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## **A Rain Simulator to Examine Green Roof and Soil Moisture Sensor Performance**

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### **ABSTRACT**

Green roof technology plays a large role managing stormwater runoff in urban areas, where impervious surfaces cause substantial amounts of stormwater runoff to enter combined sewer systems. If the stormwater flow exceeds the capacity of treatment plants, this often results in the discharge of raw sewage into nearby bodies of water. Green roofs can reduce the occurrence of raw sewage discharge by decreasing the amount of mixed wastewater and stormwater flowing into combined sewers. Engineers and designers are looking for ways to improve the performance of green roofs and to understand parameters such as field capacity and time to onset of runoff. A better understanding of field capacity could be used to test hydrologic models that predict how much water a green roof could store under different conditions and to estimate how much runoff could be reduced.

In this project, a drip-type rain simulator is used to estimate field capacity of a plot of soil and sedum taken from the green roof on the Onondaga County Convention Center in Syracuse, NY. Three soil moisture sensors placed into the plot are used with different rain intensities to track the increase in soil water content during rain and the decrease following the end of the rain. The experimental results show that the field capacity of the Convention Center green roof is about 0.081 m<sup>3</sup>water / m<sup>3</sup>soil. This value is lower than expected and additional testing is underway. It is also shown that as rain intensity increases, time to onset of runoff decreases. With additional experiments to be conducted in Summer 2018, results of this work can be used by engineers to design and install green roofs with field capacities that complement average rain intensities and peak rain intensities and effectively reduce runoff.

### **KEYWORDS**

Rain Simulator, Green Roof, Field Capacity, Runoff

### **INTRODUCTION**

Green roofs play a significant role in urban stormwater management. They can store incoming precipitation, which reduces the amount of stormwater runoff flowing to combined sewers (Mentens et al. 2006). It is important to determine how much water a green roof can store during rain events in order to estimate how much runoff can be reduced. This information is important for developing improved engineered soil as well as to further advance hydrologic models like USEPA SWMM.

Rain simulators are used to produce different intensities of rain in well-controlled laboratory experiments. Operating a rain simulator with a small plot from a green roof can help

determine the performance of the green roof under various rain intensities. A drip-type rain simulator is used in these experiments to control rain intensity, drop size, and field conditions, such as slope of the roof (Bowyer-Bower and Burt, 1989).

Field capacity is an important parameter in hydrologic modeling and can be useful for simulating infiltration and evapotranspiration. The field capacity depends on soil texture, soil structure, and organic content and is measured in units of  $\text{m}^3 \text{water} / \text{m}^3 \text{soil}$  (Narasimhan, 2009). There are many definitions of field capacity, but for the purpose of this paper it can be described as the maximum volumetric soil water content held against the force of gravity after all excess water has been drained (Fazackerley and Lawrence, 2011). According to Veihmeyer and Hendrickson (1931), this value can be measured two days after a rain event in pervious soils.

This project utilizes soil moisture sensors that are inserted into a plot of the full depth of soil with vegetation (7.6 cm soil depth, plot area 35 cm x 58 cm) taken from the green roof on the Onondaga County Convention Center in Syracuse, NY. The plot is used with a drip-type rain simulator to determine field capacity of the green roof soil under three different rain intensities.

There are two main objectives of this project. The first is to determine the field capacity of a large, extensive green roof in a four-season climate in the Northeastern US using a rain simulator in a laboratory setting. This experimental result is compared to a theoretical value based on fundamental characteristics of the soil. The second objective is to determine how different rain intensities affect the time to onset of runoff. This research is important in preparing to use computer models to predict the hydrologic performance of this green roof in both cold and hot weather. The roof is well-instrumented to provide experimental data over a wide range of conditions for comparison with computer model results to improve our understanding of the hydrology of green roofs.

## METHODS

### How rain intensities were chosen

Rain event data were collected from the Convention Center green roof tipping bucket from 2015 to 2017 in order to determine the range in rain intensities to simulate. As seen in Figure 1, four mm/hr was chosen because it represents a peak rain intensity in the 50<sup>th</sup> percentile. Fourteen mm/hr was chosen because it is a relatively high peak intensity (80<sup>th</sup> percentile). Finally, an intensity of 81 mm/hr was chosen to examine the effects of extreme peak intensities (98<sup>th</sup> percentile).

