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Water attenuation performance of experimental green roofs at Ruislip Gardens London Underground Depot

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Authors: Connop, S. Clough, J., Carneiro, M.A., and Borland, T.

Corresponding author: Stuart Connop (s.p.connop@uel.ac.uk)

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1. Introduction

Global warming induced climate change is predicted to cause an increase in the frequency and intensity of rainfall events (Atkins et al 1999, DOE 1996, UKCIP 2001 cited by the Green Roof Centre website). This brings new challenges for fluvial and pluvial storm water management. In urban areas, old and new technologies are being combined to generate sustainable urban drainage systems (SuDs) and water sensitive design in order to mitigate storm water runoff and reduce the occurrence of flooding.

One such technology is the use of green roofs as source control for storm water (Mander and Teemusk 2007). Implementation of green roofs in urban areas is becoming increasingly popular in the United Kingdom and globally.

Green roofs can provide many benefits in urban areas in addition to storm water attenuation. An increasing body of research has demonstrated that green roof can increase the lifespan of roof construction materials including water proofing, reduce a building's energy consumption, reduce the Urban Heat Island Effect (UHIE), increase biodiversity, improve air and water quality and provide sound insulation (Mentez *et al.* 2006*)*.

2. Project background

At over 1,500 km² and with an estimated 12.6 million residents, London is one of the world's megacities. Built on old models for high density living, London suffers from numerous environmental problems. Climate change is exacerbating many of these problems, the impact of which are predicted to become increasingly severe over the next 100 years.

An example of the environmental problems linked to urbanisation and climate change in London is the storm water induced flooding being experienced at London Underground depots leading to hazardous working conditions and depot downtime (personal communications LU). Due to the substantial size of depot roofs and the increased intensity of storm events, existing stormwater management drainage systems can become overloaded. This results in them backing up and overflowing into London Underground work areas making work impossible.

A potential solution to this problem is the incorporation of green roofs on depots to intercept storm events and reduce the occurrence of flooding. Green roofs are known to alleviate storm water flooding issues by significantly reducing both peak flow rates and total runoff volume of rainwater from the roofs compared to a comparable conventional grey roof. They do this by storing rainwater in the substrate, drainage layer and vegetation components of the green roof and by releasing the stored rainwater back into the atmosphere through evapotranspiration.

To assess the potential for green roofs to mitigate these problems, a knowledge exchange programme was established between the Greater London Authority (GLA) Drain London scheme and London Underground at the London Underground Depot at Ruislip Gardens. The knowledge exchange programme comprised the installation and monitoring of green roofs at the depot to assess their efficacy in comparison to the existing roof systems. Due to the unusual nature of the monitoring required the Sustainability Research Institute (SRI) of the University of East London was commissioned to create novel rainfall runoff monitoring equipment and to analyse the data generated in order to compare the green roofs with the conventional roofs.

The following report details the findings of the initial study period (July 2013).

3. Description

The Green Roof Consultancy Ltd was commissioned to design and install an extensive green roof at the Ruislip Depot. Due to the structure of the depot roofs it was necessary that the saturated weight did not exceed 100kg/m^2 (Appendix 1 details the loading of the green roof components used). In order to trial two methods of green roof design to assess which would be most applicable to widespread use by London Underground, two biodiverse extensive green roofs systems were designed and installed. Both green roofs were of equal area measuring 3.90 m X 18.45 m each (total 71.96 m^2). Both were vegetated in the same way using sedum cuttings and seeds and plugs of annual and perennial wildflowers of conservation value to regional biodiversity. Both roofs also had the same depth (65 mm) of the same extensive substrate blend. The only difference between the systems was the drainage layer used. The north end of the green roof area used a standard 10mm water reservoir drainage board. The south section used an alternative recycled waste product instead of the standard drainage board. The two sections were separated by an impermeable barrier in order to ensure they were separate hydrological units to facilitate the rainfall run off measurements.

Figure 1 shows the design of each green roof. The green roofs were located on a roof with a total area of 180.95 m^2 (4.70 m x 38.50 m).

These parameters were established according to the area characteristics and the intention to enable the widespread use in the London Underground buildings, including an accessible cost of installation and maintenance and the run off monitoring.

A control roof or ‘grey’ roof section was also established and monitored as a comparative control representative of typical rainfall runoff from the existing roof system. The area was selected to be as identical as possible to the greened area in terms of size, aspect and rain shadow. The control roof area measured 5.80 m X 43.60 m (252.88 m^2 in total).

