

Hydrologic performance of different extensive green roofs under different simulated rain intensities in Austin, Texas.

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Abstract

Although most extensive (shallow growing media) green roof research has concentrated in temperate climates, there have been few studies on the functional benefits for individual buildings (thermal cooling) and urban centers (mitigate heat island effects and storm water) in warmer climates. Existing data suggest that cities in warmer subtropical and tropical climates with higher temperatures and flash flooding events would have even more to gain from this technology. This study compares stormwater runoff performance of two extensive green roof types and traditional (flat) roof materials using roof platforms in field conditions using a precipitation generator to simulate a range of rain intensities. Results demonstrate that under very light rainfall events (6.35 mm) green roofs can retain 100% rainfall and under medium (19.05 mm) and intense (38.1 mm) rain events there are significant differences in retention amounts by green roofs compared to conventional roofs, but little difference among the green roof types tested. Time to centroid was delayed by as much as 38 min and run-off: rainfall ratios between 15% and 58%. Storm water response varied depending on green roof type suggesting attributes of green roof design, including growing media type, drainage layer, may all have a role in success or failure of green roof performance. We suggest that expected green roof storm water retention performance should be carefully specified as part of the design processes. This report also makes recommendations for local planning authorities to help facilitate the successful implementation of green roof technology.

Introduction

Although the building and environmental benefits of extensive green (vegetated or “eco-”) roofs in temperate systems have been documented in several countries (Kohler, Schmidt et al. 2001; Liu and Minor 2005; Getter and Rowe 2006), the investigation of similar benefits in other climates have been somewhat neglected. In warmer, non-temperate systems where there may be greater climatic extremes (e.g. high daytime temperatures, frequent flash flood events), green roofs may offer relatively larger intrinsic (e.g. cooling building, extension of roof membrane

lifetime) and extrinsic (e.g. flash flood mitigation, reduction of heat island effect) benefits (Niachou, Papakonstantinou et al. 2001; Wong, Chena et al. 2003). Green roof design can comprise a complex of both abiotic (substrate depth, weight, and composition, drainage layer and root barrier design) and biotic (plant species composition, substrate chemistry, and water availability) design features variables. Given the multiple claimed intrinsic and extrinsic benefits of green roofs (see (Getter and Rowe 2006) for review) reactionary adoption of green roofs has sometimes been undertaken without the understanding of the true performance. Consequently, green roofs are increasingly being incorporated as a sustainable practice in building design, often without specific attention to designing the roof to achieve specific functions, or to the conditions of a specific climatic region.

Although green roofs have been shown to both retain (hold) and detain (delay) rain water, there has been no modeling of these hydrologic characteristics among different green roof types and among a full range of different rain events in Central Texas. Previous research at this location has shown that stormwater detention from natural rain events of different extensive roofs (10 cm growing media depth) varied considerable among roof design from around 18-44% detention for a 49 mm event (Simmons, Gardiner et al. 2008). However detailed, controlled quantification of roof response to rain events is needed to acquire an accurate quantification of the performance of green roofs and the effect of the implementation of this technology across the urban landscape. The difficulty with analysis of green roofs under field conditions in Central Texas has been the reliance on a broad range of natural rain events which could provide adequate data to understand response under the full range of expected conditions suitable for hydrologic model calibration. Given the potential benefits of green roofs in high-density urban areas, a reliable, tested, model would clearly be desirable. This is particularly true for subtropical areas which can experience a greater range of intensity, duration, and total accumulation during rain events than temperate climates where most green roof research has been conducted to date.

The existing and available array of different green and conventional roofs at the Wildflower Center and custom rainfall simulator and run-off instrumentation provided the opportunity to address this issue by answering the following questions:

- How are detention amounts and patterns affected by rainfall intensity and green roof type?
- How are detention amounts and patterns among green roof types affected by pre-event moisture content of the growing media and green roof type?
- How are detention amounts and patterns affected by presence of a drainage layer?

Methods

Data Collection

This project compared the responses of two different green roofs, and conventional roof materials using a rain simulator (Figure 1) calibrated to provide simulated rain events ranging in intensities: 6.35, 19.05 and 38.1 millimeters per hour. Intensity was adjusted by varying the spray heads and water pressure within a Plexiglas enclosure designed to fit the roof experiment units. Two green roof types and one conventional (black top) roof type were subjected to a range of precipitation intensities, to the saturation point and then allowed to dry down.

- Low intensity = 6.35 mm/hr
- Medium intensity = 19.05 mm/hr
- High intensity = 38.1 mm/hr

Rain events were also conducted under two different initial soil moisture conditions which will be quantified (water potential) with a soil moisture probe (potentiometer).