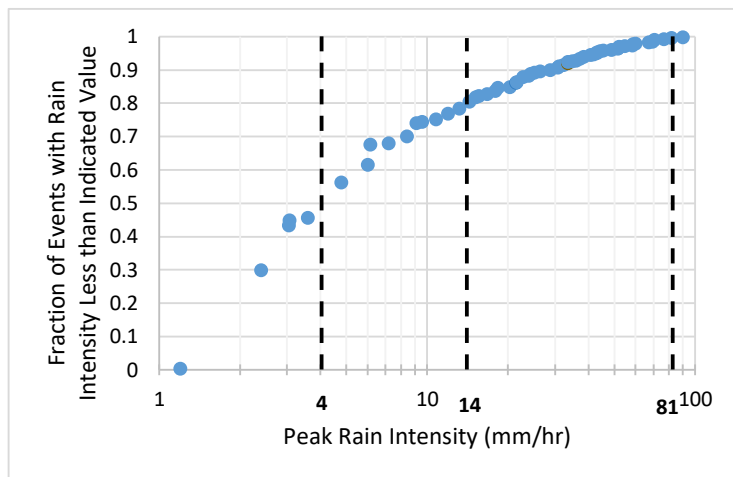


Figure 1: Fraction of rain events on the Convention Center green roof from 2015 – 2017 with peak rain intensities less than the indicated value (N=373). Each rain event has a total accumulation of 0.1 mm or greater.

### Rain simulator and experimental setup

As seen in Figure 2, the rain simulator consists of a water source that feeds into a drip former box. There are small holes in the box for droplets to fall through. The plot from the green roof is placed underneath the box.

The rain simulator is calibrated directly before each experiment to ensure a constant and accurately measurable rain intensity. The first step in calibrating the rain simulator is to place a known volume of water in the drip former box and then allow additional water to flow into the box to exactly balance the droplets falling out below the box. A bucket is used to collect the droplets while the water in the box is monitored to ensure a constant volume. A specific intensity is attained by maintaining a calibrated constant volume in the drip former box. A greater water volume and thus greater height of water in the box will result in higher intensities. Smaller intensities are obtained by inserting small pieces of fish line into the holes in the bottom of the box.

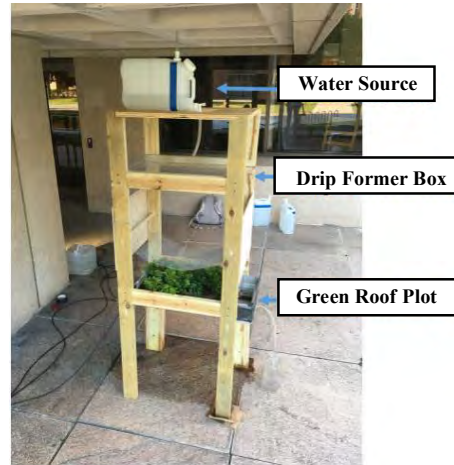


Figure 2: Drip-type rain simulator with plot from Convention Center Green Roof in Syracuse, NY

Before the green roof plot is placed under the simulated rain, three soil moisture sensors are inserted at equal depths into the side of the plot. For two experiments (reaching 4 mm/hr and 81 mm/hr intensities), Campbell Scientific 615 soil moisture sensors were used. These sensors were calibrated with one new CS655 sensor, which has a  $\pm 3\%$  volumetric water content accuracy with manufacturer calibration. The 14 mm/hr experiment used three CS655 sensors. After a desired rain intensity is reached, the green roof plot is placed at a fixed distance below the drip former box at a 1% slope to mimic the slope of the green roof, and volumetric water content data are collected.

As the experiment continues, it is noted when runoff occurs. The plot is kept under a constant rain intensity until runoff becomes steady and volumetric water content has reached a constant value. At this point, the rain is stopped and the soil moisture sensors continue to collect data for 48 hours so that field capacity is determined. Evapotranspiration is assumed to be negligible because the plot is left in a dark basement laboratory, where relative humidity is expected to be high, while data are being collected.

