Evaluating a Spreadsheet Model to Predict Green Roof Stormwater Management

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Abstract

The departments of Agricultural and Biological Engineering and Horticulture at the Pennsylvania State University have combined efforts to quantify the stormwater attenuation capabilities of extensive green-roof systems. This green-roof system consisted of a roof with a conventional flat-roof covering, a 0.5-in thick Enka-drainage layer, 3.5 in of porous medium, and S*edum spurium* planted 3.0 in on center. The combined layers of this green roof had a maximum retention of 1.5 in and a saturated hydraulic conductivity of 0.43 in/s.

The green roof system was modeled using a checkbook approach with daily rainfall depth as an input and ET and runoff as the outputs. The AGRR model was applied to 28 years (1976-2003) of rainfall data in Raleigh, NC, and showed that 45% of the annual rainfall volume (depth) can be retained on the green roof. Increasing the volume of storage does not improve the roofs ability to retain rain water. Providing only 0.125 in of roof storage will still cause over 30% of the annual rain depth to be retained on the roof.

Introduction

Green roofs are a surface treatment for rooftops involving the addition of layers of growth media and plants to create a controlled green space. Widespread use of roof vegetation has developed recently, with Germany leading in the use of green roofs, specifically in cities, since the early 1970’s (Peck *et al*., 1999).

A green roof consists of four distinct layers: an impermeable roof covering that serves as a root barrier, a “drainage net,” lightweight growth media, and adapted vegetation (PACD, 1998), see Figure 1. The drainage layer is an open, highly drainable material that quickly channels gravitational water to the roof discharge point(s). The growth medium performs several functions. In addition to providing a suitable rooting zone for the selected vegetation, the medium should be of low density and have high water-holding capability. The lighter weight allows for retrofit installation on older buildings, and also reduces the need for extra structural support in new buildings. The thickness of the medium and its capillary and gravitational water holding capacity play an important role in stormwater retention and attenuation of extreme rainfall events. The plants intercept rainfall, slow its movement into the rooting medium, and are an extensive portion of the green roof’s water storage capacity (Miller, 1998).

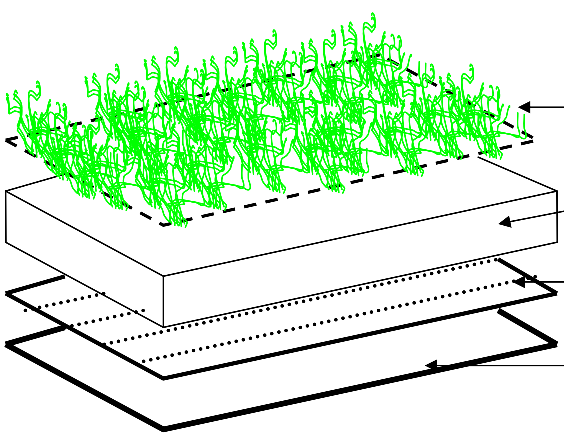

Figure 1 Typical green roof profile.

Topics addressed by European green roof researchers include air quality, stormwater runoff attenuation, plants as building insulation, sound insulation, and building envelope protection. Current research planned and ongoing in North America includes modeling the impact of green roofs on the urban heat island, modeling the amount of stormwater retained annually, and urban agriculture. The majority of these projects are ongoing in Toronto, Canada (Overview of Current and Planned Research, 2001). Other ongoing research has focused on the survival of plant species in varying substrate depths in northern latitudes (Biovin *et al*., 2001). Some of this research stems from environmental concerns with air quality and water quality. It is thought that the vegetation will filter dust particles and greenhouse gasses and serve to clean the air in urban areas.

Green roofs, as stormwater management devices, must be viewed in two different ways; (1) their ability to retain stormwater from day-to-day rainfall events, (2) their ability to attenuate the runoff expected from extreme rainfall event. From a practical, layman's perspective stormwater management is most often viewed as not having excess water to deal with from the day-to-day rainfall events. These are storms with varying depth, from a trace to the rain expected once every year that do not tax the capacity of the engineered stormwater system, but create nuisance flooding. From an engineering and land development perspective, stormwater BMPs are implemented because they have the ability to attenuate peak runoff rates from storms having frequencies ranging from 2- to 100-years. In Central Pennsylvania, these design storms have rainfall depths ranging from 2.6 to 6.0 in for a 24-hour event (Aron *et al.*, 1986). PACD (1998) and Jarrett *et al*. (2004) report that the stormwater benefits offered by green roofs include increasing the time of concentration, thus delaying the runoff peak, and decreasing the peak rate of runoff from the site. Also, green roofs intercept and retain stormwater, thus reducing the volume of water running off a roof, thereby contributing greatly to the NPDES II requirement of infiltrating the 2-year return period runoff event.

