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COMPARING THE HYDROLOGIC PERFORMANCE OF INTENSIVE AND EXTENSIVE GREEN ROOFS IN ATLANTA, GA USA

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COMPARING THE HYDROLOGIC PERFORMANCE OF INTENSIVE AND EXTENSIVE GREEN ROOFS IN ATLANTA, GA USA

by

HANNAH STEFANOFF

Under the Direction of Luke A. Pangle, Ph.D.

ABSTRACT

High concentrations of impervious surfaces are synonymous with urbanization. A heavy presence of impervious surfaces cause stormwater buildup and excessive runoff. Green roofs are designed to reduce stormwater runoff from roofs and reduce peak outflow. The range of stormwater retention in green roofs is wide, ranging from 40-80%, due to differences in soil depth, vegetation type, and local weather patterns. This study compared two green roofs located in downtown Atlanta, GA, USA, one extensive and one intensive. The extensive roof was found to reach 20% volumetric water capacity, while the intensive reached 25% for the highest capacity event, over a prolonged wetting period. The volume of outflow was higher in an intensive roof due to higher soil volume (23.27 m^3) when compared to an extensive roof (10.25m^3). A determination of superior retention amongst soil depths was not made due to variable initial soil moisture, with a regularly irrigated extensive roof kept at 10% volumetric capacity for the duration of the study.

INDEX WORDS: Impermeable, runoff, retention, stormwater, green infrastructure

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HANNAH STEFANOFF

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science
in the College of Arts and Sciences
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Georgia State University
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DEDICATION

I dedicate this thesis to my mom, Monica Stefanoff, for being a constant reminder of where persistence leads us, especially when I need reminded most.

ACKNOWLEDGEMENTS

I would like to thank Luke Pangle, whose guidance was invaluable to the completion of this project. I would like to thank Richard Milligan and Jeremy Diem for their roles on my committee. I also would like to thank the Georgia State University Department of Geosciences and Office of Sustainability for funding my education and research.

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1 INTRODUCTION

With the prevalence of impervious surfaces and lack of vegetation due to urbanization, there has been increased desire to implement green infrastructure in cities. Increased population has expanded the area of impervious surfaces. This increase not only decreases the infiltration of stormwater, but also elevates peak discharges during flood events (Du, Cheng, Zhang, Yang, & Xu, 2019). Not only is there a growing problem due to lack of water infiltration and peak discharges during all storms, but also the possibility of an increase in flood levels due to increasing climate change (Wright, Smith, Villarini, & Baeck, 2012).

Green roofs have gained traction as a form of green infrastructure, yet the storm water retention capacity of the roof media is unknown because research remains inconclusive. Hydrologic characteristics of green roofs are often considered to be constant, but actually have large sub-annual retention variations, reaching as high as 63% (De-Ville, Menon, & Stovin, 2018). The total porosity of green-roof growth media may be easily determined, yet this metric cannot be directly equated to water-storage capacity, because soils typically do not fully saturate during rainfall infiltration. The infiltration rate of the soil and subsequent retention can depend on multiple factors, including rainfall rate, storm intensity, and the level of initial soil wetness prior to precipitation events (Zhu et al., 2018)

1.1 Effects of Urbanization and Impervious Surfaces on Runoff

It is well established that an increase in the aerial coverage of impervious surfaces leads to higher peak flows of stormwater into urban stream channels (e.g. Mejia and Moglen, 2010). Clustered impervious coverage distant from streams still increase peak flow (Debbage & Shepherd, 2018). Over half of the world’s population lives in urban areas, increasing the desire to improve stormwater management and create ways to increase infrastructure mimicking natural hydrologic processes (Martinez et al., 2018) Green stormwater infrastructure, such as green roofs, rain gardens, and swale systems are commonly chosen local infrastructure additions to help in stormwater mitigation (Zölch, Henze, Keilholz, & Pauleit, 2017). Impervious surfaces cover expansive areas in urban environments, which include parking lots, sidewalks, driveways, roofs, and roads. Of these impervious surfaces, rooftops typically make up 40-50% of the total (Sims et al., 2016). Because impervious surfaces lack a storage space for storm water, there is a tendency for storm events in urban environments to generate increased peak flows with high velocity and more erosive power than occur in green spaces (Finkenbine, Atwater, & Mavinic, 2000). This water is diverted to storm-sewer systems quickly with increased impervious surfaces, leading to overflow that commonly causes flash flooding (Hilten, Lawrence, & Tollner, 2008). In urban environments, even pervious surfaces (e.g. green spaces) often have reduced permeability due to compaction. Compaction occurs due to removal of vegetation and associated macropores that shrubs and grasses provide (Wang et al., 2018). Compaction of soil decreases soil porosity, meaning there is less space in the soil for water to be held, therefore less water infiltration is happening in urban soils than natural soils (Wright et al., 2012).

1.2 Classification of Green Roofs

Green roofs have multiple benefits including improved storm water management, water quality, and reducing the urban heat island effect (Castleton, Stovin, Beck, & Davison, 2010). Green roofs are generally categorized as intensive or extensive: intensive roofs generally have thicker soils supporting a broader array of plant types, whereas extensive roofs typically have thin soil and are limited in the types of plants they can support (van der Meulen, 2019). Typically, an intensive green roof has a depth of 15 or more cm, while an extensive green roof has a depth of less than 15 cm (Guo, Zhang, & Liu, 2014). Regardless of the roof category, roofs generally contain a drainage layer, substrate layer, and vegetative layer (Figure 1).

1.3 Controls on Storm-Water Retention by Green Roofs

There are multiple factors to consider when attempting to quantify how effective a vegetated roof is in storing and attenuating the flow of rainfall. These factors include precipitation, solar radiation, temperature, relative humidity, vegetation type, soil layer properties, and the size and intensity of storm events (Cipolla, Maglionico, & Stojkov, 2016). At present, the U.S. does not have standards for green roof construction and the retention capabilities may vary from roof to roof (Carson, Marasco, Culligan, & McGillis, 2013). There is an average rain fall retention in green roofs commonly ranging anywhere from 40-80% (Sims et al., 2016). Green roof porosity represents potential storage volume making soil substrate depth a stormwater retention control, but the relationship between substrate depth and retention is strongly conditioned by other factors, including total rainfall volume, duration, and intensity, as well as antecedent wetness of the soil prior to storms (Nawaz, McDonald, & Postoyko 2015). A retention of 40 – 80% of total rainfall volume and decrease of 60 - 80% in peak runoff rate has been found in previous green roof studies, according to a review by Lamera, Becciu, Rulli, and Rosso. This range is consistent among studied climate types, with green roof studies taking place primarily in warm temperate climates and continental climates (Akther, He, Chu, Huang, & van Duin, 2018). There is little consensus on the maximum storm size that allows for best retention among green roofs.

The degree of saturation in the soil plays a role in the ability of storm water to infiltrate. In a green roof study spanning three different climates in Canada, researchers concluded that the rainfall retention was controlled by antecedent moisture conditions (AMC), where humid continental, semi-arid, and humid climates had a retention ranging from 16-29% during large rainfall events. Green-roof soil with greater antecedent wetness has less vacant pore space and capacity for infiltration, causing soil to reach capacity quicker, increasing the likelihood of saturation excess and stormwater runoff (Bai et al., 2018). Infiltration-excess runoff occurs when the rainfall rate is greater than the infiltration rate into the soil (Lahdou, Bowling, Frankenberger, & Kladivko, 2019). Saturation excess has previously been found to dominate runoff on flat, homogeneous roofs, which is synonymous with an extensive green roof (Yang, Li, Sun, & Ni, 2015).

The lack of available research on intensive roofs because of the lower cost and ease of installation of extensive roofs (Carter & Fowler, 2008) expose a need for further research on the differences in stormwater management between the two roof types. Although there is a lack of research on the efficacy of intensive green roofs for stormwater mitigation, there is also a lack of consensus on the overall performance of green roofs because hydrologic benefits have only been studied for the last decade (Nawaz, McDonald, & Postoyko, 2015). The range in retention rates of green roofs in past studies presents the opportunity to narrow the range and gain a clearer understanding of green roof effectiveness. In one study an overall mean of 56% retention was found, and in another study comparing different roof types an average retention of 74% for extensive and 88% for intensive green roofs was determined (Razzaghmanesh & Beecham, 2014). However, this study was done in dry climate and it is proven that drier climates retain a higher percentage of rainfall (Sims et al., 2016). Another study in the Pacific Northwest found that the largest difference in retention between substrate depths occurred with 5-10 mm of rainfall and storms of over 35 mm had the smallest difference at 13.2% for the thinner soil and 15.9% for the thicker soil (Schultz, Sailor et al. 2018).

This research compares two different roof locations in downtown Atlanta to answer the following: How do the efficacies of intensive and extensive green roofs compare in the humid subtropical climate of Atlanta, GA, considering the broad range of storm characteristics and antecedent wetness conditions? To compare the moisture capacity of different roof types, two green roofs in downtown Atlanta, GA were monitored for this study. To identify whether an extensive or intensive roof best mitigates stormwater runoff, soil moisture and outflow were quantified and compared at the two downtown Atlanta locations.

2 METHODOLOGY

2.1 Site Description

The intensive green roof is located on top of Georgia Tech University's Clough Commons at 266 4th St NW, Atlanta, GA 30313 and the extensive roof is located at Southface Energy Institute located at 241 Pine St. NE, Atlanta, GA 30308 (Figure2). These two locations were chosen because they have vastly different substrate depths and volume. The soil volume at the Clough Commons and Southface green roofs are 21 m^3 and 10 m^3, respectively. The roof at Southface is an extensive green roof, with average depth of 0.1 m. The roof located at Clough Commons is an intensive green roof, with average depth of 0.51 m.

The types of vegetation present on the intensive roof at Southface are all types of low-growing succulents or perennials that do well in hot, dry environments (Figure 5D). The plants present are all in genus *Sedum* or *Delosperm*, including *Sedum calycinum*, *Sedum pachyphyllum*, *Delosperma cooperii*, and *Delosperma kelaidis*. The green roof is located on the third floor and covers 185 square meters. Clough Commons at Georgia Tech is an intensive green roof with variable soil depth with green roof pods spread throughout the roof area. Walking paths also run through the various vegetated pods. The intensive site used for the study was located in one of these vegetated pods in the northeast corner of the roof (Figure 5A). The variation in vegetation on the intensive pod also makes the site more topographically variable.

Table 1 Southface and Clough comparison based on green roof type.

