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Hydrological performance of a full-scale extensive green roof located in a temperate climate

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Abstract

Increasing recognition is being given to the adoption of green roofs in urban areas to enhance the local ecosystem. Green roofs may bring several benefits to urban areas including flood mitigation. However, empirical evidence from full-scale roofs, especially those that have been operational for more than several years is limited. This study investigates the hydrologic performance of a full-scale extensive green roof in Leeds, UK. Monitoring of the green roof took place over a 20 month period (between 30th June 2012 and 9th February 2014). The results indicate that the green roof can effectively retain and detain rainfall from the precipitation events included in the analysis. Retention was found to correspond significantly with rainfall depth, duration, intensity and prior dry weather period. Significant differences in retention values between the summer and winter seasons were also noted. Regression analysis failed to provide an accurate model to predict green roof retention as demonstrated by a validation exercise. Further monitoring of the green roof may reveal stronger relationships between rainfall characteristics and green roof retention.

KEYWORDS: Urban drainage, storm water management, green roof, retention, urbanisation

Abbreviations

CSOs – Combined Sewage Overflows
SUDS – Sustainable Urban Drainage Systems
BMPs – Best Management Practices
LIDs – Low-impact Developments
SUWM – Sustainable Urban Water Management projects
ADWP – Antecedent Dry Weather Period (hours)
ET – Evapotranspiration
AWS – Automatic Weather Station
NCAS – National Centre for Atmospheric Science
RD – total rainfall depth (mm)
TR – total runoff depth (mm)
RET – retention (%)
RD – rain duration (hours)
i – rainfall mean intensity (mm/hour)
Rp – rainfall peak intensity (mm/hour)
LG1 – lag-time (1) (minutes)
LG2 – lag-time (2) (minutes)

WFD – Water Framework Directive

1. Introduction

Currently over half of the world's population live in urban areas and it is expected to reach 70% by 2050 (UN Habitat, 2013; Willuweit & O'Sullivan, 2013). From 2001-2011, the population across England and Wales increased by approximately 7% to reach 56 million (Office for National Statistics, 2012). This unprecedented rate of growth and urbanisation has considerable effects on the surrounding environment as developments replace natural lands with impervious surfaces (Vesuviano & Stovin, 2013). This alters the local hydrological cycle by preventing infiltration of rainfall into soil and increasing surface runoff (Getter et al., 2007; Dowling, 2002). Consequently, when drainage systems are unable to cope with high amounts of runoff associated with precipitation events, pluvial flooding can occur (Berndtsson, 2010; Perry & Nawaz, 2008). Furthermore, it is predicted that in the near future the UK will experience more frequent and intense precipitation events as a result of climate change (IPCC, 2012). This has the potential to increase the frequency and intensity of pluvial floods (Speak et al., 2013; Butler & Davies, 2011).

Traditionally, combined sewer systems, which account for 70% of the total sewerage system in the UK, are used to convey stormwater runoff and wastewater away from urban areas (Butler & Davies, 2011; Hall, 2001). If the system's capacity is reached during a rainfall event, Combined Sewage Overflows (CSOs) are used to discharge any excess flows into nearby water bodies (Figure 1.1) (Vesuviano & Stovin, 2013; Hall, 2001). As a result, untreated sewage often enters rivers and streams (Buccola & Spolek, 2011). This increases the risk of flooding downstream, reduces groundwater recharge and degrades aquatic ecosystems by increasing flows and transporting harmful pollutants to water bodies (Hilten et al., 2008; Carter & Jackson, 2007; Carter and Rasmussen, 2006). The inadequacy of the stormwater drainage system in the UK has been labelled as a major cause of the pluvial flooding that occurred throughout the summer of 2007 (Ellis, 2010). Moreover, despite being designed to provide emergency relief, many CSOs discharge following small rainfall events (Carson et al., 2013; Fassman-Beck et al., 2013). This highlights the need to improve the conventional urban stormwater drainage systems (Nagase & Dunnett, 2012; Newton et al., 2007; VanWoert et al., 2005).

Figure 1.1: A combined sewer outfall in Leeds (Leeds City Council, 2004).

However, there are over 20,000 CSOs throughout the UK, and it is considered economically unfeasible and impractical to upgrade the entire system (Qin et al., 2013; BBC, 2009; Water UK, 2009). Thus alternative ways to manage urban runoff and reduce urban flood risk are being explored (VanWoert et al., 2005). In the UK, the Environment Agency is promoting the use of Sustainable Urban Drainage Systems (SUDS) as a way of controlling rainfall and runoff at source (Stovin et al., 2012; Stovin, 2010; Seters et al., 2009). SUDS, also known as Best Management Practices (BMPs), Low-Impact Developments (LIDs) and Sustainable Urban Water Management (SUWM) projects can be used to increase infiltration and manage the quantity and quality of runoff in a sustainable manner (Deng et al., 2013; Carpenter & Kaluvakolanu, 2011; Damodaram et al., 2010). They include such designs as infiltration basins, permeable pavements, swales, wetlands, soakaways and green roofs (Stovin et al., 2013; Butler & Davies, 2011; Hall, 2001).

Green roofs in particular, have gained considerable attention in recent years as a potential cost-effective way to mitigate urban flood risk (Stovin et al., 2013; Beck et al., 2011). They are defined as roofs which are partially or completely covered with a growing medium (substrate) and vegetation (excluding pot vegetation) (Mickovski et al., 2013; Berndtsson, 2010; Olly et al., 2011). Whilst most SUDS require large spaces, green roofs require no additional space beyond a buildings footprint (Zhang & Guo, 2013; Stovin et al., 2012). Furthermore, green roofs can be retrofitted onto existing buildings as well as incorporated into new developments (Castleton et al., 2010). This is particularly beneficial in urban areas where roofs can account for a high proportion of the total impervious land area (Carson et al., 2013; VanWoert et al., 2005).

Amongst a range of benefits offered, green roofs allow infiltration and can retain rainfall (Mentens et al., 2006). Some rainfall is used by the vegetation and released back into the atmosphere through evapotranspiration whilst any excess rainfall which is not retained by the roof is slowly released (Zhang & Guo, 2013; Carpenter & Kaluvakolanu, 2011). Consequently, green roofs can delay the initiation of runoff, reduce total runoff volumes, reduce peak runoff rates and discharge runoff over a longer period of time, when compared to conventional roofs (Figure 1.2) (Vesuviano & Stovin, 2013; Berndtsson, 2010; Mentens et al., 2006). Additional benefits to the apparent hydrological benefits of green roofs is that they can provide a variety of further environmental and social benefits to the building owner, the occupants and the wider community (see Table 1.1) (Bianchini & Hewage, 2012; Nagase & Dunnett, 2010; Oberndorfer et al., 2007; Getter & Rowe, 2006).

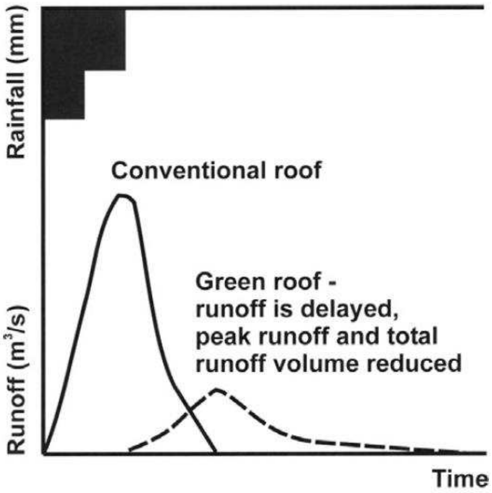
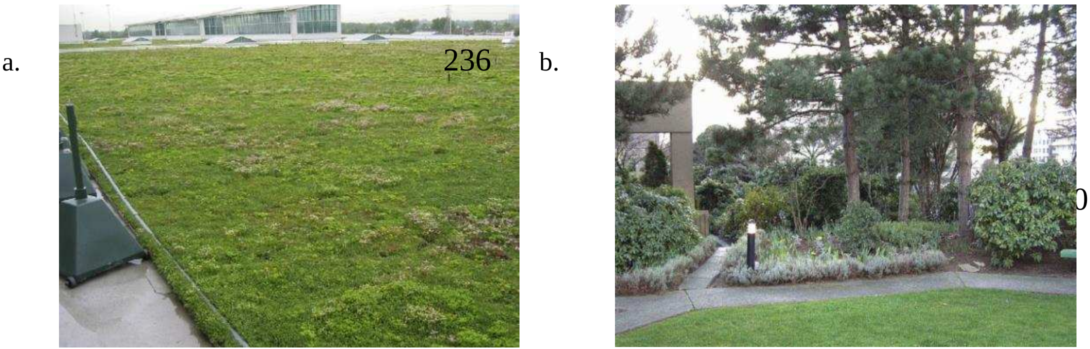


Figure 1.2: A schematic diagram showing the rainfall-runoff response from a conventional roof and a green roof (Stovin et al., 2012).

Table 1.1: The reported benefits of green roofs.

Green roof benefit	**Reference**
•Improves a buildings energy efficiency	Jaffal et al. (2012), Parizotto & Lamberts (2011); Kosareo & Ries (2007); Niachou et al. (2001)
•Reduces noise pollution	Yang et al. (2012)
•Increases the longevity of the roof membrane	Ouldboukhitine et al. (2012); Ouldboukhitine et al. (2011); Kosareo & Ries (2007)
•Improves thermal comfort conditions and acts as an insulation device for a building	Ouldboukhitine et al. (2011); Parizotto & Lamberts (2011) Barrio (1998)
•Increases the biodiversity of areas	Molineux et al. (2009)
•Improves runoff water quality	Seidl et al. (2013); Berndtsson et al. (2009)
•Mitigates air pollution	Rowe (2011); Yang et al. (2008)
•Mitigates the Urban Heat Island (UHI) effect	Susca et al. (2011)
•Sequesters carbon	Moore & Hunt (2013); Getter et al. (2009)
•Improves aesthetics of the urban landscape	Villarreal & Bengtsson (2005)

Green roofs can be extensive, intensive or semi-intensive (Figure 1.3) (Gregoire & Clausen, 2011; Berndtsson, 2010). Extensive green roofs usually have substrate depths below 150mm whereas intensive green roofs have substrate depths greater than 150mm (Carson et al., 2013; Fassman-Beck et al., 2013). This difference in substrate depth restricts extensive green roof systems to simple vegetation types and allows intensive green roofs to consist of larger vegetation such as herbs, shrubs and small trees (Berndtsson, 2010; Mentens et al., 2006). Most extensive green roofs constructed in the UK consist of sedum plant species and other succulents which do not require irrigation (Castleton et al., 2010; Nagase & Dunnett, 2010; Newton et al., 2007). Moreover, extensive green roofs are the most widespread type of green roof as they have the lightest weight requirements, are the cheapest to install and require minimal maintenance (Tota-Maharaj et al., 2012; Olly et al., 2011; Voyde et al., 2010; Hathaway et al., 2008). Semi-intensive green roofs are a hybrid of intensive and extensive green roofs (Berndtsson, 2010).



c.

Figure 1.3: An example of an extensive green roof (a.), an intensive green roof (b.) and a semi-intensive green roof (c.) (Green Roof Technology, 2014; Rowe, 2011).

It is worth noting that despite the differences between green roof types, they generally all contain the same principal components including a waterproofing membrane, a root barrier, and a drainage mechanism. Three drainage types have been reported by Conservation Technology (2008) and include Types P, G and M. Drainage Type P utilizes drainage plate, waffled plastic sheets that store water above and drain water below. Drainage plates are lightweight, are easy to install, to help meet the drainage and water storage requirements of almost any green roof. Drainage Type G utilizes a lightweight, porous inorganic granular media embedded with slotted plastic triangular drainage conduit. Granular media is heavier and is more labour-intensive to install than drainage plates, but provides a superior environment for plant root growth. Finally, drainage Type M utilises a drainage mat, a multi-layer fabric mat that combines soil separation, drainage, and protection functions into one product. This system is the fastest to install and creates the thinnest and lightest green roof assembly. However, its water storage and drainage capacity is limited, so it is primarily used for sloped roofs not suitable for Drainage Type P or Type G (Conservation Technology, 2008).

2. Rationale

Although green roofs appeared in Nordic countries centuries ago, it is widely maintained that the modern green roof movement originated in Germany during the 1970s (Berndtsson, 2010; Oberndorfer et al., 2007; Getter & Rowe, 2006). Since then, green roof construction has increased and it is estimated that 14% of all the flat roofs in Germany are now green (Getter & Rowe, 2006; VanWoert et al., 2005). Several other countries including Japan, Singapore and parts of the US have developed incentive programs to encourage green roof installations (Zhang & Guo, 2013; Mentens et al., 2006). However, barriers preventing widespread installations of green roofs still exist in other countries (Zhang et al., 2012; Williams et al., 2010; Getter & Rowe, 2006).