Stormwater research on green roofs has included both model simulations and actual trials with full-scale and pilot-scale installations. Miller (1998) and Scholz-Barth (2001) reported annual runoff reductions of 38 to 54% and 38 to 45%, respectively for a 3-in. thick green roof media. Peak flow rate reductions approximated 50%. Moran *et al*. (2003) reported that based on six April to May, 2003, rain events in Goldsboro, NC, a 100-mm thick green roof was able to retain approximately 0.51 to 0.59 in of rain. They also observed up to 90% reduction in peak flow from their experimental roofs. Additionally, Michigan State University has initiated a large green roof research program focusing on various aspects, including stormwater retention, on the Ford Motor Company's 11 acres extensive green roof on their new assembly plant in Dearborn, MI, and the City of Portland is encouraging the placement of green roofs on all new construction within the city. Their design specifically states that some jurisdictions may reduce water and sewer charges or may provide financial incentives to developers who retain stormwater on site and that green roofs can help reduce the size of stormwater management ponds, thus recognizing the importance of water retention on green roofs. DeNardo *et al.*, (2004) reported that green roofs retained 100% of rains smaller than 0.6 in and 25% of larger rains in October and 43% of larger rains in November. Jarrett *et al*. (2004) reported that green roofs retained 48, 53 and 78% of larger rains in May, June and July in central PA, respectively. These benefits, in combinations with limited open space in cities make green roofs a practical method for easing the pressure on storm sewer systems.

The research reported herein provides the results of a stormwater modeling study designed to determine the ability of a green roof to attenuation annual depth of rain in Raleigh, NC.

Green roof hydrologic response models. Following the experimental green roof research conducted on six 48 ft^2 buildings at the Russell E. Larson Research Center of the Pennsylvania State University (DeNardo *et al*., 2004; Jarrett *et al*., 2004), we began to extend these results to include modeling the green roof and its influence on hydrologic events. To this end, an Annual Green Roof Response (AGRR) Model that predicted annual roof runoff as the sum of the daily roof responses using daily rainfall depths and daily ET as input.

The green roofs modeled in this work consisted of the waterproof membrane, a drainage layer, the growth medium, and green-roof plants. Above the roof membrane was a 0.5-in thick layer of plastic/geotextile Enka-drain material designed to facilitate drainage of the overlying green-roof medium, Figure 1. Above the drainage layer was 3.5 in of growth medium consisting of 12.5% sphagnum peat moss, 12.5% coir (coconut fiber), 15% perlite, and 60% hydrolite with a saturated weight of 6.23 lb/in.-ft^2. The vegetation used was *Sedum spurium*.

Annual green roof response (AGRR) model. The AGRR model is based on three assumptions; (1) that a daily (24-hour) rainfall record is available to be used as input, (2) that a reliable estimate of daily evapotranspiration (ET) can be provided, and (3) that the maximum water retention available within the roof and its vegetation is known or available. This "checkbook-type" model computes the depth of water storage available in the green roof and its vegetation on a daily basis. This depth of available storage, or water deficit, D_{gr} is defined as the pore-space available in the drainage layer and roof media below field capacity plus the water holding capacity of the plants. Both the capillary and hygroscopic water in the drainage layer and roof media are considered to be part of the retention storage and can be depleted by evaporation and transpiration. In addition, the deficit, D_{gr} includes the water within the roof vegetation. One unique feature of the plants we used was that they increase and decrease in size depending on the amount and availability of water. When water is readily available (it has rained or the soil is well watered), the plants swell to maximum size and provide excellent cover to the green roof. When water is not readily available (during drought conditions) the plants actually take a portion of their needed water from within themselves for plant functions and transpiration, thus from day to day they decrease in physical size. By the later stages of an extended drought, the plants may only contain 50 to 70% of the plant mass (and volume) they had when fully watered. When a drought period is followed by a wetter period, the plants quickly (within a day or so) re-expand to their full size. Therefore, the plants we use on our green roofs actually provided a measurable depth of water retention roof storage.