Location	Roof Type	Average Depth	Vegetation
Southface Energy Institute	Extensive	10 cm	Low lying (Genus *Sedum* and *Delosperma*)
Clough Commons	Intensive	51 cm	Grasses, shrubs, trees (eg. Genus *Carex*)

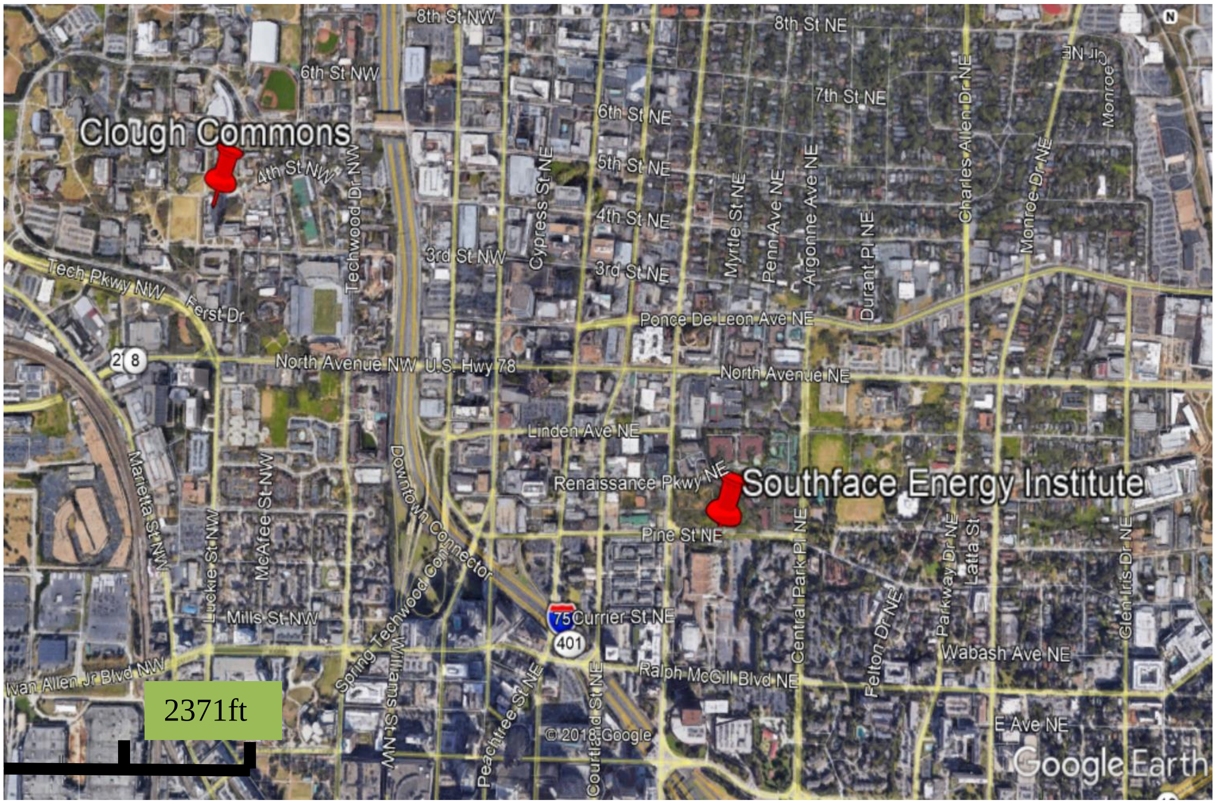

Figure 1 Map of study site locations in downtown Atlanta, GA.

Figure 2 Aerial view of extensive green roof at Southface Energy Institute.

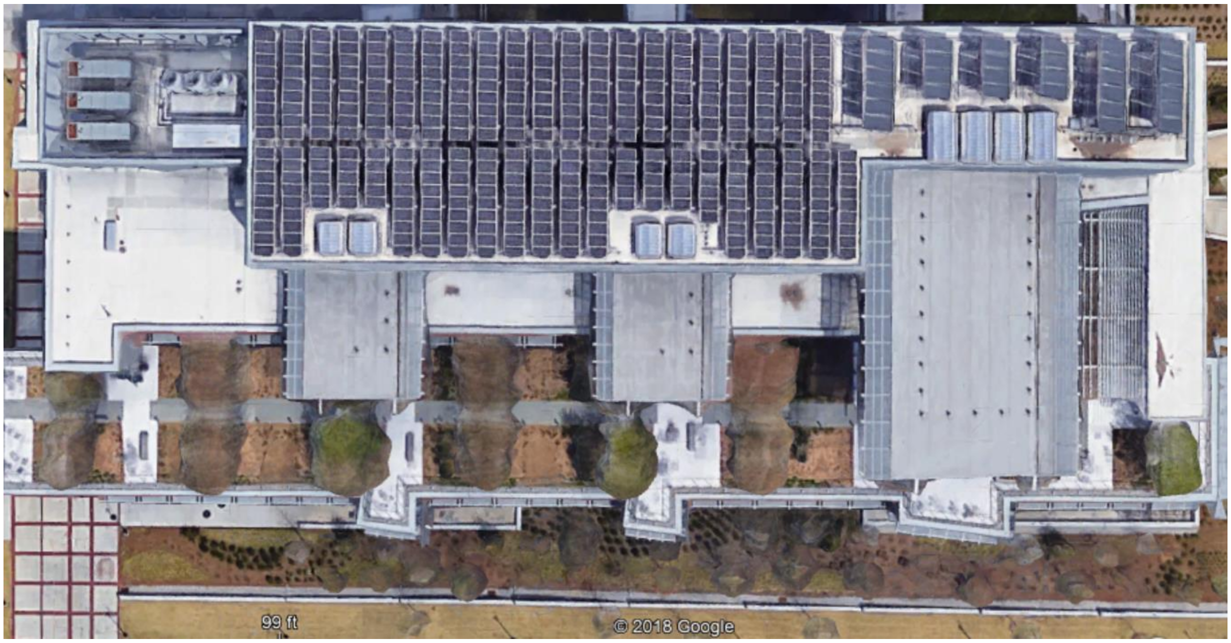

Figure 3 Aerial view of intensive green roof at Clough Commons.

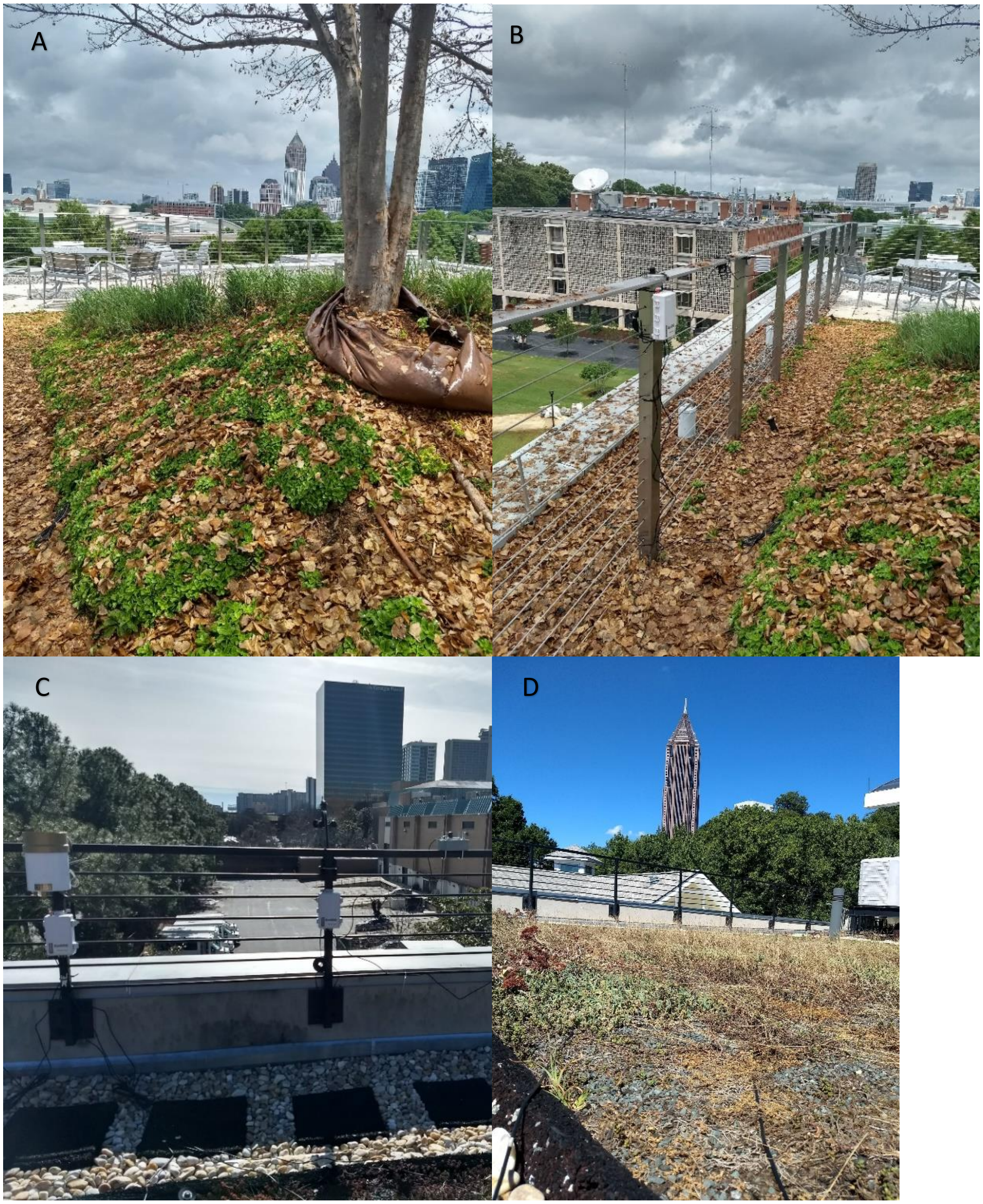

Figure 4 Study Sites
(A) *Green roof at Clough Commons.*
(B) *Clough Commons roof with data logger*.
(C) *Tipping bucket rain gauge and data loggers at Southface Energy Institute.*
(D) *View from Southface of uniform substrate*

2.2 Substrate Depth Measurements

Due to the irregular dimensions of the substrate area at Southface, the roof had to be separated into four separate geometric shapes. The average depth of the roof was measured by inserting a metal rod, 2.54 cm in diameter, at ten different points in the soil. This average depth was used in the soil volume calculation. All measurements were recorded to the nearest centimeter.

Table 2 Southface Substrate Dimensions

Shape	Dimensions (m)	L (m)	W (m)	Avg. Soil Depth (m)	Volume (m^3)
A	7.92 X 7.47	7.92	7.47	0.10	6.04
B	7.47 X 2.59	7.47	2.59	0.10	1.98
C	7.92 x 1.68	7.92	1.68	0.10	1.36
D	5.64 X 1.52	5.64	1.52	0.10	0.88

Due to the heterogeneous nature of the Clough roof substrate, more depth measurements were taken at this location than at Southface. The rod was inserted into the soil at various points, marked at the soil surface, and measured with a tape measure. The depth was recorded thirty-five times, at equidistant points across the substrate. The average of all depth measurements was used when calculating the volumetric soil content. The study site at Clough is a rectangle so only one width and length measurement was needed to calculate the substrate volume after the average depth was calculated (Table 3).

Table 3 Clough Substrate Dimensions

Length (m)	Width (m)	Avg. Depth (m)	Volume (m^3)
8.08	5.64	0.51	23.27

2.3 Automated-Environmental-Data Collection

Precipitation data was collected at the Southface Energy Institute using a Texas Electronics tipping bucket rain gauge. These data were used as the inflow volume for both roof locations. An ATMOS 14 produced by Meter Group was used on both roofs. This sensor provides the air temperature, relative humidity, and barometric pressure. A Davis Cup Anemometer produced by Meter Group was used to measure wind speed. The Meter Group PYR Solar Radiation Sensor was used to measure solar radiation in W/m^2. The volumetric water content (VWC) and temperature of the soil on both roofs were measured with ECH_2O 5TM. Five probes were placed on each roof. Each of the five probes on Southface were place equidistant apart due to the uniformity of the soil. On Clough, three probes were placed in visibly deeper soil, and two were placed at shallow soil depth to provide measurement coverage of the entire soil profile. Each probe was placed perpendicular to the soil surface, 5 cm below the substrate surface. Probes were place this way to minimize the error with water flowing downward in the substrate (Group, 2018).

2.4 Storm Categories

A frequency distribution for precipitation was made covering the entire study period (Figure 5). The precipitation categories used were 0-2.5mm, 2.5-5 mm, 5-7.5 mm, and 10+ mm. These categories are for cumulative rainfall over each fifteen-minute time interval in the entire dataset where rainfall occurred. A frequency distribution puts the maximum storm intensities into context, as a percentage of total storm events in the analysis.

2.5 Data Analysis

A general water budget equation was solved for each green roof. Outflow was calculated for each fifteen-minute time increment during each analyzed time series. Outflow here represents both evapotranspiration and drainage through the soil. The two flows were not readily distinguishable due to the unknown flow path of drainage through the plumbing systems at each site. The equation below was used:

$$O = P - \Delta S$$

O = outflow
P = precipitation
ΔS = change in substrate storage

The soil storage was calculated from the volumetric water content (VWC) measured via the 5TM probes. The VWC is the volume of water per unit volume of soil, and can be expressed as a unitless ratio or percentage. To calculate the soil storage at each time increment of measurement, the VWC was converted to an actual water volume (m^3) by multiplying by the total soil volume (Table 1 and 2). This equation is shown below.

$$S = VWC * V$$

S = storage

VWC = volumetric water content (m^3/m^3)

V = total substrate volume ($m^{3)}$

The change in soil moisture (ΔS) during each fifteen-minute increment was calculated simply as the difference between S at the end of a time increment and S at the beginning, as below:

$$\Delta S = S_f - S_i$$

ΔS = change in soil-water storage (m^3)
S_f = final soil moisture volume (m^3)
S_i = initial soil moisture volume (m^3)

All input volume was assumed to come from precipitation at both locations. The Clough locations received irrigation water midway through the summer of 2018, so if the data showed irrigation peaks during storm events, these were not analyzed for retention performance.