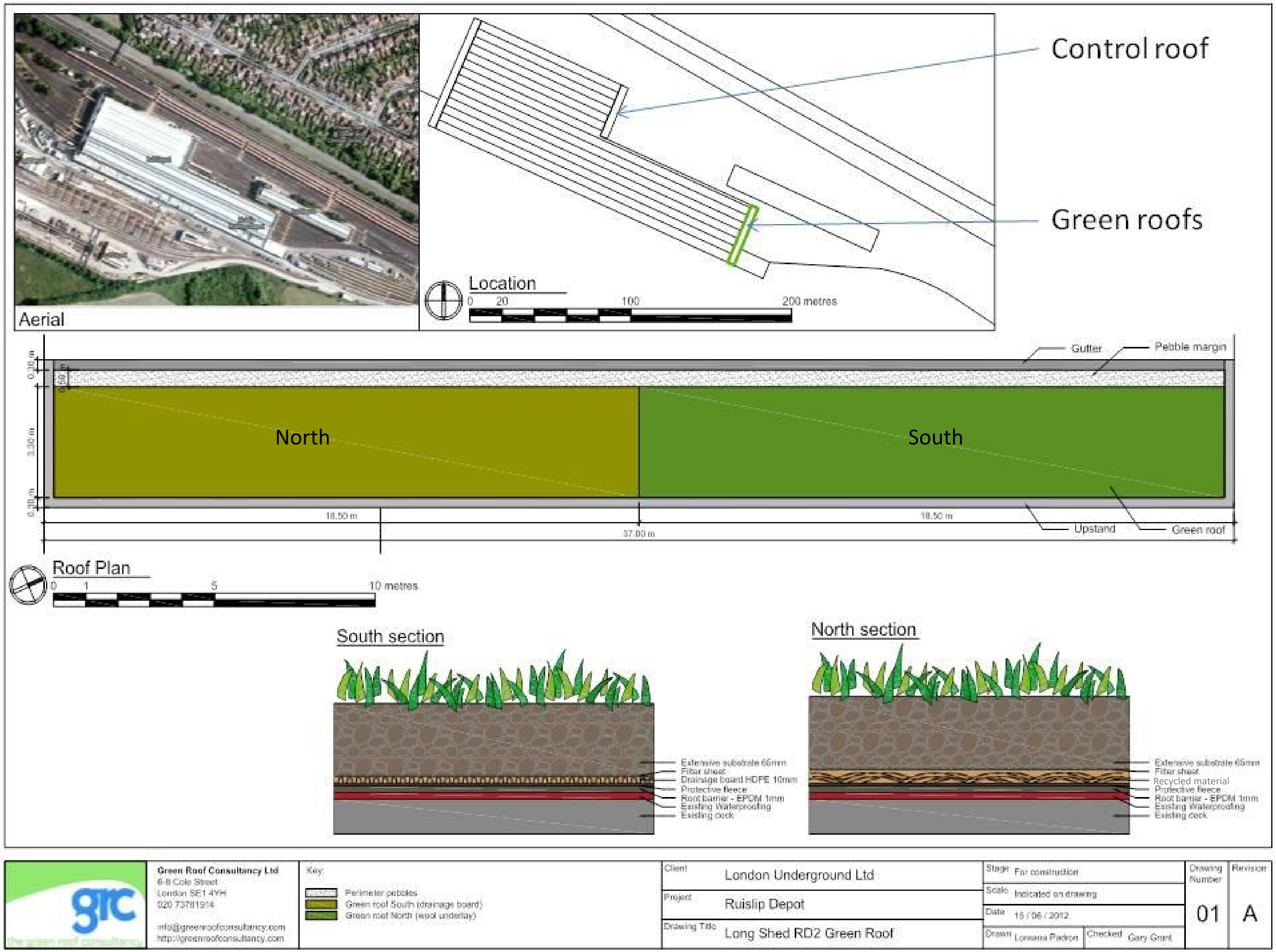

Figure 1. : Design of experimental green roofs – north and south section (© Green Roof Consultancy Ltd)

Prototype gauges

At the time of green roof construction the Sustainability Research Institute were developing in-line rainfall runoff gauges for installation in the downpipes of green roofs to monitor coarse rainfall runoff patterns. London Underground contacted the SRI to investigate whether the gauges could be used on the Ruislip depot roof. Due to logistical issues related to the depot, it was not possible to access downpipes on site or utilise the depot's power supplies. As such, it was necessary for the SRI to develop an entirely novel gauge that could be inserted into the top of downpipes draining the green and control roof areas. It was also necessary to develop a solar panel system to provide power to these systems for long periods of active monitoring.

To meet the project specifications, prototype V-notch capacitance sensor monitoring devices were developed and installed in the down pipes of each green and control roofs respectively (Figure 2). The v-notch systems limited the rate of flow from the roofs gutter system. The gauges were calibrated so that they could detect changes in height of the water in the gutter systems and this could be converted to a relative flow rate of rain water leaving each roof.

Figure 2. V-notch capacitance sensor monitoring device.

During field testing on this project the prototype gauges suffered from several issues that it was not possible to detect nor predict from the short-term lab-based trials that were carried out with the gauges prior to the initiation of the experiment. This included issues related to the solar power supply and long term pooling of rain water caused by the large atypical gutter network on the depot roof. These issues meant that data loss on the project was not uncommon and a large part of the early monitoring process on the roof was spent investigating, identifying and rectifying these issues. Nevertheless, numerous rain events have been monitored and comparisons between the water attenuation performance of the green and grey roofs was carried out.

The location of each of these devices and the roofs is displayed in Figure 3. For the purpose of this report, the devices are numbered 1 to 4. These numbers refer to rainfall runoff gauges monitoring the following roofs:

1 - Green roof with the recycled waste drainage layer (southern-most half of the green roof);
2 - Green roof with the standard 10mm drainage layer (northern-most half of the green roof);
3 - Southern-most section of control roof;
4 - Northern-most section of the control roof.

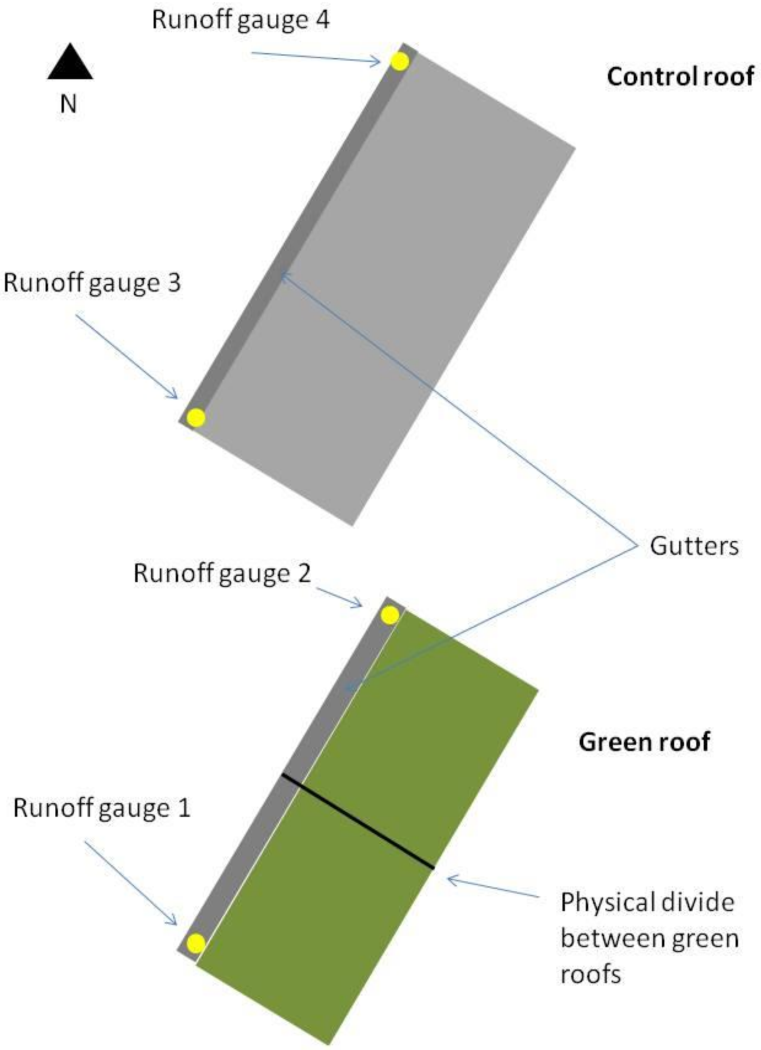

Figure 3. Location of the runoff gauges (1, 2, 3 and 4) on the roofs

4. Results

Prototype gauges were calibrated and installed in June 2013 to provide continuous runoff rate data. The gauges were in situ on the roofs continuously until December 2014. Unfortunately, due to the technical issues discussed above, continuous data for the whole period could not be obtained. Nevertheless, data for numerous rain events was obtained and the results are presented below.

Figure 4 represents an example of the weather station data for the June and July 2013 monitoring period. A Vantage Pro 2 weather station was positioned on a neighbouring roof at the Ruislip Gardens depot, approximately twenty metres from the number 1 runoff gauge. As such the weather station data provided an accurate representation of the prevailing weather conditions experienced on the monitored roofs.