The daily roof deficit, D_{gr} can be expressed as

$$D_{gri} = D_{gri-1} + ET_i - R_i \quad (1)$$

where D_{gri-1} is the roof water deficit on Day i-1, ET_i is the evapotranspiration on Day i, R_i is the rain on Day i, and D_{gri} is the roof water deficit on Day i. The daily deficit is not permitted to exceed the maximum retention in the roof (D_{gri} may not be larger than D_{max}). Rain on the roof decreases the daily deficit, but the daily deficit may never be less than zero (0), the condition that represents the green roof system filled to field capacity. If, on any day, the daily deficit reaches zero (0), any remaining water is assigned to runoff – water the green roof cannot retain.

This series of logic was applied to each day during the year in question to estimate how much of each day's rain was expected to runoff the green roof. Rainy days following several days without rain had more storage available, thus less runoff. Rainy days following other rainy days yielded a large portion of the rain as runoff.

Results and Discussion

Annual green roof response (AGRR) model

Twenty-eight years of daily rainfall data from Raleigh, NC, were evaluated using the AGRR model. The input rainfall series had an average annual rainfall depth of 42.7 in of which 23.6 inches, or 45%, was retained on the green roof. The Log Pearson Type III return periods were determined for the annual rainfall depths and these are plotted against the percent of rain retained on the green roof in Figure 2. Percent retention, R was related to return period, T as $R = 71.0T^{0.0947}$; $r^2 = 0.578$.

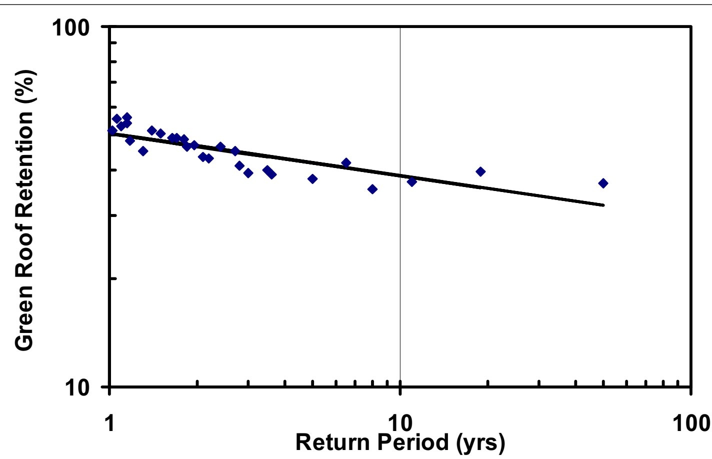

Figure 2. Percent retentionas a function of the precipitation return period in Raleigh, NC

These results can be viewed very positively by considering that 45% of the rain falling on a green roofed building in Raleigh, NC, will be retained on the roof and this depth of rainwater does not require any stormwater attention. The stormwater collection and piping infrastructure can be smaller. Forty-five percent less water will runoff from this development site than from similar development sites without green roofs. There is also evidence from our research that green roofs will neutralize acid rain from pH = 5.2 for our non-greened roofs to pH = 7.2 for our greened roofs. Other green roof researchers have also claimed (often without hard data) that green roofs also reduce the "heat-island" effect, especially in large cities, improve air quality by capturing and retaining air-born pollutants, that the plants and media add to the building's insulation, and that they help to insulate against sound pollution (Liesecke, 1988; Niachaou *et al*., 2001).

On the other hand, there is a less positive way of looking at the stormwater impacts of green roofs. That being that rain water that falls on and is retained on a green roof has no opportunity to infiltrate into the soil profile and becoming part of the local water supply.

Figure 3 shows the daily rain depths and the associated runoff depths for each rainfall event in 1992 (an average year, precipitation wise). It should be noted that only larger rain events produced runoff from the green roof and these only yielded runoff during the dormant season. Based on the results shown, roof runoff was greatly reduced. The events most likely to produce roof runoff were those that occurred immediately following rainy days.

