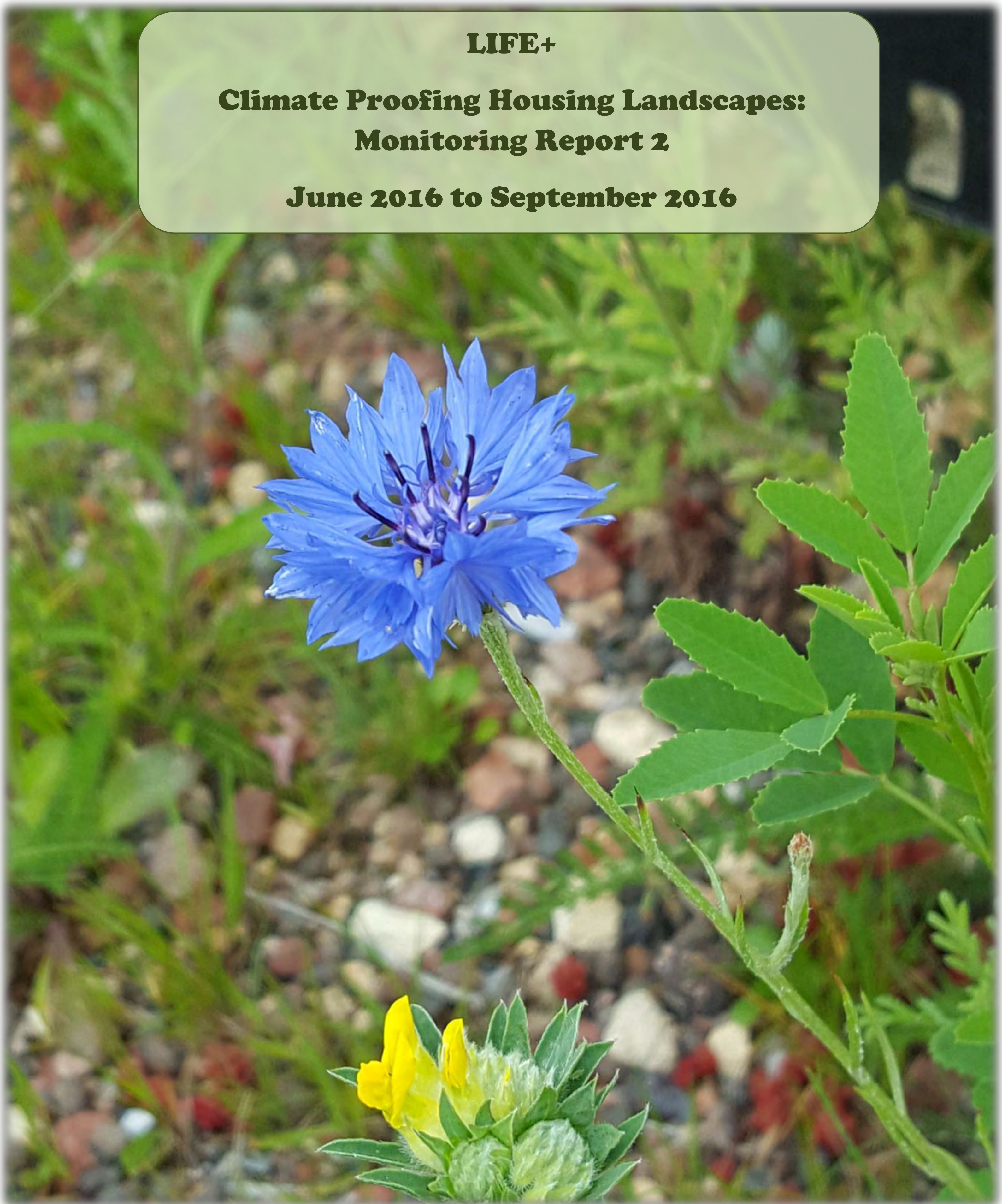
UEL University of East London

SRI Sustainability Research Institute

LIFE+

Climate Proofing Housing Landscapes: Monitoring Report 2

June 2016 to September 2016



LIFE+ Climate Proofing Housing Landscapes: Monitoring Report 2 - June 2016 to September 2016

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Cover photo: Cornflower (*Centaurea cyanus*) on the Richard Knight House green roof, Queen Caroline Estate, London Borough of Hammersmith & Fulham © Stuart Connop

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1. Background

Groundwork London, in partnership with Hammersmith & Fulham Council, has been working with local residents to design and implement climate change adaptation measures on three housing estates, making them more resilient and adapted for the future. Interventions have comprised a series of green infrastructure and engineered interventions to:

- manage stormwater
- create urban comfort zones
- support biodiversity
- provide opportunities for grow-your-own initiatives
- make the public realm spaces within the estates more attractive and functional for local residents (Figure 1).

In order to ensure that lessons are learned from this process so that similar schemes can be rolled out across London and globally, it was vital that the benefits derived from these interventions were quantified. As part of this process, the University of East London's Sustainability Research Institute were commissioned to carry out a programme of retrofitted monitoring to assess the biodiversity, water attenuation and thermal benefits of the green infrastructure interventions.