3 RESULTS AND DISCUSSION

The overall time series displaying precipitation (A), volumetric water content in the soil (B), and solar radiation (C) shows the relationship between precipitation peaks and soil moisture peaks. When there is a peak in precipitation, the soil moisture at both locations increase simultaneously due to the influx in water (Figure 6). There is a gap in data in late July because there was not available soil moisture data for this time period due to instrument failure. The dark blue and dark orange points represent the average volumetric water content of the five soil probes from each location during 15-minute time increments, with Southface in blue and Clough in orange. The light blue and light orange show the standard deviation of each probe from the average.

The study spanned six months, with temperatures remaining consistent until a drop in late September (Figure 6A). There is little difference in temperature and relative humidity between either roof from May – November 2018.

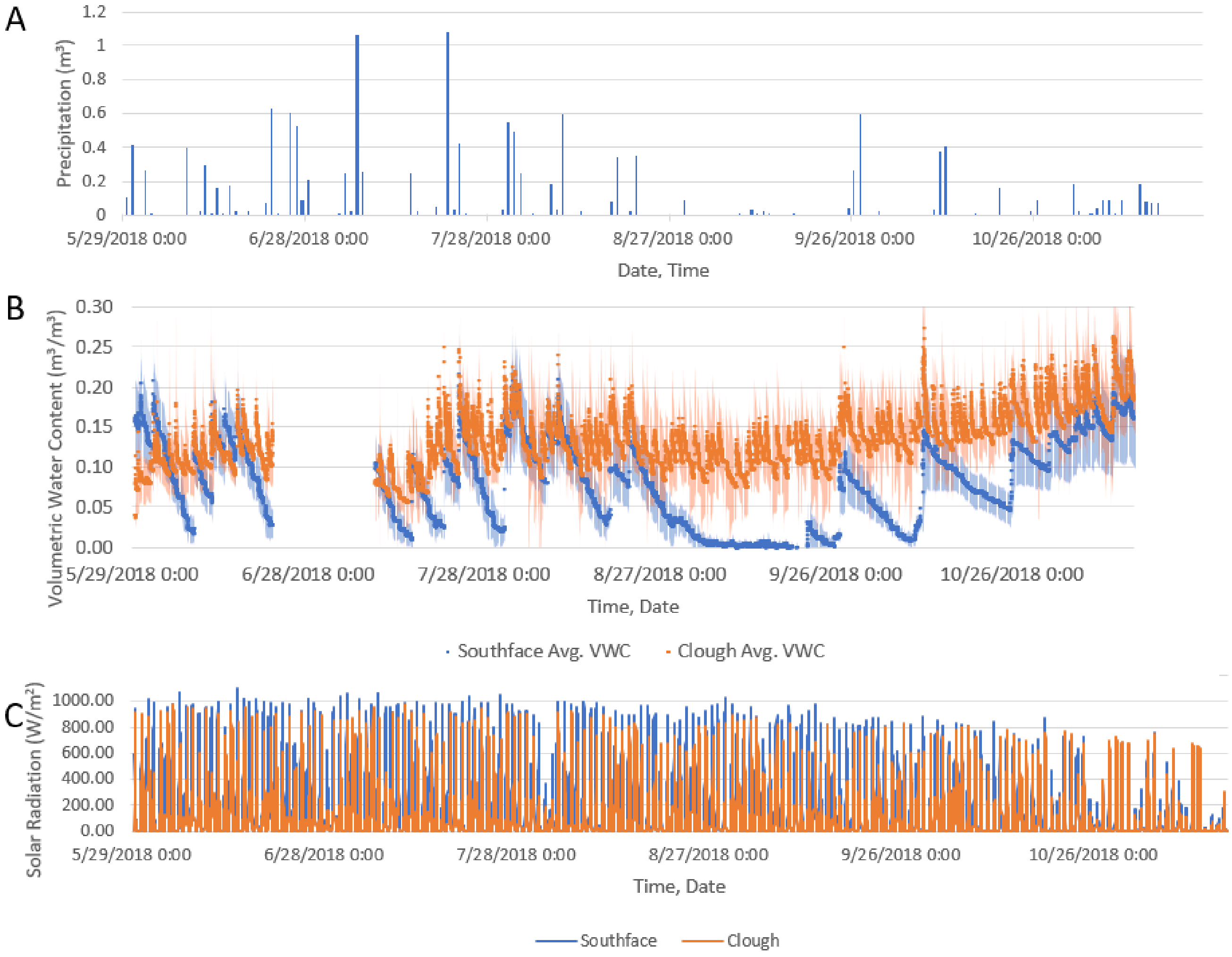

Figure 5 Total time series of precipitation (A), soil volumetric water content (B), and solar radiation (C) at both roof locations.

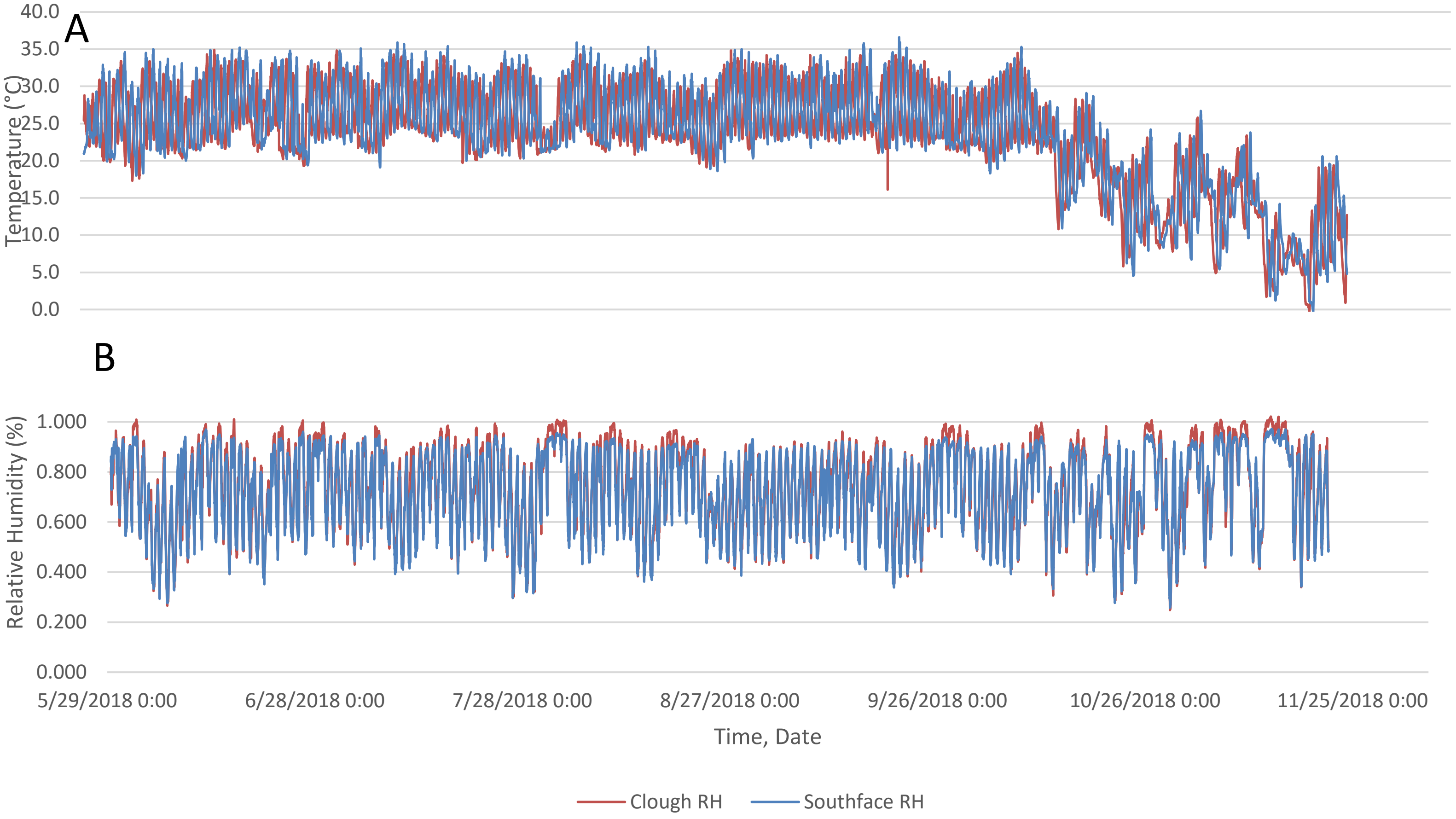

Figure 6 Total time series of temperature (A) and relative humidity (B) at both roof locations.

Each analyzed storm event was given a letter identification. The letter ID’s assigned to each event are used in subsequent sections. The start and end time of each event, total precipitation, average intensity, maximum intensity, and antecedent moisture at both locations for the previous two hours were recorded. The duration is defined as the time span from the beginning to the end of a storm event. A rain event was considered complete when no precipitation had occurred for six or more hours. The storm durations ranged from fifteen minutes to fifteen hours. The maximum intensity of each storm is also listed and defined as the highest rainfall volume occurring in a fifteen-minute period during the event. The antecedent moisture content (AMC) is the average soil moisture content over the two hours prior to a storm (Table 4).

Table 4 Analyzed storm events, separated by date and time.

Storm ID	**Start Time**	**End Time**	**Total P (mm)**	**Avg. Intensity (mm)**	**Max Intensity (mm)**	**Clough AMC (Previous 2 hrs)**	**Southface AMC (Previous 2 hrs)**
A	6/1/2018 13:00	6/1/2018 19:00	21.43	1.43	5.94	0.097	0.123
C	8/9/2018 13:45	8/9/2018 18:00	23.5	2.61	13.17	0.14	0.125
D	9/26/2018 16:15	9/26/2018 19:15	10.92	1.21	5.84	0.116	0.016
E	9/27/2018	9/27/2018	16.51	2.39	13.21	0.142	0.073
F	10/10/2018 8:45	10/11/2018 5:15	109.73	2.11	8.38	0.134	0.03
G	10/25/2018 21:30	10/26/2018 11:30	24.38	0.53	1.52	0.148	0.047
H	11/12/2018 4:45	11/14/2018 0:30	81.28	0.89	4.06	0.145	0.137
I	11/14/2018 7:15	11/14/2018 9:15	1.27	0.25	0.25	0.185	0.167
J	11/14/2018 16:00	11/15/2018 7:30	32	0.58	1.52	0.185	0.169

Storm intensities ranged from 0- 12.5 mm in total rainfall. Over this 6 month analysis, storm events with 15 minute rainfall intensities of 0-2.5 mm were the highest percentage of events with almost 90% of the rainfall periods having this intensity (Figure 8). A storm intensity of over 10 mm was highly unikely, with under 5% of the total 15 minute periods of rainfall having this level of instensity.

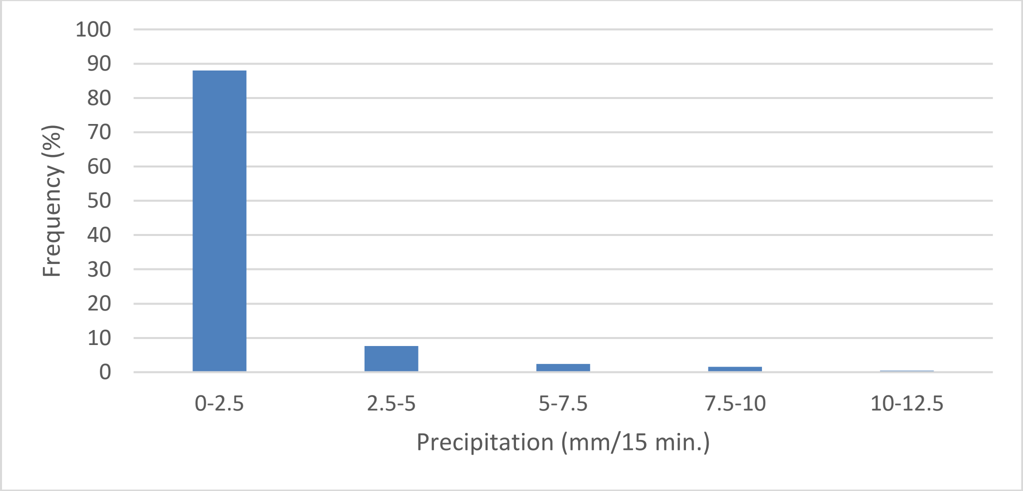

Figure 7 Frequency distribution of fifteen-minute rainfall totals.