In the UK, one of the major barriers is a lack of quantifiable data which illustrates the hydrological benefits of green roofs (Fioretti et al., 2010). Experiments which specifically investigate a green roof's ability at effectively managing stormwater have only begun in the last decade and whilst the benefits of green roofs are often claimed, there is insufficient scientific evidence demonstrating their hydrological performance (Zhang & Guo, 2013; Berndtsson, 2010; Dvorak & Volder, 2010), especially of full-scale roof installations. Thus, more research is required on green roofs in the UK to investigate their potential as possible SUDS and their effectiveness at reducing urban flood risk (Vijayaraghavan et al. 2012; Butler & Davies, 2011). This is an essential step which needs to be undertaken before policies and incentives can be developed and implemented to increase green roof uptake in the UK (Green Roof Guide, 2011; Bell & Alarcon, 2009; Carter & Keeler, 2008).

Previous studies investigating the hydrological performance of extensive green roofs have reported various retention values, peak runoff reductions and delays in runoff, when compared to conventional roofs (Li & Babcock, 2014 Forthcoming; Berndtsson, 2010). The average retention value observed from previous extensive green roof studies appears to be 57%, although it ranges between 15% and 83% (Table 2.1). Note that retention here is defined as the percentage of rainfall captured by a green roof following a precipitation event (Carpenter & Kaluvakolanu, 2011). The prominent differences observed between extensive green roof retention values can be attributed to differences in climate, green roof design, the duration of the study, the slope of the green roof, the type and depth of the substrate used, the vegetation used and the age of the green roof (Morgan et al., 2013; Nagase & Dunnett, 2012; Beck et al., 2011; Buccola & Spolek, 2011; Gregoire & Clausen, 2011; Berndtsson, 2010).

Table 2.1: The reported retention values (%) from various studies undertaken on extensive green roofs.

Reference	Retention value observed (%)	Location
Fassman-Beck et al. (2013)	56.0	Auckland, New Zealand
Voyde et al. (2010)	66.0	Auckland, New Zealand
Hathaway et al. (2008)	64.0	North Carolina, USA
Buccola & Spolek (2011)	54.0	Portland, USA
Gregoire & Clausen (2011)	51.4	Connecticut, USA
Carpenter & Kaluvakolanu (2011)	68.3	Michigan, USA
VanWoert et al. (2005)	82.8	Michigan, USA
Getter et al. (2007)	80.8	Michigan, USA
Morgan et al. (2013)	50.0	Illinois, USA
Carson et al. (2013)	36.0	New York, USA
Carter and Rasmussen (2006)	78.0	Georgia, USA
Tota-Maharaj et al. (2012)	15.5	Salford, UK
Stovin et al. (2013)	59.0	Sheffield, UK
Stovin et al. (2012)	50.2	Sheffield, UK
Stovin (2010)	34.0	Sheffield, UK
Mentens et al. (2006)	45.0	Germany
Seters et al. (2009)	63.0	Toronto, Canada
Fioretti et al. (2010)	68.0	Northwest and Central Italy
Palla et al. (2011)	68.0	Genoa, Italy

There is also large variation in a green roof's hydrological performance within studies. This can be explained by differences in the characteristics of a rainfall event and green roof composition. Rainfall characteristics include rainfall depth, duration and intensity (Kok et al., 2013; Speak et al., 2013; Stovin et al., 2013). In addition, the antecedent dry weather period (ADWP) which separates rainfall events has also been identified as an important factor influencing retention (Zhang & Guo, 2013). This can be explained as the ADWP is the primary control on the time allowed for a green roof to dry out between rainfall events (Hathaway et al., 2008). If, for instance, the ADWP is relatively long between rainfall events, the substrate may have sufficient time to dry and recharge its retention capacity (Fassman-Beck et al., 2013). Conversely, if the ADWP is short, the substrate will have less time to dry out prior to the next rainfall event (Hathaway et al., 2008). Therefore the substrate may be saturated and at its field capacity before any rainfall has fallen onto the roof (Berndtsson, 2010).

The ADWP and rainfall characteristics are also responsible for the reported seasonal differences in green roof retention performances (Graceson et al., 2013; Seattle Public Utilities, 2012; Palla et al., 2011; Seters et al., 2009). This is explained as evapotranspiration (ET) rates, the mechanism by which green roofs restore their water retaining capacity, are higher in warmer seasons and lower in colder seasons (Stovin et al., 2013; Zhang & Guo, 2013; Kasmin et al., 2010; Mentens et al., 2006). Therefore lower retention values observed during winter months may be attributed to lower ET rates (Speak et al., 2013). The ADWP and local ET rates have also been identified as key factors influencing the detention properties of green roofs (Voyde et al., 2010).

It is apparent that there are a large number of factors that influence green roof hydrological performances between regions (Buccola & Spolek, 2011; Berndtsson, 2010). So whilst inter-regional comparisons may be helpful, consideration of site-specific factors must be taken into account (Bonoli et al., 2013; Newton et al., 2007; Teemusk & Mander, 2006). Consequently, to assess the effectiveness of green roof systems in the UK, more studies located in various cities throughout the UK are required (Carpenter & Kaluvakolanu, 2011). Green roofs in the UK may show distinct hydrological performances as it is has a temperate maritime climate which is characterised by frontal rainfall (Nagase & Dunnett, 2010; Stovin, 2010). This study will address this research requirement by studying an extensive green roof in Leeds, UK.

Furthermore, the majority of previous studies investigating green roof hydrological performances have been conducted on test beds and laboratory set-ups (Lee et al., 2013; Morgan et al., 2013; Stovin, 2010; Uhl & Schiedt, 2008; Getter et al., 2007; Carter and Rasmussen, 2006; Liu & Minor, 2005; VanWoert et al., 2005). These experiments are useful for investigating a green roof component in isolation (Yio et al., 2013). However, the artificial test beds often have 100% vegetation cover and fail to give an accurate representation of actual green roof conditions in urban environments (Speak et al., 2013; Carpenter & Kaluvakolanu, 2011; Berndtsson, 2010). Most full-scale extensive green roofs actually have lower than 100% vegetation cover as they often have conventional roof surfaces at the periphery (Speak et al., 2013). As a result, test beds can have altered detention times and retention values, when compared to full-scale green roofs (Carson et al., 2013; Stovin et al., 2012). Similarly, rainfall simulations undertaken in some studies can be considered 'unnatural' and do not provide real-life conditions experienced by full-scale green roofs (Kok et al., 2013; Tota-Maharaj et al., 2012 Vijayaraghavan et al., 2012; Villarreal & Bengtsson, 2005).

Where full-scale installations have been the subject of investigation, this has been limited to roof systems that are younger than three years (Hathaway et al., 2008; Liu & Minor, 2005). It is known that an older green roof can result in a higher retention capability than a younger green roof system as the substrate develops over time (Bonoli et al., 2013; Berndtsson, 2010). For example, Getter et al. (2007) reported that over a 5 year period the organic matter content of an extensive green roof's substrate doubled.

Consequently, the pore space doubled and the water holding capacity increased substantially (Getter et al., 2007).

This study aims to fill this apparent research gap by investigating the hydrological performance of a full-scale extensive green roof installed in 2007. This will reduce the effect of uncertainties which are associated with test bed and laboratory facilities (Carson et al., 2013) and also generate new data on the performance of a roof system between 5-7 years old. The study focuses on the performance of an extensive green roof system as they are the most commonly used type of green roof and can be constructed on roof slopes of up to 45° (Zhang & Guo, 2013; Yio et al., 2013; Mentens et al., 2006).

As extensive green roofs have the widest applicability, are commercially viable and can be retrofitted onto most roofs, they have substantial potential to be constructed throughout the UK (Castleton et al., 2010; Nagase & Dunnett, 2010). A further benefit of this study is that a very particular type of green roof (Type G – see section 1) comprising a drainage mat is investigated which will reveal new insights into how this type of green roof performs during storms. The data provided by this study may also help develop models which aim to predict an extensive green roof’s hydrological performance in response to a certain precipitation event (Kasmin et al., 2010). Such models are reliant on observed data obtained from field measurements for calibration and verification (De Munck et al., 2013; Palla et al., 2009; Hilten et al., 2008). As the performance of full-scale extensive green roofs in urban environments is relatively little understood, field monitoring is continuing to drive design guidance and policy development for green roofs in the UK (Bonoli et al., 2013; Stovin et al., 2013; Butler

& Davies, 2011; Fioretti et al., 2010; Berndtsson, 2010). Hence this study will provide valuable data which quantifies the hydrological performance of an extensive green roof and may demonstrate an extensive green roof's effectiveness at lowering flood risk and reducing the load on CSOs and subsequent pollution incidents.

3. Aims & Objectives

This study aims to investigate the hydrological response of a full-scale extensive green roof in the city of Leeds in the UK. Particular attention will be focused on the green roof's ability to retain rainfall during storms (Carter and Rasmussen, 2006). The key objectives of the study are as follows:

- Assess the ability of a full-scale extensive green roof to retain and detain rainfall from individual precipitation events.

- Assess the importance that rainfall and other characteristics have on the green roof’s hydrological performance.
- Investigate any potential seasonal differences in the hydrological performance of the green roof.
- Compare the rainfall-runoff response of a nearby conventional roof to the rainfall-runoff response of the green roof for individual precipitation events (Seters et al., 2009; Vesuviano & Stovin, 2013).
- Conduct a regression analysis to develop an accurate model which can predict the retention (%) of the green roof (Stovin et al., 2012; Stovin, 2010).

4. Methodology

4.1 Site location and green roof properties:

The study was carried out on a full-scale extensive green roof located at the University of Leeds city campus (Figure 4.1.1). Constructions such as these are increasingly being seen as helping to reverse the trend of increased ground soil sealing seen in parts of the city. For example, Perry & Nawaz (2008) noted that front garden paving by residents over the course of 33 years (1971-2004) in the Halton Moor area, to the north East of the city had resulted in a 13% overall increase in impervious.

In terms of the potential flood footprint of the University campus, it is worth noting that it lies close to the floodplains of the River Aire, an area of Leeds which is at risk of flooding (Hall, 2001). As the campus has a combined drainage system throughout, any reduction in surface runoff is likely to reduce the number of CSOs (Hall, 2001).

The extensive green roof, installed in August 2007, is situated on top of the School of Performing Arts building at the University of Leeds (Figure 4.1.1) (Jones, 2007). One of the primary motives for the green roof’s construction was for its acoustic properties, as it can absorb the ‘drumming’ effect of rainfall on the rooftop surface (Jones, 2007).

The total roof area is 830m^2 and it has two main sections; a higher level which is externally drained by 4 drainage pipes and a lower level which is internally drained. The externally drained section is 396m^2 (Figure 4.1.2) (Daft Logic, 2013). Note that drainage areas were calculated using a Google Maps Area Calculator Tool (Daft Logic, 2013). As the green roof’s runoff is monitored for the upper section of the roof, the presence of glass windows on the lower, internally drained, section should not affect the results (Speak et al., 2013). It is also important to note that the roof has a slope of less than 2%.

a.

b.

Figure 4.1.1: The extensive green roof above the University of Leeds Performing Arts building in 2007 (a.) and 2014 (b.) (McLaw Living Roofs, 2007).

The roof has more than 80% vegetation cover (given a 300mm gravel margin around the edge) and is typical of a well-established extensive green roof system (Speak et al., 2013; Zhang et al. 2012; Green Roof Guide, 2011; Nagase & Dunnett, 2010; Kosareo & Ries, 2007; Newton et al., 2007). The roof requires minimal maintenance and does not have an irrigation system (Jones, 2007). This means that any runoff measured from the green roof can be attributed to rainfall (Fassman-Beck et al., 2013; Castleton et al., 2010).

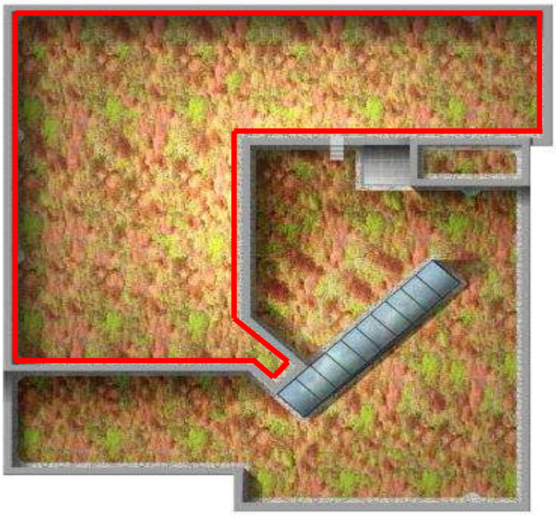


Figure 4.1.2: An aerial view of the extensive green roof. The externally drained section of the roof is outlined in red (Jones, 2007).