Further background on this project, the monitoring methodologies adopted, and results from the initial monitoring period from August 2015 to May 2016 are detailed in the first monitoring report from this project:

Connop, S. and Clough, J. 2016. LIFE+ Climate Proofing Housing Landscapes: Interim Monitoring Report - August 2015 to May 2016. London: University of East London.

This second report details the monitoring methods adopted, monitoring equipment installed and the results of the various monitoring methodologies adopted during the second monitoring period (June 2016 to September 2016). This also includes a running total of stormwater attenuated throughout the project period.

Figure 1. Green infrastructure retrofit at Queen Caroline Estate, London Borough of Hammersmith & Fulham. Raised planters, permeable pathways, ornamental planting, pollinator-friendly swales and detention basins.

2. Monitoring methods

Monitoring methods used during this second monitoring period included all of those adopted for the first monitoring period (Connop and Clough 2016). This comprised:

Stormwater management monitoring

- Time-lapse cameras positioned so that they face a selection of the key ground level SuDS features (swales and rain gardens) installed at Queen Caroline Estate and Richard Knight House.
- Vantage Vue weather stations installed to monitor the environmental conditions at Queen Caroline Estate and Richard Knight House.
- A series of flowmeters and pressure sensors at Queen Caroline Estate to monitor the fine performance of a selection of the retrofitted green infrastructure components.
- An additional barologger installed at UEL to act as an atmospheric pressure control.

Thermal monitoring

- A FLIR B335 thermal imaging camera was used to capture thermal images of key aspects of the green infrastructure retrofit on particularly hot days and particularly cold days.

Biodiversity monitoring

- Vegetation surveys to assess the colonisation of various green roof components. Including:
  - *Inventory surveys* to record every floral species observed on the roof in order to make a list of all herbaceous species.
  - *Quadrat surveys* to quantify floral change in relation to the experimental treatment plots on Richard Knight House.

Photographic monitoring

- Taking photographic records whilst on site of interesting species and features on retrofitted green infrastructure components.

For further details on these monitoring methods adopted, please refer to the first period monitoring report (Connop and Clough 2016).

In addition to these initial monitoring protocols, additional monitoring equipment and an additional monitoring methodology were adopted in the second monitoring period:

Equipment

Four pressure sensors were installed at Cheesemans Terrace.

Storm event simulation

Monitoring the selection of retrofitted SuDS features in the first monitoring period of the project using time-lapse fixed-point cameras and v-notch weirs during natural rainfall events was very successful. However, the SuDS features installed were designed to retain and attenuate rain events up to and including 1 in 100 year rainfall events (rain events of such magnitude and intensity that they would only be expected to occur once every 100 years). Current predictions of climate modelling linked to climate change predict that such events will occur in the UK with increased frequency (Atkins et al. 1999, DOE 1996, UKCIP 2001). As part of UEL's monitoring programme, it is therefore important to proof test the design of the features against such rainfall events and to assess infiltration rates following such events to generate understanding on how quickly recharge volumes are available following significant rain events. Only by doing this is it possible to generate the understanding necessary to establish the cost/benefits of such systems and, in so doing, to unlock barriers that currently stand in the way of broader roll out of green infrastructure SuDS solutions.

By definition, waiting for a 1 in 100 year rain event could take an extremely long time. Certainly no rain events of such magnitude occurred within the initial monitoring time period on this project (Connop and Clough 2016). Moreover, it would be pertinent to test performance prior to such an event occurring to ensure that the features were installed and are functioning correctly. As such, monitoring during this second period included simulating substantial rain events on SuDS elements installed across the Hammersmith sites to confirm that the designs meet the design specifications. This included a 1 in 100 year event on the Beatrice House swale and a 1 in 5 year event on the Cheeseman Terrace rain gardens.

It is important to note that the SuDS features that were tested had been designed to attenuate rainfall of the volumes being planned:

- The installed features had inbuilt safety systems designed to cope with large volumes of water;
- The slope of the features were shallow, typically a gradient of 1 in 3 to ensure that anything falling in was able to get out easily;
- The SuDS elements were generally no deeper than 400 mm;
- The SuDS elements had a water limit of no deeper than 300 mm;
- The SuDS elements were connected to a flow controlled outlet, which was connected to the Thames Water sewer. Therefore, in the event of greater water than designed entering the system, the excess water would flow into the Thames Water sewer at a controlled rate, preventing flooding (Figure 2).