Figures 9-14 below show the change in the soil volumetric water content over the course of each analyzed storm event, where the peaks during each event represent the maximum water content reached during that storm. The letter identifications given to these events correspond with those listed in Table 4 above. Multiple storms were combined when they took place over consecutive days or a second storm occurred close to the soil moisture recession stage from a past event. This occurred for storms H, I, and J, where three storms took place close together and each event impacted the antecedent moisture of the next, occurring with the recession of one another (Figure 14). The first storm event in this series (Storm H) had a total rainfall volume far above the rest of the events over the three-day period. The total was 81 mm compared to the 1.27mm and 32 mm of the final storm. The final VWC that was reached at Southface was 19%, while Clough was 26%, so during this large storm event with almost the same initial VWC, Clough increased the soil moisture capacity by 12% and Southface by 6%. After the slight recession in response to the peak of storm H on November 12, between 18:00 and 19:00, soil moisture stays consistent until November 14.

The next storm in the series, I, had the lowest total precipitation and maximum intensity, and began and ended with almost the same soil moisture content. There was a clearer difference in the behavior at each roof during the final analyzed storm. This final storm was the third largest storm out of the ten, with an excess of antecedent moisture from the previous two storms. The initial soil volumes were similar, with Southface at 17% and Clough at 18%, but they were able to increase to 18 and 23%., concluding that after prolonged, intense saturation, an intensive roof (Clough) is better equipped to handle an influx of precipitation.

The difference in outflow rate from the first storm (Figure 21), compared to the final storm (Figure 22) shows an increase in deterioration in retention performance at Clough. The ouflow trend at Southface stayed about the same, but Clough had a discernible outflow increase by storm J. The analyses for storms H, I, and J exhibit the effects of an increasing AMC with little recession time between storms. Storm J has a high AMC as a result of the two previous days of storms. When the AMC's at both locations were the same in this later scenario, Southface was superior in maintaining retention capabilities throughout a high volume storm event.

The intensive (Clough) and extensive (Southface) display moisture peaks at the same time because of the influx of precipitation at both sites. This can be seen in each soil moisture graph (Figure 9-14). An example of this can be seen in Figure 12 on October 10. The peak precipitation, represented by the highest blue bar on October 10, at 16:45, is also when the soil moisture at both Clough (black) and Southface (green) reach a high point. This coinciding precipitation and soil moisture peak also occur on August 9 at 17:00 (Figure 10). Both Clough and Southface peak just after the point of maximum rainfall intensity.

Storm E, on September 27, 2018, totaled 16.51 mm of precipitation, and had a maximum intensity of 13.21mm/15 minutes (Table 4). The substrate at Clough reached a soil moisture content 10% higher than Southface at the peak of the storm, with volumetric water contents of 25% and 15%. The peak outflow volume from this event was higher at Clough (Figure 18), while the ratio of outflow to average unit volume stored in the soil at both sites, Clough is lower, appearing to hold more water per volume (Table 6).

Storm F is a significant storm out of this group because it was part of Hurricane Michael and the highest total precipitation, 109.73 mm, of all storm events (Table 4). The max intensity for event F was 8.38 mm, with an average intensity of 2.11mm so there was an average of two millimeters of rain falling over a 21-hour time period. There were two separate times when the rain intensity was noticeably higher than the rest of the storm. These occurred at 10:45 and 16:30 (Figure 12), which also aligned with soil moisture peaks at both locations. During the first precipitation maximum, the soil moisture at Southface increased from 3-10% and Clough changed from 16-22%. During the second soil moisture peak, and overall maximum intensity for the entire storm, the VWC at Clough increased to 27%, while Southface increased to 14% (Figure 12). This means that both roofs had an overall increase of 11% soil moisture content during the storm.

The precipitation peaks seen in Figures 10 and 11 are also the two highest storm intensities of the ten storms. The soil moisture content increased more dramatically at Clough than at Southface during storm E (Figure 11). The opposite is true of storm A, where the VWC at both roof locations peak at similar values a recede identically (Figure 9).

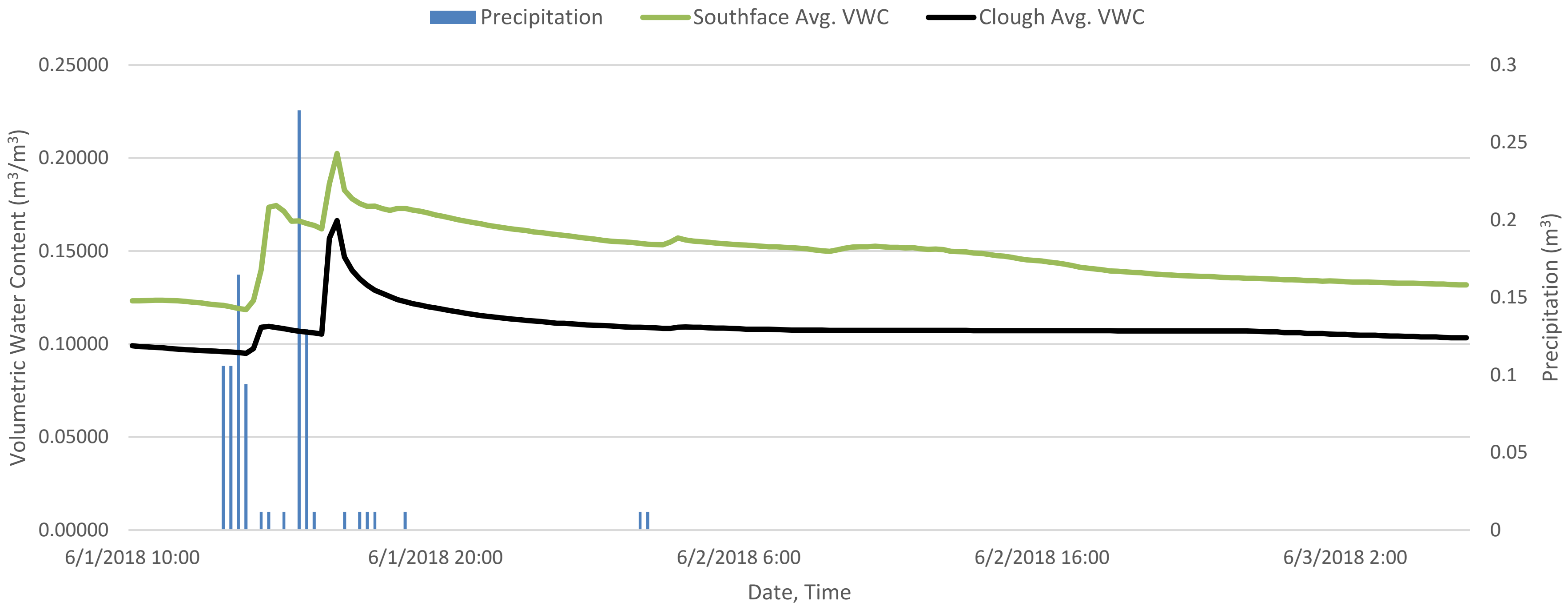

Figure 8 Soil moisture content and precipitation at Southface and Clough during Storm A.

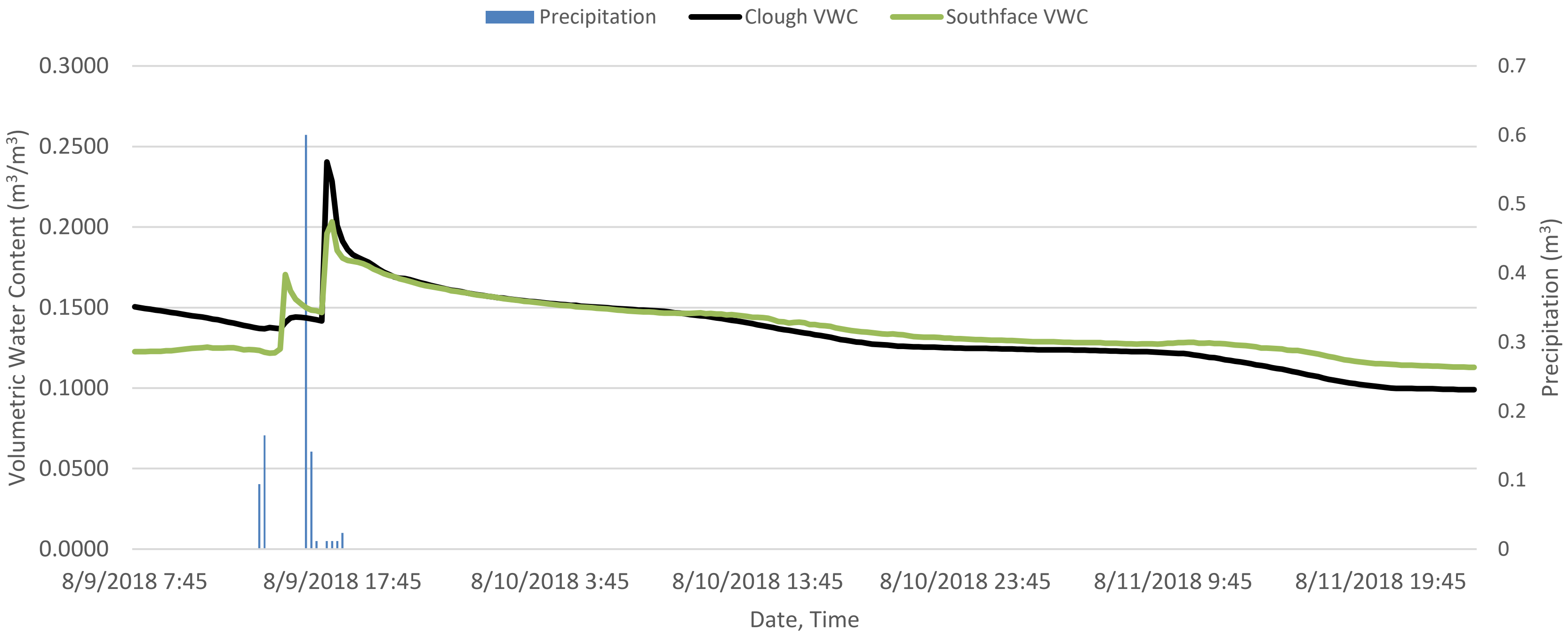

Figure 9 Soil moisture and precipitation at Southface and Clough during storm C.