- Dry growing media condition: sub-field capacity to simulate no irrigation/rain input for approximately 3 days to achieve a volumetric water capacity of circa. 1-7%
- Wet growing media condition: close to field capacity to simulate recent irrigation/rain input event within 24 hours volumetric water capacity of circa. 10-16%

Experimental platforms were erected in a former pasture in Austin, Texas (30° 11'N, 97° 52'W; elevation 247 m; mean annual rainfall 810 mm). Climate is sub-humid, subtropical with a bimodal rainfall pattern peaking in spring (April – June) and fall (September – October). Tests were conducted March – June 2011.

The constructed roof platforms represented conventional black unvegetated roofs (2-ply APP modified bituminous membrane), and two different green roof designs (each replicated three times), both modified bituminous with polyester reinforcement membrane. The first green roof type featured expanded shale and sand (hereafter “shale”) as the primary growing medium and the other a mix of perlite and decomposed granite (hereafter “perlite”) (Table 1). The coarse structure of the green roofs was identical for both types: a waterproof membrane, root barrier, drainage layer and 100 mm of growing media, however actual materials and some vertical arrangement varied among manufacturers (Table 1). Water retention and structural and chemical composition of the growing media sample was provided by Soil Water and Forage Testing Laboratory, Texas A&M University, College Station, Texas, and the drainage layer retention capacity and drainage hole area by direct measurement. Specific substrate composition was proprietary information, however both substrate types contained one or more of the following: expanded shale, perlite, sand, decomposed granite, and organic matter (Table 1). Media was planted with single grass species perennial rye (*Lolium perenne* L.)

Each test platform comprised 1.83 m by 1.52 m metal platform with prefinished metal skinned insulated siding. Roof system assembly was 22 gauge galvanized metal deck. Run-off was collected through a single 10 x 10 cm scupper and directed into a catchment pan and water level monitored with an ISCO 4230 bubbler flow meter (Teledyne Isco, Lincoln, NE).

Water events were supplied by brass nozzles calibrated to supply 6.35 mm (0.25 inch), 19.05 mm (0.75 inch) and 38.1 mm (1.5 inches) per hour over the entire roof platform surface. The nozzle spray cone was protected from water loss due to splash-out or wind drift by a 1.83m by 1.52m by 1m high Plexiglas screen (Figure 1).

Factorial comparison of media type, rainfall depth and initial moisture condition were not practical due to the limited number of replicates, variability in results and missing data points.

Table 1. Conventional and green roof structural components by manufacturer.

<u>SUBSTRATE</u>	Shale	Perlite
Decomposed granite		●
Expanded clay	●	
Expanded shale	●	
Sand	●	
Perlite		●
Large size organic matter (> 5mm)	●	
Small size organic matter (< 5mm)	●	●
Clay content %	4	4
Silt content %	3	9
Sand/gravel content %	93	87
Media nitrate – N ppm	13	4
Media phosphorus ppm	36	46
Media potassium ppm	81	59
Media calcium ppm	2307	1822
Media magnesium ppm	334	365
Media sulfur ppm	21	16
Media sodium ppm	37	34
Organic Matter %	3.61	5.54
Water content % at 0.33 bar mean (n=2)	23.5	56.9
Water content % at 15.0 bar mean (n=2)	12.4	20

DRAINAGE/MEMBRANE

Filter fabric/root barrier: polyester		
Filter fabric: polyester	●	●
Drainage layer: undulating spun plastic		●
Drainage layer: plastic retention cups	●	
Retention cup capacity (l m ⁻²)	3.33	n/a
Drainage hole area in retention layer (%)	0.06	n/a
Maximum retention capacity (mm)	14.4	36.9
Filter fabric/water detention: spun plastic		●
PVC single ply membrane		●
Water retention mat	●	
Root barrier plastic sheeting	●	
Protection layer: 1-ply modified bituminous membrane	●	
Membrane: hot-melt modified bituminous with polyester reinforcement	●	●



Figure 1. Rain simulator and truck.

Data Analyses

Level data recorded in the catch pans were converted to a volume, creating a cumulative hydrograph. These data were loaded into Hydstra T/S 10 (Kisters, 2009) for further analyses. Five metrics were computed for each hydrograph in Hydstra for further analyses. These metrics are total runoff (L), runoff- rainfall ratio (Rv), peak flow rate (L/s), the time to centroid of runoff (min) delay in runoff (min), difference between start of rain and start of runoff. The final two metrics, time to centroid and delay, are valuable in examining the potential impact of a green roof on the runoff from a larger site.