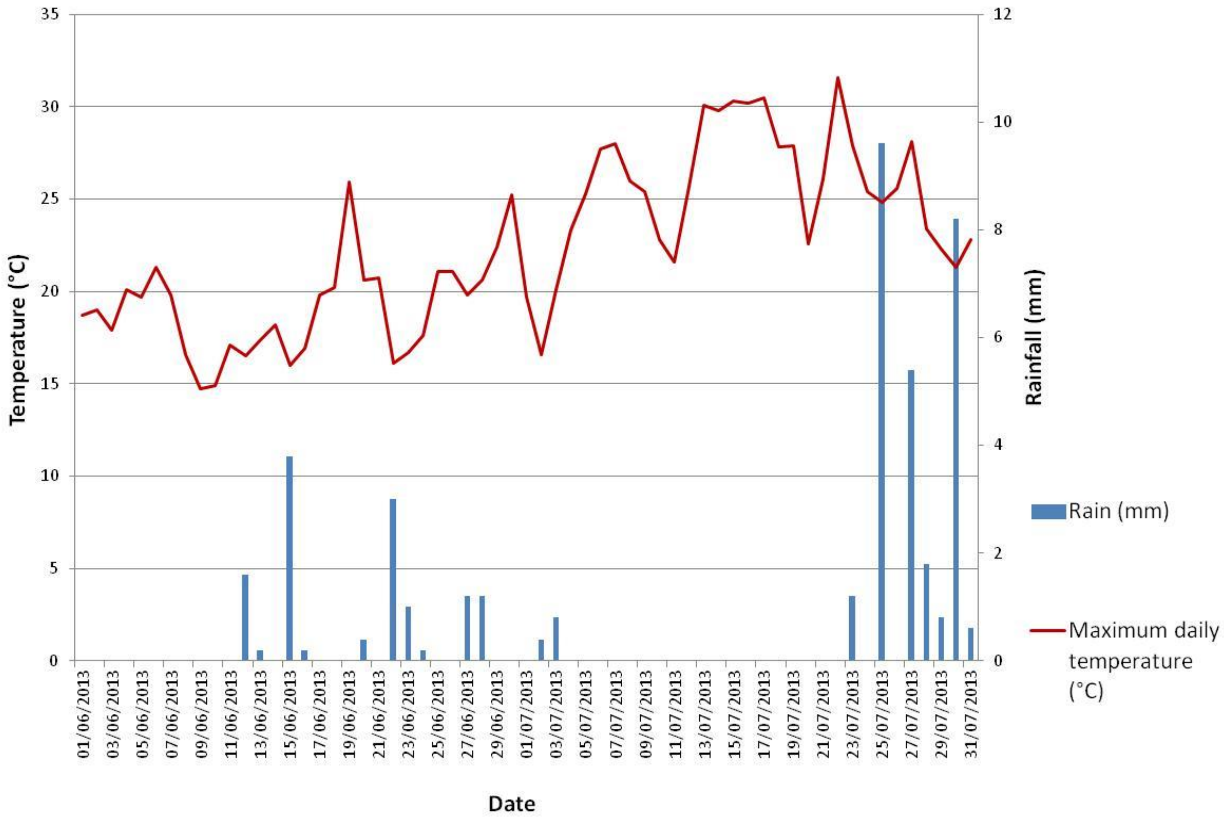

Figure 4. Weather station data from Ruislip Gardens London Underground Depot. Data generated by Vantage Pro 2 weather station and data logger for the period June to July 2013.

In developed catchments typical of urbanized areas, large swathes of hard impermeable surfaces cause large volumes of rainwater to rapidly transfer into storm drain systems following major rain events. This can lead to flooding, as has been experienced at the Ruislip Depot and as is becoming increasingly common in large cities where such rain events are known to cause significant disruption. This can be exacerbated further during spells of very hot dry weather when ground level green infrastructure can becoming extremely dry and compacted and thus perform like hard surfaces hydrologically rather than soft catchments (Figure 5). Climate change predictions indicate that such weather patterns will become more frequent in future and the impacts of these will be sever. Such impacts were reported in Central London during the green roof monitoring period including a period of very heavy rain (9.4 mm) falling in one hour (BBC 2013).

The key aim of the use of SuDs components, and particularly green infrastructure SuDs components, is to mimic the hydrological runoff patterns more typical of natural catchments where plants and substrates intercept and delay the runoff of rain water to such an extent that peak run offs are reduced and overall run off volumes are more diffuse over longer time periods (Figure 5). Central to the assessment of the efficacy of such SuDs components is an assessment of their ability to reduce and delay the peak flows leaving the roof system by the downpipes following large rainfall events. Thus reducing the probability that the existing storm drainage system would get overloaded and back up causing flooding and downtime at the depot.

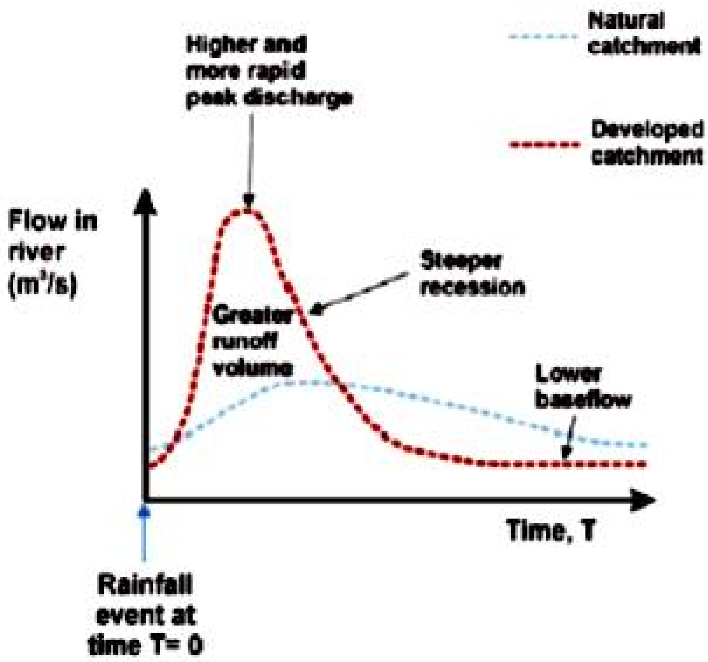

Figure 5. Natural and developed catchment hydrograph (CIRIA 200). Hydrograph demonstrating the differences in peak flow, run off rates and run off volumes between developed catchments (with large areas of hard surfaces) and natural catchments (green infrastructure.

With this key aim in mind, the prototype rain gauges installed were designed to capture a precise comparison of patterns of peak flows leaving the green and control roofs following rain events. Due to the necessity of using v-notch systems to achieve this, however, accurate quantification of precise runoff volumes at very low flow rates was not possible due to the reduced accuracy of flow rate at the very bottom of the v-notch range. This lack of accuracy of volume quantification at very low flow rates had implications for this study as, similarly to natural catchments, green roofs can release excess rainwater very slowly over long periods of time following heavy rainfall events. Moreover, due to the design of the gutters at the London Underground depot, the gauges sat in pooled water for prolonged periods of time following the cessation of rainfall. This pooling sat at a level relative to the bottom of the v-notch gauges and added additional uncertainty to the calculation of precise volumes of runoff at very low flow rate.

In addition to the issues related to low flow highlighted above, prolonged pooling at the bases of the gauges also led to unexpected changes in the baseline level readings (i.e. 0 mL/m² flow rate) for the gauges. Nevertheless, the gauges were designed to capture raw capacitance sensor data in addition to processed calibrated data. This meant that it was possible to post-process raw data to ascertain baseline levels (zero flow rate levels) by careful analysis of the raw data recorded by each gauge to identify the baseline at the time of pooling. Whilst this added an additional level of complication preventing the precise measurement of overall volumes at very low flow rates, it would not be expected to significantly affect the results of the gauges during peak flow events.