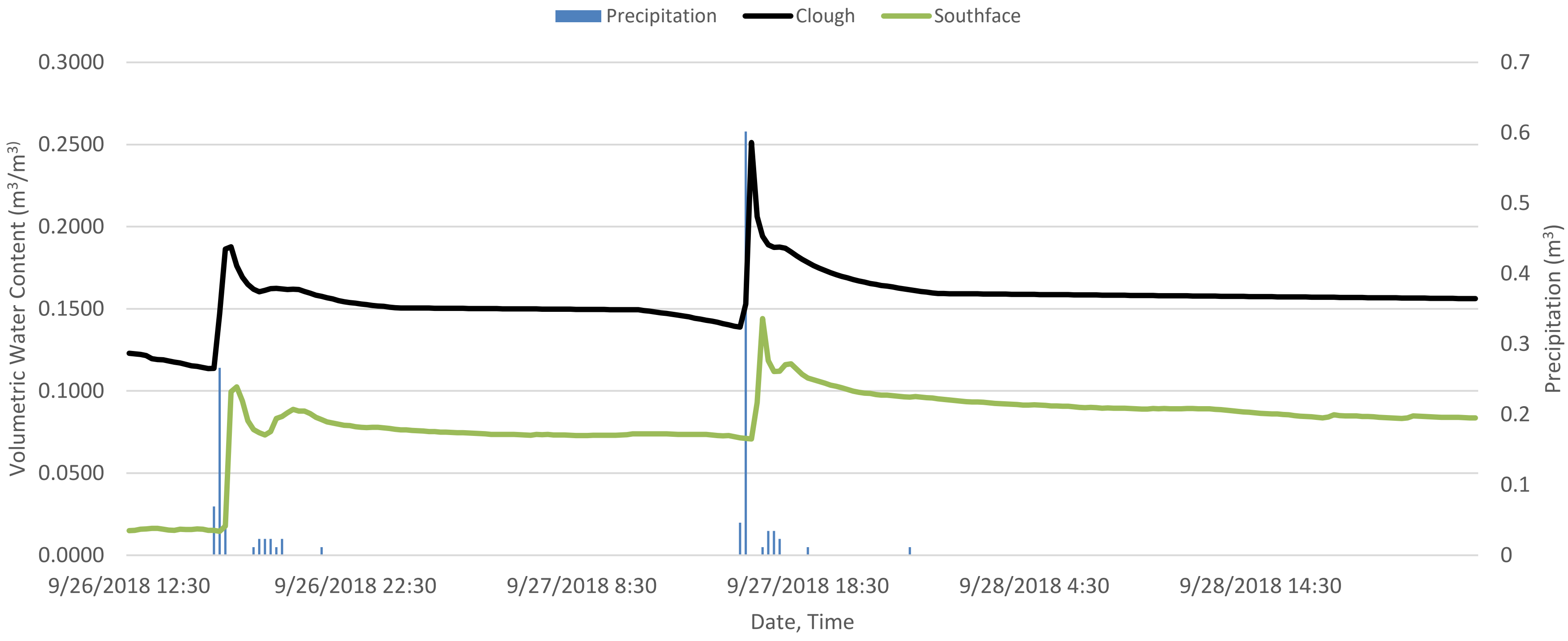

Figure 10 Soil moisture and precipitation at Southface and Clough during storm D and E.

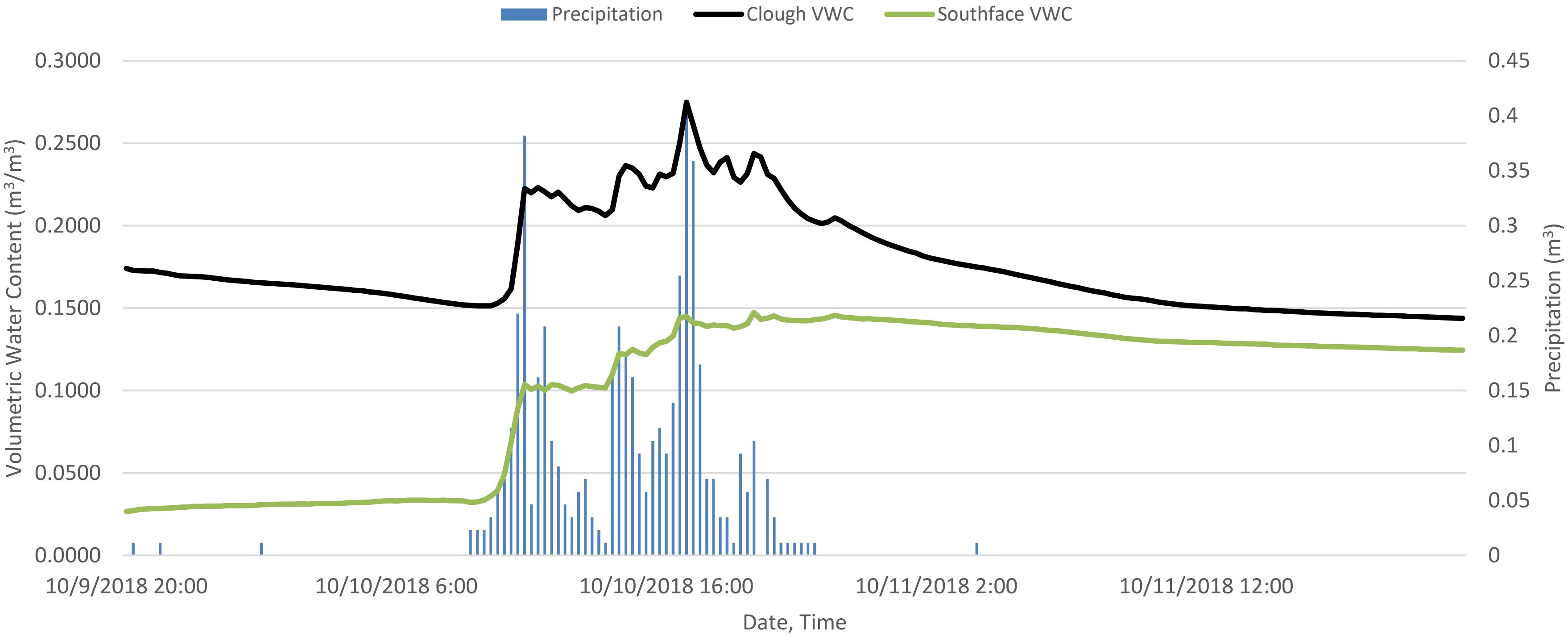

Figure 11 Soil moisture and precipitation at Southface and Clough during storm F.

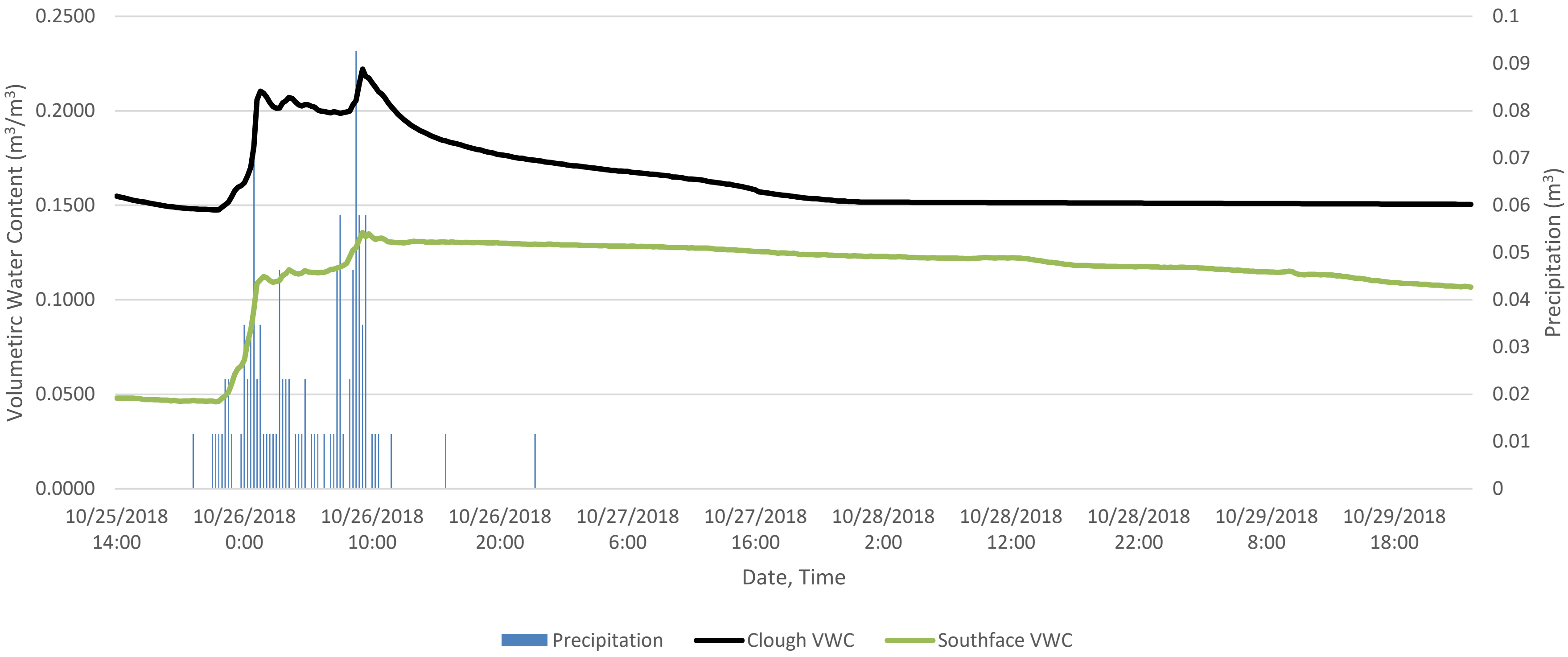

Figure 12 Soil moisture and precipitation at Southface and Clough during storm G.

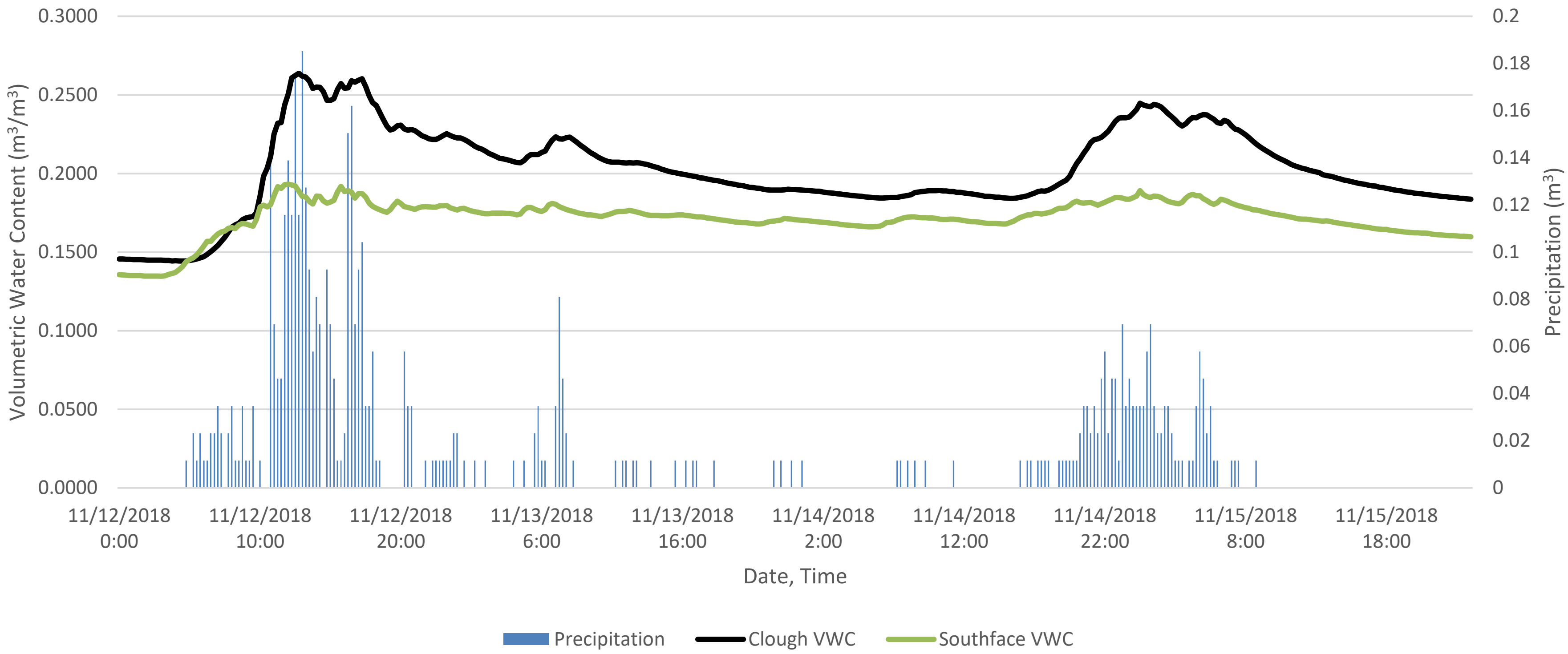

Figure 13 Soil moisture and precipitation at Southface and Clough during storm H, I, and J.

