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Hydrologic Performance of an Extensive Green Roof in Syracuse, NY

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Abstract: Green roof performance reported in literature varies widely—the result of differences in green roof design and climate, as well as limitations in study design and duration. The need exists for full-scale studies under real climate conditions to inform the design, modeling, and planning of new green roof installations. The purpose of this study is to quantify hydrologic performance of a large green roof and characterize its dominant physical processes. To achieve this, a 5550 m^2 extensive green roof in Syracuse, New York, designed to hold a 25.4 mm rain event, is monitored for 21 months. Over the monitoring period, the roof retains 56% of the 1062 mm of rainfall recorded. Peak runoff is reduced by an average of 65%. Eleven events exceed 20 mm and are responsible for 38% of the rainfall and 24% of the annual retention. Retention in the summer is lower than that in the fall or spring, as a result of greater rainfall intensity during the period sampled. Soil moisture during winter months remains high, reducing the ability of the roof to retain rainfall volume from new events. Comparison of seasonal data demonstrates the strong influence of rainfall intensity on runoff and the effect of initial soil moisture on event retention.

Keywords: green roof; seasonal hydrologic performance; retention; stormwater; soil moisture; detention; green infrastructure

1. Introduction

Increases in impervious urban land cover have altered natural hydrologic processes, overwhelming urban drainage systems during wet weather [1]. This has resulted in occasional flooding with resultant loss of life and property [2]. In communities with combined sewer systems, the rapid runoff from impervious surfaces has led to the release of sewage to natural water bodies, which can damage ecosystems [3]. To reduce such problems, more regional treatment facilities, storage tanks, and other gray infrastructure have been constructed. These solutions are effective, but they are expensive, and they commit a community to use large amounts of energy and materials for the long-term future [2]. Furthermore, gray infrastructure provides only one service, storm and wastewater management, and can negatively impact quality of life in urban neighborhoods.

As an alternative to gray infrastructure, the use of green infrastructure, such as green roofs, is gaining acceptance. Green roofs can reduce total stormwater flow into sewer systems, reduce peak flows, and delay stormwater entry into sewers—all of which can mitigate flooding and combined sewer overflow [4]. However, despite thousands of green roofs being constructed in cities around the world, our understanding of roof performance in terms of these functions is still far from complete.

Retention is the most commonly reported green roof performance metric in the literature [5–9]. Early studies in Germany between 1987 and 2003 found that extensive green roofs (those with substrate thickness less than 15 cm) retained between 27% and 81% of rainfall on an annual basis [10]. More recent studies have found volume retention for extensive roofs in the range of 15%–83% [9]. Such wide ranges in performance are attributed to variation in the multiple factors which influence individual green roof performance, such as climatic patterns and roof design. The large variability in reported performance suggests that more research is needed to narrow anticipated performance of roofs based on design and climate parameters.

A high frequency of rain events and low evapotranspiration rates can result in poor green roof retention performance. Studies in the Pacific Northwest report low average event retention—12%–28% during their cool rainy winters [11,12]. In addition to retention, shape and layout of drainage systems on a roof can influence detention performance: by lengthening the flow pathway through the substrate or drainage layer, peak flow is reduced [6,8]. Study design also influences performance reported in the literature. Many plot-scale studies take place immediately following construction and have 100% vegetative coverage [13]. Further, studies with short duration may miss the impact of seasonal effects, both on precipitation patterns and roof performance.

This study takes advantage of year-round monitoring on a large extensive green roof with an integrated drainage structure in Northeast U.S. to accomplish two goals: (1) to quantify detention and retention performance under a variety of weather conditions, and (2) to identify the dominant physical processes driving performance. To do this, rainfall, runoff, soil moisture, and meteorological data have been collected over 21 months from a full-scale green roof in Syracuse, New York. The data are used to identify 165 rainfall events for which various hydrologic parameters are quantified. The rainfall record is first placed in an historic regional context to support interpretation of study results across longer time periods. Hydrologic performance on the roof is then considered using common performance metrics.

2. Materials and Methods

2.1. Study Site Details

The study site is on the Nicholas J. Pirro Convention Center owned by Onondaga County (OnCenter) in Syracuse, NY (43.04368° N, 76.14824° W). The green roof was retrofit onto the existing structure in 2011. The 5550 m^2 rectangular roof covers the ceiling of the main exhibit hall. The roof is sloped at −1% from the north–south centerline in both east and west directions. There are 13 roof drains along the east side of the building and 12 along the west side. A gravel perimeter runs along the edge of the roof, including the area where the drains are located, accounting for approximately 1.7% of the total roof area. The mineral-based substrate was sprayed onto the roof with an average 7.6 cm depth. Growth medium samples collected in 2011 were found to have an average organic content of 2.7% by mass. Analysis shows a relatively coarse composition, with 5.9% of the mass having a diameter less than 0.05 mm and an average bulk density of 0.79 $g \cdot cm^{-3}$ [14]. Lab measurements undertaken on substrate samples extracted from the roof in June 2016 found a porosity of 43% and a saturated hydraulic conductivity of 0.42 $cm \cdot s^{-1}$ [15]. Vegetation, established by sprayed cuttings, includes *Sedum album, Sedum sexangulare, Sedum rupestre, Sedum spurium, Sedum floriferum, and Phedimus taksimense*.

The roof's drainage structure includes drain conduits and a drainage mat below the substrate designed to convey excess water to the roof drains. Perforated triangular drain conduits, 5.1 cm in height, begin 5.1 m from the centerline of the roof and run diagonally to each roof drain (Figure 1). The substrate and drainage layer are underlain by a single ply waterproofing membrane and traditional roofing structure. More detail on roof layers is given by [16].

2.2. Syracuse Climate and Precipitation

Syracuse, like much of the Northeast U.S., has a humid continental climate—Köppen classification Dfb [17]—with warm summers and cold snowy winters. The average annual precipitation between 1950 and 2010 was 93.5 cm, with approximately two-thirds of this total falling as rain, mainly between April and October. The work reported here focuses only on rain events.