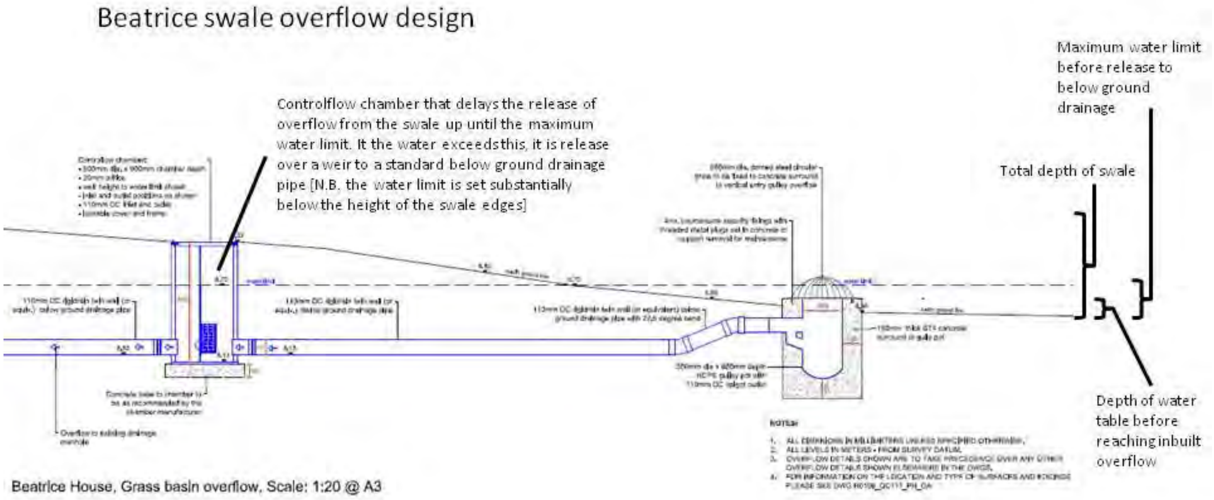


Figure 2. Beatrice Swale overflow design. The overflow features a control flow chamber which facilitates controlled release of stormwater once the storage volume of the swale has been exceeded and standard release into the stormwater system in the event that the control flow capacity is exceeded. This ensures that there is no greater risk of flooding due to swale malfunction/huge storm event, than there would have been from the pre-existing stormwater management system.

Moreover, similar stress testing had also been done previously by Thames Water on a small-scale SuDS project (Ashby Grove) with great success (Alves et al. 2014).

The aim of the simulation was to mimic the inflow of a 1 hour 1 in X year rainfall event to judge the performance of the installed SuDS features (X being the rain event capacity for which the SuDS component being test had been designed). This was done by calculating the volume of rainfall for each standard rainfall event in London over a 1 hour period and multiplying this by the as-designed/-built catchment area for each individual SuDS feature that was to be tested. The calculated volume of water was then pumped into each SuDS element selected for testing gradually over the 1 hour period.

A selection of monitoring methodologies were then used to assess the effects of this on the SuDS feature and control flow chamber. This included pressure sensors, photographic documentation and visual assessment.

The SuDS components that were tested were:

The Beatrice House swale (Figures 3 and 4) at Queen Caroline's Estate and the Cheeseman Terrace rain garden, Sun Road (Figures 5 and 6).

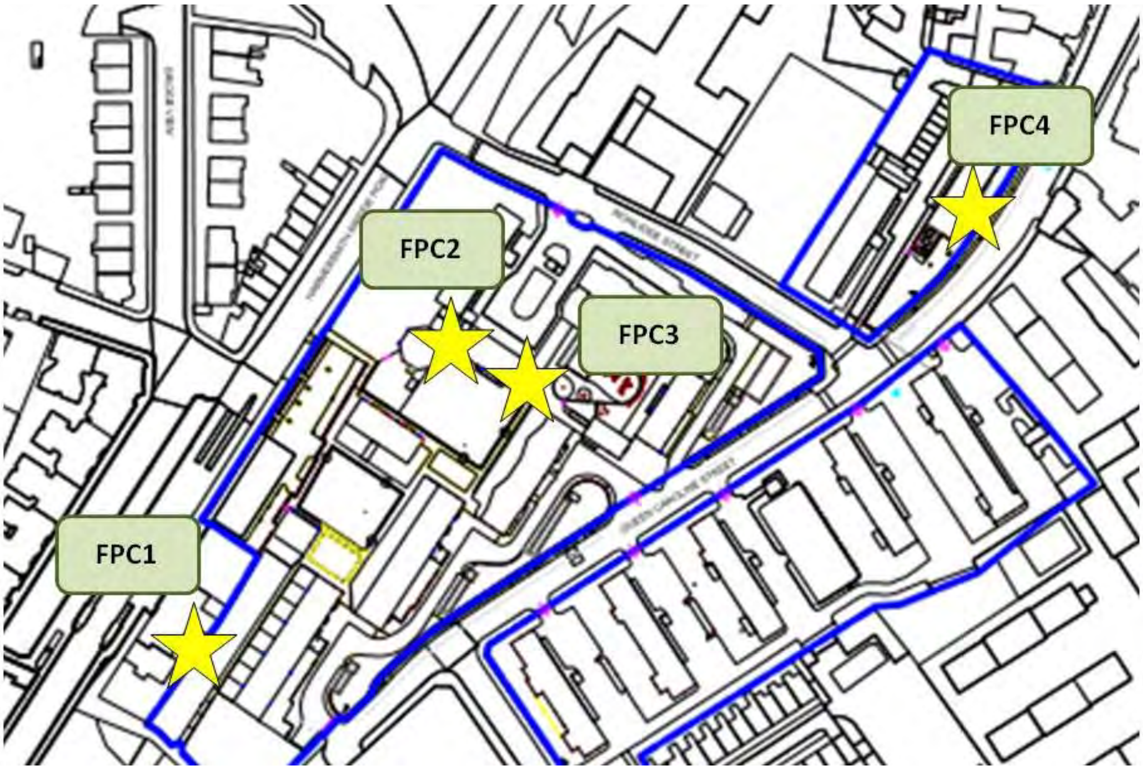


Figure 3. Location of the Beatrice House swale at Queen Caroline Estate in the London Borough of Hammersmith and Fulham. The swale location is represented by the star with the text FPC4 (representing the location of Fixed-point camera 4 (Connop and Clough 2016).