Clough and Southface typically followed the same pattern of outflow during each storm event. The period of peak outflow and the subsequent recession are shown for each event. The peaks on each graph represent the periods of largest volume of outflow and the stretch of time after the last peak, where the graph flattens back to pre-storm outflow represents the recession of each event. The peak discharge times closely align at both sites. These peak discharges also correspond to the times where the maximum VWC was reached during each event. Although Clough and Southface peak simultaneously during most storm events, the higher peak occurs at Clough. Clough has more soil volume and intakes more total rainfall, expelling more at the peak of the storm, causing a higher outflow than Southface at all, but one storm (Figure 15). Most storm events were graphed separately, but if events took place very close together, as is the case with storm H and I (Figure 21), multiple events were combined in one visual.

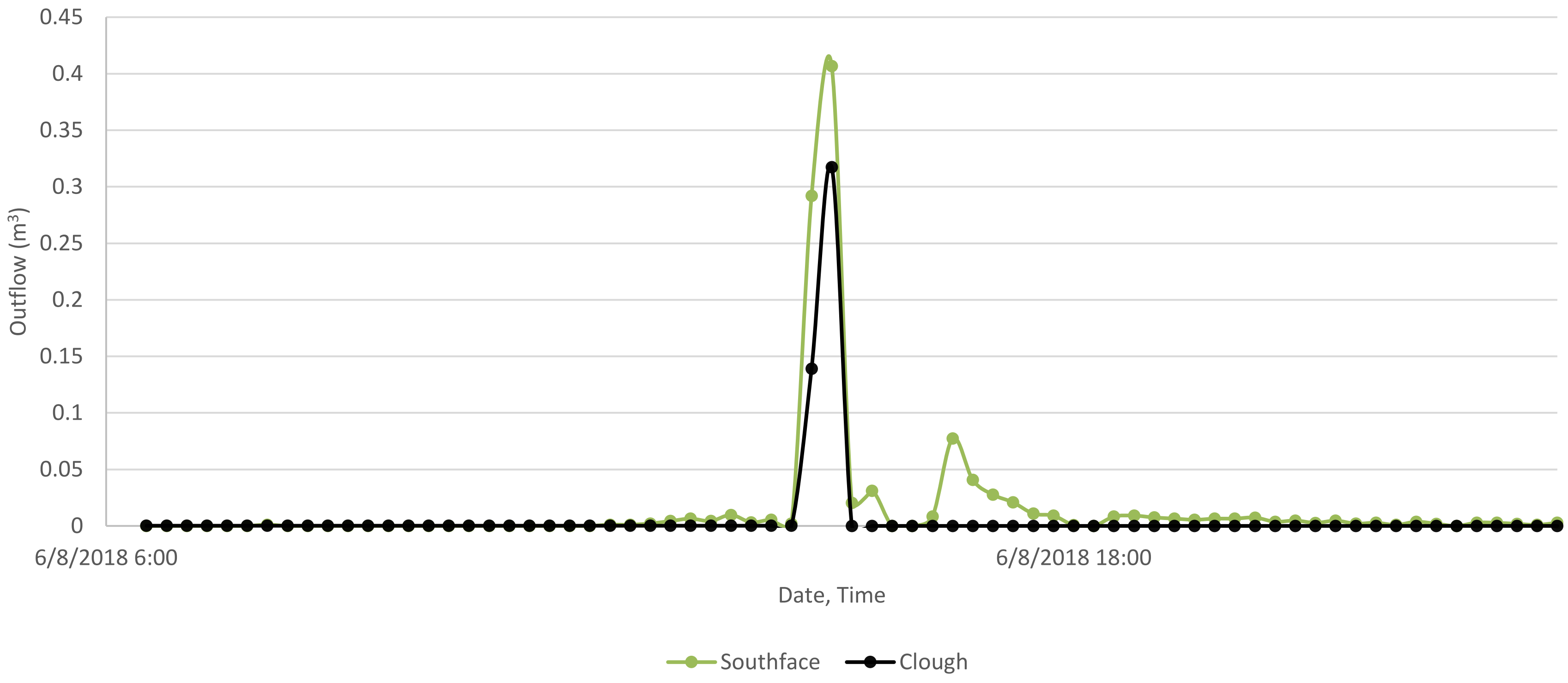

Figure 14 Outflow comparison during peak soil moisture and recession for Storm A.

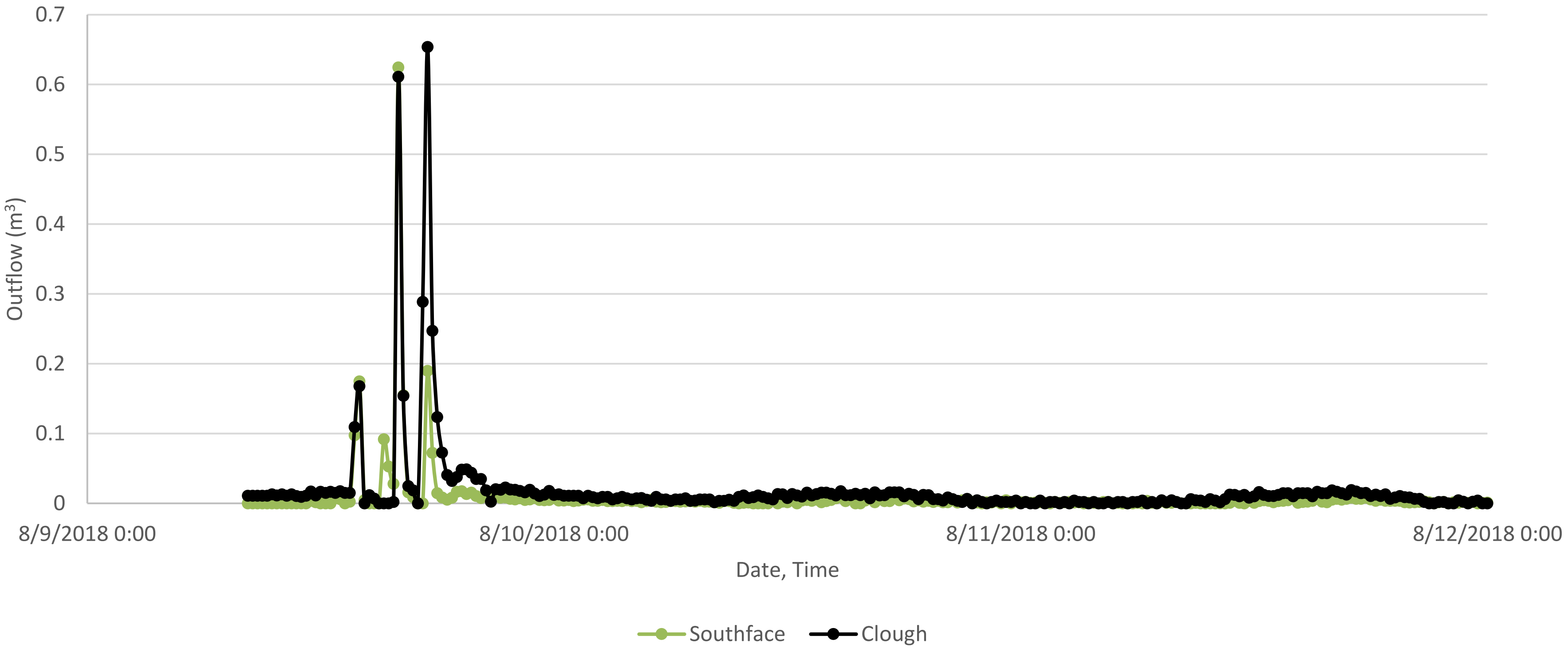

Figure 15 Outflow comparison during peak soil moisture and recession for Storm C.

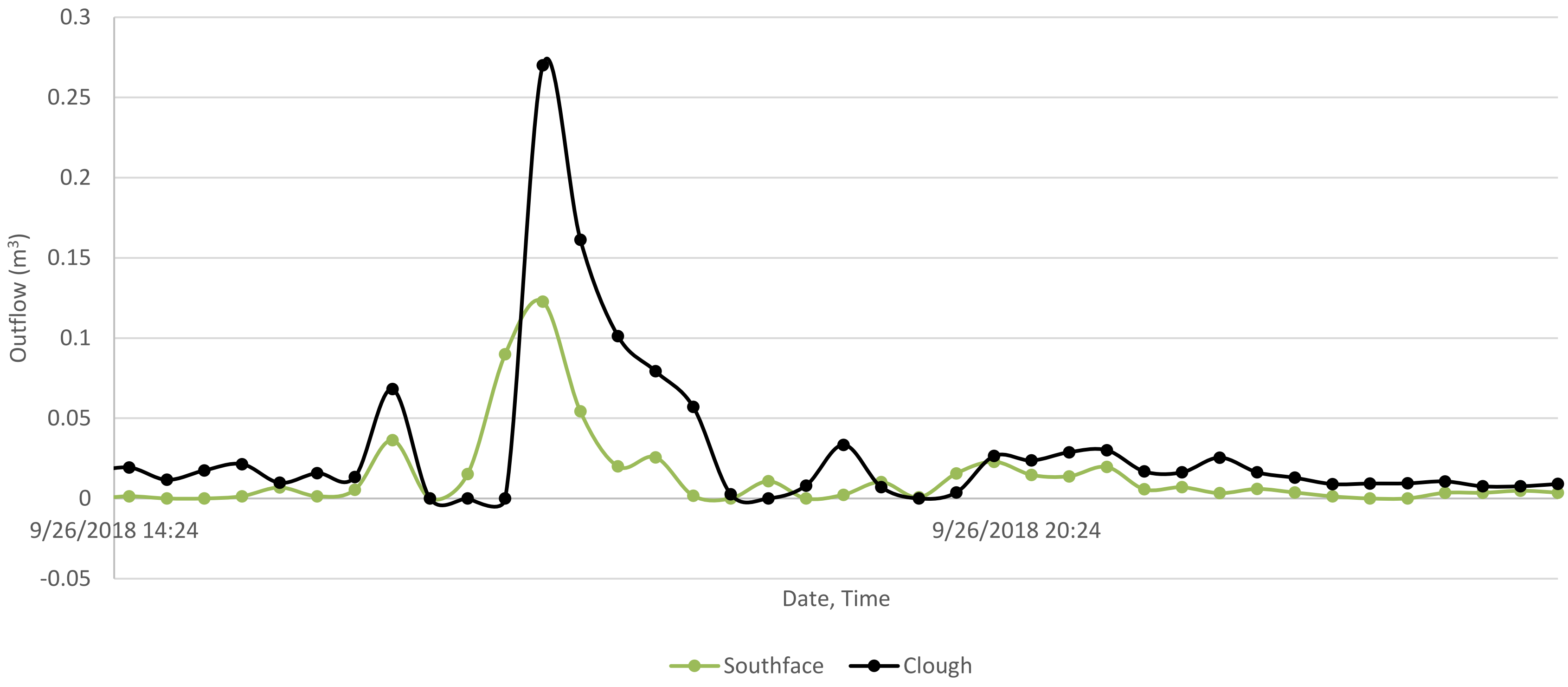

Figure 16 Outflow comparison during peak soil moisture and recession for Storm D.