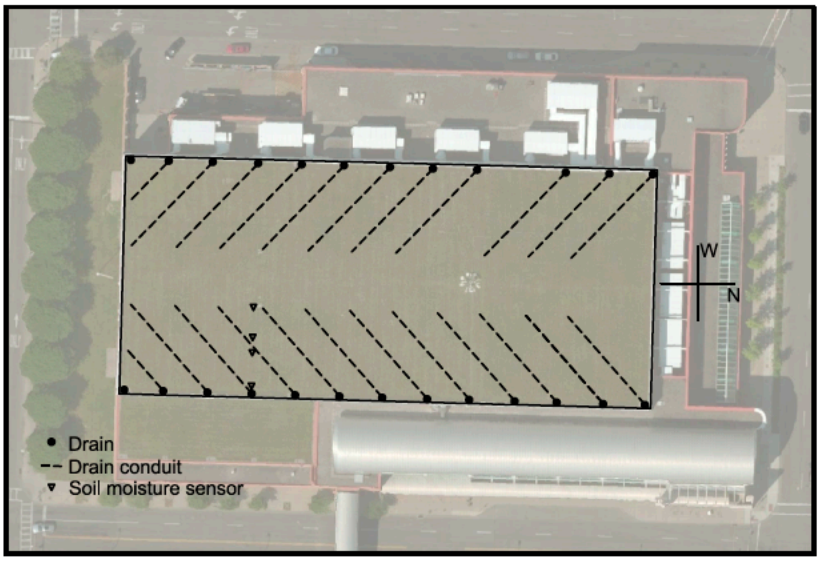

Figure 1. Location of roof drains and drain conduits on the OnCenter green roof. Soil moisture sensors located along a transect on the eastern side of the roof are shown.

2.3. Monitoring System and Data Collection

A CR1000 datalogger (Campbell Scientific, Logan, UT, USA) and two AM 16/32B multiplexers are used to collect data from hydrologic, meteorological, and thermal instrumentation in place on the roof. Rainfall is measured by a tipping bucket (TE 525, Campbell Scientific, Logan, UT, USA) secured to a tripod approximately 29 m from the southern end of the roof. Runoff from a 1792 m^2 region of the roof is collected from the eight drains in the southeast portion of the roof and measured using an electromagnetic flowmeter (M2000, Badger Meter, Milwaukee, WI, USA), which has been field calibrated with a nutating disk meter (Model 170, Badger Meter, Milwaukee, WI, USA). The electromagnetic flowmeter is configured such that full-pipe conditions are always maintained.

Soil moisture sensors (CS616, Campbell Scientific, Logan, UT, USA) were installed along a transect, as shown in Figure 1, to measure the change in soil moisture across the lateral distance of the roof. Sensors were buried midway through the substrate layer, 3.8 cm from the surface. Sensors were calibrated following manufacturer specifications using site samples of substrate. Meteorological instrumentation, sourced through Campbell Scientific, are located on tripods south of the center of the roof. Temperature sensors deployed within the layers of the roof have been used to calculate heat flow [16].

Data reported here are collected between 14 October 2014 and 8 July 2016. Meteorological data are measured at hourly intervals. Hydrologic data are measured at 15-minute intervals between October 2014 and April 2015, after which they are measured at 5-minute intervals.

2.4. Data Analysis

2.4.1. Event Analysis

Continuous event data were sequenced using the eventseq function from the Hydromad package in R [18] using the following criteria:

(1) No precipitation for 6 h prior to the start of an event, and
(2) Runoff from any previous event must have ceased prior to the start of an event.

In addition, days where snow was falling and days with visible accumulated snow on the roof were eliminated. These days were identified using records collected by the U.S. National Oceanic and Atmospheric Administration at the Syracuse Hancock International Airport [19]. Of the 634 days included in the study period, 177 were eliminated by the snow criteria, and 72 events occurring on these days were removed. Six additional events were removed due to flowmeter failure as a result of vandalism. Buried soil moisture sensors were found to migrate upwards slightly during the winter. While soil moisture is reported for events in 2016, the sensors may not have been measuring at the same depth as previous events.

Descriptive parameters considered in the study include rainfall depth (RD), runoff depth (RuD), and initial soil moisture, measured as volumetric water content (aVWC). In lieu of reporting antecedent dry weather period (ADWP), soil moisture is reported for the timestep preceding the start of an event. While ADWP has in the past been used as a proxy for substrate conditions at the onset of an event [20–22], recovery of the substrate between rain events is complex and an exclusive relationship between the two does not exist [8,9,23].

Common retention and detention metrics are used to quantify performance (Figure 2). For the purposes of comparison, rainfall and runoff are expressed as equivalent depth in mm. Events are furthered categorized by event size, adapted from classifications previously reported in the literature [22,24]. Meteorological seasons are used for seasonal analysis.

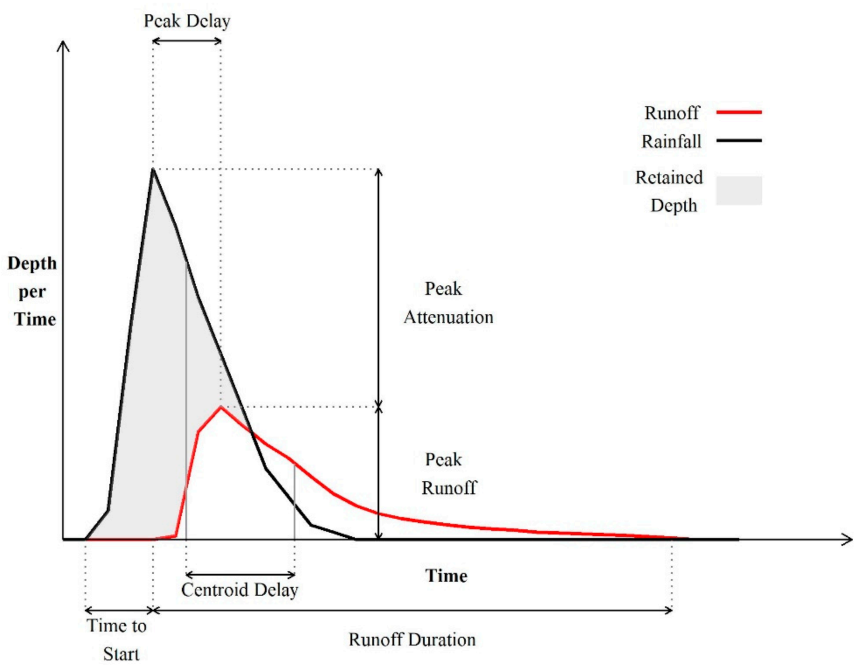

Figure 2. Retention and detention metrics.

