7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

The Use of a Large, Extensive Green Roof for Multiple Research Objectives

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ABSTRACT
The Green Roof on the Onondaga County Convention Center in Syracuse, NY is planted with several varieties of sedum over an area of 0.56 hectares. The roof was constructed in 2011, and has been instrumented with sensors to enable research and education over an extended period. The purpose of the current work on this roof is to quantify its performance with respect to water storage and energy transfer, and to identify chemical constituents in the runoff that might be contributed by the growth medium. The scope of the project also includes a number of measurements on traditional roofs in the vicinity of the Convention Center as controls. Experimental methods include measurements with temperature probes installed in different layers of the green roof, a meteorological station, soil moisture sensors positioned around the roof, and an electromagnetic flowmeter connected to the roof drains. Chemical analysis of incoming precipitation and stormwater runoff is conducted by ion chromatography.

Besides the research underway, an educational website is under construction that shows real-time data from many of the instruments. The website includes explanations of the energy flow through the roof layers, water flow and water storage in the growth medium, and runoff through the roof drains. The website is designed for use by teachers of K-12 and undergraduate courses to enable students to learn about green roofs as a tool for managing urban stormwater.

Results of the research show that heat flow through the roof is largely controlled by extruded polystyrene insulation below the growth medium, and that the growth medium is not a major barrier to heat flow. Substantial amounts of stormwater can be stored by the roof, as long as the growth medium is able to dry somewhat between storms. Precipitation events in close succession may cause the growth medium to stay saturated, preventing the roof from storing additional stormwater. The results of this work are important for assisting designers and engineers to improve the performance of green roofs.

KEYWORDS
Green roof, water balance, evapotranspiration, soil moisture, stormwater, runoff chemistry

INTRODUCTION
Green roofs can benefit urban areas in many ways. Much has been written about urban heat islands, where densely populated cities experience higher air temperatures compared with vegetated landscapes just outside the city (e.g., Golden et al., 2004); green roofs can help reduce high urban temperatures. In climates where heating in winter or air conditioning in summer is needed, a green roof may offer some additional insulation to reduce heating or

cooling costs (Zhang et al., 2017). Furthermore, green roofs can provide wildlife habitat, e.g., for birds, and vegetation on a green roof can reduce concentrations of certain air pollutants.

Especially important is the role of green roofs in reducing flooding and combined sewer overflow. In this regard, many studies have investigated the hydrologic performance of green roofs. For example, Stovin et al. (2017) present data from several green roofs on metrics to define stormwater detention, such as time delay between peak rainfall and peak runoff, time delay between 50% cumulative rainfall and 50% cumulative runoff, and attenuation of peak runoff flowrate compared with peak rainfall flowrate. Elliott et al. (2016) examine the hydrologic performance of a green roof with thick growth medium (100 mm) and a green roof with thin growth medium (31 mm) in different seasons in New York City. Cipolla et al. (2016) report on the total amount of stormwater runoff prevented by a green roof in Bologna, Italy during 69 storms over a full year. They compare their experimental data with predictions from the commercial software SWMM 5.1, and conclude that SWMM results show reasonable agreement with data under certain conditions.

In this paper, we report on preliminary results on the performance of the green roof on the Onondaga County Convention Center in Syracuse, New York. This facility offers opportunities to expand green roof research in new directions. The climate of Syracuse includes more extremes of temperature and precipitation compared with other instrumented green roof sites. For example, according to the National Weather Service, the average accumulated snow depth for the season over the past 66 years in Syracuse is 299.5 cm, making it one of the snowiest cities in the country. The green roof measures 50 meters by 111 meters and is fully instrumented to enable energy flow as well as hydrologic studies.

There are three objectives of the research described in this paper. First, the hydrologic behavior of the roof is studied to examine factors influencing the amount of water the roof can store. Second, the benefit of the green roof in reducing heat loss from the building in winter is considered. Finally, the role of the green roof in altering the chemistry of incoming rain is examined. Besides these research goals, there is an educational goal, namely to use the green roof as an educational tool to help students learn about the benefits and challenges of using green roofs for urban stormwater management.