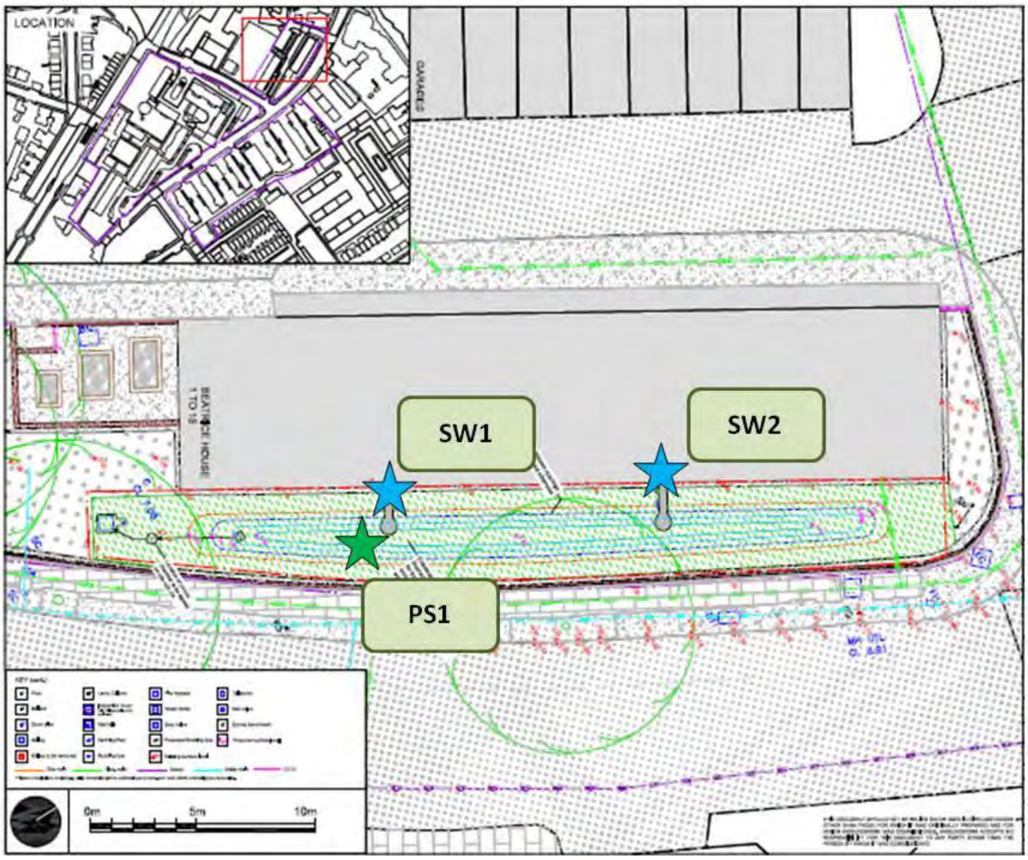


Figure 4. Plan of the Beatrice House swale and monitoring equipment. SW represents flowmeters monitoring stormwater from Beatrice House roof. PS represents a pressure sensor installed beneath the swale.