2.4.2. Event Plot Statistical Analysis

To identify the influence of season on runoff behavior, a one-way analysis of covariance (ANCOVA) was conducted to determine whether a statistically significant difference exists between seasons based on exceedance probability controlling for runoff data. Runoff data are transformed as log $(n + 1)$ to include zero value events and meet the requirements of normality.

2.4.3. Evapotranspiration Analysis

Evapotranspiration (ET) is quantified using a mass balance approach for hourly data collected between 25 April 2015 and 8 July 2016, following Equation (1):

$$P - RO - ET = \Delta S \quad (1)$$

where P is precipitation, RO is runoff, ET is evapotranspiration, and ΔS is change in soil moisture, all expressed in mm h^{-1}. Steady state conditions are necessary for this approach, which under real-world conditions requires P = RO = 0 at the site. Additionally, sensor reliability issues for potentially frozen substrate require the removal of all days where temperature in the substrate is at or below 0 °C. Days with the potential for snowpack are removed due to complex mechanisms of snowmelt and unknown conditions within the substrate. Daily change in soil moisture is taken as the difference between the hourly values recorded at 0:00 and 23:00 for each day meeting the above conditions. The daily ET is averaged across the four soil moisture sensor locations.

3. Results and Discussion

The raw data collected at the OnCenter and used in this study by the research team, along with a graphic illustrating days excluded per the criteria in Section 2, can be accessed on the website (http://greenroof.syr.edu), with a password that can be provided upon request by contacting the authors.

3.1. Weather during the Study Period

Weather during the study period was generally consistent with historic temperatures (Figure 3). Total precipitation in the region was higher than the historic regional precipitation for 9 of the 21 months in the study period. A total of 1062 mm of rainfall was measured at the site during this period, excluding snow events. Measured total precipitation averaged between 1950 and 2010 at the Syracuse Hancock International Airport, located 8.3 km north of the OnCenter, is compared with the rainfall measurements taken at the OnCenter between November 2014 and May 2016 (Figure 4). Daily total rainfall during these periods are comparable, with reasonable differences attributed to the spatial variability of rainfall.

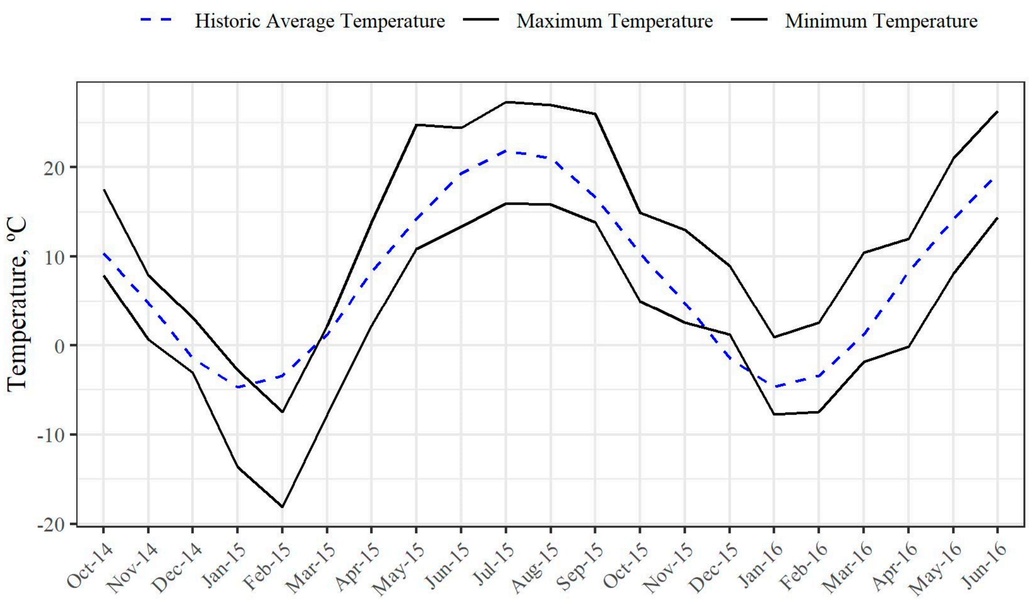

Figure 3. Historic temperatures as recorded between 1950 and 2010 at the Syracuse International Airport and actual temperatures measured on the OnCenter green roof from October 2014 to July 2016 [19].