### Calculation of field capacity based on soil characteristics

Dingman (2002) provides the following equation for field capacity:

$$\theta_{fc} = \phi * \left(\frac{|\psi_{ae}|}{340}\right)^{\frac{1}{b}} \quad (1)$$

where  $\theta_{fc}$  is the soil field capacity,  $\phi$  is the porosity,  $\psi_{ae}$  is the air-entry tension in cm, and  $b$  is the exponent describing the moisture characteristic curve. The data collected in the rain simulation experiments can be compared to this model.

## RESULTS

Figure 3 shows volumetric soil water content measured during a period of 48 hours for three rain intensities: 4 mm/hr, 14 mm/hr, and 81 mm/hr. The point shown in the first 5-hour period represents when runoff is first observed for each experiment. During each test, the water content increases during the simulated rain event, levels out once soil is saturated and rain is stopped, then gradually decreases until the decline can be considered negligible and field capacity is measured. The results of Figure 3 show that the water content in all three experiments reaches a maximum of around 0.12 when the soil is fully saturated and that the field capacity reached is about the same for the three intensities, as shown by the dashed lines, at 48 hours.

The findings presented in Table 1 show that the field capacities reached for the three intensities range from 0.069 to 0.088, averaging 0.081. Table 1 also indicates that as rain intensity increases, time to onset of runoff decreases.

Table 1: Field Capacity and Time to Onset of Runoff for Different Rain Intensities

Rain Intensities	4 mm/hr	14 mm/hr	81 mm/hr
Field Capacity	0.086 $\frac{m^3}{m^3}$	0.088 $\frac{m^3}{m^3}$	0.069 $\frac{m^3}{m^3}$
Time to Onset of Runoff	2 hours 42 minutes	1 hour 30 minutes	14 minutes

## DISCUSSION

As seen in Figure 3, there is a noticeable increase in soil water content during each simulated rain event. A greater rain intensity gives a sharper increase in water content. Figure 3 shows that after water content has reached a maximum value of 0.12, the curve remains at this value for a short time and rain is stopped. At this point, a gradual decrease in water content can be noted in the three graphs. All three plots show an initial steeper decrease directly after the rain is stopped followed by a more gradual decrease. At the time when the curve becomes less steep, percolation occurs and the water begins moving out of the large soil pores and is being replaced by air (Zotarelli, 2010). The water content curves continue to decrease as water slowly drains from the soil. After 48 hours, the drainage rate becomes negligible and field capacity is determined (Dingman, 2002). At this point, the large soil pores are filled with both air and water, and the smaller pores are still full of water (Brouwer et al. 1985). In general, green roof soil is made up of mostly large pore spaces rather than the small pore spaces that contribute to water retention at field capacity (Stovin et al. 2015). The mass median diameter of the soil particles at the Convention Center green roof is 4.0 mm, suggesting a similar size for pore spaces (Wu, 1987). The soil porosity is  $0.512 \frac{m^3}{m^3}$ .

The results in Table 1 show that the rain intensity does not seem to have an impact on field capacity. A particle size analysis of the green roof soil indicates the soil texture to be similar to sand, which provides parameter values used in Equation 1. From this equation, the predicted field capacity of the Convention Center green roof is 0.17. This value is also smaller than the typical value of 0.3 noted by Jarrett (2009), although roughly double the value measured in the current work. There is some uncertainty in the value generated by the equation. Further analysis of the green roof soil texture will be completed in future work.