The green roof under investigation is a rather particular type drained by a fabric mat called a ‘drainage mat’. This type of roof is the fastest to install and creates the thinnest and lightest green roof assembly. The 20mm drainage mat is overlain by a substrate with sedum (30mm depth). The drainage mat overlays a single ply waterproof roof membrane which is installed on a 120mm insulation layer, a water proofing membrane and a galvanised steel profiled deck as shown in Figure. 4.1.3. The sedum carpet consists of a variety of sedum species including Sedum Acre ‘aureum’, Sedum Reflexum ‘blue spruce’ and Sedum Album ‘coral carpet’ (McLaw Living Roofs, 2014). The drainage mat combines the functions of protection, water storage, and drainage in one product (Jones, 2007). The roof is drained through four outlets connected to external downpipes. It is worth noting that this is a very particular green roof composition since the majority of installed green roofs comprise a polyethylene drainage layer. Given the ease of installation and its lightweight, it is likely to become more widespread.

a.

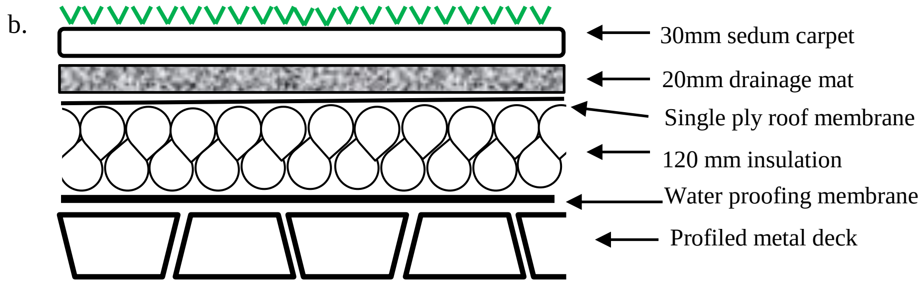


Figure 4.1.3: A picture (a) and a schematic (b) of the green roof cross-section,

The conventional (control) roof, situated 50m from the green roof, is located on the Leeds University Union building (Figure 4.1.4). This roof was selected due to its close proximity to the green roof and its similar elevation (and slope). This ensures that the precipitation measurements are the same for both roofs (Gregoire & Clausen, 2011). This roof is externally drained by 6 drainage pipes and has an area of 800m^2 (Daft Logic, 2013). It should also be noted that neither the conventional roof nor the extensive green roof are within rain shadows of any surrounding buildings.

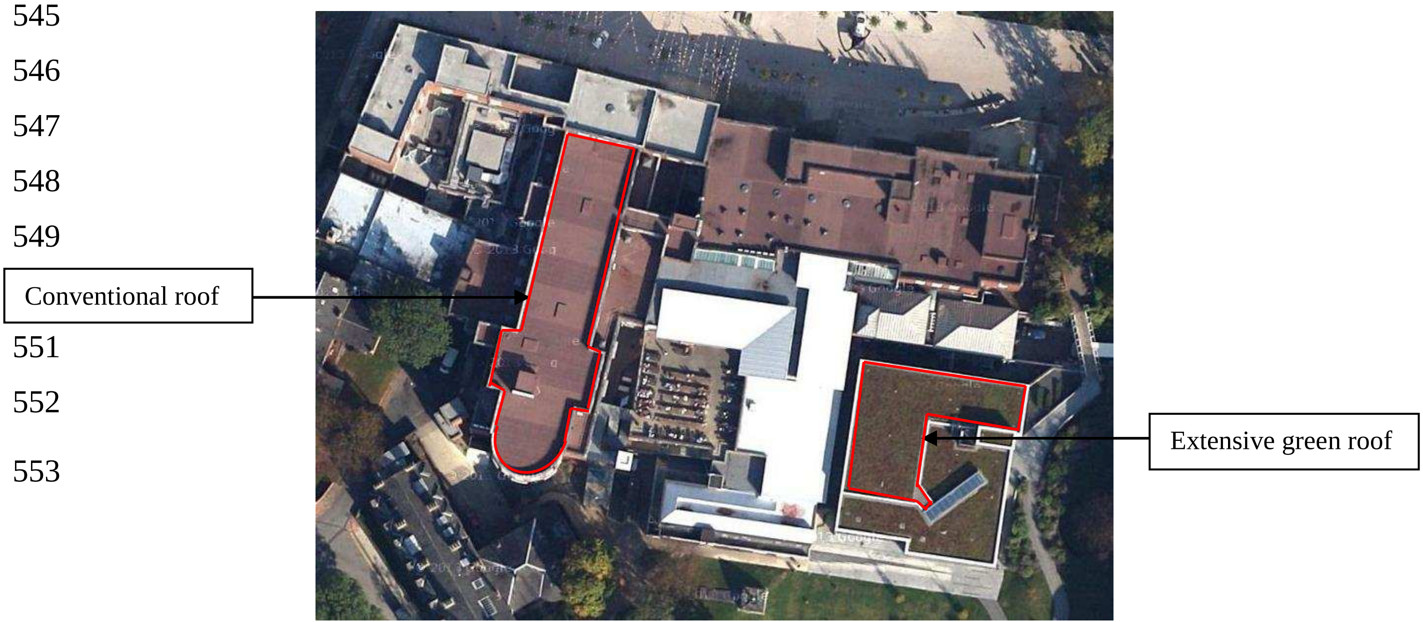


Figure 4.1.4: The location of the Leeds University Union conventional roof and the extensive green roof above the Leeds Performing Arts building. The drainage areas monitored for runoff are outlined in red (Google Maps, 2013).

4.2 Data collection:

Rainfall data was measured using a tipping bucket rain gauge located on the extensive green roof (Figure 4.2.1). It has a tipping threshold of 35ml which equates to 1.02mm of rainfall per tip. A HOBO^{TM} data logger and a laptop were used to download the data approximately once every two weeks (Figure 4.2.1). A nearby UK Meteorological Office (Met Office) Automatic Weather Station (AWS), located on the University campus, provided additional rainfall data whilst the National Centre for Atmospheric Science (NCAS) weather station located in Leeds provided mean monthly climate data. Comparisons between the tipping bucket rainfall data and the hourly AWS data ensured that the data collected was reliable and accurate (Voyde et al., 2010; Seters et al., 2009).

Figure 4.2.1: The tipping bucket rain gauge, HOBO data logger and laptop used to obtain rainfall data.

Runoff was measured from the green roof and the conventional roof using tipping buckets (Fassman-Beck et al., 2013). Runoff was measured using tipping buckets located at the base of one of the drainage pipes connected to each of the roofs (Figure 4.2.2) and factored accordingly. It was assumed that the drainage pipes draining from each roof discharge equal volumes of runoff. Runoff is drained in equal proportions by each of the drain pipes, which is an over-simplification.

The green roof tipping bucket has a tipping threshold of 335ml whilst the conventional roof tipping bucket has a tipping threshold of 290ml. Dividing by the drainage areas of each of the roofs, this equates to 3.38×10^{-3} mm runoff depth for the green roof and 2.18×10^{-3} mm runoff depth for the conventional roof to produce 1 ‘tip’.

The monitoring took place over a period of three years (2012-2014) with some notable gaps resulting from equipment failure, vandalism and delays in equipment orders. A total of ten months data was gathered over the three years which contained 30 storms according to the definition outlined in the next section. The first monitoring period lasted three months (June-August 2012) with some notable storms during what turned out to be the wettest summer for 100 years. This monitoring period was followed by a second, longer period of five months (April-August 2013). A further two months data was gathered from January to February 2013.

Between June 2012 and December 2013, runoff data was collected using a HOBO^{TM} data logger, which records the time of every ‘tip’. However, from January 2014 onwards, runoff from both the conventional roof and the green roof were measured at 5-

minute intervals using Tinytag data loggers (Figure 4.2.2). This ensured high-resolution runoff data was obtained.

Figure 4.2.2: The tipping bucket located at the base of one of the drainage pipes for a. the green roof and b. the conventional roof. From January 2014, Tinytag data loggers were used (c.)

4.3 Data analysis:

Rainfall and runoff data was downloaded using BoxCar Pro 4.3 and Tinytag Explorer software. Statistical analysis was performed in Minitab 16. Analysis of the hydrological performance of the roofs was conducted on an event-by-event basis, rather than cumulatively (Carson et al., 2013; Palla et al., 2011; Fioretti et al., 2010; Voyde et al., 2010). This meant that a range of rainfall events could be examined, and allowed for gaps in the dataset (Speak et al., 2013; Qin et al., 2013; Simmons et al., 2008; Uhl & Schiedt, 200**8**). Each individual rainfall event was separated by a continuous dry period of at least 6 hours (Speak et al., 2013; Zhang & Guo, 2013; Hathaway et al., 2008). In addition, if runoff from the green roof was still discharging at the onset of a rainfall event, the two rainfall events were combined and treated as a single, larger event (Carson et al., 2013; Fassman-Beck et al., 2013; Voyde et al., 2010; Seters et al., 2009; VanWoert et al., 2005). This ensures that the retention values reported for the green roof are accurate.

Each event was organised by season and various characteristics were calculated (Teemusk & Mander, 2007). These included the total rainfall depth (TR), total runoff depth (R), retention (%) (PR), rain duration (hours) (RD), duration of the antecedent dry weather period ADWP (hours), rainfall mean intensity (mm/hour) (i), rainfall peak intensity (mm/hour) (Rp), lag-time (1) (minutes) (LG1) and lag-time (2) (minutes) (LG2) (Speak et al., 2013; Stovin et al., 2012; Palla et al., 2011; Mentens et al., 2006.). PR was calculated as the percentage of rainfall which did not run off from the roof using the following equation (Stovin et al., 2012; Carpenter & Kaluvakolanu, 2011; Fioretti et al., 2010; Getter et al., 2007):

$$\text{Retention (\%)} = \frac{\text{total rainfall depth (mm)} - \text{total runoff depth (mm)}}{\text{total rainfall depth (mm)}} \text{ x } 100 \qquad \text{(Equation 1)}$$

i was calculated as the total rainfall depth divided by the rain duration. Lag-time (1) was calculated as the time difference between the first measurement of rainfall and the first measurement of runoff whereas lag-time (2) was calculated as the time difference between the peak rainfall (as an hourly interval) and the peak runoff (as an hourly interval) (Stovin et al., 2012; Carpenter & Kaluvakolanu, 2011; Berndtsson, 2010).

In order to categorise the magnitude of each event, return period analysis was conducted by comparing the RD and TR values against design rainfall return period estimates for Leeds, generated by the Flood Estimation Handbook (FEH) (NERC, 1999).

Given the need for practitioners to identify rainfall predictors of runoff and retention for purposes of urban water management, it was decided to investigate the relationship between several rainfall variables and retention.

The data was subjected to Anderson-Darling normality tests (Ebdon, 1985) and suitable transformations were applied to improve normality. Statistical analysis was conducted to determine whether there were any significant relationships between rainfall characteristics and the percentage of rainfall retained by the roof. This was done by conducting correlation analysis using Pearson's correlation coefficients and stepwise multiple linear regression. Principal component analysis was also conducted to provide an alternative way in which the proportion of variance explained by the measured variables could be measured, due to the potential problem with regression arising from highly related variables (Bowerman & O'Connell, 1990). Statistical analysis was conducted using SPSS 19.

Regression analysis was undertaken to develop predictive relationships between rainfall characteristics (TR, RD, ADWP, i and Rp) and green roof retention. The strength of correlation was indicated by the coefficient of determination (R^2). Furthermore, the non-parametric Kruskal-Wallis test was performed to identify any potentially significant seasonal variations in retention values (Fassman-Beck et al., 2013; Ebdon, 1985).

5. Results

5.1 Rainfall analysis

A total of 30 individual rainfall events were identified, none of which were snow events. The rainfall characteristics stated in section 4.3 were calculated for each event (Appendix A). The rainfall data obtained from the AWS allowed validation of the tipping bucket rainfall data and ensured that any gaps in the dataset were filled. For example, the ADWP of the first rainfall event which occurred on the 30th June 2012 was obtained from the AWS rainfall data.

Based on records from 1981-2010, the UK receives an average of 1154mm of rainfall a year and the annual mean temperature is 8.9ºC (Met Office, 2014a). 2013 followed a similar pattern to the overall average UK climate (Met Office, 2014a). However, the study period was notably wetter than average (National Centre for Atmospheric Science, 2014) with the summer of 2012 being the wettest for 100 years and January 2014 also receiving a significant amount of rainfall. In some parts of the UK, January 2014 was one of the wettest months ever recorded (Met Office, 2014b).

23 events were below the threshold for a rain event with a 1 year return period (Figure 5.1.1) and the largest rainfall event recorded, which occurred on the 06/07/12 was approximately a 1 in 61 year event (Appendix A). The mean lag-time (1) was 95 minutes whilst the mean lag-time (2) was 224 minutes (Table 5.1.1). This clearly illustrates the green roofs ability to detain rainwater, although there was a wide range of values observed across all events.