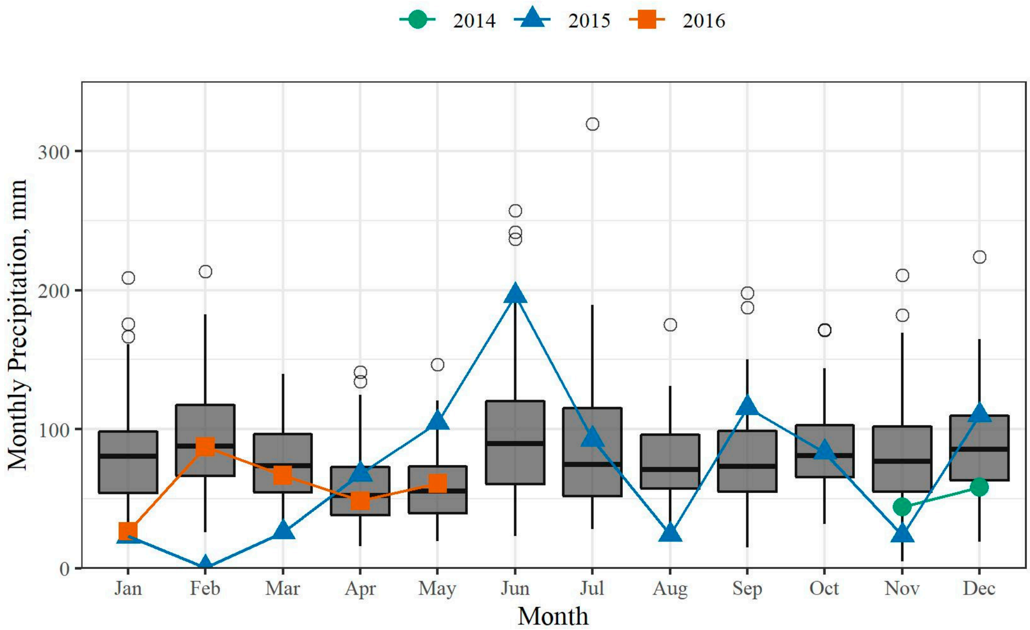

Figure 4. Tukey box and whiskers plots for the monthly historical precipitation between 1950 and 2010 as recorded at the Syracuse Hancock International Airport [19]. The bottom and top of the box represent the first and third quartiles, and the band inside the box represents the median; whiskers are presented in the style of Tukey [25–27]. Data not included in the whiskers are plotted as outliers. Monthly rainfall as recorded at the OnCenter green roof between November 2014 and May 2016 are reported as colored lines. Snow is not included in monthly totals at the OnCenter green roof but is included in the historic averages recorded at the airport. Months where rainfall is recorded for only part of the month (14–31 October 2014 and 1–16 June 2016) are included in the monitoring period but are not included on this plot.

Following removal of the non-qualifying events, 165 events remain. Rainfall duration and depth for each event are given in Figure 5 overlain by updated recurrence intervals for the region based on historic precipitation records through 2008 [28]. Of these events, three exceed the 1-year recurrence interval—one of which nears 5-year recurrence. Despite the high frequency of events, the 84 very small (<2 mm) events comprise only 5% of the measured rainfall during the study period. The 11 large events (>20 mm), however, account for 38% of the total rainfall measured. It is important to note that the green roof was designed to hold a 25.4 mm rain event.

3.2. Green Roof Performance

Cumulative retention on the green roof is 56% over the study period, a total retained depth of 599 mm. Given the 5550 m^2 roof area, a total of 3350 m^3 of rainfall is retained during the study period. Full capture occurred for 106 events, or 64% of the events. Overall mean event retention is 85%. Nawaz et al. found that cumulative retention for 19 studies varied widely, between 15% and 83%, with average and median retentions of 57% and 59% respectively [9]. One experimental study in New York City found a 55% cumulative retention during their study period for a roof with a 25.4 mm growth medium depth [9,29]. Studies with growth media of similar depth to the study (70–100 mm) reported overall mean event retention between 52% and 74% [24,30–33], though comparison to other studies has limited value as many factors influence performance of individual roofs. Note that three of the above-mentioned studies are also cited by Nawaz et al. [24,30,33]. In contrast, a study in Norway reported an annual retention of 11%–30% across multiple green roofs including both rain and snow, with a higher range of 22%–46% reported between May and October for rain only [34]. On ten plot-scale green roofs, Liu et al. reported overall mean event retention between 23% and 33.2% [35]. Significant variation exists across experimental studies reported in the literature, and recent studies have begun to consider the influence of multiple factors on the reported performance [36].

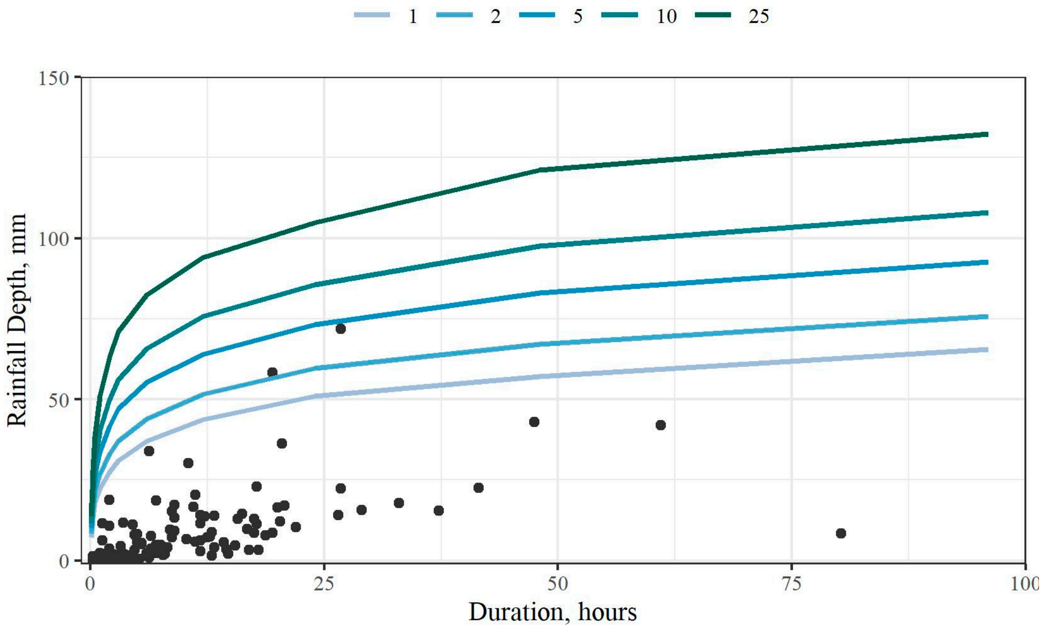

Figure 5. Rainfall duration and depth with recurrence intervals in years for Syracuse, New York. Recurrence intervals are based on historic data measured between 1950 and 2008 for the region [28].

Detention metrics, summarized in Table 1, are calculated for the 39 events where 5 min data are available and runoff occurred. Peak attenuation ranges from 0.11 to 5.2 mm/5 min, with an average of 1.3 mm/5 min. Runoff delay is calculated from peak to peak and centroid to centroid.

Table 1. Detention metrics for 39 events where runoff occurred and data are collected at the 5-minute timestep. A visual definition of detention metrics is given in Figure 2.