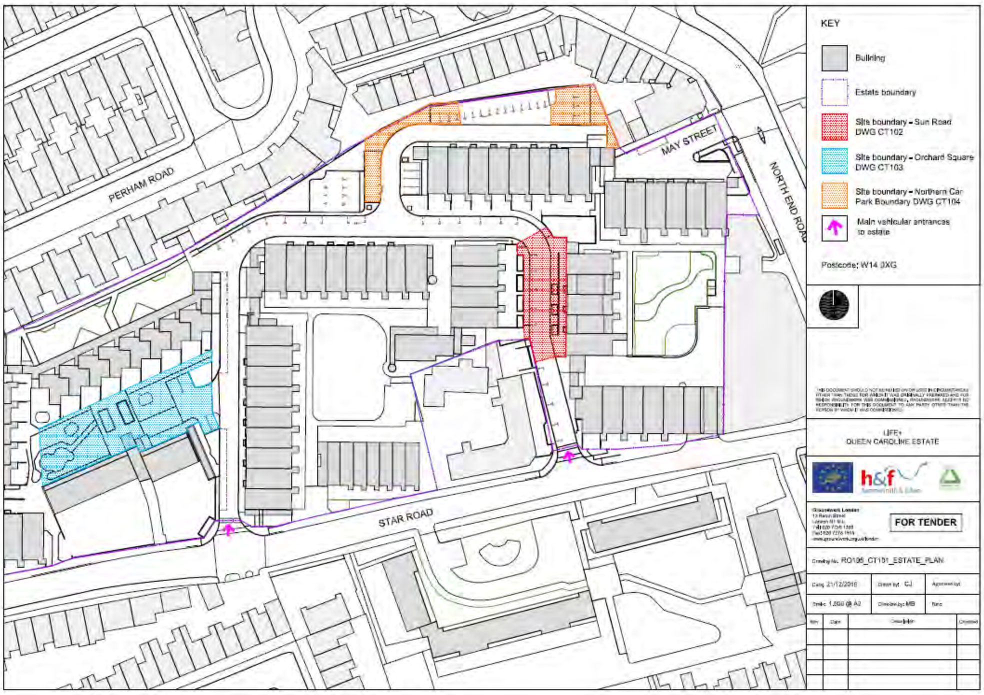


Figure 5. Location of Cheeseman Terrace rain gardens. The rain gardens are located on Sun Road at the Cheeseman Terrace Estate in the London Borough of Hammersmith and Fulham. On the diagram the area of the rain gardens is represented in red.

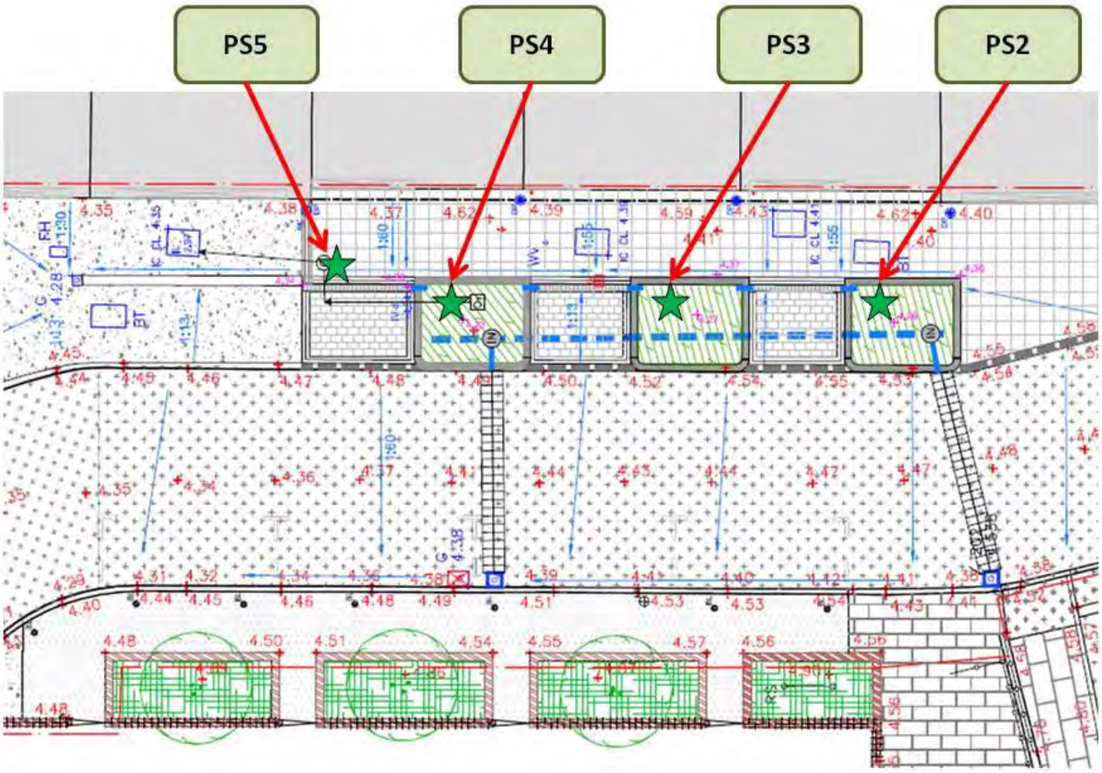


Figure 6. Plan of the Cheeseman Terrace rain gardens and monitoring equipment. PS represents the pressure sensors installed beneath each rain garden and the one installed in the control flow chamber.

3. Summary of results from June to September 2016

3.1 Fixed-point photo monitoring

During the second monitoring period there were several large rain events recorded across the monitoring sites. Two of these were particularly large with the Henrietta House weather station recording 39 mm on the 23rd of June 2016 and 37.2 mm on the 16th of June 2016. Of these two events, the most intense (largest volume of rainfall over the shortest period) was on the 16th June. The pattern of this rainfall is represented in Figure 7.