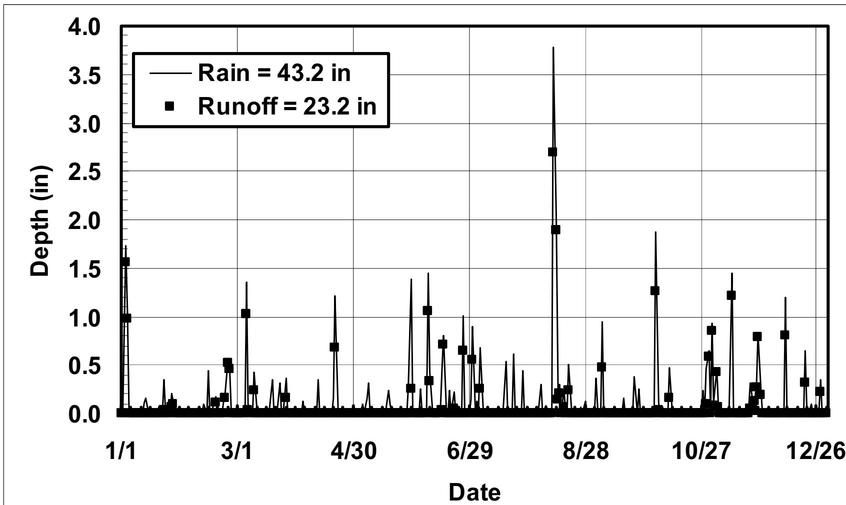

Figure 3. Daily rain and runoff for 1992.

In addition, the AGRR Model was very useful in assessing the impact green roofs of varying retention depths would have on the precipitation regime in NC. The model was setup so that the maximum depth of the green roof's retention storage could be varied. The green roof modeled to produce the results shown above had maximum retention storage of 1.6 in. We varied the roof's maximum retention storage, which was equivalent to making the green roof (primarily the media depth) thicker (> 3.5 in) of less thick (< 3.5 in). The roof's maximum retention was varied from a low of 0.125 in to a high of 3.0 in. The percent of the annual rainfall depth retained on the roof for each retention amount is shown in Figure 4. There are two rather striking results that come from this evaluation. First, when the roof's maximum retention was increased (the roof's media was made thicker) there was not a great deal of decrease in the runoff expected from the roof. In other words, making the roof thicker did not improve the roof's ability to retain rain on the roof. Secondly, when the roof's maximum retention was decreased, in our case to as low as 0.125 in, there was still an important reduction in annual runoff caused by this small amount of roof storage. The horticulture professionals make it clear that these plants (most plants in fact) need at least 3.0 to 3.5 in of media to provide adequate rooting and support. Thus a roof with only 1/8 to ¼ in of retention storage would no longer be a green roof, but it could be as simple as placing one or two layers of a heavy-grade (16-oz) geotextile on the roof's surface. With this small amount of retention storage, this model predicts that we can retain as much as 27% of the annual rainfall on the roof.

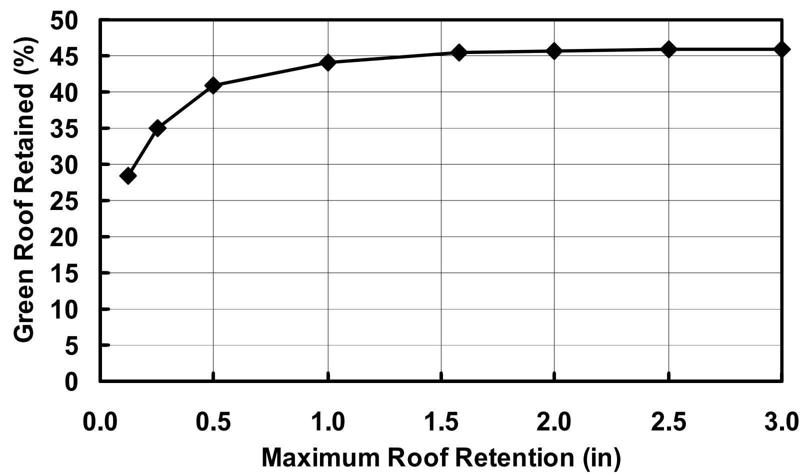

Figure 4. Annual rain retained as a function of the roof's maximum retention.

Summary and Conclusions

The water retention and detention properties of extensive green roof has been demonstrated to greatly improve stormwater conditions on developing sites. The AGRR Model showed that a 3.5-in thick green roof with 1.6 in of retention capacity will retain an average of 45% of average annual rainfall depth in North Carolina. This simple check-book model was also able to show that roofs with more retention capacity will not greatly improve the roofs ability to retain rain. In addition, this model also showed that roofs with smaller retention capacities can have an important effect on retaining annual rainfall depth, even to the point where 1/8 in of retention storage can retain as much as 27% of the annual rainfall depth.

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