Metric	Minimum	Maximum	Average	Median
Peak Delay, h	−0.92	30	3.3	0.75
Centroid Delay, h	0.18	17	3.2	2.5
Peak Attenuation, mm/5 min	0.11	5.2	1.3	0.68
Peak Runoff, mm/5 min	0.01	1.4	0.31	0.26
Time to Start, h	0	12	3.6	2.8
Runoff Duration, h	0.5	48	13	11

The peak delay, calculated for the 5-minute timestep, ranges from −0.92 to 30 h, with a mean and median of 3.3 and 0.75 h, respectively. Despite the wide range, most events have a short delay, with 71% falling between 0 and 2 h. Only one event had a negative delay. The peak in runoff occurring prior to the peak in rainfall is a result of the natural variability of rainfall during an event and calls into question the appropriateness of the peak delay metric. In contrast, the centroid delay for this event is 1.5 h, demonstrating that the center of the rainfall event still preceded the center of the runoff event. One long event with a 30-hour delay had 41.9 mm of rainfall over 61 h, with most of the rainfall occurring in the first few h of the event. The green roof growth medium had the capacity to retain almost all of the first few hours of rainfall. However, the event continued at a slower rate until the capacity of the roof was exceeded and some runoff occurred, with only 63% of the total event being retained. Both of these peak delays are a result of the temporal variability of rainfall within an event and the time scale over which the roof responds. Peak delay, among other detention metrics used in green roof research, is borrowed from the field of hydrology where response times on a watershed scale are considerably longer. Other researchers have found similar behavior and also question whether the peak delay provides an accurate interevent comparison [37–39].

The delay between the onset of rainfall and runoff is, in part, a product of the antecedent soil moisture which will be discussed in Section 3.3. As rainfall continues, the retention capacity of the substrate is exceeded, and runoff begins. The wide range of detention metrics results from the temporal patterns of precipitation within an event and the initial conditions of the substrate which also influence retention. Detention metrics cannot be separated from initial losses. After moisture within the substrate exceeds field capacity, runoff response is quick and predictable. Each peak in precipitation is followed by a corresponding peak in runoff, not unlike a small watershed whose runoff is strongly governed by hill-slope mechanics [40]. The time response of the green roof results in multiple peaks within a single event definition. Previous observations on a plot-scale suggest runoff will follow rainfall almost immediately after the retention capacity of the roof is exceeded [38]. Observations on this full-scale roof suggest a delay of 15 min after the retention capacity of the substrate is met, though some of this may be attributed to the time required to travel the distance between the roof drain and the in-line flowmeter and to the equipment measurement interval. Further, this roof design incorporated drain conduits across the roof, as shown in Figure 1. As the designers intended these drain conduits aid in the removal of excess water from the growth medium, decreasing the detention time during large events.

3.2.1. Performance by Event Size

The largest events are responsible for a smaller portion of overall retention, while most of the rain falling as small and very small events is retained, as shown in Figure 6. Only one event less than 2 mm experienced any runoff. This event generated 0.03 mm of runoff from 0.65 mm of rainfall occurring on an already very wet substrate (aVWC = 0.20). The event occurred just outside the 6 h event definition allowing it to be separated from the previous event. Only 24% of the measured retention occurred within the 11 large events, detailed in Table 2. Further discussion of the effect of aVWC on evapotranspiration is included in Section 3.3.

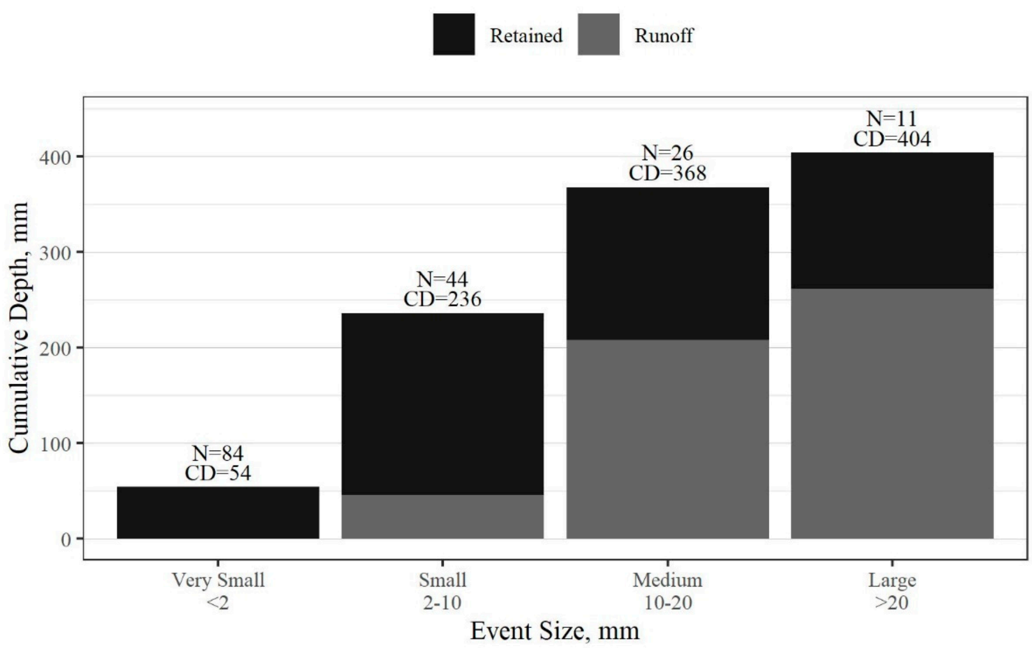

Figure 6. Runoff and retention from the OnCenter green roof, designed to hold a 25.4 mm rainfall event, grouped by event size. Cumulative depth (CD) is the sum of runoff and retained depth. Total rainfall over the 21-month study period, excluding snow days, is the sum of cumulative depths in each range—1062 mm in total.

Table 2. Details for 11 events which exceed 20 mm in total depth. Retention depth is calculated as the difference between rainfall and runoff depth. Initial soil moisture is the average of the four sensors for the timestep preceding the onset of rain.