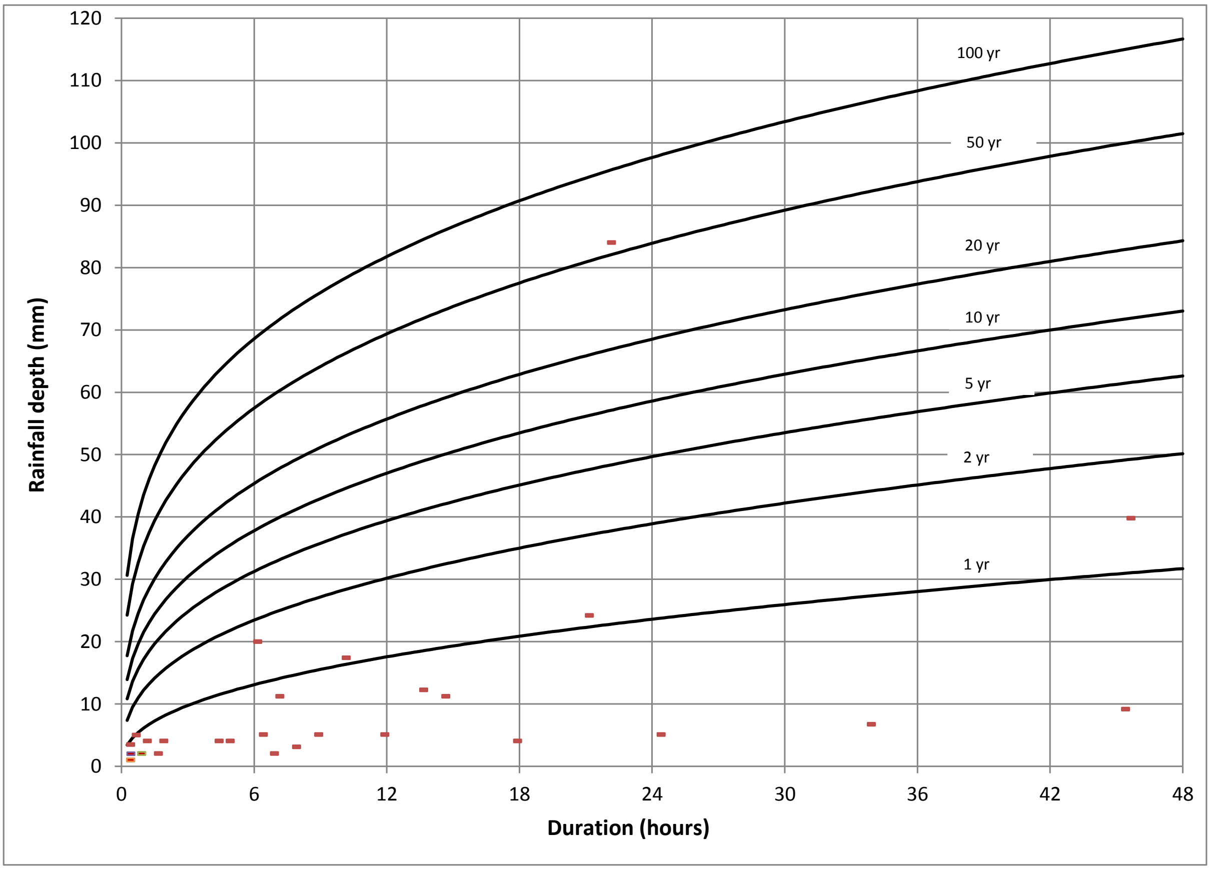


Figure 5.1.1: Rainfall return period for the study period based on Flood Estimation Handbook (FEH) rainfall-depth-duration estimates for Leeds

Table 5.1.1: Rainfall-runoff characteristics associated with each of the storms.

Date	Total rainfall (TR) (mm)	Total runoff (R) (mm)	Lag$_1$ (min)	Lag$_2$ (min)	Retention depth (R(mm)	Retention (PR) (%)
30/06/2012	17.4	11.4	60	60	6	34
06/07/2012	84	75	240	180	9	10.7
07/07/2012	20	14	120	60	6	30
09/07/2012	24.2	19	60	0	5.2	21.5
03/08/2012	5	3.23	0	0	1.77	35
04/08/2012	3.5	1.36	60	0	2.14	61
12/04/2013	2.04	0.01	403	420	2.03	99.34
12/04/2013	5.1	0.39	20	1500	4.71	92.44
17/04/2013	11.22	0	-	-	11.22	100
23/05/2013	1.02	0	-	-	1.02	100
24/05/2013	5.1	0.15	11	180	4.95	97.15
14/06/2013	3.06	0.14	139	240	2.92	95.36
15/06/2013	2.04	0.01	709	720	2.03	99.67
20/06/2013	5.1	0.72	53	120	4.38	85.95
22/06/2013	4.08	0.39	26	60	3.69	90.56
22/06/2013	4.08	0.61	7	60	3.47	85.09
27/06/2013	1.02	0.01	130	180	1.01	99.34
28/06/2013	4.08	0.3	114	120	3.78	92.71

02/07/2013	4.08	0.01	209	0	4.07	99.75
23/07/2013	12.24	1.9	8	60	10.34	84.48
27/07/2013	39.78	29.48	53	60	10.3	25.90
31/07/2013	4.08	1.29	8	240	2.79	68.35
03/08/2013	1.02	0	-	-	1.02	100
04/08/2013	11.22	0.99	38	780	10.23	91.2
19/01/2014	2.04	1.97	0	60	0.07	3.57
21/01/2014	9.18	8.17	15	60	1.01	11.04
31/01/2014	7.14	6.72	3	120	0.42	5.84
04/02/2014	2.04	0.59	35	120	1.45	71
08/02/2014	2.04	1.72	1	60	0.32	15.83
09/02/2014	5.1	3.61	43	600	1.49	29.29
Mean	**10.07**	**5.44**	**95.0**	**224.44**	**4.63**	**66.21**

Lag_1: time difference between first measurement of rainfall and runoff

Lag_2: time difference between peak rainfall and peak runoff

5.2 Relationships between rainfall characteristics and green roof retention

Rainfall amounts during seven of the storm events were retained in their entirety by the green roof, and there were no instances in which all rainfall became runoff (Table 5.1.1). Retention values ranged from 3.6% to 100% and the mean value was 66%. The total rainfall depth for all the events varied between 1mm and 84mm. Similarly, the duration of the rainfall events varied considerably from 0.17 hours to 45.4hours. This indicates that numerous events with a variety of different rainfall characteristics were included in the analysis.

Storm events with return periods greater than 1 year are shown in Figure 5.2.1 along with the corresponding retention values. For return periods of between 1 and 2 years, retention varied between 20% and 100%. For the storm with the much larger return period, retention has reduced to almost 10%. The results indicate that there is no clear relationship between storm return period and retention.

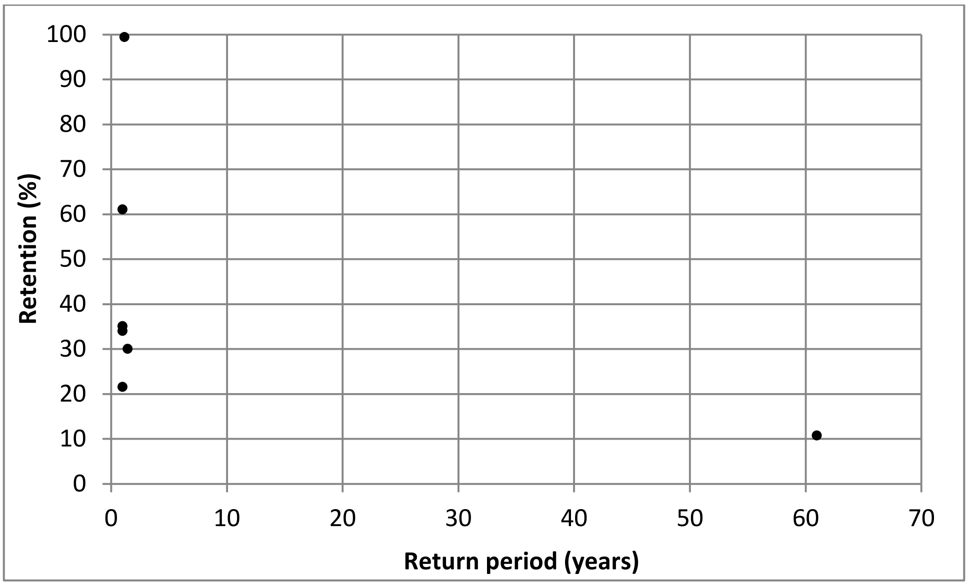
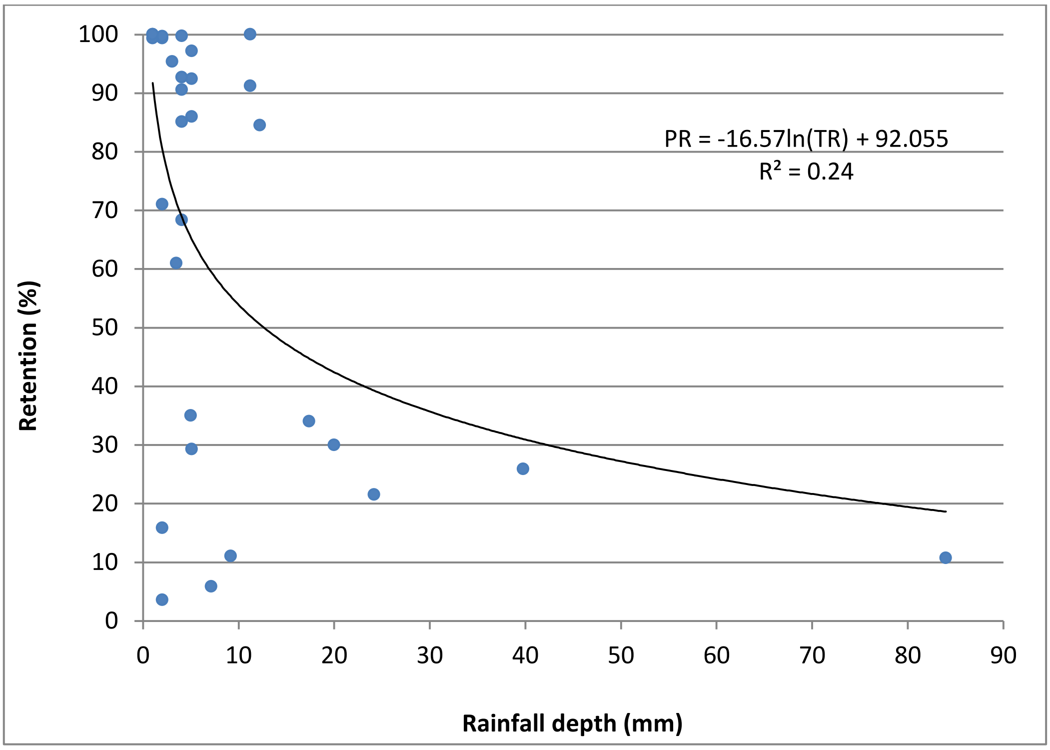


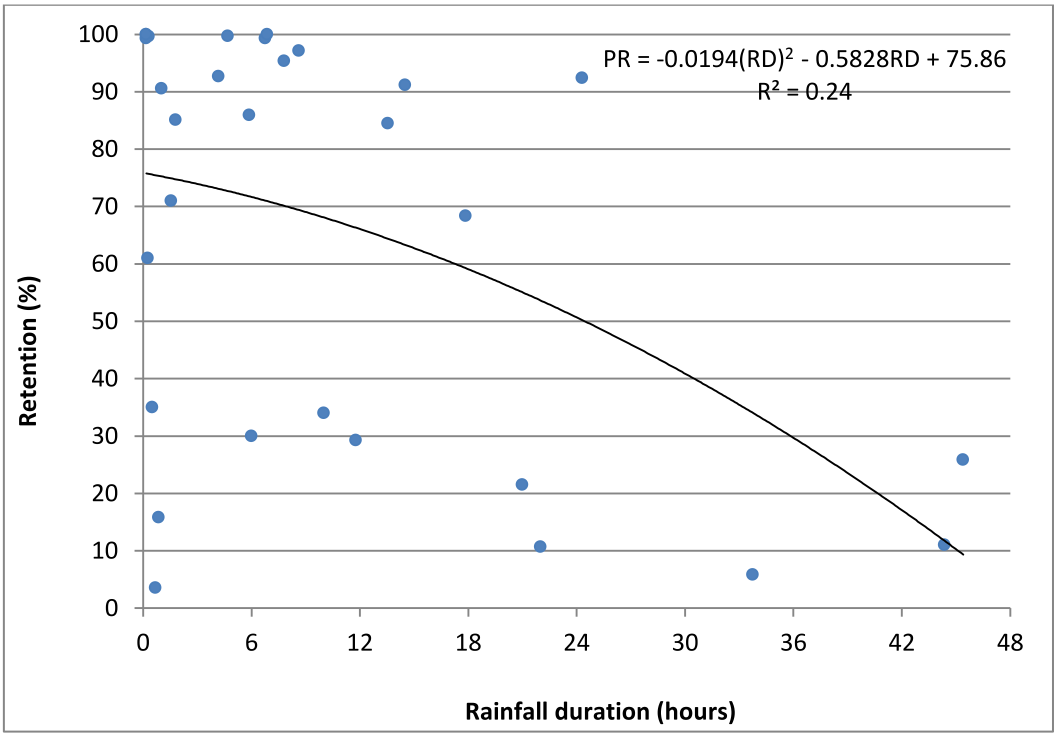
Figure 5.2.1: Storm return period versus green roof retention.