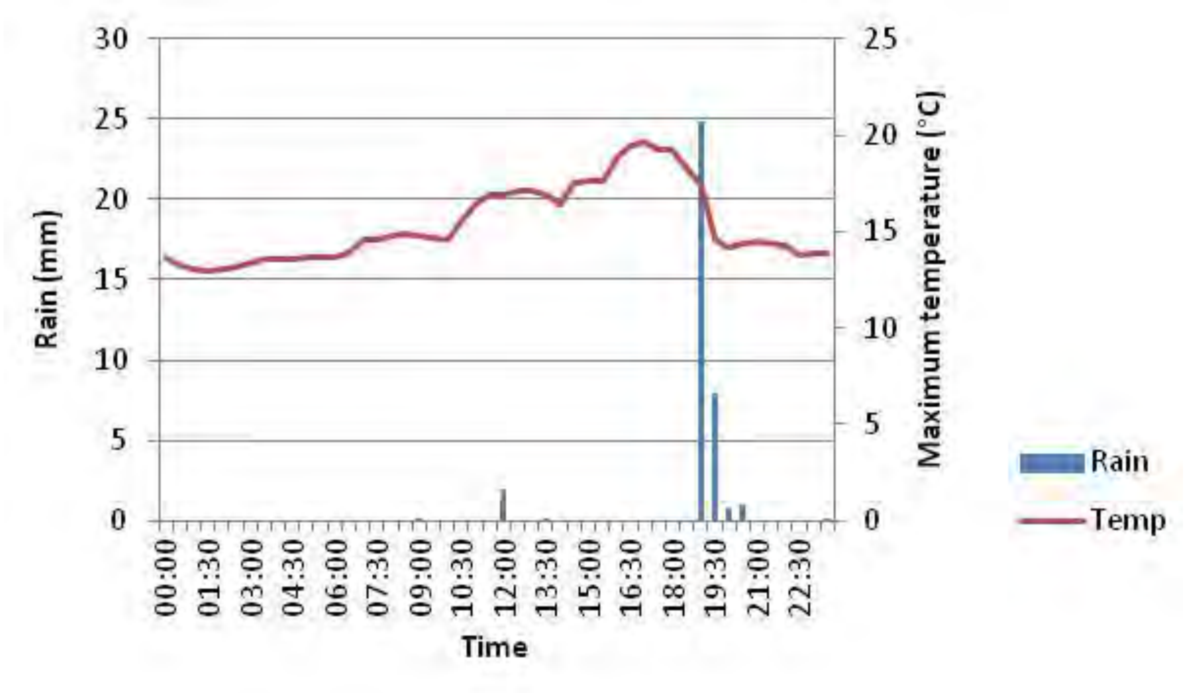


Figure 7. Rain event on the 16th June 2016 at Henrietta House, Queen Caroline Estate, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes

The highest volume and intensity of rainfall during this event fell between 19:00 and 20:00, with the highest rain volume of 32.8 mm in an hour and the highest rain rate recorded as 188.8 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as 'slight', 'moderate', 'heavy', or 'violent' for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

The time-lapse cameras recorded the performance of the SuDS features during this intense rain event on the 16th June.

Beatrice House swale (FPC4) performance during 37.2 mm rain event on 12th June 2016

A complete collection of the images from the Beatrice swale during the heaviest rain event recorded since the monitoring equipment was installed (from 18:30 to 20:00 on the 12th June 2016) are presented in Appendix A. They demonstrate that the swale was able to retain and attenuate all of the rainfall that fell directly onto the area and that which was diverted from the roofs of Beatrice House. The images also demonstrate that at around 18:45 during the peak of the rainfall, despite substantial input from the downpipe, there was no obvious standing water within the swale (Figure 8.i). The light conditions immediately after this time make it difficult to see whether pooling occurred after this (low light levels causing a switch between day vision and night vision - see Appendix A), but by the time of the next clear images at 20:00, at the end of the intense rain event, there was no obvious pooled water (Figure 8. ii) indicating that the swale was releasing the stomrwater by infiltration and/or conveyance.

i)

ii)

Figure 8. Time-lapse camera images from Beatrice House swale (FPC4). Images show i) evidence of swale filling during period of highest rain intensity at 18:45 on 16/06/2016 [32.8 mm of rain at maximum intensity of 188.8 mm/hr] and ii) evidence of infiltration/conveyance by the end of the intense rain event at 20:00 on the same day.

Alexandra House swale (FPC1) performance during 37.2 mm rain event on 12th June 2016

Images showing the performance of the Alexander House swale for the same rain event are presented in Appendix A2. The swale was designed to take stormwater from the surrounding ground level permeable and hardstanding areas and from the roof of the neighbouring Alexandra House. Whilst the fixed point photos showed evidence of the intensity of the rain event in relation to pooling on the ground, there was no evidence of any substantial filling or overflowing of the swale. This was the case even during the most intense period of rainfall (Figure 9). This indicated that the swale was performing as expected for this rain event. It is important to note at this point, however, that lack of maintenance of the guttering on Alexandra House might mean that not all of the rain falling on the areas of the roof that should be diverted to the swale is actually reaching the swale.

Figure 9. Time-lapse camera images from Alexandra House swale (FPC1). Image shows no evidence of swale filling excessively during period of highest rain intensity 18:30 to 20:00 on 16/06/2016 [32.8 mm of rain at maximum intensity of 188.8 mm/hr].