Start Date and Time	Rain Depth, mm	Retention Depth, mm	Initial Soil Moisture, $m^3\ m^{-3}$
15 October 2014 11:15	36.3	7.46	0.084
18 May 2015 17:00	34	17.3	0.038
30 May 2015 17:30	41.9	26.4	0.019
14 June 2015 16:30	20.3	8.15	0.120
27 June 2015 14:00	43	23.5	0.040
30 June 2015 19:45	58.3	0.615	0.148
29 September 2015 11:00	71.8	16.1	0.040
9 October 2015 1:45	23	12.3	0.075
1 December 2015 23:15	22.3	3.16	0.157
29 December 2015 11:45	22.6	3.9	0.158
29 May 2016 13:30	30.1	23.1	0.017

3.2.2. Performance by Season

Event average retention is lowest during the winter and not substantially different in the remaining seasons, as shown in Table 3. Cumulative seasonal retention is highest in the fall and spring and lowest in the winter. Lower retention during the winter is explained by lower rates of evapotranspiration during interevent recovery periods. Climatic conditions during the summer months, however, promote the highest rates of evapotranspiration, which should result in high overall retention in the absence of other influencing factors. Yet summer cumulative retention is only 35%, lower than both the fall and spring. Rainfall patterns vary with the season. Summer has both less rain events and higher average event intensities than the spring or fall. During the study period, rainfall for the months of May, June, and July is higher than the median historical data. The average event peak intensity during the summer exceeds 8 mm·h^{-1} while the next highest, during the spring, does not exceed 5 mm·h^{-1}. It appears that the higher intensity, lower frequency rainfall patterns experienced during the summer contribute to the season's lower performance.

Table 3. Retention by season for the OnCenter green roof.

Season	Seasonal Retention		Rainfall	Event Count		Average Intensity	
	Event Average, %	Cumulative, mm	Depth, mm	Full Capture	Total	Event Mean, mm·h^{-1}	Event Peak, mm·h^{-1}
Fall	89.2	141	310	34	52	0.654	4.12
Winter	70.1	44.5	158	12	25	0.479	2.45
Spring	88.7	160	329	36	53	0.525	4.92
Summer	85.3	93	265	24	35	1.01	8.17

Probabilities of exceedance for runoff depth separated by season are given in Figure 7. Winter events are more likely to result in greater runoff depth, consistent with the behavior reported in the literature [24,41], and the low average retention for this season. The results of a one-way ANCOVA found that the difference in runoff behavior is statistically significant at the 0.05 level only for winter and summer. Weather conditions between the spring and fall are not statistically different, but an increase in the number of events in future data collection periods along with consideration of other weather factors may provide more insight into these trends.

3.3. Evapotranspiration

Retention performance has an inverse relationship with aVWC. The substrate has a finite capacity to hold water, after which all incoming precipitation enters the drainage structure. The difference between the soil moisture level in the substrate and its maximum capacity is the available water retention capacity. During interevent periods, the retention capacity of the substrate is restored via ET.

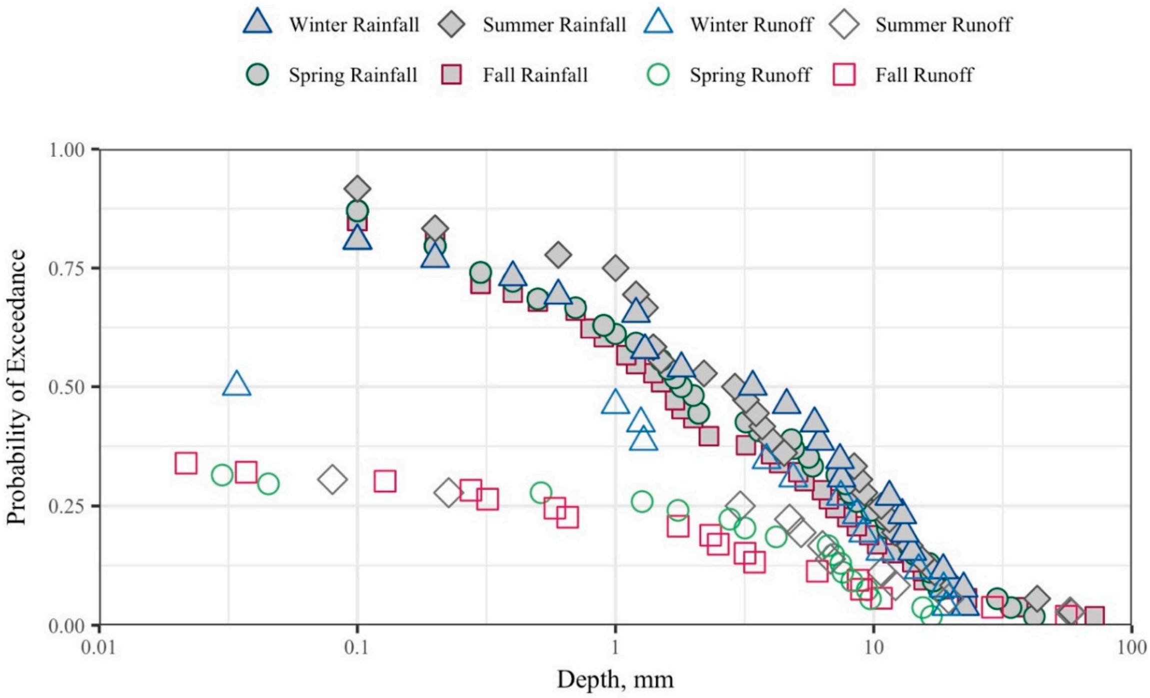

Figure 7. Event exceedance probability for runoff depth separated by season for the OnCenter green roof.

