the pressure transducers in each drain should provide a more accurate measure of the true water balance. The high percentage of pavers also hinders the green roof's ability to dampen hydrographs peaks, though soil moisture data suggested that the peak could be delayed.

Data collected from this green roof will be used to predict the environmental benefit of installing more green roofs on campus. Our hope is that because this green roof is publically accessible, future green roofs will focus less on usability and more on sustainability.

NOMENCLATURE

C	correction coefficient	($cm^{0.5}/s$)
Cd	discharge coefficient	(–)
g	acceleration due to gravity	(cm/s^2)
H	height	(cm)
Q	volumetric flowrate	(L/min)
WS	weather station	(–)
θ	notch angle	(degrees)

Subscripts

base	weir box base
lg	large weir
sm	small weir

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