METHODS

The temperatures in the various layers of roof are measured using Campbell Scientific T109 probes, while the air temperature and relative humidity are measured using a Vaisala HMP-155 sensor. Windspeed and wind direction data are obtained using an R.M. Young 03-002 anemometer and wind vane set. Precipitation is measured with a Texas Electronics TE-525 tipping bucket as well as a Belfort AEPG-1000 weighing gauge for rain and snow using a double alter-shield to reduce the influence of wind. Soil moisture is measured using Campbell Scientific CS-616 reflectometers calibrated in our laboratories using samples of growth medium taken from the green roof. Runoff through the roof drains is measured with an M-2000 Badger electromagnetic flow meter calibrated on-site. All of the instruments are connected to CR-1000 Campbell dataloggers, and the data are subjected to quality assurance/quality control procedures.

Fresh rain samples are collected on the roof of the Biological Research Laboratory building at Syracuse University, about 1.6 km east of the green roof, simultaneous with collection of runoff samples from the roof drains on the green roof. Sampling during rain events usually takes place over several hours, hence the distance between the University site and the green roof is expected to be negligible compared with the movement of rain clouds during the sampling intervals. Both sets of samples are analysed using a Dionex DX-500 ion chromatography system with anion columns to enable analysis of Cl-, SO_4^{2-}, and NO_3^-. Field and lab blanks are collected during every experiment to estimate uncertainties in the concentrations. Additional experiments are conducted to estimate dry deposition of these chemical species onto the green roof during periods of dry weather.

The experiments related to the chemistry of precipitation, runoff, and dry deposition are conducted as the weather permits. Weather and hydrology data are collected continuously, allowing interpretation of data for any periods of interest.

Modeling of the hydrology is underway using the U.S. Environmental Protection Agency Stormwater Management Model (SWMM). Modeling of heat flow through the roof makes use of the model Combined Heat, Air, Moisture and Pollutant Simulations in Building Envelope Systems (CHAMPS-BES).

RESULTS

Hydrology of the Green Roof

For each rain event, the tipping bucket and weighing gauge are used to determine the intensity as well as the total amount of precipitation. Using the magmeter data, it is also possible to determine the partitioning of the precipitation between storage in the growth medium and runoff exiting the roof via the drainage system. Figure 1 shows an example of this type of data.

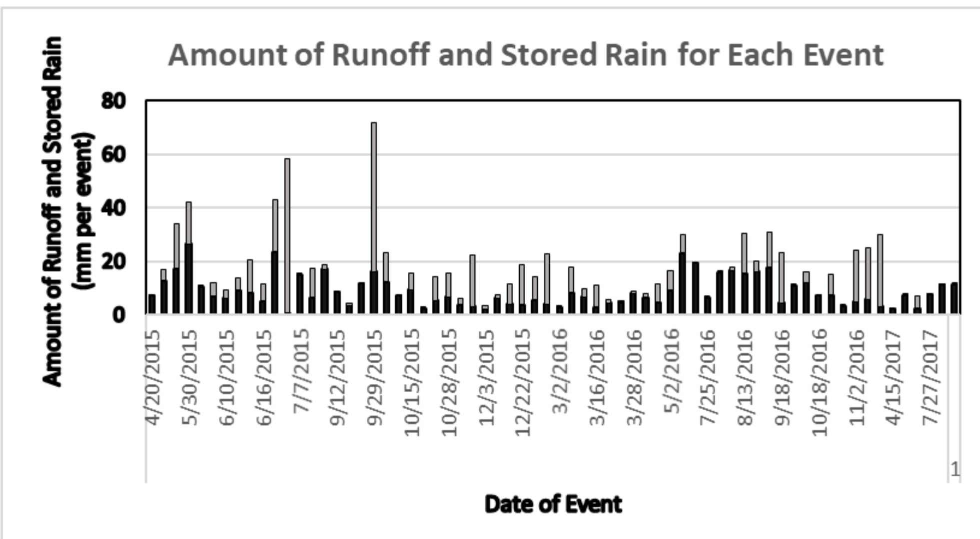

Figure 1. Partitioning of rain between runoff and storage in the growth medium of the green roof between April 20, 2015 and July 31, 2017. Events with snow are excluded. Black portion of each bar represents amount stored in the growth medium, while the gray portion indicates amount of runoff flowing into the roof drains.