Daily ET rates for dry days averaged across a transect of the roof, as shown in Figure 8, range from 0 to 2.5 mm·day^{-1}. On this same roof, daily ET measurements for both wet and dry days during warm months between 2015 and 2017 are found to range from 0 to 5.4 mm·day^{-1}, with a daily average of 0.76 [42]. Plot-scale studies planted with *Sedum mexicanum* and *Disphyma australe* in New Zealand found ET rates from 1.9 to 2.2 mm·day^{-1} under unstressed water conditions [33]. Measurements made on two green roofs in New York City in 2009 and 2013 found an average daily ET of 0.24 and 0.72 mm·day^{-1} in December and 4.80 and 4.94 mm·day^{-1} in July [43]. The ET measurements here are within these ranges measured on other roofs. Differences between measurements made in Syracuse and New York City may result from differences in weather as well as in roof construction, i.e., substrate retention properties. A consistent drying curve for ET is visible for multiple periods throughout the data set as a series of points decreasing in a nearly vertical line. A longer dry period results in a nearly vertical line with slight curvature near the bottom of the graph, due to decreasing ET as the soil dries, e.g., between 25 April and 9 May 2015, as available soil moisture has a direct relationship with rates of ET. As weather cools through fall 2015 and the available energy for ET decreases, there are fewer points with large ET. The current method of estimating ET cannot be used with snowstorms, but there are some rains in December and February which enable estimates of ET that are less than 1 mm day^{-1}. Rising temperatures in March, April, and May result in increasing maximum values of ET. Between late May and early July infrequent and intense storms result in high ET rates immediately following an event and long consistent decay in the period June–July 2016.

ET rates are limited by the availability of energy and water. Daily maximum insolation and initial daily soil moisture are considered relative to daily ET rates as proxies for available energy and water on the roof, as shown in Figures 9 and 10, respectively. As insolation increases, the maximum ET rates (corresponding to sunny days) show an approximately increasing pattern. Days with low maximum insolation, less than 250 W·m^{-2}, are cold weather days in the period late November–December 2015, where lower ambient temperatures also contribute to the low ET rates. While cloudy summer days are included in the study, all days between 27 October 2015 and 6 February 2016 have a maximum solar insolation of less than 500 W·m^{-2} and insolation values measured for only 9–11 h. In contrast, many late spring and summer days report insolation measured for 14–16 h per day and reach maximum values above 750 W·m^{-2}.

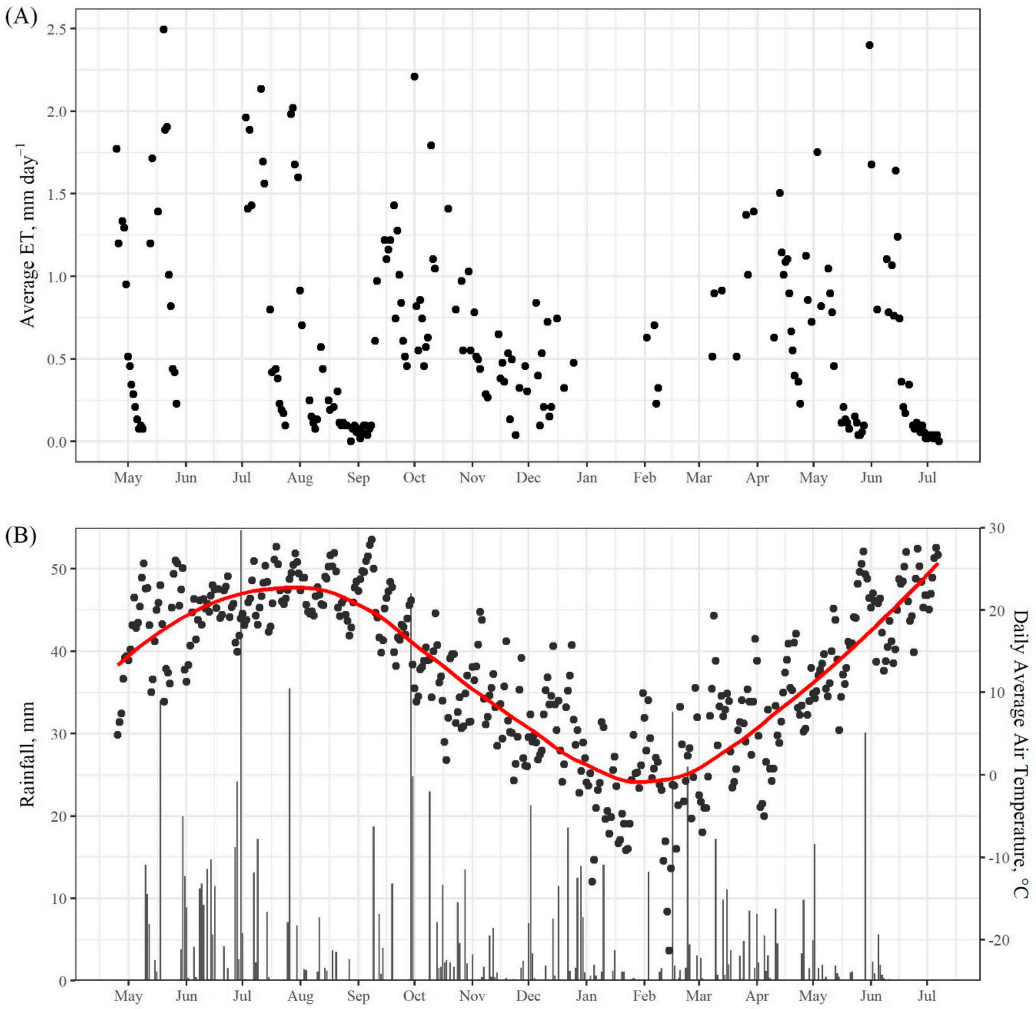

Figure 8. (**A**) Average evapotranspiration as quantified on the OnCenter green roof for dry days between 25 April 2015 and 8 July 2016. (**B**) Daily average temperature with a local linear regression and daily rainfall, as measured on the OnCenter green roof between 25 April 2015 and 8 July 2016.