Correlation analysis indicated that there was a significant inverse relationship between retention and TR (P = 0.047) as well as retention and RD (P = 0.048). A negative correlation was also apparent between retention and RPI and ADWP, however, this was not deemed statistically significant (P = 0.153 & 0.082). A positive correlation was noted between retention and RMI and again, this was not statistically significant (P = 0.954).

The regression results are presented in Figure 5.2.2 with accompanying equations and coefficient of determination (R^2) values. As noted from the correlation analysis, both the rainfall depth and rainfall duration appear to be the best predictors of retention. As expected, rainfall was a good predictor of runoff (Figure 5.2.3) and tended to be between 0-13mm below the total rainfall (indicating that the storage capacity was 13mm).

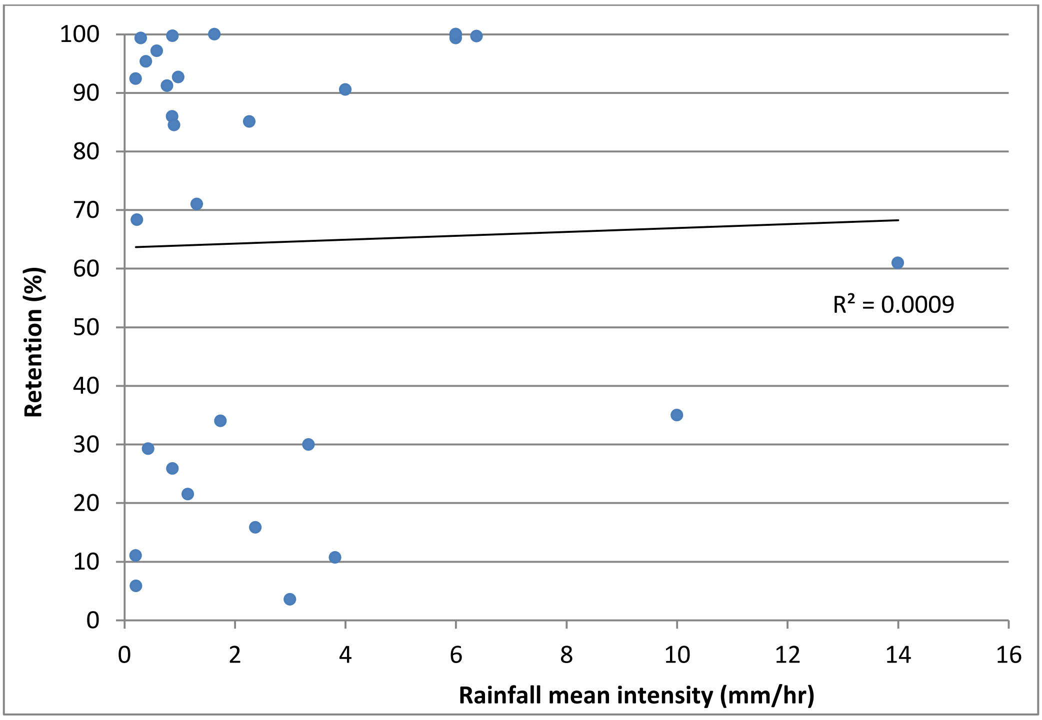

Retention (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
Rainfall depth (mm)
PR = -16.57ln(TR) + 92.055
$R^2 = 0.24$

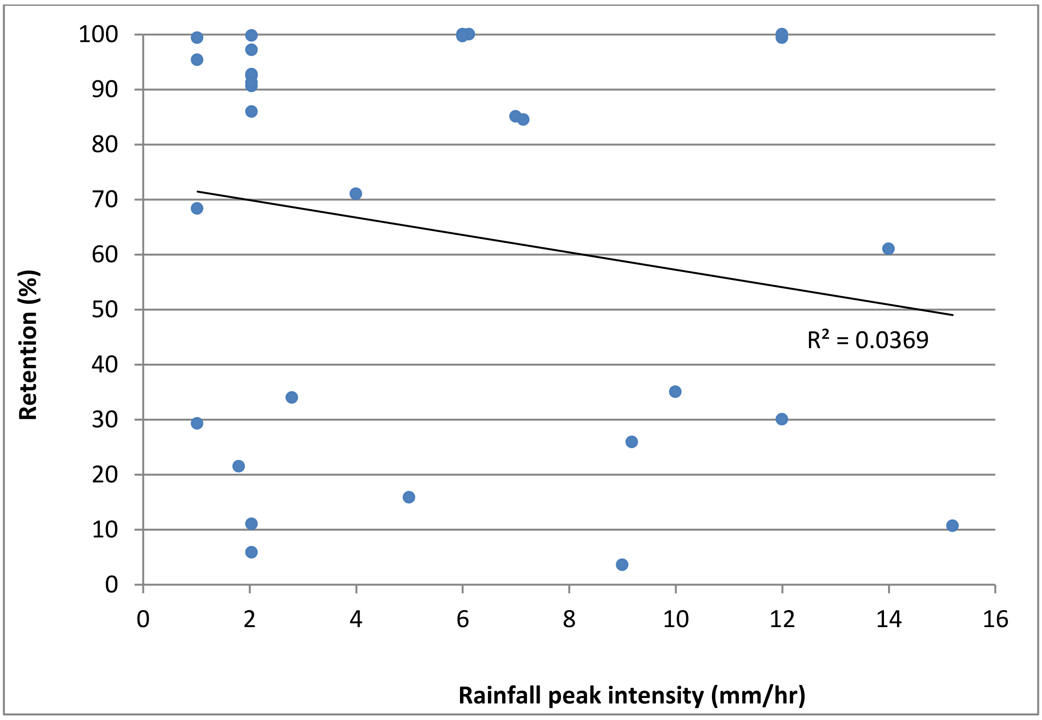
(a)


Retention (%)
100
90
80
70
60
50
40
30
20
10
0
0
6
12
18
24
30
36
42
48
Rainfall duration (hours)
PR = -0.0194(RD)^2 - 0.5828RD + 75.86
$R^2 = 0.24$

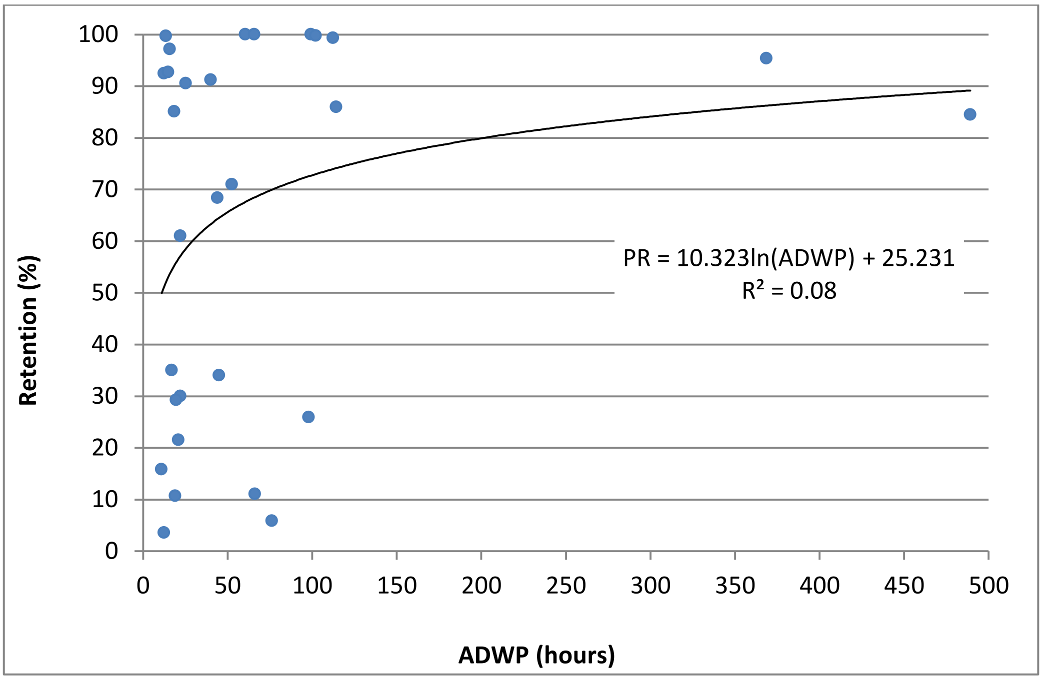
(b)

(c)


Retention (%)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Rainfall mean intensity (mm/hr)
R² = 0.0009


Retention (%)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Rainfall peak intensity (mm/hr)
R² = 0.0369

(d)



(e)

Figure 5.2.2: Scatterplots showing the relationship between retention (%) and a range of rainfall variables for the 30 rainfall events.