Community Hall and Sofia House grass basins (FPC2) performance during 37.2 mm rain event on 12th June 2016

Images showing the performance of the Community Hall and Sofia House grass basins for the same rain event are presented in Appendix A3. The basins were designed to take stormwater from the surrounding ground level permeable and hardstanding areas and from the roof of the neighbouring Community Hall and Sophia House. Whilst the fixed point photos showed evidence of the intensity of the rain event in relation to pooling on the ground, there was no evidence of any substantial filling of the basins. This was the case even during the most intense period of rainfall (Figure 10). This indicated that the basins were performing as expected for this rain event.

Figure 10. Time-lapse camera images from Community Hall and Sophia House basins (FPC2). Image shows no evidence of swale filling excessively during period of highest rain intensity 18:30 to 20:00 on 16/06/2016 [32.8 mm of rain at maximum intensity of 188.8 mm/hr].

Adella House grass basin and Adella House stoney basin (FPC3) performance during 37.2 mm rain event on 12th June 2016

Images showing the performance of the Adella House grass basin and Adella House stoney basin for the same rain event are presented in Appendix A4. The basins were designed to take stormwater from the surrounding ground level permeable and hardstanding areas and from the roof of Adella House. Whilst the fixed point photos showed evidence of the intensity of the rain event in relation to pooling on the ground, there was no evidence of any substantial filling of the basins. This was the case even during the most intense period of rainfall (Figure 11). This indicated that the basins were performing as expected for this rain event. It is important to note at this point, however, that lack of maintenance of the guttering on Adella House might mean that not all of the rain falling on the areas of the roof that should be diverted to the basins is actually reaching the basins.

Figure 11. Time-lapse camera images from Adella House grass basin and Adella House stoney basin (FPC3). Image shows no evidence of swale filling excessively during period of highest rain intensity 18:30 to 20:00 on 16/06/2016 [32.8 mm of rain at maximum intensity of 188.8 mm/hr].

The largest rain event recorded by the Richard Knight House weather station during the second monitoring period was 48.8 mm on the 23rd of June 2016. The pattern of this rainfall is represented in Figure 12.

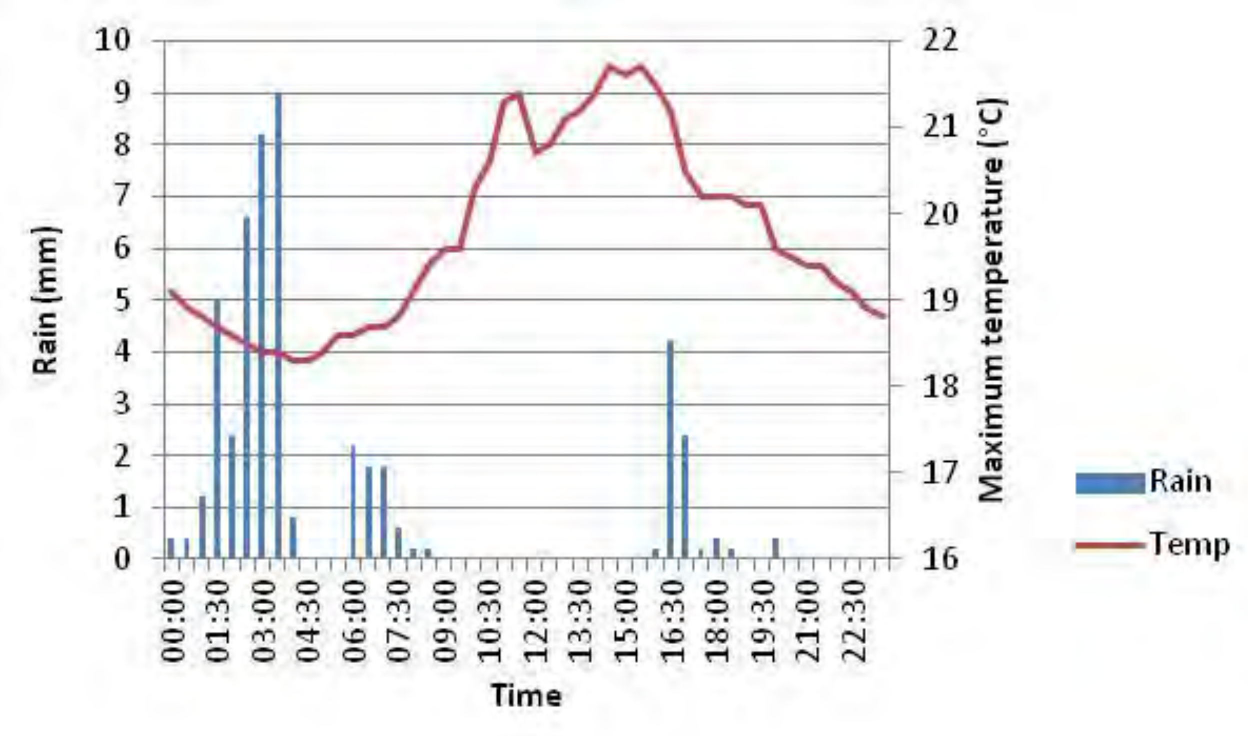


Figure 12. Rain event on the 23rd June 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes.