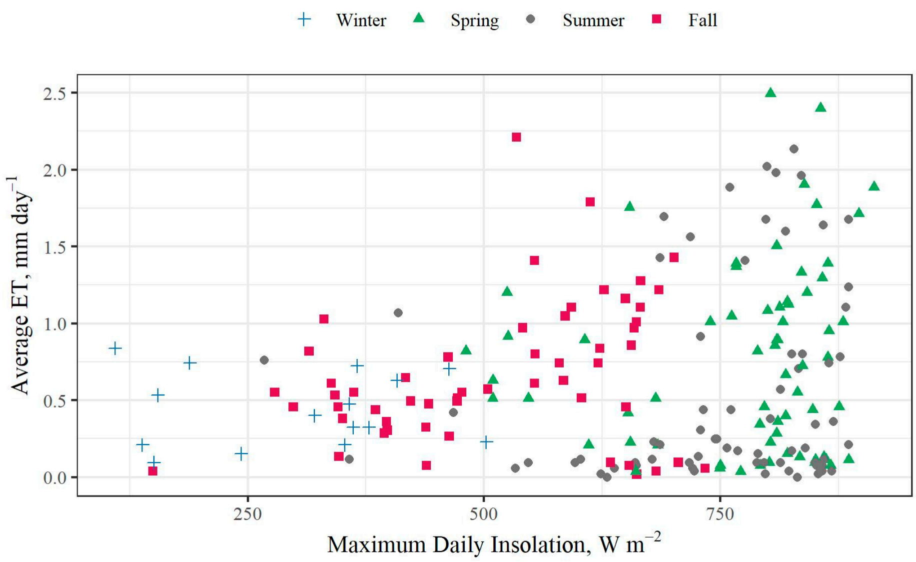

Figure 9. Seasonal trends in average daily evapotranspiration relative to maximum daily insolation on the OnCenter green roof.

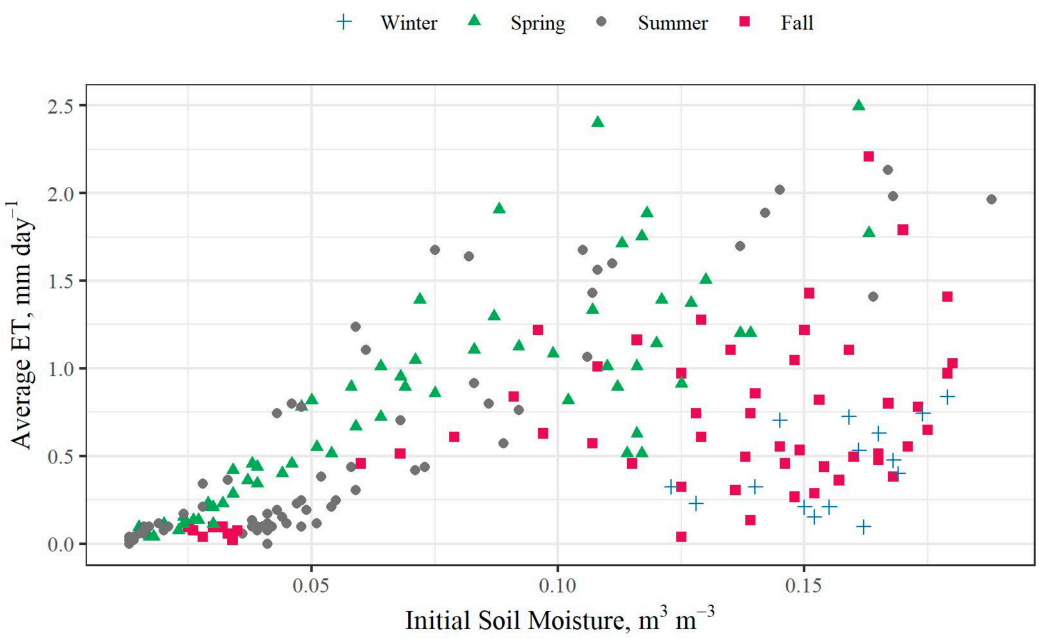

Figure 10. Average daily evapotranspiration relative to daily initial soil moisture on the OnCenter green roof.

Under conditions with significant available energy for ET, limited available water results in low rates of ET. During water-limited periods, the range of ET rates is small. In contrast, during periods of abundant available water, ET rates have a larger range as the amount of energy available for ET varies. Water-limited conditions, although infrequent, occur primarily in the summer. Under rare drought conditions in the summer of 2016, a minimum soil moisture of 0.009 m^3 m^{-3} was recorded on 8 July 2016, after 13 mm fell in 39 days during a period of high incoming solar radiation. This value is significantly lower than the wilting points reported in the literature [33,44,45]. With the annual cycling of incoming solar radiation, energy available for ET varies, influencing the available water retention capacity of the substrate and therefore seasonal retention performance. Field capacity on the roof as estimated from the observed soil moisture after runoff has ceased is approximately 0.22 m^3 m^{-3}, but varies spatially across the roof due to localized differences in substrate structure and flow pathways.

4. Conclusions

This study examined the rainfall–runoff response of the Onondaga County Convention Center green roof, a large extensive green roof in Syracuse, NY. Dominant hydrologic processes were investigated for their contribution to the overall hydrologic function of the roof. A monitoring program was conducted to measure components of the water mass balance from a 1792 m^2 section of the roof. The roof retained a significant amount of rainfall on an annual basis, but most of that retention occurred during small rainfall events. For large rainfall events, runoff occurred after the retention capacity of the roof was exceeded. The roof was designed to hold a 25.4 mm rain event. Evapotranspiration was found to drive the recovery of the retention capacity between rainfall events. Evapotranspiration can be limited by the availability of water at times and by the availability of energy at other times—which of these is more important varies with season. Coupled with differences in rainfall characteristics, the variation in evapotranspiration with season is responsible for the difference in performance between winter and summer.

Detention performance metrics, commonly used in the green roof literature, were reported here despite their limitations. Peak delay, the temporal difference between the peak in rainfall and peak in runoff, yields a wide range of values which provided minimal information without additional context.

This study further supports the need for care in reporting detention and comparing detention metrics among different roofs. Characteristics of drainage structures on this green roof and on other green roofs can markedly affect detention of stormwater.

This work advances the understanding of extensive green roof performance by considering events across a multiple season-duration study period and in an inland Northeast U.S. climate. This research further supports the need for long-term studies on full-scale green roofs in multiple climates and under natural conditions, as it demonstrates how performance is closely coupled with localized weather patterns. Future studies should consider green roofs as part of a larger system for managing stormwater in the urban environment. More work is needed to understand how green roofs could fit within the larger urban system.

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