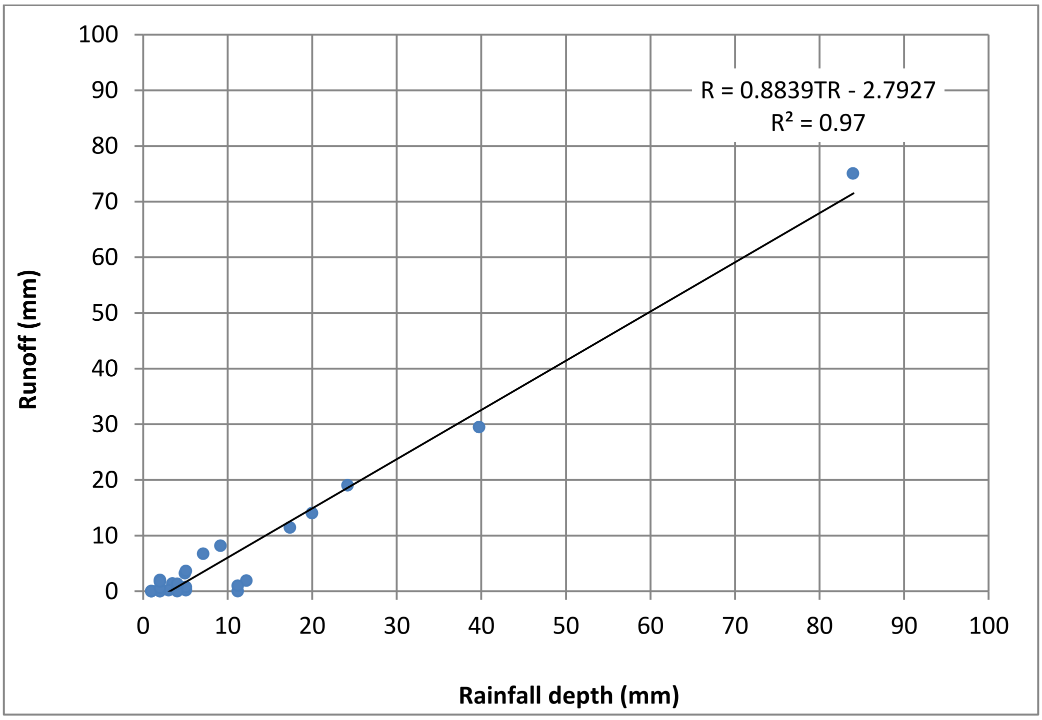


Figure 5.2.3: Scatterplot showing the relationship between rainfall and runoff

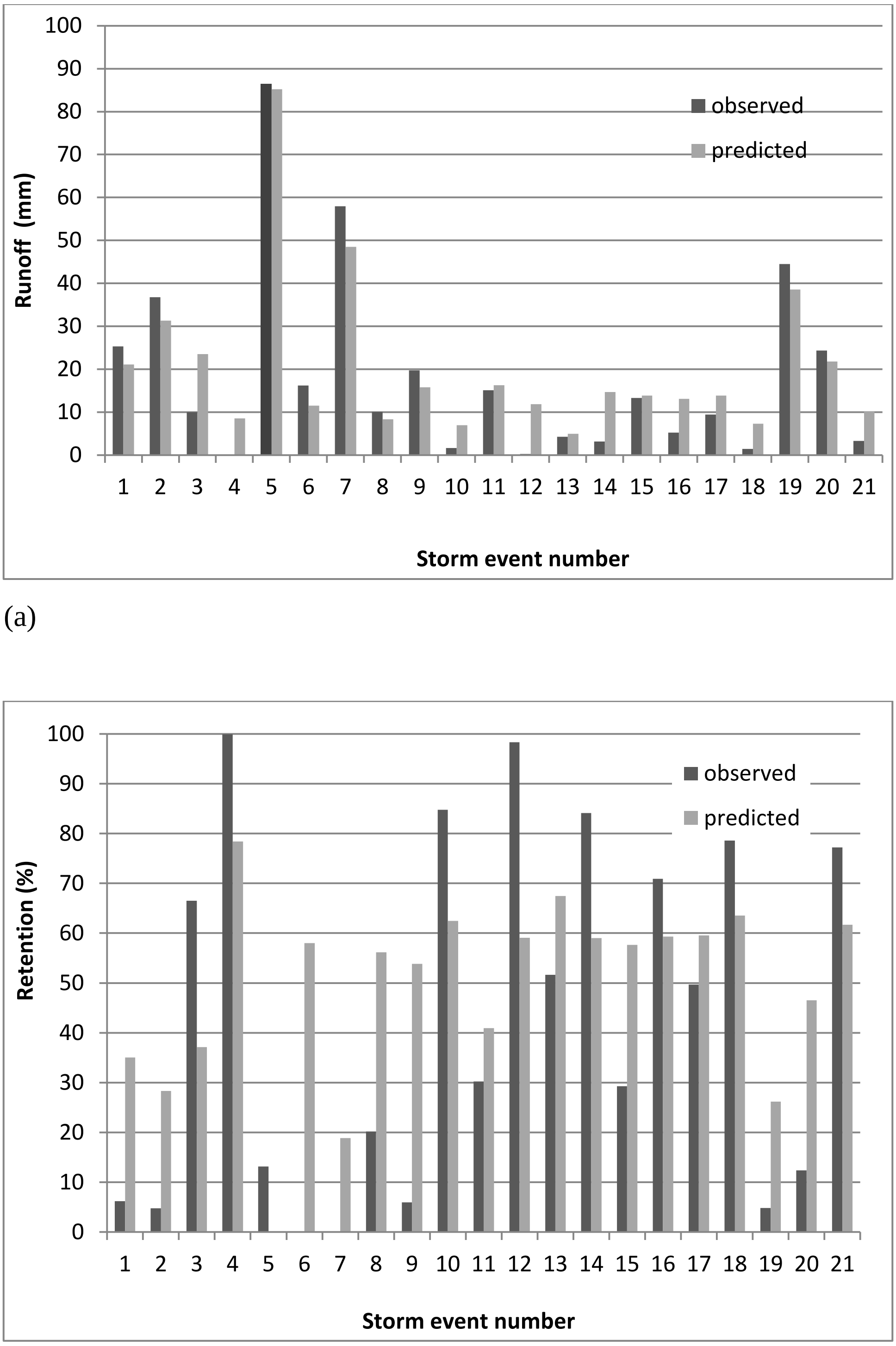
In an attempt to produce a stronger relationship between rainfall variables and retention, stepwise multiple regression was undertaken. Collinearity diagnostics revealed that the Variance Inflation Factor (provides a measure of how much the variance for a given regression coefficient is increased compared to if all predictors were uncorrelated) associated with the Rp variable was above the threshold of 3 (Cohen et al., 2003) and was therefore removed from the subsequent regression analysis to yield equation 2.

$$\text{Retention (\%)} = -0.513TR - 1.228RD - 1.233i + 0.080ADWP + 79.29 \qquad \text{(Equation 2)}$$

(F = 3.994, p-value =0.01, R-squared = 39%)

5.3 Validation of regression relationships

To validate the regression equations, they should ideally have been applied to data from the same experiment or at least to data based on the same roof type. Due to limited data availability, it was decided to test the model performance against data from a green roof study in the neighbouring city of Sheffield, situated 70km to the south of Leeds and subject to a similar climate. The extensive green roof mounted on a test-bed has a slope of 1.5% and comprises a sedum layer on 80mm substrate, significantly thicker than the roof under investigation as part of the current study. It is categorised as roof type G comprising a drainage layer (see section 1). Using data from 21 storms collected by Stovin et al (2012), the equations were applied to obtain predicted runoff depth and retention depth. Runoff depth is clearly being reproduced very well by the regression equation (Figure 5.3.1a) whilst the smaller observed retention percentage are being over-estimated and vice versa (Figure 5.3.1b).



(a)

(b)

Figure 5.3.1: Regression equation validation using data from 21 storms in Sheffield.

5.4 Seasonal variation in green roof retention

Out of the 30 events included in the analysis, 21 occurred in summer and 6 occurred in winter. Only 3 occurred in the spring and no events occurred in the autumn. Figure 5.4.1 shows the boxplots based on the summer and winter data (autumn is excluded due to the small sample size). It is clear that higher retention rates are observed in the summer.

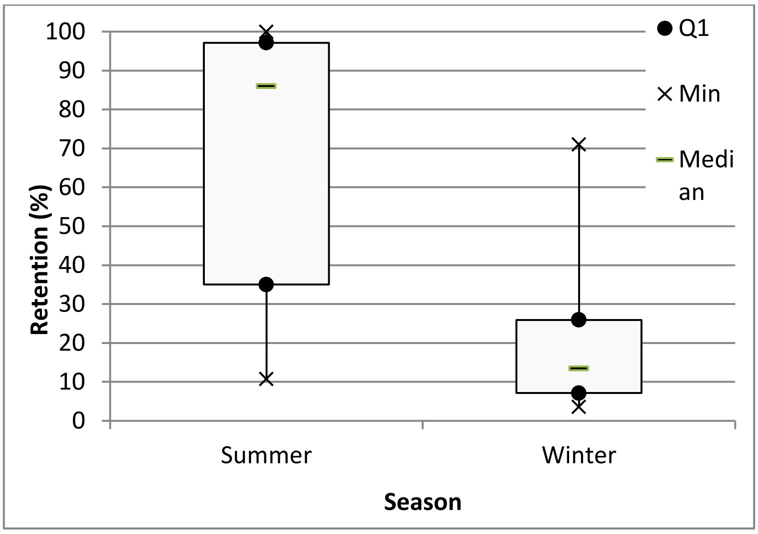


Figure 5.4.1: A boxplot showing green roof performance over the summer and winter (%).

5.5 Comparison of rainfall-runoff responses

Due to unexpected equipment failures and vandalism, only two rainfall events were deemed suitable for rainfall-runoff response comparisons between the green roof and the conventional roof. It should be noted that these events have not been included in the retention analysis as a small amount of runoff was still discharging from the green roof prior to the first recording of rainfall. Nevertheless, these events can still be used to demonstrate the green roof’s ability to reduce peak runoff, delay peak runoff and distribute runoff over a longer period of time, when compared to the conventional roof (Figure 5.5.1 and 5.5.2). The event which occurred on 12th-13th January 2014, for example, saw 9.18mm of rain fall over 4.65 hours. The green roof's peak runoff was 23% lower than the conventional roof's peak runoff (Figure 5.5.1). Moreover, the conventional roof peak runoff was recorded just 0.16 hours (10 minutes) after the first rainfall measurement whereas the green roof's peak runoff was recorded 4.25 hours (255 minutes) after the first rainfall measurement.

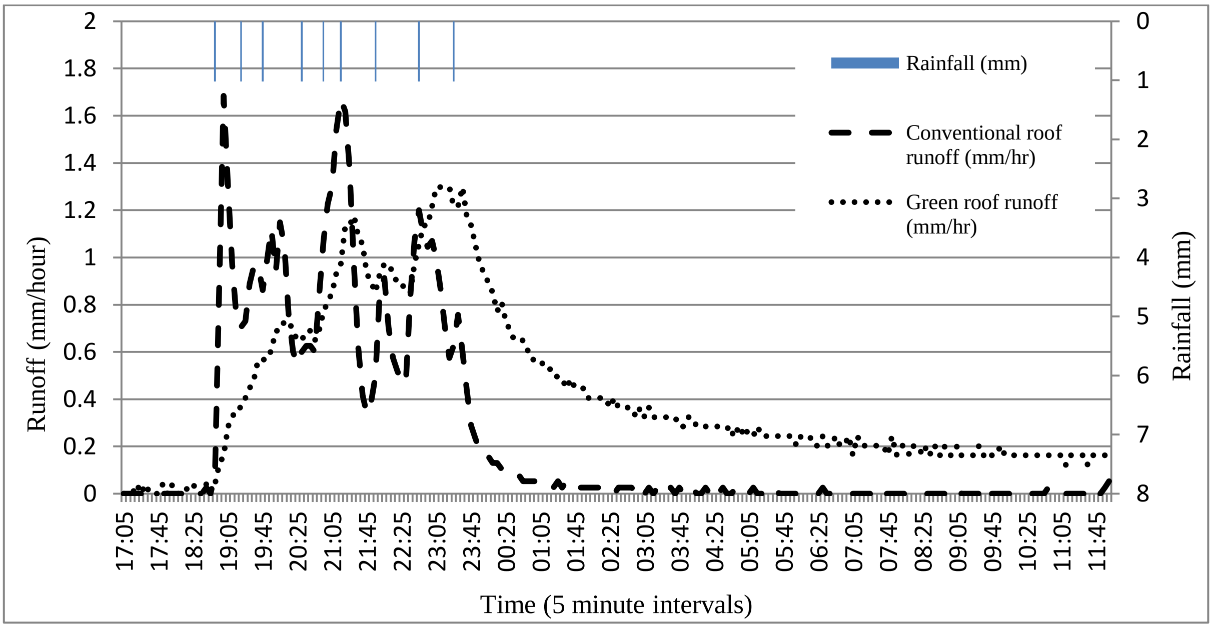


Figure 5.5.1: The green roof and conventional roof rainfall-runoff response for an event which occurred on 12th-13th January 2014. Runoff was measured at 5 minute intervals and converted to mm/hour.

The 14th-15th January 2014 rainfall event saw 4.08mm of rain fall over a period of 7.95 hours. The green roof's peak runoff was 28% lower than the conventional roof's peak runoff (Figure 5.5.2). In addition, the conventional roof peak runoff occurred 2.42 hours (145 minutes) after the first measurement of rainfall whereas the green roof peak runoff occurred 8.25 hours (495 minutes) after the first recording of rainfall. Therefore, this event also demonstrates the green roofs ability to attenuate and detain peak runoff rates.

This rainfall-runoff time series also gives us an indication of how the green roof’s hydrological performance can vary between events. Although it is a single rainfall event, it is clear from Figure 5.5.2 that there are two peaks in both the conventional roof and green roof runoff; a peak between 23:30-01:00 and a peak between 04:30-06:30. These peaks in runoff are due to the rainfall which occurred between approximately 20:30-01:00 and 04:00-06:30. The difference between the conventional roof peak runoff and the green roof peak runoff between 23:30 and 01:00 is much greater than the difference between the conventional roof peak runoff and the green roof peak runoff between 04:30 and 06:30. In other words, the green roof’s ability to reduce peak runoff rates appears to decrease for the second occurrence of rainfall. When the first measurement of rainfall is recorded for this event, the green roof’s drainage mat may have been relatively dry. However, at the onset of the rainfall which occurred between 04:00-06:30, the roof’s drainage mat is likely to be at, or close to, saturation. Thus, the peak reduction, when compared to the conventional roof, is lower for the second peak. These mechanisms and processes which affect the green roof’s hydrological performance are discussed further in the next section.

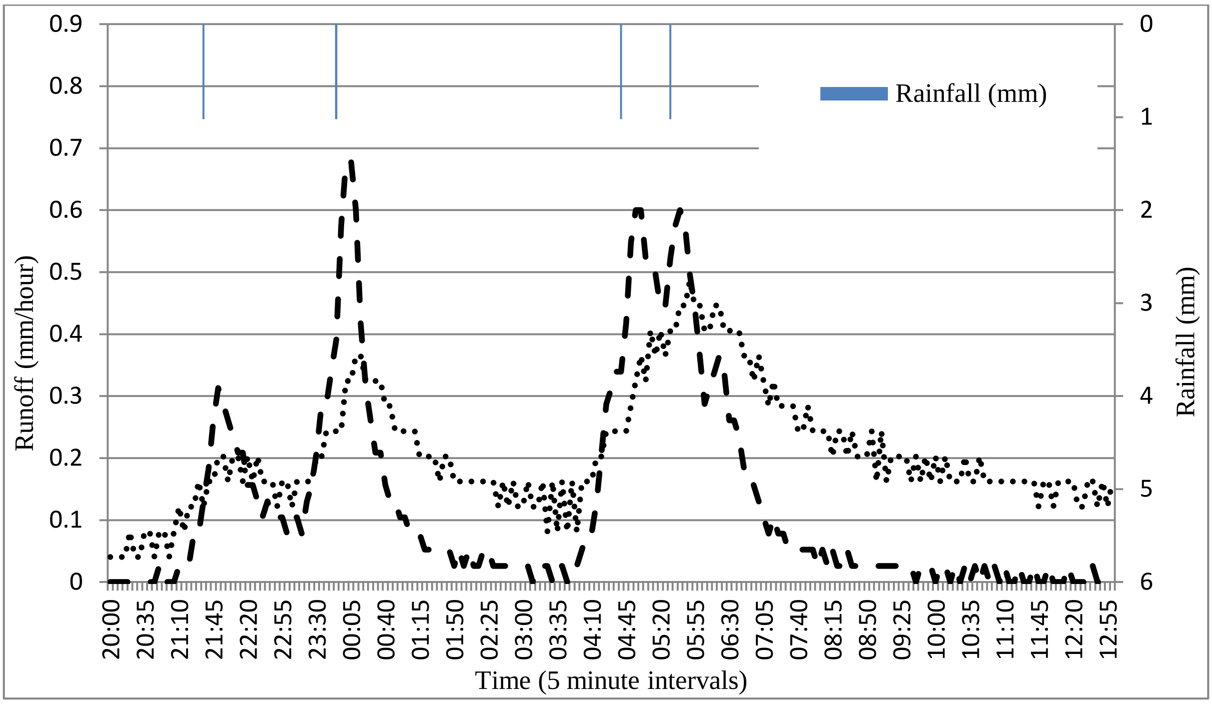


Figure 5.5.2: The green roof and conventional roof rainfall-runoff response for an event which occurred on 14th-15th January 2014. Runoff was measured at 5 minute intervals and converted to mm/hour.