Average cumulative hydrographs for the various moisture and rainfall combinations from each roof type were plotted against the controls for comparisons (Figures 2 and 3). Analyses of variance test were conducted on the five metrics using Statistica 10 (StatSoft, Inc., 2011) to test the following hypotheses: a) the five metrics are significantly different between green roofs and conventional roof, b) the metrics are significantly different for the different types of green roofs, c) the performance of the green roofs is affected by moisture content and d) the performance of the green roofs is affected by rainfall intensity.

Results

Green roofs with a perlite media reduced the runoff volume and delayed the onset of runoff 20-40 minutes depending on the moisture content and intensity of the rainfall (Figure 2). The effectiveness appears to decrease significantly once the roof is saturated, where peak runoff rates approach that of the controls. Similarly, shale-based green roofs retain and delay runoff, and moisture content is likely more of a factor in performance of the lower rainfall rates. However, Peak runoff rates were not greatly reduced. This may be due to the lower water holding capacity of the media.

At higher rainfall rates, performance of perlite roofs is greatly impacted by moisture content. In these tests, the runoff was almost three times greater with a high starting moisture content. Once the perlite roofs were saturated, the runoff rates were similar to that of the controls. The performance of shale media roofs was not impacted by moisture content and the peaks were reduced. However, the volume of runoff was almost that of the high moisture content perlite roof, possibly indicating an inferior water holding capacity. This may also explain that although at lower rainfall rates, the perlite roofs and the shale media roof with low moisture content performed in similar fashions, the shale roof with high starting moisture demonstrated reduced effectiveness.

Tests were conducted using a rainfall rate of 0.25 in/hr but runoff in all cases was negligible (data not shown).

It can be easily seen from the average cumulative hydrographs (Figures 2 & 3) that the total volume of runoff is reduced and the start of runoff is delayed by the perlite roofs. There are only small differences in the total volume of runoff from the 19.05 mm rainfall events and the 38.1 mm events with a dry antecedent condition had only slightly more runoff (see also Table 2). This can be attributed to the high maximum retention capacity of the perlite roof. However, with a 38.1 mm rainfall rate and high initial moisture content, the performance was greatly reduced and the peak runoff rate was similar to the control. Drainage from the perlite roofs general ended with rainfall.

The dry shale roof (Figure 3) with a 19.05 mm rainfall performed similar to the perlite roof under similar condition. With higher rainfall rates and/or wet initial conditions the performance of the shale roof was reduced, probably attributable to the lower retention volume compared to the perlite roof. The tail of the hydrograph for the shale roofs was also extended compared to the perlite roof, likely due to the retention cups and porosity of the media. This extended drainage accounted for 15-30% of the total runoff from the shale roofs.

Statistical comparison of the runoff metrics (Table 2) demonstrated that green roofs had significantly lower runoff volumes R_v s and peak flow rates and longer times to centroid and delays in runoff compared to the controls in all cases ($p < 0.001$). When the perlite and shale roofs were compared without controlling for rainfall rate or initial moisture content, none of the metrics were significantly different.

The R_v with a wet initial condition was significantly higher than the dry initial condition ($p = 0.041$). Not unexpectedly, both total volume and peak flow rate were significantly higher ($p < 0.001$) with higher rainfall rates.

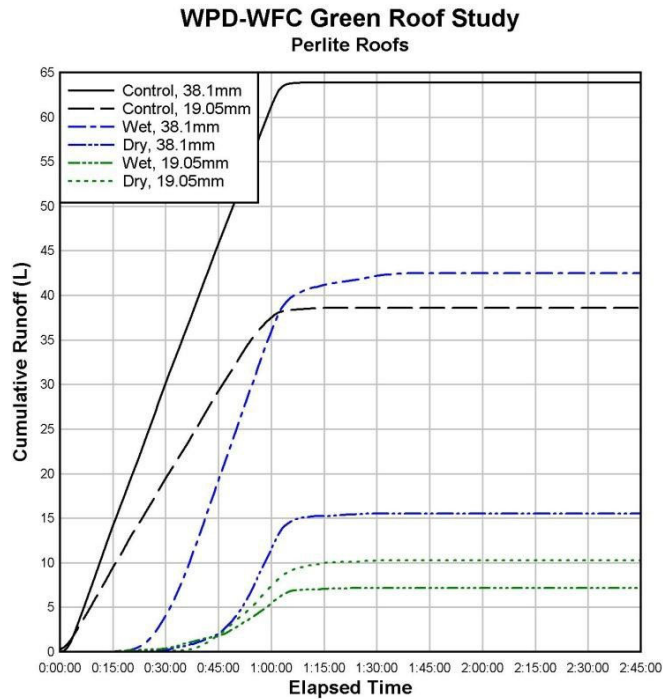


Figure 2. Average response of perlite roofs at different moisture content and rainfall rates.