Energy Flow through the Green Roof

Temperature data from various layers of the roof are used to estimate the performance of the roof in providing a barrier for energy flow from indoors to outdoors during cold weather. A cross section of the roof with locations of the temperature probes is shown in Figure 2. The layer providing the greatest barrier to heat flow is the 7.6 cm thick extruded polystyrene insulation with a value of R = 2.6 m^2 K per watt, as given by the manufacturer. If we choose a time period when the heat flow is in quasi steady state, we can assume the heat flow in watts/m^2 is constant through the roof and thus use the temperature data to estimate values of R for the other roof layers.

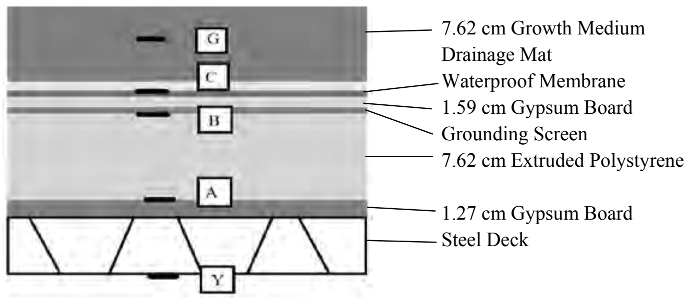

Figure 2. Cross section of the green roof, showing locations of temperature probes installed at A, B, C, and G. This sequence of 4 probes was installed at 5 locations across the roof. Three more widely spaced probes were affixed to the ceiling below the roof at Y.

Preliminary data for this roof reported by Squier and Davidson (2016) show that the total thermal resistance across all layers of roof is about 3.1 m^2 K per watt, including the extruded polystyrene. Data obtained during the winter of 2017-2018 confirm this value based on a larger dataset. The R values of the other roof layers are in the range 0.14 to 0.3 m^2 K per watt, which is very low compared with the extruded polystyrene. This suggests that the growth medium does not provide a significant barrier to heat loss in cold weather.

Chemistry of Green Roof Runoff

Concentrations of several anions have been measured in fresh precipitation and runoff from the green roof during measurement campaigns over the past few years. Results show that chloride and sulfate concentrations are generally much greater in green roof runoff than in the incident rain. Nitrate in runoff, on the other hand, can be either greater than or less than the levels in the rain.

Examples of concentration data for sulfate are shown in Figure 3 for 2014 and 2017. The levels in rain are small compared with the runoff draining from the growth medium of the green roof.

DISCUSSION

Figure 1 shows that the fraction of rain stored in the roof for each event varies between 0% and nearly 100%, depending on the intensity and total amount of rain in the storm. The fraction of rain stored also depends on the timing of the previous rainstorm and whether the growth medium had a chance to regenerate its storage capacity through evapotranspiration. The overall average storage per event is 51% over this time period, although many of the larger storms have much lower storage capability.

The wide range of values for the fraction of rain stored in the roof agrees with prior studies, and the overall average value of 51% is also within the range of prior work. Analysis is underway to compare values for specific events with results of modeling which accounts for the timing of successive rain events, evapotranspiration during dry periods between storms, and characteristics of the growth medium and vegetation on the roof.