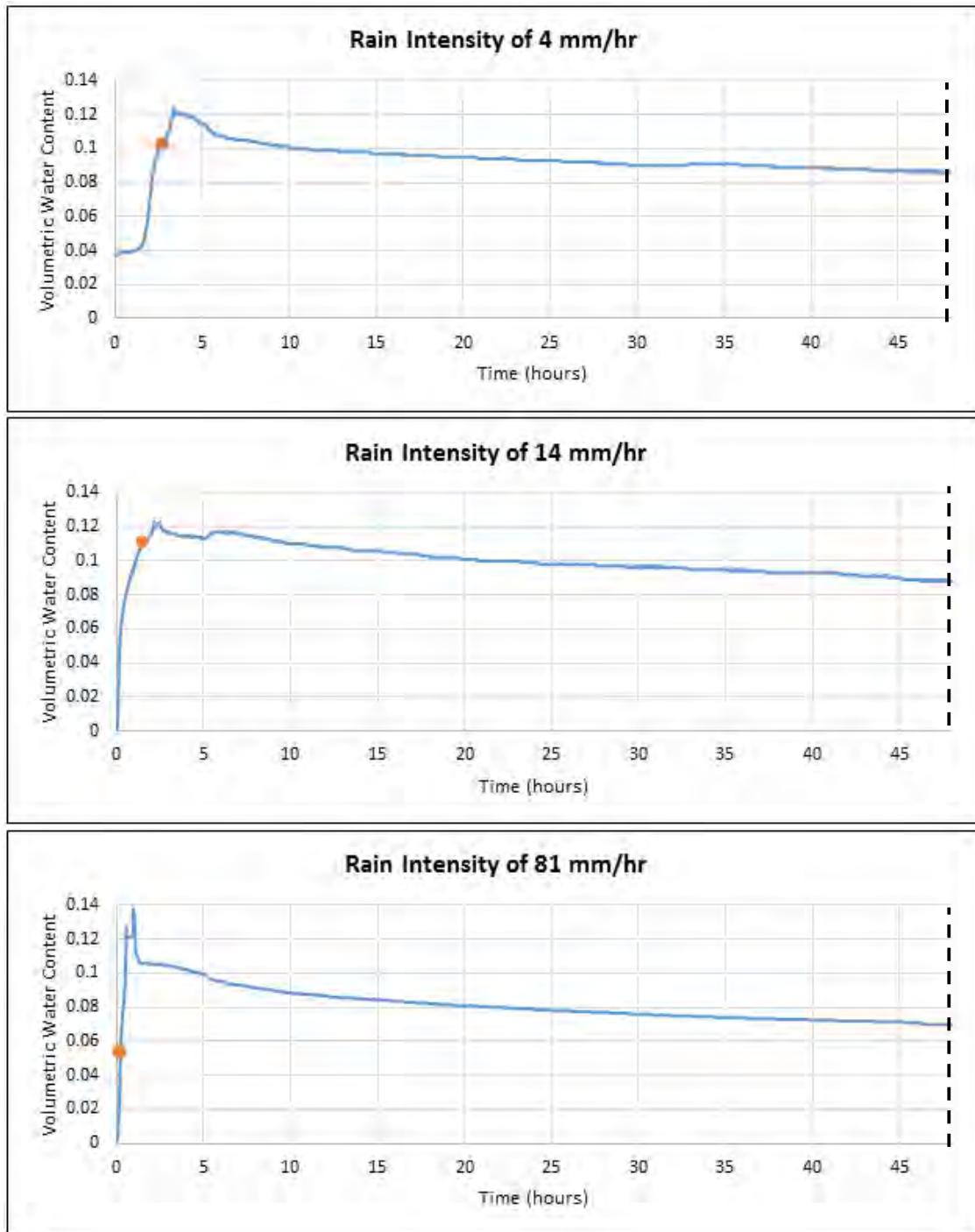


Figure 3: Volumetric Water Content vs. Time for Rain Intensities of (a) 4 mm/hr (b) 14 mm/hr, and (c) 81 mm/hr

The average field capacity of a green roof is said to be about 0.3 (Jarrett, 2009). Therefore, the field capacity measured in this project is low. Experiments are currently underway to investigate this low value.

## CONCLUSIONS

A critical parameter of green roof models is the estimation of field capacity. The findings of this work indicate that the field capacity for the green roof on the Convention Center in Syracuse, NY is about 0.081. This result can be incorporated into green roof models to predict maximum soil storage capacity under various conditions. The results of this project also show that the time to onset of runoff decreases as rain intensity increases. This information will help green roof designers improve the performance of engineered soil and estimate how much runoff can be reduced. In addition, the use of a rain simulator and soil moisture sensors can be valuable for collecting data on a small scale for a green roof that does not have a monitoring system installed. This can be valuable for modeling green roof performance in a variety of climates.

## ACKNOWLEDGMENT

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