6. Discussion

6.1 Rainfall event characteristics

The majority of rainfall events were not classified as extreme or significant events. Return period analysis is frequently used to establish a threshold for what is defined as an extreme of significant event (Chu et al., 2009; Sanderson, 2010). Based on recommendations in the literature (Stovin et al., 2012), the threshold in this study was set as events with a return period greater than one year resulting in there being limited examples of green roof performance under extreme conditions (Figure 5.1.1). However, despite this, the dataset did comprise storms of return periods ranging from 1 year to 61 years (the latter due to an exceptional storm during 6th July 2012 with a return period of 61 years).

The specifications chosen to define what constitutes as a rain event, and factors chosen to separate individual events, are also important to consider as it can significantly skew the calculations of rainfall characteristics. These vary widely between different studies and research applications, which results in potential discrepancies between different studies due to its direct influence on runoff analysis. Guidelines established by the WaPUG Code of Practice (2002) states that for drainage design applications, a rainfall event should be defined by an ADWP of at least 24 hours, with rainfall depths that exceed 5 mm with a peak intensity of at least 6 mm/hr that is sustained for a minimum of 4 minutes. However, as outlined in the methodology, a dry period of at least six hours was required within this study to separate each event. This criterion was chosen in order to allow for comparisons to be made with specific green roof studies, most notably with Stovin et al. (2012), which was also conducted in the UK. In addition, there was no minimum volume defined for the classification of a rain event, and due to temporal limitations of the rainfall monitoring it was not possible to conduct in depth intensity analysis.

Therefore, the definition of a rainfall event used in this study may firstly result in total rainfall volumes being underestimated when compared against more commonly used storm event definition, as a greater ADWP would have resulted in the joining of several individual events (Appendix A). However, this would be likely to exclude the events with higher retention percentages, resulting in an overall reduction of the average retention value across all storm events (Stovin et al., 2012).

6.2 Overall green roof hydrological performance

The mean retention value of 66% indicates that the green roof is effective at retaining rainfall from the individual events monitored in this study. Furthermore, the rainfall-runoff response comparison visually illustrates the green roof’s ability to reduce peak runoff rates, delay peak runoff and discharge runoff over a longer period of time, when compared to the conventional roof. The mean LG1 and LG2 values of 95 minutes and 224 minutes, respectively, demonstrate the green roof’s ability to detain rainwater. Therefore, overall, it appears that the green roof is effective at lowering surface runoff from precipitation events.

An understanding of the hydrological processes that occur within the green roof system can provide an insight into some of the factors influencing its hydrological performance. When rain falls onto it, a portion of the rainwater will be intercepted by the vegetation. Some rainwater will be used by the vegetation and released back into the atmosphere through evapotranspiration (Nagase & Dunnett, 2012). The remaining rainwater will infiltrate into the substrate layer (Zhang & Guo, 2013). Once in the substrate layer, the rainfall will be stored, evaporated, or drained through to the drainage mat (Stovin et al., 2012; Berndtsson, 2010). Whilst some storage of rainwater will occur in the drainage mat, the majority is likely to be stored in the substrate layer (Bianchini & Hewage, 2012). The temporary storage of rainfall and its slow release will allow the system to detain rainfall, attenuate peak runoff flows and discharge runoff for a longer period of time, when compared to a conventional roof (Fioretti et al., 2010; Teemusk & Mander, 2007; Getter & Rowe, 2006).

Direct comparisons with other studies are difficult to make given a whole range of conditions unique to each study including slope, climate and green roof composition. However, indications are that the average 66% retention reported in the current study is higher than figures reported in previous studies – twelve of the nineteen retention values reported in previous investigations are below the 66% noted in the current study (see Table 2.1).

This is surprising since green roofs with drainage mats are expected to have relatively smaller retention capability. The difference could be partly due to the fact that the green roof in this study is relatively flat (2% slope). Numerous studies have reported that an increase in green roof slope reduces the retention performance of a green roof (Carpenter & Kaluvakolanu, 2011; Getter et al., 2007; VanWoert et al., 2005). This is potentially due to a flat roof experiencing lower lateral flow rates of rainwater through the green roof system (Uhl & Schiedt, 2008). A flat roof may also experience lower evapotranspiration rates when compared to a sloped roof (Getter et al., 2007). This is because a sloped roof can be exposed to a greater amount of solar radiation, depending on its orientation (Jim & Peng, 2012; Uhl & Schiedt, 2008).

The green roof examined in this study also has a high percentage of vegetation cover given that it has been in operation for over five years prior to the commencement of this study. Higher vegetation cover ensures that more rainwater is evapotranspired hence more rainfall can be retained (Morgan et al., 2013; Speak et al., 2013; Berndtsson, 2010). An older green roof can result in a higher retention capability than a younger green roof system as noted in section 2. Therefore the green roof in this study can be expected to have a higher retention capability than green roofs used in previous studies.

Other green roof properties which can influence the retention of a green roof include the substrate depth and composition, the number of layers the green roof system consists of, the vegetation species and the material properties of the drainage layer (Bonoli et al., 2013; Vesuviano & Stovin, 2013; Zhang & Guo, 2013; Nagase & Dunnett, 2012; Buccola & Spolek, 2011; Simmons et al., 2008). As the substrate layer is the main component of rainwater storage in a green roof system, the depth of the substrate is a major determinant of retention (Fioretti et al., 2010; Carter and Rasmussen, 2006; Mentens et al., 2006). VanWoert et al. (2005), for example, documented that a green roof with a deep substrate will retain more rainfall than a green roof with a shallow substrate. This is because a deeper substrate allows more water to be stored in the green roof system for an individual rainfall event (Graceson et al., 2013; Berndtsson, 2010). Consequently, less runoff discharges and the green roof's water retention capacity increases (Zhang & Guo, 2013).

Similar retention values reported from previous green roof studies can also be attributed to similar green roof properties. For example, Voyde et al. (2010) reported 66% retention from of a full-scale extensive green roof in Auckland, New Zealand. The green roof used in the study had a slope of 1.2% and over 60% plant coverage, akin to the green roof investigated in this study (Voyde et al., 2010). Furthermore, a comparable substrate depth between the green roof used in this study and previous studies can explain similar retention performances (Palla et al., 2011; Fioretti et al., 2010; Hathaway et al., 2008). Several studies conducted on full-scale extensive green roofs of similar sizes to the green roof examined in this study have reported similar mean retention values (Carpenter & Kaluvakolanu, 2011; Seters et al., 2009).

6.3 Rainfall characteristics influencing green roof retention

Numerous studies have reported a wide range of retention values similar to this study (Carson et al., 2013; Stovin et al., 2012; Palla et al., 2011; Fioretti et al., 2010). This is primarily due to various characteristics of individual rainfall events (Berndtsson, 2010). This study has identified that the rainfall depth and rainfall duration are significant factors influencing retention. The rainfall depth and rainfall duration both have an inverse correlation with the green roof retention. Therefore, as the size and duration of the individual rainfall event increases, the retention tends to decrease. For example, the green roof produced a retention value of 99.3% for the rainfall event which occurred on 12th April 2013 (Table 4). This event saw 2.04mm of rain fall over 6.77 hours.

Conversely, the retention based on an event that took place on 9th February 2014 (rainfall depth of 5.1mm over 11.8 hours) was just 29.3%. This relationship between rainfall size and retention is consistent with the findings reported from previous studies (Carson et al., 2013; Fassman-Beck et al., 2013; Stovin et al., 2012; Carpenter & Kaluvakolanu, 2011; Simmons et al., 2008; Teemusk & Mander, 2007; Carter and Rasmussen, 2006). As the green roof's substrate has a finite storage capacity, a larger rainfall event produces a greater proportion of runoff, when compared to a smaller event (Getter et al., 2007). Likewise, a green roof will retain a greater proportion of rainfall from a smaller event (Stovin et al., 2013). So the finite storage capacity of a green roof notably restricts its ability to retain rainwater from larger events (Stovin et al., 2013).

This study shows a weak positive correlation between the rainfall mean intensity and the retention. Despite some studies reporting a significant influence of rainfall mean intensity on the retention, the trend observed in this study is the reverse of the expected relationship (Lee et al., 2013; Buccola & Spolek, 2011; Voyde et al., 2010; Liu & Minor, 2005). The rainfall mean intensity for an individual event can be expected to have an inverse relationship with the retention of a green roof (Bonoli et al., 2013; Lee et al., 2013; Kok et al., 2013; Stovin, 2010). This is explained by the finite retention capacity of a green roof (Stovin et al., 2012; Carter & Jackson, 2007). The correlation reported in this study may be the result of a few rainfall events having a large influence on the overall pattern shown by the data. For example, the events which occurred on 23rd May 2013 and 15th June 2013 had relatively high rainfall mean intensities (> 6 mm/hour) and produced no runoff (100% retention) (Table 4). In contrast, the rainfall event which occurred on 31st January 2014 had a relatively low rainfall mean intensity of 0.21mm/hour and produced a retention value of 5.84%. Further monitoring of the green roof’s hydrological performance may reveal a different relationship between the rainfall mean intensity and the retention as individual events have less potential to skew the overall pattern shown by the data (Speak et al., 2013).

In addition, the trend between the rainfall mean intensity and the retention observed in this study could potentially be due to the low-resolution rainfall data obtained from the tipping bucket rain gauge. The low-resolution rainfall data may also be responsible for the lack of correlation between the rainfall peak intensity and the retention. Several studies have reported that as the rainfall peak intensity increases, the retention decreases (Bonoli et al., 2013; Buccola & Spolek, 2011). However, Speak et al. (2013), akin to this study, found that the rainfall peak intensity was not a significant factor influencing retention.

Evapotranspiration is the primary mechanism which allows the green roof to restore its retention capacity between events (Zhang & Guo, 2013; Kasmin et al., 2010; Voyde et al., 2010). Therefore, it is expected that the longer the dry period between events, the longer the green roof has to restore its retention capacity (Bonoli et al., 2013; Stovin et al., 2013). In other words, if the ADWP increases, the retention of the green roof should increase, as the ADWP influences the green roof's antecedent substrate moisture conditions (Buccola & Spolek, 2011; Stovin, 2010; Hathaway et al., 2008; Liu & Minor, 2005; Villarreal & Bengtsson, 2005).

However, results presented in this study indicate that the ADWP is not a significant influence on the green roof retention. This is most probably due to the low evapotranspiration rates experienced by the green roof. The temperate maritime climate experienced in the UK means that the green roof is subjected to low evapotranspiration rates for most of the year. Indeed, Kasmin et al. (2010) state that the evapotranspiration rates experienced by a green roof under UK climatic conditions can often be below 1mm/day. So whilst green roof studies performed in such climates as the Mediterranean report a significant influence of ADWP, studies conducted in climates such as the UK are unlikely to report such an influence (Stovin et al., 2012; Palla et al., 2011; Fioretti et al., 2010; Stovin, 2010).

Moreover, the ADWP can be misleading when explaining green roof retention as it fails to provide a complete insight into the antecedent substrate moisture conditions (Stovin et al., 2012). For example, the ADWP before a rainfall event could be relatively short, suggesting that the retention will be relatively low. However, if the previous rainfall event was relatively small, the roof's substrate will have a high water retention capacity (Stovin et al., 2012; Seters et al., 2009). Therefore, the antecedent moisture condition of a green roof also depends on the size of the preceding rainfall event.