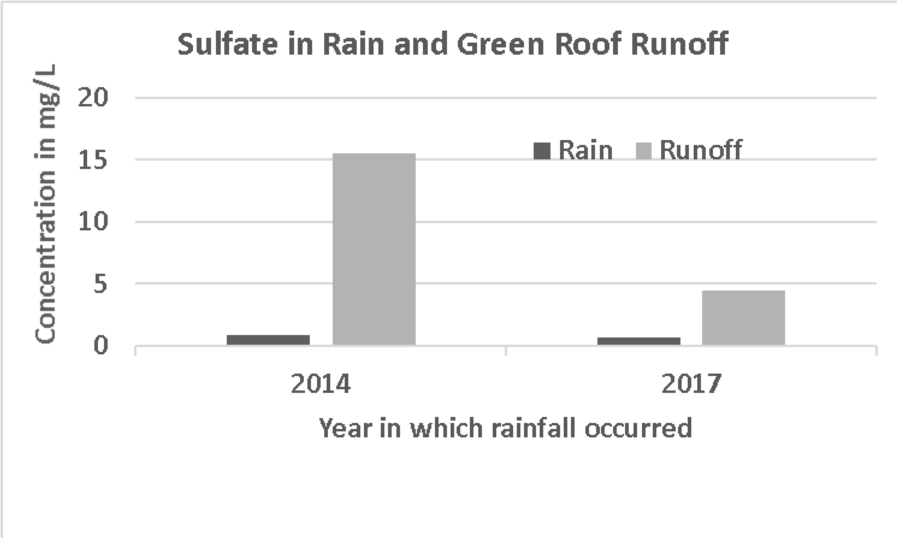

Figure 3. Average concentration of sulfate in fresh rain and in runoff from the growth medium of the green roof for storms sampled in 2014 and in 2017. Measurement campaigns included four storms in 2014 and ten storms in 2017.

The studies of energy flow using temperature data from layers of the roof show that the presence of a snowpack can serve as insulation when air temperatures drop below freezing. Data from the past three winters show that the temperature of the growth medium remains at or near 0^{o} C when a snowpack is present, even when the air temperatures fall to minus 20^{o} C.

Although not significant as an insulator in winter, the growth medium and vegetation of the green roof can prevent temperatures from reaching high values in bright daylight conditions in summer, relative to a traditional roof surface such as asphalt. This can result in reduced space cooling demand during the short air conditioning season in summer in Syracuse.

The CHAMPS-BES model is being used to estimate heat flow through the green roof under different conditions. Results of this modeling agree with estimated heat flow based on the temperature data from the roof layers for certain conditions.

Finally, the chemistry data in Figure 3 suggests a source of sulfate associated with the green roof. Todorov et al. (2018) report higher concentrations of sulfate in runoff from a different green roof compared with incident precipitation in Syracuse. The source of this sulfate is currently being investigated. Other researchers have reported high concentrations of phosphate and nitrate in green roof runoff, e.g., Hathaway et al. (2008) and Gregoire and Clausen (2011). These nutrients are often in fertilizer added to the growth medium when a green roof is first installed to assist growth of the vegetation on the roof. High levels of nitrate were measured in runoff from a few storms in the current study, although phosphate was not observed at detectable levels in any of the samples from the Convention Center green roof.

CONCLUSIONS

The green roof on the Onondaga County Convention Center in Syracuse, NY can store incident rain at times when the growth medium is not saturated. The stored rainwater can then evapotranspire to the atmosphere rather than contributing runoff to the combined sewers. Given the amounts of rain per event, its intensity, and the timing of rain events, the fraction of rain in each event that was stored in the roof averaged 51% over the period April 2015 to July

2017. Small events generally had most of their rain stored, but large storms had smaller fractions. The factors that influence this fraction are under investigation, and the results are expected to help designers of green roofs achieve greater amounts of rainwater storage. The growth medium and vegetation of this green roof are not observed to be significant barriers to heat loss from the building in cold weather. The extruded polystyrene insulation has a greater capacity to reduce heat loss. The chemistry of the runoff from this roof is different from the chemistry of the incident precipitation. Consistently higher levels of chloride and sulfate in the runoff compared with incoming rain are observed; the results for nitrate are mixed, with some events showing higher concentration in runoff but others showing lower concentrations. This work is important in assessing which contaminants can be contributed to runoff by a green roof, and which contaminants in incoming rain can be removed by a green roof.

ACKNOWLEDGMENT

This work was supported in part by NSF grant #1444755, Urban Resilience to Extremes Sustainability Research Network (UREx SRN), by the NSF EMPOWER NRT program, and by Syracuse University Water Fellowships. The authors acknowledge Onondaga County Department of Facilities Management, especially Han Phan and Archie Wixson, for the use of the Convention Center green roof. The authors also acknowledge the help of many undergraduate students at Syracuse University for assistance in different parts of this project.

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