Due to these issues and the focus of the study being on the performance of the roofs in relation to reducing peak flows rather than overall volumes, results are presented for a series of rain events throughout the study period each represented by a graph showing:
i) rainfall timing and volume;
ii) differences in peak flow intensity and timing between the control grey roofs and the two green roof treatments
iii) percentage reduction in peak flow for each green roof system compared to the grey roof controls

Nevertheless, green roof trials using the same design set ups as installed at the Ruislip Depot project are being carried out by the SRI using a rain simulator to test performance under various storm scenarios (e.g. 1 in 30 year storms). Data from these studies will provide additional data on peak flow reduction, but will also provide accurate assessment of overall volume attenuation using a more comprehensive monitoring system that could not be installed at the London Underground depot.

Data presented below represent a relative comparison of peak flow from grey roof control and green roof experimental systems. Data has been standardised due to the different area of the green and control roofs. Data ahs also been divided between summer performance and winter performance due to the substantial effect that seasonality can have on green infrastructure SuDs components.

4.1 Summer events

Key to the assessment of green roof performance as SuDs components is their performance under heavy rainfall conditions following periods of hot dry weather. Not only is this the time that green roofs should perform at their maximum (as evapotranspiration during the dry spell should ensure that the green roofs are at their maximum storage capacity), as discussed previously, such rain events are increasing in frequency and intensity and are known to cause significant disruption in urban areas due to ground level green infrastructure becoming extremely dry and compacted.

4.1 Winter events

In addition to the performance of green roofs under summer weather conditions and also prolonged cool wet weather. Unlike more engineered SuDs components, such as geo-cellular modules with throttle release valves, the performance of green infrastructure SuDs components can change significantly seasonally as attenuation is directly related to water storage recharge which is controlled by rates of evapotranspiration.

Figures 6 & 7 below detail the runoff patterns from the green and control roofs during the first two rain events to occur following this dry spell, on the 23rd and 25th July

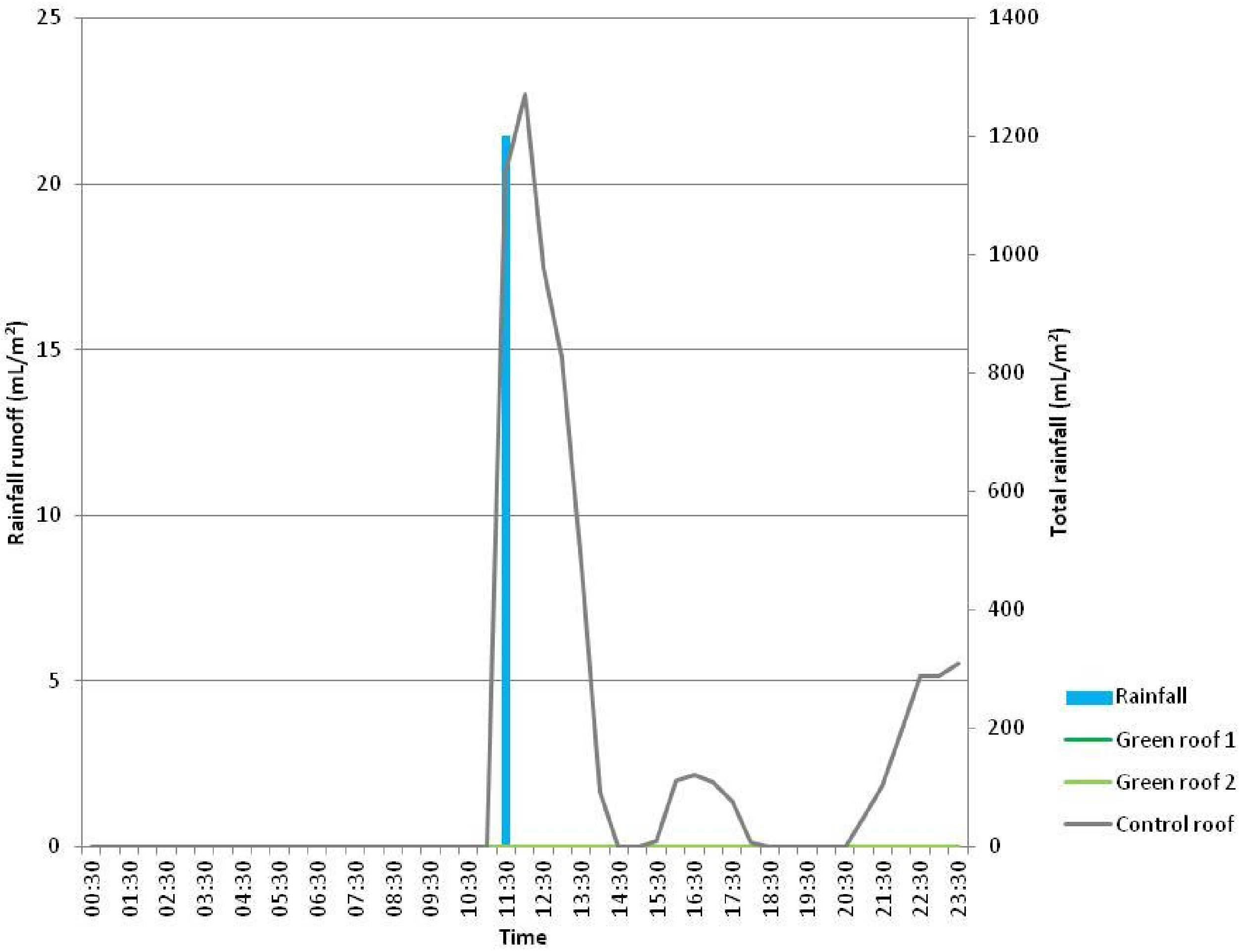

Figure 6. Rainfall and rainfall runoff patterns from green and control roofs at Ruislip Gardens London Underground depot, 23rd July 2013. First axis represents the runoff from the control and green roof areas in terms of mL of rainfall per square metre of roof area (this includes the non-greened areas between the green roofs and gutters on the green roofs). The second axis represents the size of the rain event recorded by the weather station (in mL/m²). The two axis have been normalized for purpose of display.

On the 23rd July 2013, during the first rain event following the dry spell, 1.2 mm of rainfall was recorded by the weather station falling between 11:00 and 11:30am. The maximum rain rate recorded during this period by the weather station was 55 mm/hr. Despite this high intensity rainfall, the short duration of the event meant that it would be classified as a 'slight' shower (Met Office 2007). A 1.2 mm rain event corresponds to 1200 mL/m^2 of rainfall. In total 115 mL/m² of rain water was recorded running off the control roofs. The remainder of the rain water must have been stored as pooled water and/or lost through evapotranspiration. No rainfall was recorded running off either of the green roofs for this rainfall event meaning that all of the rainfall that fell on the green roofs was stored by them.