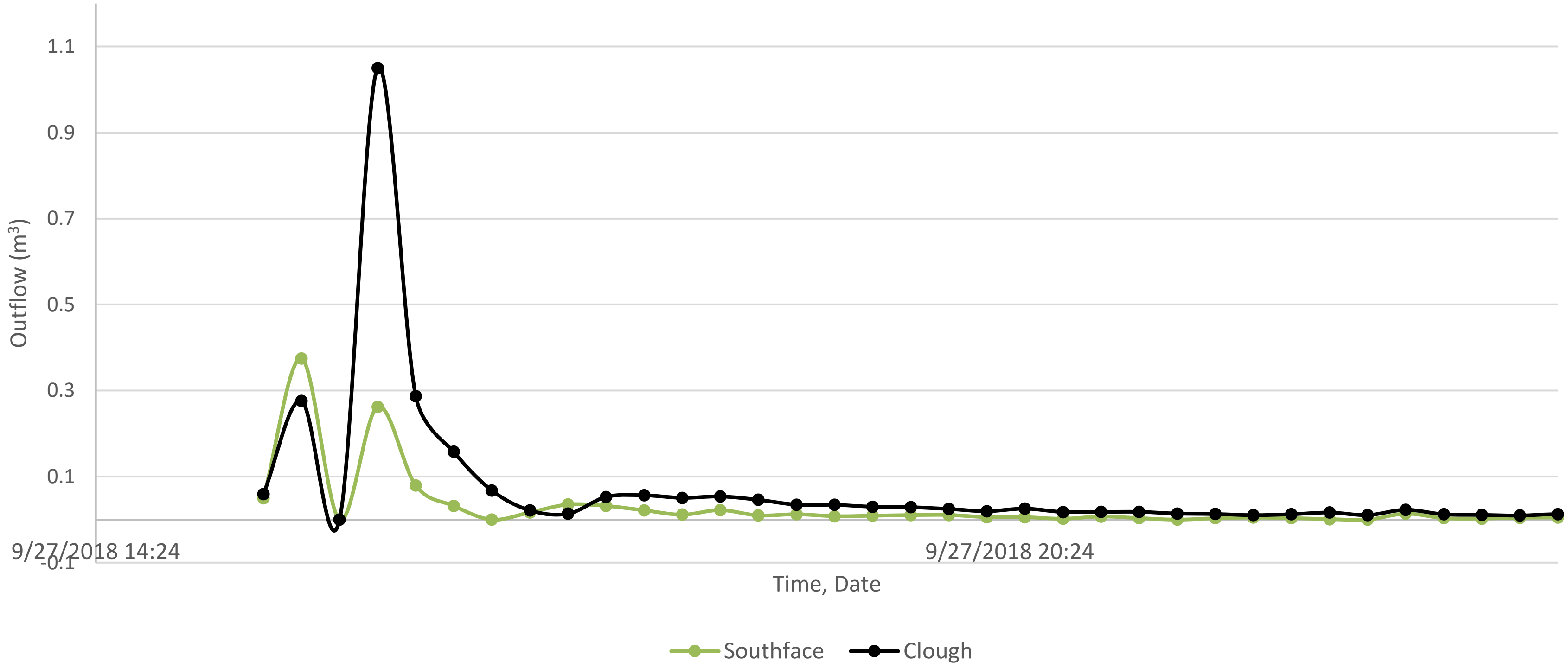

Figure 17 Outflow comparison during peak soil moisture and recession for Storm E.

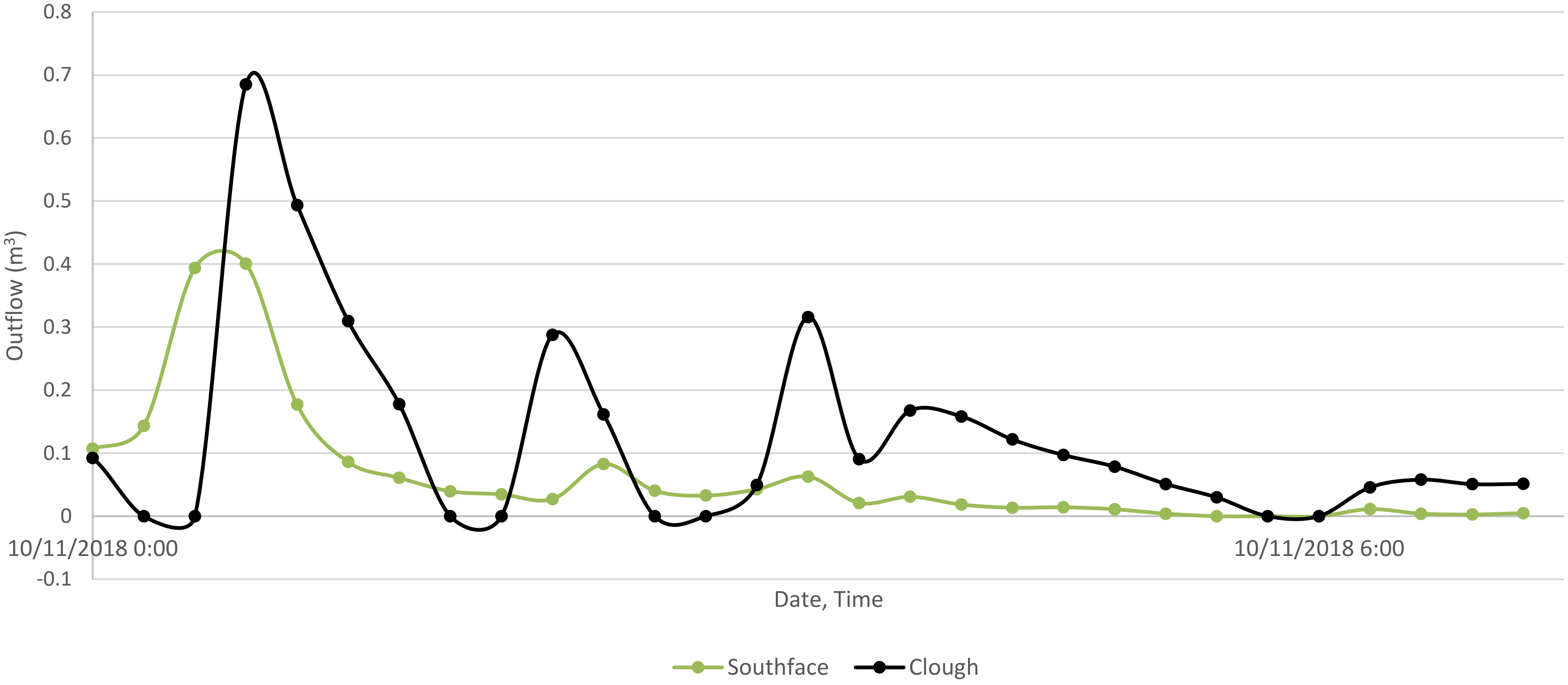

Figure 18 Outflow comparison during peak soil moisture and recession for Storm F.

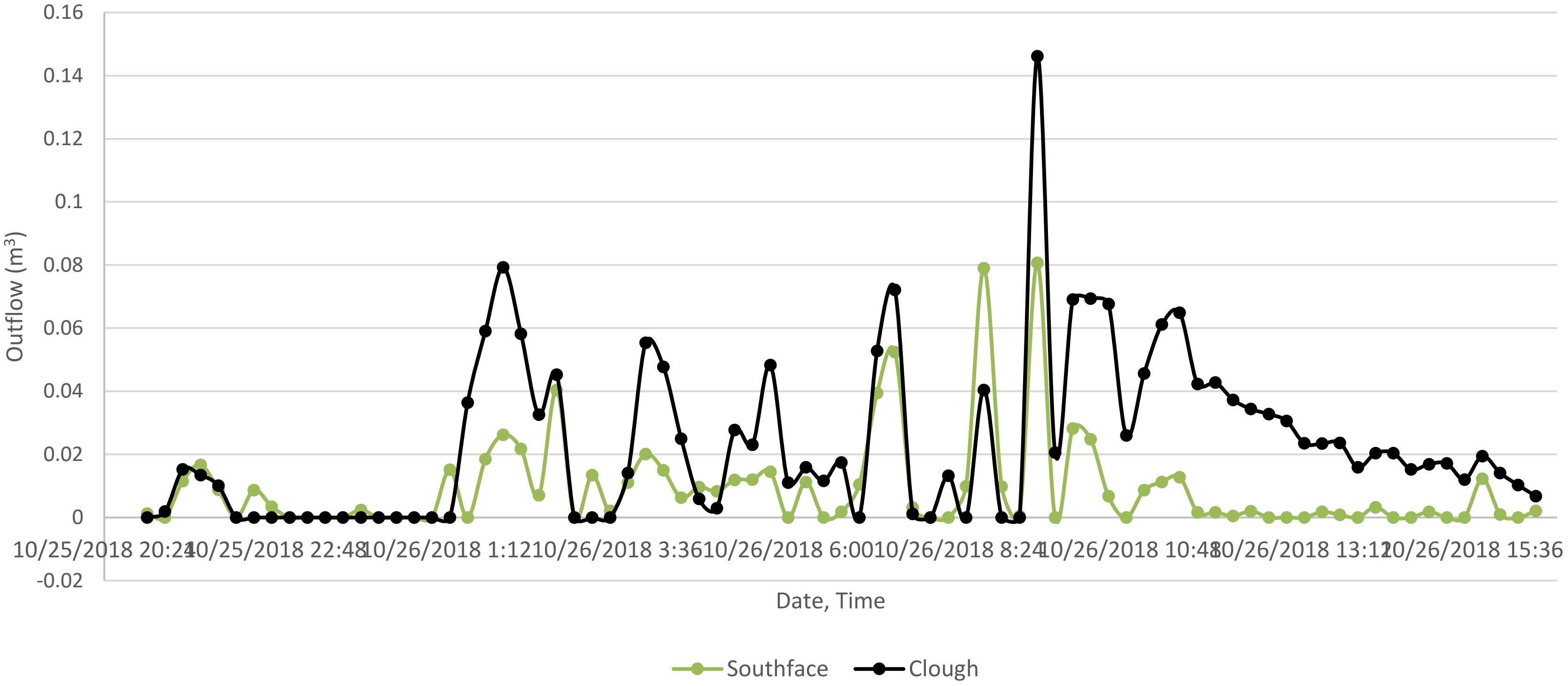

Figure 19 Outflow comparison during peak soil moisture and recession for Storm G.

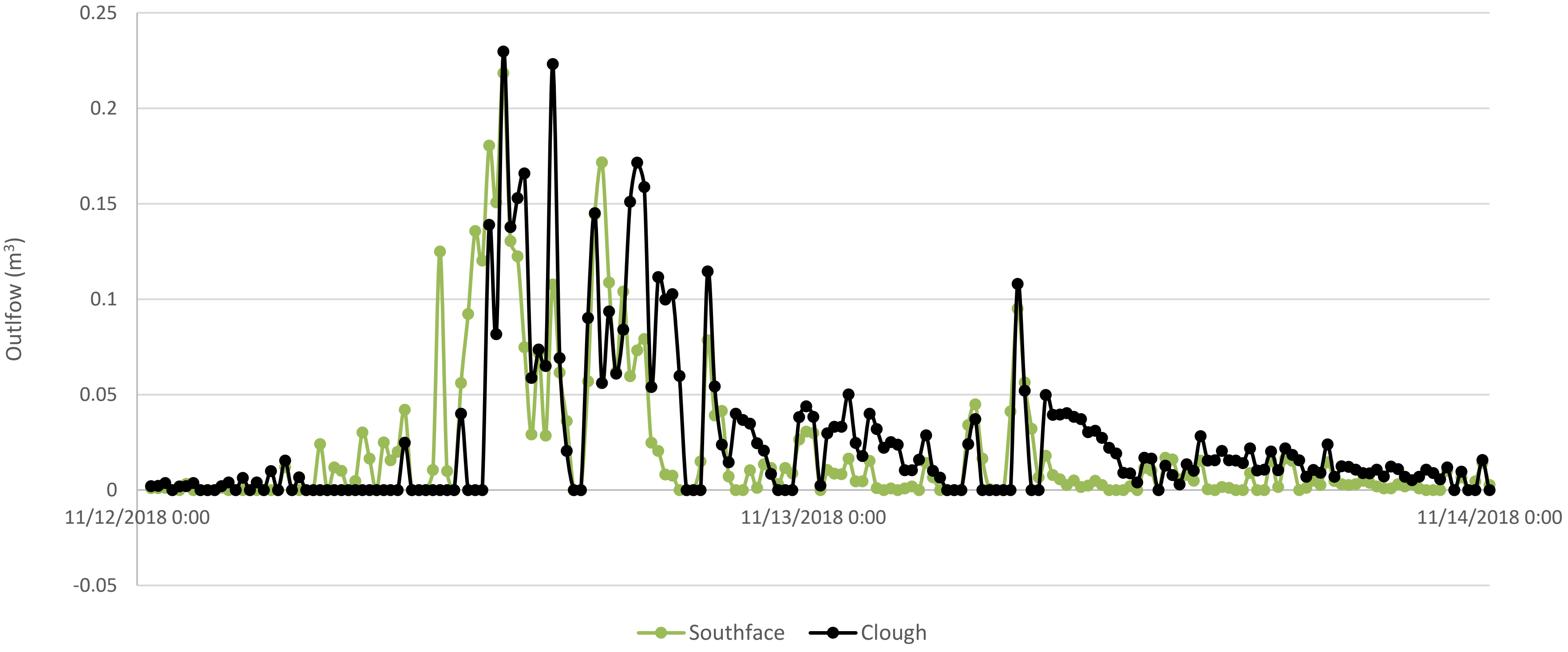

Figure 20 Outflow comparison during peak soil moisture and recession for Storm H and I.