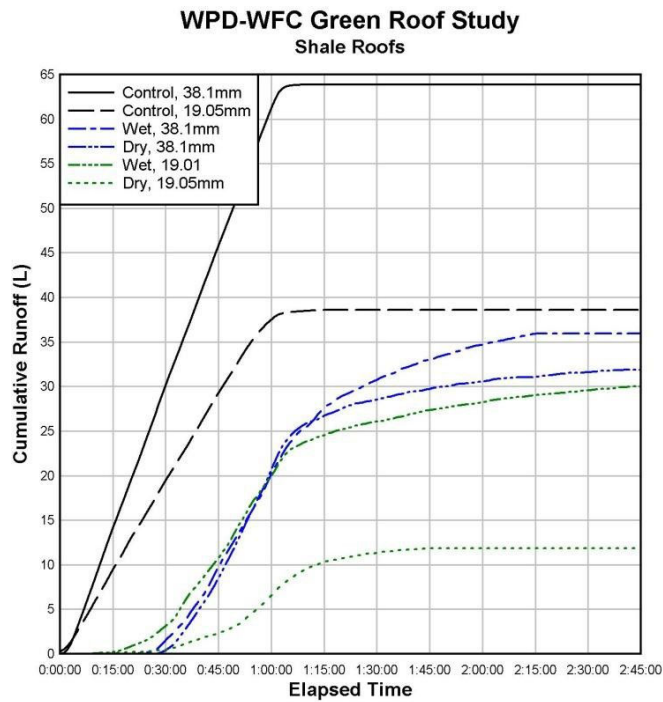


Figure 3. Average response of shale media roofs at different moisture content and rainfall rates.

Table 2. Runoff metrics for different treatments and controls

Roof Type	Rainfall (mm)	Moisture Level	Runoff-Rainfall Ratio	Peak Flow Rate (L/s)	Time to Centroid (min)	Delay in Runoff (min)
Control	38.1	---	0.601	0.020	33.0	0.00
	19.05	---	0.757	0.014	33.2	0.00
Perlite	38.1	wet	0.400	0.021	48.5	21.67
	19.05	wet	0.134	0.007	56.1	38.33
	38.01	dry	0.146	0.016	55.3	26.00
	19.05	dry	0.193	0.008	56.1	34.50
Shale	38.1	wet	0.338	0.017	62.6	23.00
	19.05	wet	0.565	0.015	58.6	13.67
	38.1	dry	0.300	0.017	64.6	28.00
	<u>19.05</u>	<u>dry</u>	<u>0.223</u>	<u>0.008</u>	<u>58.6</u>	<u>30.00</u>

Conclusions

All green roofs will retard the start of runoff and reduce runoff volumes. The influence on the peak runoff rate will be minimal once the roof media is saturated. It may be possible to use a green roof in conjunction with other water quality controls and marginally reduce the size of the control by counting the green roof as 65-80% impervious, instead of 100%, for sizing computation.

With respect to detention requirements, green roofs as designed in this study show less promise. Once saturated there appears to be little reduction in peak flow rate. Since the design storms for flood control are much larger than those in this study, little benefit on peak runoff rate would be expected. Since flow is delayed from the rooftop analyses based on peak timing may be of some use, however the delay for the 38.1 mm/hr rainfall rates was on the order of 20-30 minutes. If the green roofs are scaled to full-size, the delay may be longer. However, for a 24-hr design storm, the media will likely be saturated before the peak rainfall intensity occurs, possibly reducing any runoff delay. This assumes any drainage layer can pass the larger flows associated with design storms. The primary benefit of green roofs with respect to flood control appears to be a reduction in total runoff and should be modeled as such, similar to water quality controls.

However, appropriate planting could improve performance as extraction of water by roots and transpiration out of the media could affectively dry out the media before the next rain event, thus increasing retention. This would only work where the roots had access to water. Therefore this process would be inhibited where the drainage layer does a significant proportion of the retention and the reservoir is capped by a root barrier as in the shale-media roof in this study (Table 1). Additionally, further modifications to the green roof media profile in terms of additional porous material or additional layers engineered specifically to increase detention could increase performance.

This study adds to the existing data collected in the Austin area which all point to the same conclusion: Given the climatic conditions in the central Texas area, green roofs as designed in this experiment are of limited benefit as stormwater controls with respect to quality and quantity. However the positive responses indicate that improvements in design (media depth and advanced media components) could improve overall performance.

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