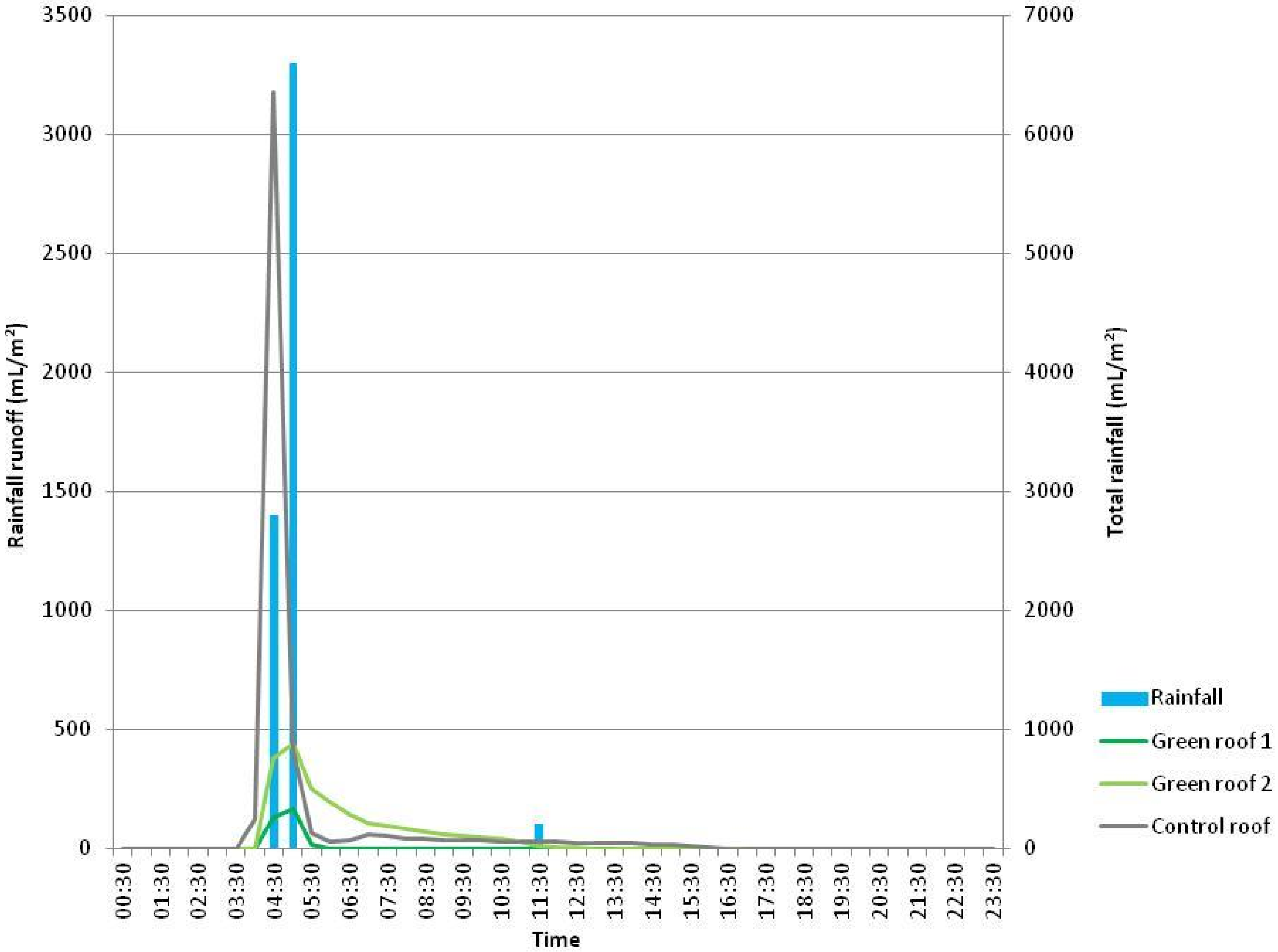

Figure 7. Rainfall and rainfall runoff patterns from green and control roofs at Ruislip Gardens London Underground depot, 25th July 2013. First axis represents the runoff from the control and green roof areas in terms of mL of rainfall per square metre of roof area (this includes the non-greened areas between the green roofs and gutters on the green roofs). The second axis represents the size of the rain event recorded by the weather station (in mL/m²). The two axis have been normalized for purpose of display. *N.B. due to data loss from one of the rain gauge units from the control roof, the peak flow measurement for the control roof may be underestimated.*

For the second rain event, 25th July 2013, 9.6 mm of rainfall was recorded by the weather station falling over the 24hr period. Of this, 9.4 mm fell during between 4am and 5am at a maximum rate of 72.4 mm/hr. This high intensity rainfall combined with its relatively short duration mean that it would be classified as a 'moderate' shower (Met Office 2007). A 9.6 mm rain event corresponds to 9600 mL/m^2 of rainfall. In total 4391 mL/m² of rain water was recorded running off the control roofs. It must be noted, however, that an interruption in the power supply of one of the gauges on the control roof meant that the actual value could be substantially higher than this. Of the green roofs, green roof 1 with the experimental drainage layer recorded 308 mL/m² of runoff during the 24 hr period and green roof 2 recorded 2009 mL/m² of runoff during the same period. This indicated that the experimental system performed better than the standard green roof system as a SuDs component during this rain event.

Due to their design being for a broad range of ecosystem services rather than purely storm water management systems, green roof storm water management performance varies depending on environmental conditions. Environmental factors such as temperature (and thus evopotranspiration rate), time since previous rainfall event, and size of previous rainfall event have a direct impact on a green roof's ability to mitigate subsequent rain events. Figures 8 to 10 represent control and green roof performance under the series of rain events from the 27th to the 31st of July that followed the initial breaking of the dry spell on the 23rd and 25th July.

For the 27th July 2013 rain event (Figure 8), 5.4 mm of rainfall was recorded by the weather station falling over the 24hr period. All off this, fell between 19:30 and 22:00 at night with a maximum rate recorded of 6.8 mm/hr. Due to the relatively low intensity of this rain event, it would be classified as a 'slight' shower (Met Office 2007) despite its duration over several hours. A 5.4 mm rain event corresponds to 5400 mL/m^2 of rainfall. In total 2460 mL/m^2 of rain water was recorded running off the control roofs. Of the green roofs, green roof 1 with the experimental drainage layer recorded no runoff during the 24 hr period and green roof 2 recorded 118 mL/m^2 of runoff during the same period. This indicated again that the experimental system performed better that the standard green roof system as a SuDs component during this rain event.

For the 28th July 2013 rain event (Figure 9), 1.8 mm of rainfall was recorded by the weather station falling in two bursts over the 24hr period. Of this, 0.4 mm fell between 15:30 and 16:00 with a maximum rate recorded of 2 mm/hr and 1.4 mm fell between 23:00 and 23:30 with a maximum rate of 9.8 mm. Due to the relatively low intensity of these rain events, they would be classified as a 'slight' showers (Met Office 2007). A 1.8 mm rain event corresponds to 1800 mL/m^2 of rainfall. In total 1030 mL/m^2 of rain water was recorded running off the control roofs. It must be noted, however, that an interruption in the power supply of one of the gauges on the control roof meant that the actual value could be substantially higher than this. Of the green roofs, green roof 1 with the experimental drainage layer recorded no runoff during the 24 hr period and green roof 2 recorded 696 mL/m^2 of runoff during the same period. This indicated again that the experimental system performed better that the standard green roof system as a SuDs component during this rain event. Of note from the 28th of July hydrograph (Figure 9) was the record of runoff prior to the rainfall event recorded for the control and green roofs. Whilst the runoff from the green roof is typical of that found for such systems with slow gradual release over an extended time period (i.e. from the previous day's rain event. It is unlikely that the same occurred for the control roof. It is more likely that the runoff recorded from the control roofs was an artefact of the gutter system on the control pooling water. However, this would have to be confirmed with further analysis of runoff patterns.