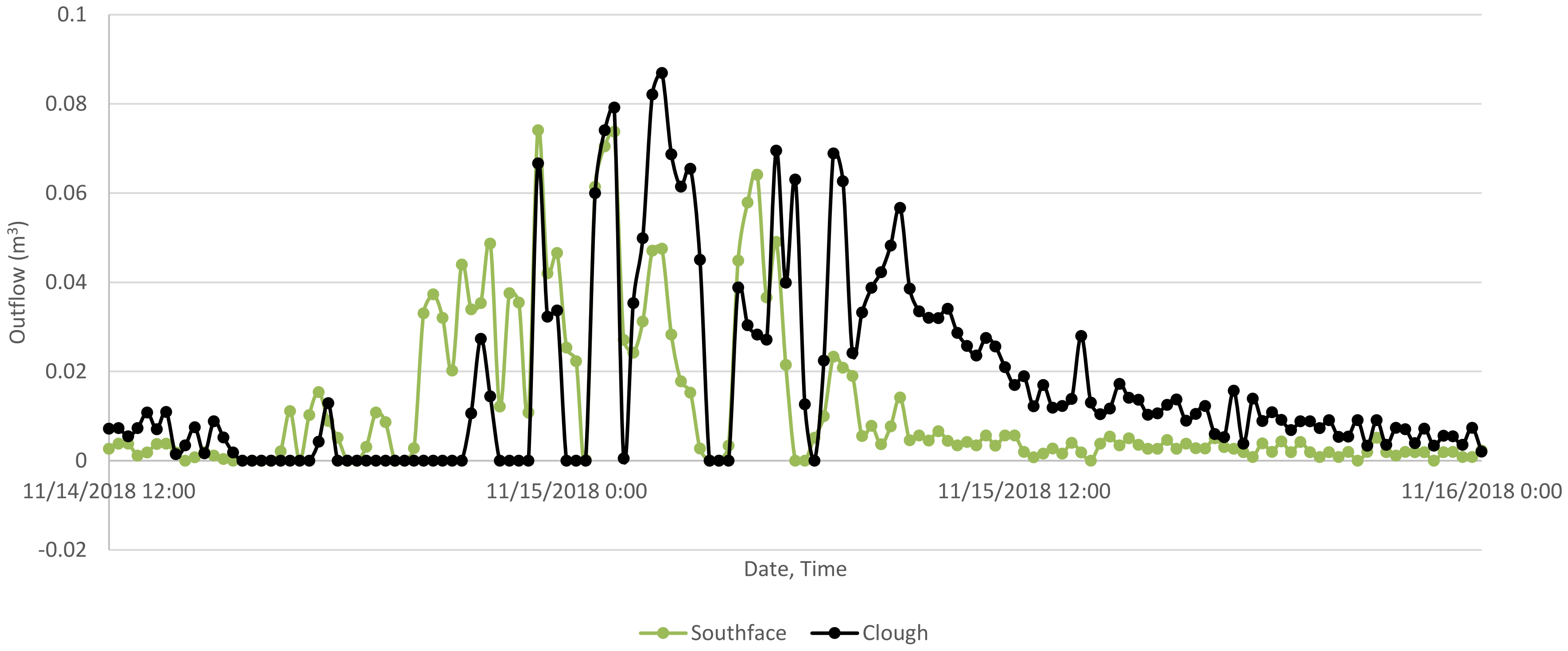

Figure 21 Outflow comparison during peak soil moisture and recession for Storm J.

The total outflow volumes during storm events that occurred overnight, as well as the average rate of outflow and ratio of average rate of outflow to change in soil storage were calculated for these overnight events due to the water balance method used in the study. A separate evapotranspiration calculation was not performed, so closely analyzing the outflow during periods of no solar radiation allows us to assume that all outflow is runoff. Only storm event C displays a lower total outflow volume from Clough

Commons than at Southface (Tables 5 and 6). While the outflow volume is consistently higher at Clough Commons, when the average rate of outflow compared to change in VWC, the higher rate fluctuates between the two locations from storm to storm.

Table 5 Outflow at Southface Energy Institute during overnight storm events.

Storm ID	Time Interval	Total O (m^3)	Avg. Rate of O (m^3/15 min.)	Avg. Rate of O/S (m^3/m^3 15 min.)
A	6/2/18 21:00 - 6/3/18 6:00	5.03E-02	1.36E-03	9.47E-04
C	8/9/18 21:00 - 8/10/18 6:00	1.72E-01	4.65E-03	2.76E-03
E	9/27/18 20:00 - 9/28/18 6:00	1.23E-01	2.99E-03	3.09E-03
F	10/10/18 22:00 - 10/11/18 6:00	2.63E+00	7.97E-02	5.64E-02
G	10/26/18 20:00 - 10/27/18 6:00	3.10E-02	7.56E-04	5.72E-04

Table 6 Outflow at Clough Commons during overnight storm events.

Storm ID	Time Interval	Total O (m^3)	Avg. Rate of O (m^3/15 min.)	Avg. Rate of O/S (m^3/m^3 15 min.)
A	6/2/18 21:00 - 6/3/18 6:00	8.60E-02	2.32E-03	9.48E-04
C	8/9/18 21:00 - 8/10/18 6:00	4.15E-01	1.12E-02	3.07E-03
E	9/27/18 20:00 - 9/28/18 6:00	3.70E-01	9.02E-03	2.41E-03
F	10/10/18 22:00 - 10/11/18 6:00	3.11E+00	9.43E-02	1.77E-02
G	10/26/18 20:00 - 10/27/18 6:00	2.24E-01	5.47E-03	1.37E-03

When comparing stormwater storage capabilities of soil at extensive versus intensive green roofs, neither was absolutely superior to the other. The maximum VWC was greater at Clough, suggesting greater water-holding capacity. However, antecedent moisture was also generally greater at Clough, which is likely the reason why peak outflow values were also greater at Clough (see Figures 11, 12, and 13). These three storms, storm G had a higher ratio of outflow volume to water storage volume at Clough (Tables 5 and 6). While this shows a higher moisture holding capacity for Southface, the large difference in AMC makes it inconclusive. For most of the study period, a regular irrigation schedule was adhered to, as is typical for an intensive roof. Differences in retention capacity would be more likely to occur with an extended dry weather period, which would only occur in the absence of irrigation, but intensive green roofs commonly have high water using species that are more easily exposed to drought stress, making irrigation nearly essential (Szota, Farrell, Williams, Arndt, & Fletcher, 2017)

Each roof has a finite retention capacity so the substrate at Clough started closer to capacity than at Southface for all events with higher AMC, resulting in more effective peak runoff reduction at this location. Previous research has shown that for intensive roofs to perform better, the initial moisture must be low enough for the soil capacity to be higher than the extensive roof at the start of a storm (Schultz, Sailor, & Starry, 2018). The infiltration rate during storm events is reduced with higher antecedent moisture. If a roof starts an event with initial moisture, little or no rain is needed to have some amount of outflow (Villarreal & Bengtsson, 2005).

The similar AMC's, high average and maximum precipitation intensities, and mid-range precipitation total of storm C make peak outflow a decisive parameter when choosing which roof type was more effective during this event. The VWC at both locations were similar after this event, with Southface at 20% and Clough at 24% (Figure 10). The VWC at Southface and Clough increased to 17% and 14% during the initial peak and first intense rainfall period of storm C. During this first peak, Southface allowed more initial precipitation intake than Clough with similar concurrent outflow volumes. There was not only a higher volumetric intake at Southface, but also a higher overall outflow to soil moisture volume ratio, indicating a higher volume retained in Southface. This is evidence of better performance at Southface when there is a small to mid-sized storm with periods of high intensity.

The reason for the more drastic increase in soil moisture in these scenarios at Clough is likely the overall greater soil moisture capacity in the intensive roof. When a storm begins with higher AMC, like in storms A, C, and J, Southface has a less dramatic moisture peak. The maximum VWC at Southface was around 20%, while Clough was around 25%. This increased capacity is likely due to the increased soil depth, but also increased pore space created by increased root density of an intensive roof (Yu et al., 2018).

Storms B and D had the lowest AMC for both locations. The outflow rate is higher for Southface than for Clough during both events. B was a low intensity storm and D was mid-intensity and the retention response for both nearly mirrored one another with Southface having slightly higher outflow rates during both events. The outflow at Southface was higher for B, the lower intensity storm. As discussed earlier, Southface had a larger outflow initially during the H, I, and J series, but by the last storm (J), was performing better. An event with consecutive storms provide more information on hydrologic performance than stand-alone events due to the likelihood of combination events covering up to three days (Bettella, D'Agostino, & Bortolini, 2018). These factors combined show that with increasing storm intensity there is little difference between stormwater retention after a storm reaches a high enough intensity, but overall an extensive roof (Southface) tends to perform slightly better over an extended period of substrate saturation. There also seems to be a decrease in retention as AMC rises, as displayed in the H, I, and J storm series, which is consistent with previous research (Baryla, Karczmarczyk, & Bus, 2018). Previously, the increased depth of an intensive roof has been shown to improve hydrologic performance of green roofs for storms from 5-10mm (Schultz et al., 2018). Of the storms analyzed in this study, only two were 10mm or less. This 5-10mm standard also can be used for the effectiveness of substrate when maximum intensity is considered. Storms C and E have the highest maximum intensities and both display higher outflow during these times (Figure 16 and 18). The maximum intensity during both events are above 10mm, showing less effective retention for an intensive roof during these short, high volume time periods.

4 CONCLUSION

The water budgets at two green roofs, intensive and extensive, were compared in Atlanta, based on differences in soil depth, vegetation, and topography. The intensive green roof had deeper soil, greater foliage area of vegetation, and greater values of maximum volumetric-water content (suggesting greater porosity of the soil). Yet, we found that across a broad range of storm events—varying by an order of magnitude in both precipitation depth and maximum intensity—the extensive green roof generally stored more water for a longer period of time following precipitation. The apparent explanation for this difference is the persistent differences in antecedent wetness of the soil prior to storm events. The intensive green roof at Clough Commons consistently had greater antecedent soil moisture prior to storms, and as would be anticipated from existing quantitative models of infiltration into soils, yielded greater rates and overall amounts of drainage. The greater antecedent moisture at the intensive green roof was a direct result of the irrigation regime utilized to maintain the more water-demanding vegetation.

When we normalize the drainage rates by dividing by the average volume of stored water in the soil, we find that the water-holding capacity per unit volume of stored water was not consistently different between the two roofs—being greater for the intensive roof in some cases, and the extensive roof in others. Uncovering the explanation for this variation is an area for future research.

An intensive roof system allows more precipitation to pass through due to the increased availability of substrate. Regardless of substrate, when rainfall is at an extreme level of intensity, there is going to be a visible decrease in the retention ability of a vegetated roof. Because of the knowledge that AMC plays a large role in the ability of green roofs to perform in variable rainfall, future studies would be more effective if performed on non-irrigated sites. In the future, a closer look at the current soil properties at existing roofs may provide further explanation into the difference in hydrologic capabilities between intensive and extensive roofs.

The deterioration of retention capacity with prolonged wet conditions and high intensity storm events make a case for an extensive green roof to be used if investing in green infrastructure to improve local hydrologic conditions. The need to alter existing infrastructure for installation would be a reason to choose a less weight intensive roof if deciding solely based on hydrologic benefits. There is also a greater water requirement for intensive roofs due to the less drought resistant vegetation common on these roofs. The frequent irrigation at an intensive roof limit rainfall storage, as well as increasing building water usage for the purpose of irrigation.

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