6.4 Seasonal variation in green roof retention

The results from this study show that there is significant variation in the green roof retention performance during summer and winter. Most studies on green roofs attribute the seasonal variation in a green roof’s hydrological performance to changes in evapotranspiration rates between seasons (Fassman-Beck et al., 2013; Graceson et al., 2013). In summer, it is expected that relatively high evapotranspiration rates lead to high retention values as the green roofs retention capacity is restored quickly (Berndtsson, 2010; Berghage et al., 2009; Seters et al., 2009; Mentens et al., 2006). However, as the evapotranspiration rates can remain relatively low in the UK climate, and ADWP is not a significant factor influencing the retention of the green roof, an alternative explanation is proposed.

In fact, seasonal variations in retention values reported in this study are associated with the seasonal distribution of rainfall events (Carson et al., 2013; Stovin et al., 2012). On average, the rainfall depths for the events monitored in this study are 7.38mm and 8.93mm for summer and winter events, respectively. In addition, the average rainfall duration is 9.02 hours and 33.19 hours for summer and winter events, respectively. As discussed above, the rainfall depth and duration are both significant factors which influence the retention capacity of the green roof. Therefore, the smaller and shorter rainfall events which occurred in summer can be responsible for the relatively high retention values observed. Likewise, the prevalence of larger and longer rainfall events which occurred in winter are responsible for the relatively low retention values observed. These findings are consistent with a previous green roof study conducted on a green roof test bed under UK climatic conditions (Stovin et al., 2012).

6.5 Modelling green roof retention

Regression analysis suggested that 39% of the variance in retention percentage could be determined by TR, RD, I and ADWP. This relationship, although significant at the 1% significance level, is relatively weak. The predictive power may have been increased with an increase in sample size or higher data resolution as more detailed analysis of the potential relationships could be investigated (Kelley & Maxwell, 2003). In addition, the inclusion of other variables, such as those that have not been monitored in this study including soil moisture and evapotranspiration could have strengthened the relationship (Kasmin et al., 2010).

Validation of the regression equation for 21 storms showed relatively poor performance in predicting the retention percentages. This is not unexpected given the reasons noted above coupled with the fact that the validation dataset was based on another roof type.

To improve predictive capability, more detailed empirical evidence is required regarding all aspects of green roof monitoring, due to the complex relationships of the key controlling variables (Carter & Rasmussen 2006). It has also been suggested that regression analysis cannot account for the complex inter-event processes which affect green roof retention (Stovin et al., 2012). In order to model the retention performance of a green roof accurately, the substrate moisture flux concept must be considered (Stovin et al., 2013; Stovin et al., 2012). This encompasses additional processes which affect the amount of moisture in a green roof’s substrate, and includes such aspects as the maximum water holding capacity of the substrate. Hence this approach to modelling should be more accurate than regression analysis.

Additional factors which may affect the green roof retention include the relative humidity, the air temperature, the solar radiation and the wind speed (Berndtsson, 2010; Voyde et al., 2010; Uhl & Schiedt, 2008). These factors all influence evapotranspiration rates and can be expected to contribute to green roof retention (Jim & Peng, 2012). Furthermore, the inter-particle pore space distribution can affect green roof retention (Graceson et al., 2013). Freezing conditions experienced by a green roof can also affect the amount of runoff discharged from a roof (Graceson et al., 2013; Berghage et al., 2009). Equally, melting of snow may increase the runoff discharged from a roof and reduce the retention value calculated for an individual event (Teemusk & Mander, 2007; Teemusk & Mander, 2006). In addition, changes to the size and structure of the vegetation throughout the seasons may alter retention values for individual precipitation events (Nagase & Dunnett, 2012).

Therefore it is apparent that there is a myriad of factors which can potentially interact and influence the hydrological performance of a green roof (Speak et al., 2013; Voyde et al., 2010). So whilst a conventional roof may have a linear rainfall-runoff relationship, a green roof can have a quadratic factor as the rainfall-runoff relationship is often non-linear (Yio et al., 2013; Mentens, 2006). This complexity of green roof systems indicates that a regression analysis is unlikely to provide an accurate model to predict green roof retention for individual precipitation events (Simmons et al., 2008).

6.6 Limitations and further work

One of the major limitations of this study is the duration of the monitoring period. The nature of event-based analysis means that the overall mean retention value reported for the green roof is heavily dependent on the characteristics of the individual rainfall events which have been included in the analysis (Carson et al., 2013; Fassman-Beck et al., 2013; Stovin et al., 2012; Buccola & Spolek, 2011). For instance, out of the 30 rainfall events which were included in the analysis, only 7 have return periods greater than or equal to one year. The limited number of larger return period events will skew the pattern shown by the data (Fassman-Beck et al., 2013). Consequently, the overall mean retention value reported in this study may be an over-representation of the green roof's ability to retain rainfall events. Furthermore, equipment failures meant that several large rainfall events were excluded from the event-based analysis, and the seasonal analysis was limited to summer and winter. This highlights the need for long-term monitoring of green roofs to reduce the bias created by the duration of the monitoring period (Zhang & Guo, 2013; Gregoire & Clausen, 2011; Berndtsson, 2010; Voyde et al., 2010). Studies which examine cumulative green roof retention over a continuous period may provide a more accurate indication of green roof retention (Fassman-Beck et al., 2013).

The relatively low-resolution data provided by the tipping bucket rain gauge limits the lag-time calculations and the rainfall peak-intensity calculations (Shaw et al., 2011). Previous studies have indicated that peak-to-peak lag-times can be inaccurate (Yio et al., 2013; Stovin et al., 2012). The calculation of LG2, in particular, does not account for multiple peaks in rainfall and runoff discharges (Carpenter & Kaluvakolanu, 2011). Therefore further work could attempt to obtain more accurate calculations of lag-times. This could be achieved by calculating the difference between the mean centroids of the hydrograph and the hyetograph for each individual precipitation event (Palla et al., 2011; Fioretti et al., 2010; Carter and Rasmussen, 2006).

This study has investigated green roof hydrologic performance at the roof-scale. Future work could investigate the hydrologic performance of green roofs at the watershed and landscape scale (De Munck et al., 2013; Palla et al., 2011; Damodaram et al., 2010). This could demonstrate the effectiveness of widespread green roof implementation on runoff reductions (Carter & Jackson, 2007). For example, Mentens et al. (2006) reported that if 10% of all the buildings in Brussels were covered in extensive green roofs, there would be a 2.7% reduction in runoff for the region. Further work is also needed to develop green roof conceptual rainfall-runoff models that may have wider transferability than the regression based approach reported here.

7. Conclusion

This study has demonstrated the ability of a full-scale extensive green roof to retain rainfall from individual precipitation events. This results in the green roof being able to detain rainfall and attenuate peak runoff flows, when compared to a conventional roof. However, the roofs retention performance reduces for larger rainfall events, due to its finite retention capacity. Moreover, the overall mean retention of 66% should be treated with caution as it is heavily influenced by the characteristics of the rainfall events included in the analysis. Further monitoring of the green roof may reduce the effect of this apparent bias and may produce stronger correlations between rainfall characteristics and green roof retention (Carson et al., 2013; Emilsson, 2008; Hilten et al., 2008).

The results presented here emphasize the need for climate-specific green roof studies as, contrary to previous studies, the ADWP was found to not be a significant influence on green roof retention (Kok et al., 2013; Carpenter & Kaluvakolanu, 2011; Teemusk & Mander, 2006). This is associated with the relatively low evapotranspiration rates experienced by the green roof in the UK climate (Kasmin et al., 2010). Retention values also vary between studies due to differing green roof properties such as the slope of the green roof and the depth of the substrate (Li & Babcock Jr., 2014 Forthcoming; Bonoli et al., 2013). Thus green roofs are complex, living systems and can offer varying levels of stormwater management (Olly et al., 2011; Simmons et al., 2008).

Whilst the green roof’s ability to retain rainfall from larger precipitation events is limited, their ability to retain small rainfall events remains an essential component of urban runoff management (Damodaram et al., 2010; Carter and Rasmussen, 2006). The retention of relatively small rainfall events can still prevent CSOs, which in turn, can reduce the amount of pollutants entering water bodies (Fassman-Beck et al., 2013; Getter et al., 2007). Consequently, green roofs may contribute to achieving targets outlined by the Water Framework Directive (WFD) (Newton et al., 2007). However, to provide full protection from pluvial flooding, additional SUDS may be required (Stovin et al., 2013; Tota-Maharaj et al., 2012; Mentens et al., 2006). The concept of using a variety of SUDS is central to the philosophy of sustainable urban drainage (Stovin, 2010). Green roofs, for instance, fail to contribute to groundwater recharge, whilst permeable pavements, which may have poor retention capability, encourage groundwater recharge (Seters et al., 2009).

Despite their inability to provide a complete solution to urban runoff, green roofs provide numerous additional environmental and economic benefits (Olly et al., 2011; Getter et al., 2007). Once the full range of benefits is appreciated, green roofs can be considered a useful tool for addressing a variety of issues in urban areas (Berndtsson, 2010). Therefore encouragement of their widespread implementation should be based upon the range of benefits they can offer to building owners, occupants and the wider community (Zhang et al., 2012). By the same token, future green roof research should be multidisciplinary to provide a more holistic investigation of their performance (Jim, 2013; Zinzi & Agnoli, 2012; Oberndorfer et al., 2007). This will ensure that any compromises or trade-offs between green roof designs and their benefits will be identified (Bates et al., 2009; Morgan et al., 2013; Wolf & Lundholm, 2008). For instance, to increase plant biodiversity, a green roof may be designed with varying substrate depths, but to maximise retention, a deeper substrate would be more beneficial (Bates et al., 2013; Emilsson, 2008).

The data provided here should guide policy development in the UK for widespread green roof implementation (Dowling, 2002). Currently, there is a lack of policy encouraging the uptake of green roofs in the UK (Green Roof Guide, 2011; Bell & Alarcon, 2009; Hall, 2001). This study has provided evidence for their effectiveness at contributing to stormwater management. Therefore, incentives to encourage green roof uptake, based on field results, could be developed (Butler & Davies, 2011; Fioretti et al., 2010; Clark et al., 2008). For example, reduced surface water and highway drainage charges could be offered to increase green roof installations throughout the UK (Zhang et al., 2012; Bell & Alarcon, 2009). These initiatives will ensure that the hydrologic benefits of green roofs are appropriately considered. Through effective policy development, widespread green roofing can help cities become more sustainable.

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Appendix A: The measured individual rainfall events and their characteristics.

Date	Season	RD (hr)	TR (mm)	i (mm/hr)	Rp (mm/hr)	ADWP (hours)	T (years)
30/06/2012	Summer	10	17.4	1.74	2.8	45.12	1.01
06/07/2012	Summer	22	84	3.82	15.2	19.03	61
07/07/2012	Summer	6	20	3.33	12.03	22.09	1.45
09/07/2012	Summer	21	24.2	1.15	1.81	21.42	1.01
03/08/2012	Summer	0.5	5	10	10.1	17.21	1.01
04/08/2012	Summer	0.25	3.5	14	14.07	22.16	1
12/04/2013	Spring	6.77	2.04	0.3	1.02	442.38	<1
12/04/2013	Spring	24.3	5.1	0.21	2.04	12.38	<1
17/04/2013	Spring	6.87	11.22	1.63	6.12	99.38	<1
23/05/2013	Spring	0.17	1.02	6.14	6.04	60.5	<1
24/05/2013	Spring	8.62	5.1	0.59	2.04	15.76	<1
14/06/2013	Summer	7.8	3.06	0.39	1.02	368.6	<1
15/06/2013	Summer	0.32	2.04	6.46	6.09	13.52	<1
20/06/2013	Summer	5.88	5.1	0.87	2.04	114.18	<1
22/06/2013	Summer	1.02	4.08	4.02	2.04	25.23	<1
22/06/2013	Summer	1.8	4.08	2.27	7.01	18.43	<1
27/06/2013	Summer	0.17	1.02	6.14	12.06	112.37	<1
28/06/2013	Summer	4.17	4.08	0.98	2.04	14.8	<1
02/07/2013	Summer	4.68	4.08	0.87	2.04	102.23	<1
23/07/2013	Summer	13.55	12.24	0.9	7.14	489.2	<1
27/07/2013	Summer	45.4	39.78	0.88	9.18	97.93	1.19
31/07/2013	Summer	17.85	4.08	0.23	1.02	44.02	<1
03/08/2013	Summer	0.17	1.02	6.14	12.09	65.72	<1
04/08/2013	Summer	14.5	11.22	0.77	2.04	40.02	<1
19/01/2014	Winter	0.68	2.04	3	9.02	12.42	<1
21/01/2014	Winter	44.37	9.18	0.21	2.04	66.25	<1
31/01/2014	Winter	33.75	7.14	0.21	2.04	76.23	<1
04/02/2014	Winter	1.55	2.04	1.32	4.11	52.55	<1
08/02/2014	Winter	0.86	2.04	2.37	5.03	10.97	<1
09/02/2014	Winter	11.78	5.1	0.43	1.02	19.68	<1

RD= Rainfall duration; TR=total rainfall; i=rainfall intensity; Rp=peak hourly rainfall rate; ADWP=duration of the antecedent dry weather period; T=rainfall return period.