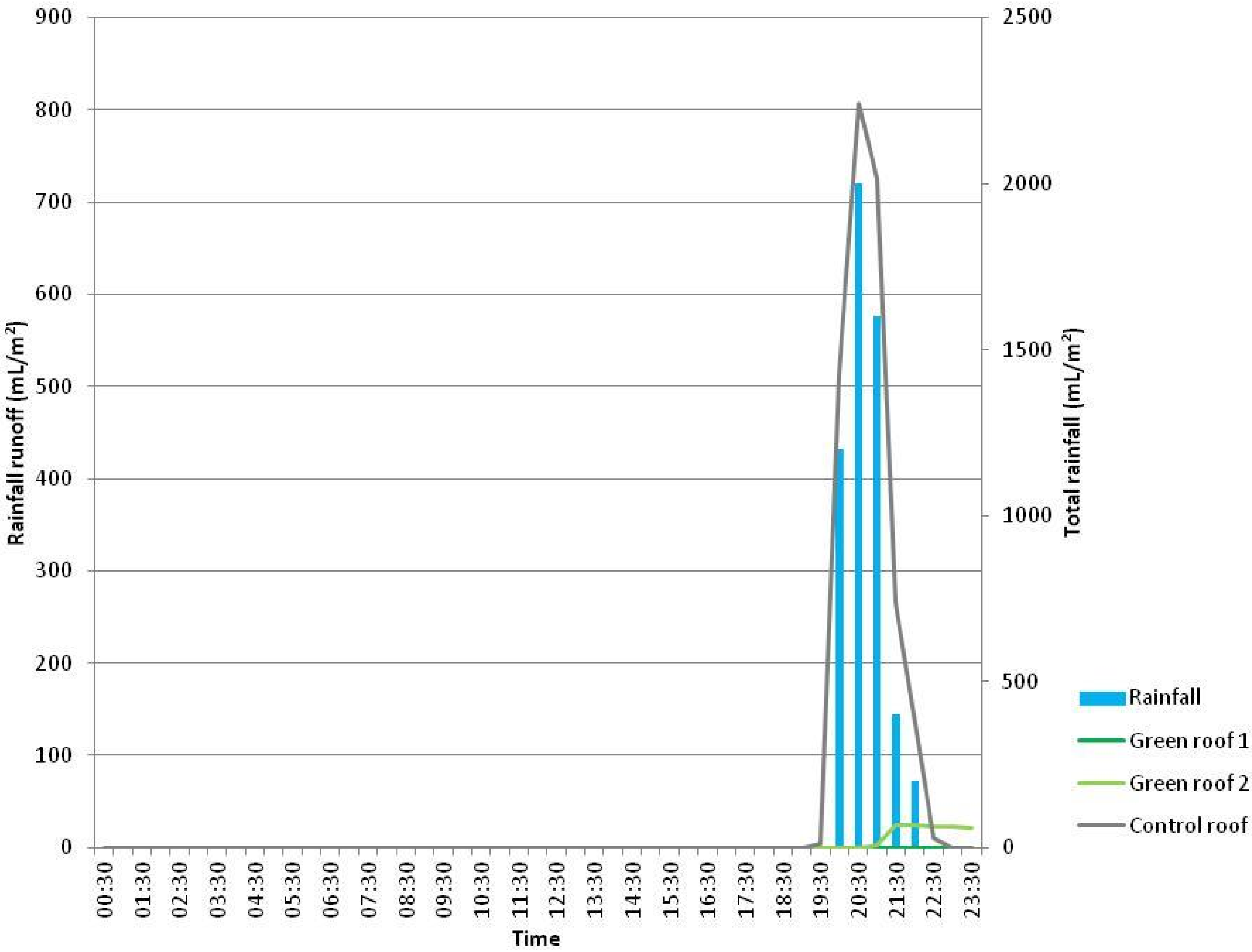

Figure 8. Rainfall and rainfall runoff patterns from green and control roofs at Ruislip Gardens London Underground depot, 27th July 2013. First axis represents the runoff from the control and green roof areas in terms of mL of rainfall per square metre of roof area (this includes the non-greened areas between the green roofs and gutters on the green roofs). The second axis represents the size of the rain event recorded by the weather station (in mL/m²). The two axis have been normalized for purpose of display.

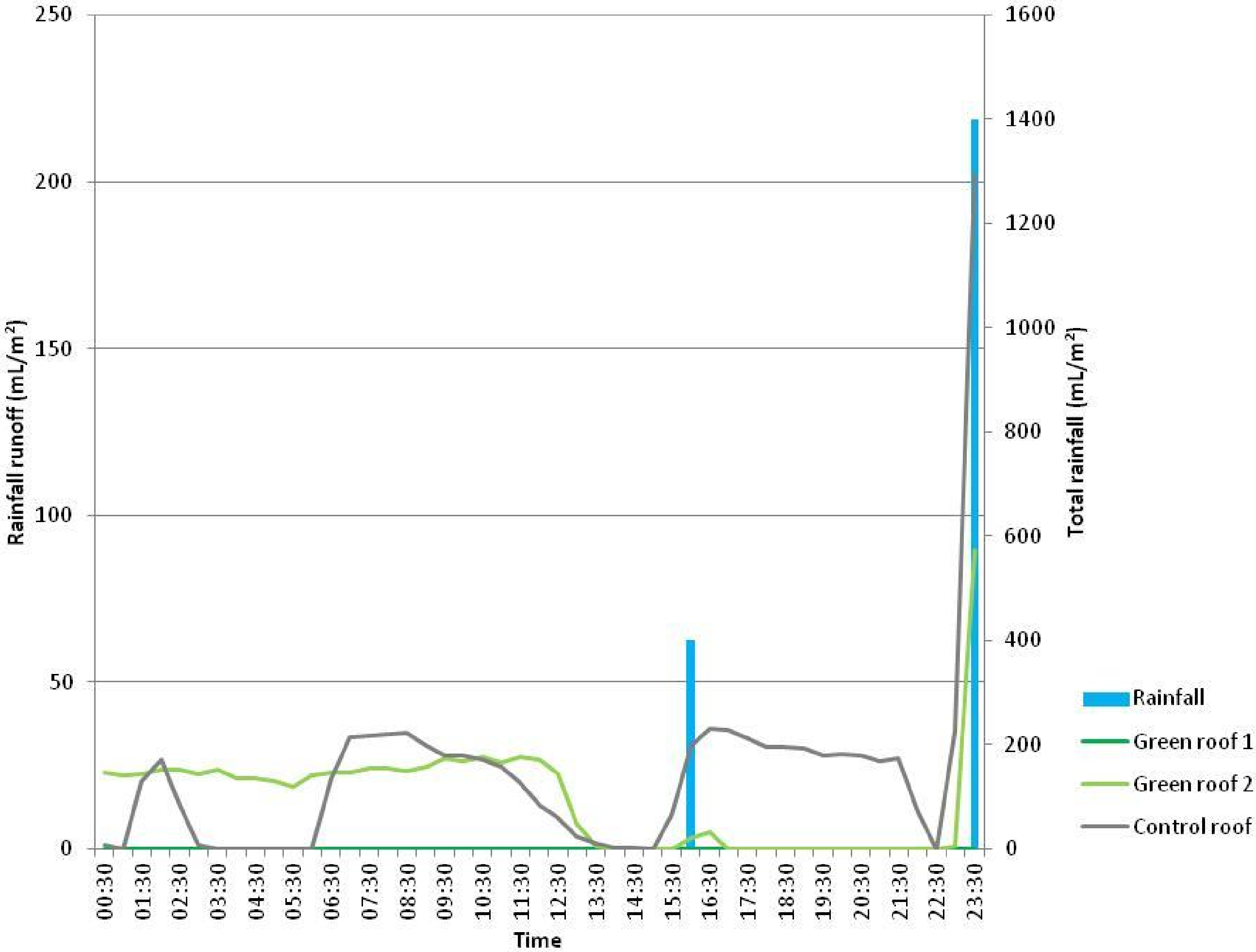

Figure 9. Rainfall and rainfall runoff patterns from green and control roofs at Ruislip Gardens London Underground depot, 28th July 2013. First axis represents the runoff from the control and green roof areas in terms of mL of rainfall per square metre of roof area (this includes the non-greened areas between the green roofs and gutters on the green roofs). The second axis represents the size of the rain event recorded by the weather station (in mL/m²). The two axis have been normalized for purpose of display.

For the 30th July 2013 rain event (Figure 10), 8.2 mm of rainfall was recorded by the weather station falling in two bursts over the 24hr period. Of this, 4.2 mm fell between 08:30 and 10:00 with a maximum rate recorded of 12 mm/hr and 4.0 mm fell between 11:00 and 13:00 with a maximum rate of 9.8 mm. Due to the relatively low intensity of these rain events, they would be classified as a 'moderate' showers (Met Office 2007). An 8.2 mm rain event corresponds to 8200 mL/m^2 of rainfall. In total 5694 mL/m² of rain water was recorded running off the control roofs. Of the green roofs, green roof 1 with the experimental drainage layer recorded 1116 mL/m² during the 24 hr period and green roof 2 recorded 8951 mL/m² of runoff during the same period. This indicated that again the experimental system performed better than the standard green roof system as a SuDs component during this rain event. The standard green roof, however, performed worse in terms of total volume runoff than the control roofs and indeed released more than fell during the rain event. Such a pattern is not uncommon on green roofs, and was most likely due to a slow controlled release over a longer time period (including from the previous rain event). This theory is supported by the substantial difference in the peak flows recorded between the control roof and green roof 2 for the rain event (Table 1).

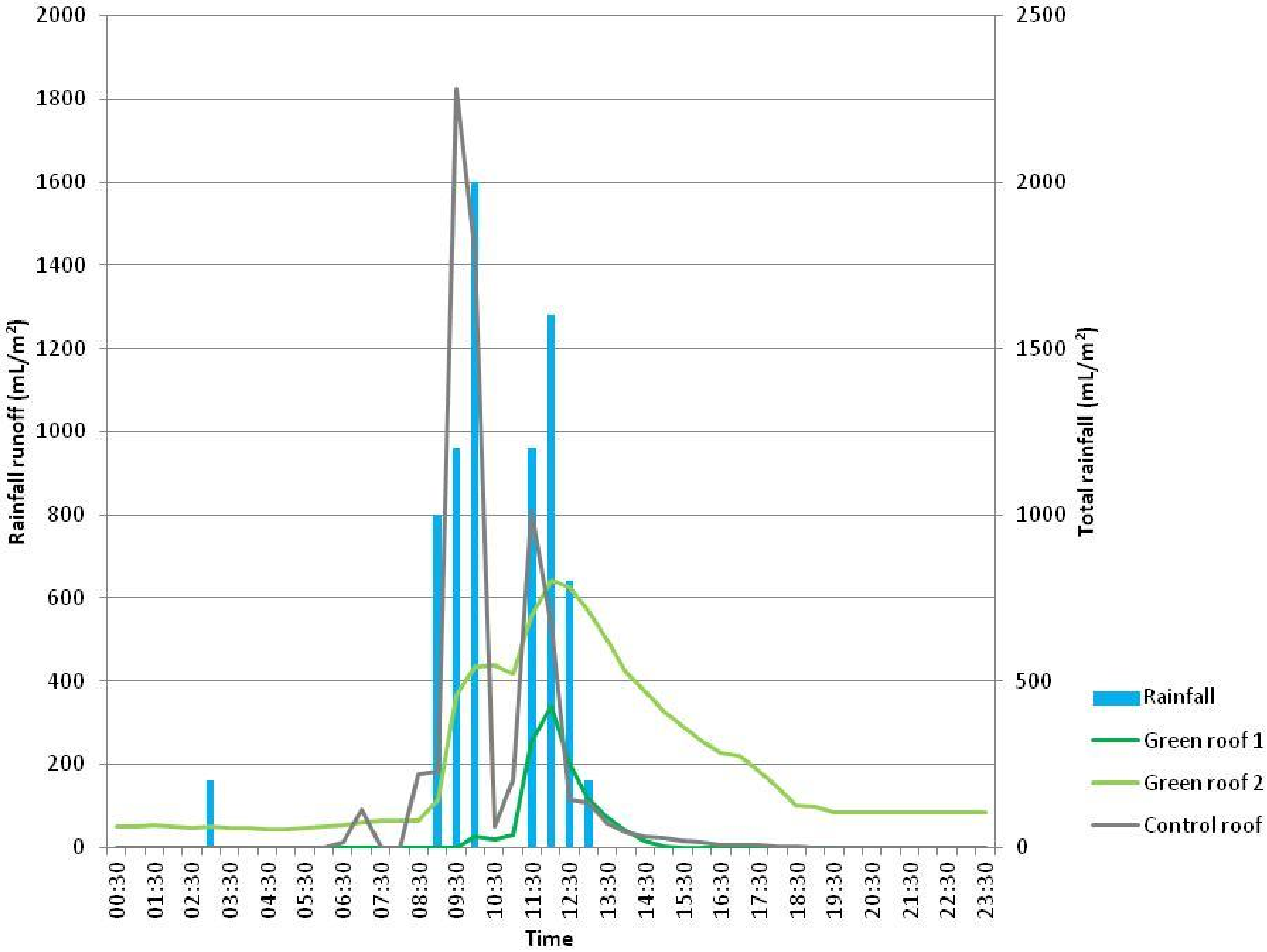

Figure 10. Rainfall and rainfall runoff patterns from green and control roofs at Ruislip Gardens London Underground depot, 30th July 2013. First axis represents the runoff from the control and green roof areas in terms of mL of rainfall per square metre of roof area (this includes the non-greened areas between the green roofs and gutters on the green roofs). The second axis represents the size of the rain event recorded by the weather station (in mL/m²). The two axis have been normalized for purpose of display.

Peak Flow

In addition to total storage, peak flow of runoff from a roof system is critical in assessing whether storm drains are overloaded. Peak flow is the maximum flow rate recorded running of the roof system. In a typical of a hard catchment system (Figure 4), the majority of rain falling during a short high intensity rain event runs directly into the storm drains in a very short time period. This can lead to overloading of storm drains, as is occurring at London Underground depots and is typical of many urban areas. Even if the overall volume of runoff entering the drains is the same, by reducing the peak flow and attenuating the rate that the rainfall runs into the drains it is possible to reduce the loading and prevent flooding issues. As such, one of the key features of green roof design is to attenuate the rate at which rainfall run off is fed into the storm drain system in terms of maximum rate of peak flow and delay in peak flow.

Maximum rate of peak flow and time of peak flow have been calculated for each rain gauge for each rain event and are presented in Tables 1 & 2 respectively. Values for the control roofs have been standardized so as to be representative of an equivalent area to each of the green roofs.

Table 1. Maximum peak flow rate for each rain gauge unit for each rain event. N.B. Values for the control roof have been standardised to the equivalent areas of each green roof.

Date	Total Rain (mm)	Peak Flow (mL/S)			
		Green Roof		Conventional Roof	
		Unit 1	Unit 2	Unit 3	Unit 4
23/07/2013	1.2	0	0	0	1.4
25/07/2013	9.6	13.9	31.3	*3.7	**635.6
27/07/2013	5.4	0	1.3	50.2	41.0
28/07/2013	1.8	0	6.6	*2.3	**21.9
30/07/2013	8.2	18.1	32.2	134.4	134.3

* *Anomalous result related to power outage of rain gauge*

** *Normalised using an assumption that half of the control roof would flow to this gauge as other gauge on control roof not recording at the time of peak flow*

Table 2. Peak flow time registered in each rain gauge unit for each rain event. Time rain event started is rounded to the nearest 30 mins prior to the rain event.

Date	Time rain events started	Peak Flow time			
		Green Roof		Conventional Roof	
		Unit 1	Unit 2	Unit 3	Unit 4
23/07/2013	11:00	N/A	N/A	N/A	11:51
25/07/2013	04:00	04:57	04:48	*07:02	04:42
27/07/2013	19:30	N/A	22:16	21:02	20:27
28/07/2013	23:00	N/A	23:58	*08:58	23:40
30/07/2013	08:30	11:56	12:29	09:42	09:41

* *Anomalous result related to power outage of rain gauge*

For the rain event on the 23rd of July, no runoff was recorded entering the storm drain systems from the two control roofs. Thus the peak flow rate was 0 mL/m². In comparison, the peak flow rate of the runoff from the control roofs was 1.4 mL/s at 12:00pm.

For the rain event on the 25th of July, peak flow from the experimental green roof 1 was 13.9 mL/s recorded at 4:57am. Peak flow from the standard green roof 2 was 31.3 mL/s recorded at 4:48am. Peak flow rate for control gauge 3 was 3.7 mL/s (standardised to the equivalent of the green roof area) at 7:02am (N.B. it must be noted however that this is likely to be an anomalous result due to a power supply issue for this gauge at the time when the peak flow was recorded for the other gauge on the control roof). Peak flow for control gauge 4 was 635.6 mL/s (standardised to the equivalent of the green roof area) at 4:42 am. This flow rate was adjusted to take into account the fact that rain gauge 3 was not recording at the time of the peak flow on unit 4. The adjustment was made based on the assumption that approximately half of the roof area would drain into each of the two gauges on the control roof.

For the rain event on the 27th of July, no flow was recorded coming from the experimental green roof 1. This indicated that all the rain that fell on it was either absorbed and/or pooled on the roof and gutter in insufficient volumes to be released into the storm drain system. Peak flow from the standard green roof 2 was 1.3 mL/s recorded at 22:16am. Peak flow rate for control gauge 3 was 50.2 mL/s (standardised to the equivalent of the green roof area) at 21:02am. Peak flow for control gauge 4 was 41.0 mL/s (standardised to the equivalent of the green roof area) at 20:27 am. Thus, the green roofs again demonstrated their ability to not only reduce runoff volumes, but also to reduce peak flow and delay it by nearly two hours.

For the rain event on the 28th of July, no flow was recorded coming from the experimental green roof 1. This indicated that all the rain that fell on it was either absorbed and/or pooled on the roof and gutter in insufficient volumes to be released into the storm drain system. Peak flow from the standard green roof 2 was 6.63 mL/s recorded at 23:58am. Peak flow rate for control gauge 3 was 2.30 mL/s (standardised to the equivalent of the green roof area) at 08:58am. This is an anomalous result due to a power outage when the solar panel ceased working during the night the time of the main rain event. Peak flow for control gauge 4 was 21.9 mL/s (standardised to the equivalent of the green roof area) at 23:40 am. Thus, the green roofs again demonstrated their ability to not only reduce runoff volumes, but also to reduce peak flow, this time by only 20 minutes (for green roof 2). This reduction in lag time is likely to be due to the standard green roof system reaching saturation due to the regular rain events and thus not being able to store as much of the rain event before beginning to release it. Nevertheless, the experimental green roof did not appear to have reached this 'tipping point' with no rain released during this event.

For the rain event on the 30th of July, peak flow from experimental green roof 1 was 18.1 mL/s recorded at 11:56am. Peak flow from the standard green roof 2 was 32.17 mL/s recorded at 12:29am. Peak flow rate for control gauge 3 was 134.4 mL/s (standardised to the equivalent of the green roof area) at 09:42am. Peak flow for control gauge 4 was 134.3 mL/s (standardised to the equivalent of the green roof area) at 09:41 am. Thus, the green roofs again demonstrated their ability to not only reduce runoff volumes, but also to reduce peak flow, this time by 2hrs 20 minutes. This delay corresponded to the second downpour of the day. Peak flow results demonstrated that despite the runoff volume from the standard green roof, the rate that this rainfall ran off was slower and over a longer time period and thus therefore less likely to overload existing storm drain systems.

5. Conclusions

Based on these initial results, the green roofs consistently outperformed the control roofs in terms of rainfall runoff volume, peak flow, delay in peak flow, even when some data was lost due to incorrectly functioning solar power storage. Moreover, the experimental green roof consistently outperformed the corresponding standard green roof system.

It will be interesting to continue this monitoring to see how performance changes as the environmental conditions change moving from summer into winter.

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Appendix 1 - North Section (with drainage board): Weight according to green roof components

Layer	Saturated weight[1]	Note
Root barrier EPDM (1mm)	1.27 kg/m^2	Manufacturer's figures
Protection fleece	0.1 kg/m^2	Manufacturer's figure
10mm HDPE drainage board	0.75 kg/m^2	http://www.optigruen.de/Datenblaetter/Verkehrsdach_Fuss_Loesung_1+2_DE.pdf
Filter sheet	0.1 kg/m^2	Manufacturer's figure
65mm extensive substrate (20% organic content)	87.75 kg/m^2	13.5 kg/10mm depth/m^2
Plants	5 kg/m^2	Based on typical German extensive system
Total	94.97 kg/m^2	
Maximum Load	100.00 kg/ m^2	