The highest volume and intensity of rainfall during this event fell between 01:00 and 04:00, with the highest rain volume of 17.2 mm in an hour and the highest rain rate recorded as 91.4 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

Despite the majority of this rain event occurring at night, the time lapse cameras recorded the performance of the SuDS features during this rain event.

Richard Knight House rain garden (FPC5) performance during 48.8 mm rain event on 23rd June 2016

Images showing the performance of the Richard Knight House rain garden for the rain event on 23rd June 2016 are presented in Appendix A5. The basins were designed to take stormwater from the ground level permeable and hardstanding areas surrounding the rain garden, from the green roofs on the pram sheds and from the roof of a neighbouring house. Whilst the fixed point photos showed evidence of the intensity of the rain event in relation to pooling on the ground, there was no evidence of any substantial filling of the basins. This was the case even during the most intense period of rainfall (Figure 13). This indicated that the basins were performing as expected for this rain event.

Figure 13. Time-lapse camera images from Richard Knight House rain garden (FPC5). Image shows no evidence of rain garden filling excessively during period of highest rain intensity 01:00 and 04:00 on 23/06/2016 [17.2 mm of rain at maximum intensity of 91.4 mm/hr].

3.2 Other notable rain events or photography monitoring images for rainfall attenuation:

Richard Knight House on the 16th June 2016

On the 16th June 2016 a 23.8 mm rain event occurred at Richard Knight House with a maximum rainfall intensity of 311.4 mm/hr. The pattern of this rainfall event is represented in Figure 14. The time lapse-cameras were taking images every 15 minutes so a comprehensive catalogue of images during the rain event was captured. Two images are presented in Figure 15, one during and one after the peak rainfall during this event.

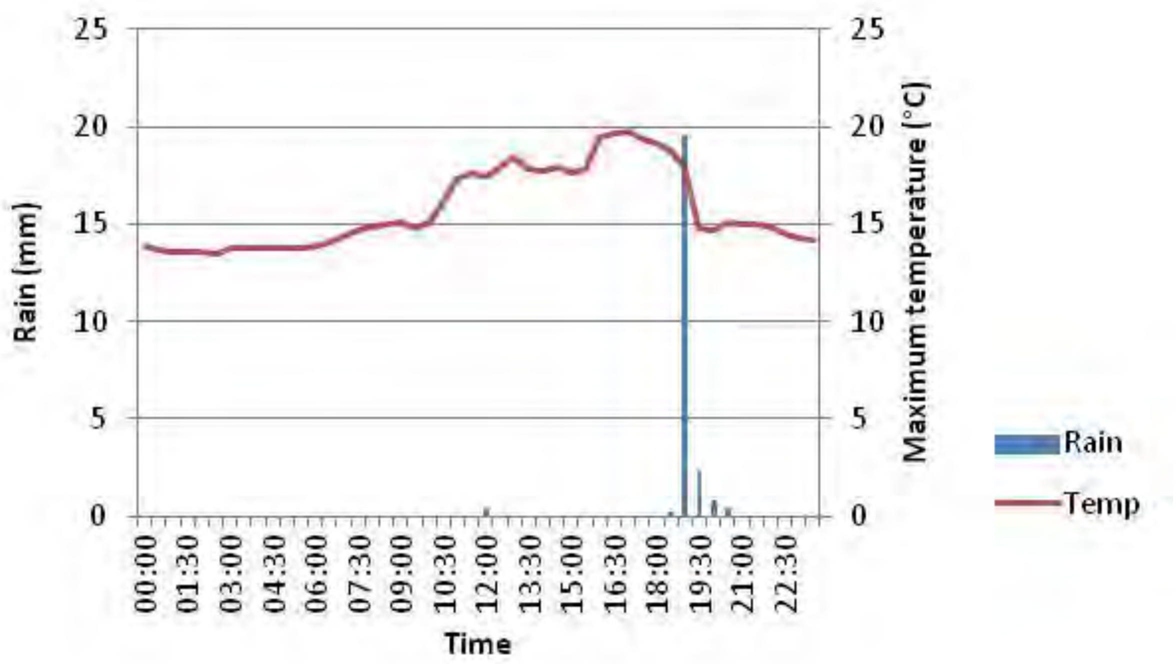


Figure 14. Rain event on the 16th June 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes.

The highest volume and intensity of rainfall during this event fell between 19:00 and 20:00, with the highest rain volume of 22 mm in an hour and the highest rain rate recorded as 311.4 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

Despite this intense and substantial nature of the rainfall over a short period, the time-lapse camera images revealed no evidence of excessive filling of the Richard Knight House rain garden (Figure 15).

Figure 15. Time-lapse camera images from Richard Knight House rain garden (FPC5). Images show i) rain garden during the period of rain building up to the highest rain intensity and ii) following the period of highest intensity.

Richard Knight House on the 17th June 2016

On the 17th June 2016 a 10.2 mm rain event occurred at Richard Knight House with a maximum rainfall intensity of 182.8 mm/hr. The pattern of this rainfall event is represented in Figure 16. The time lapse-cameras were taking images every 15 minutes so a comprehensive catalogue of images during the rain event was captured. Two images are presented in Figure 17, one during and one after the peak rainfall during this event.

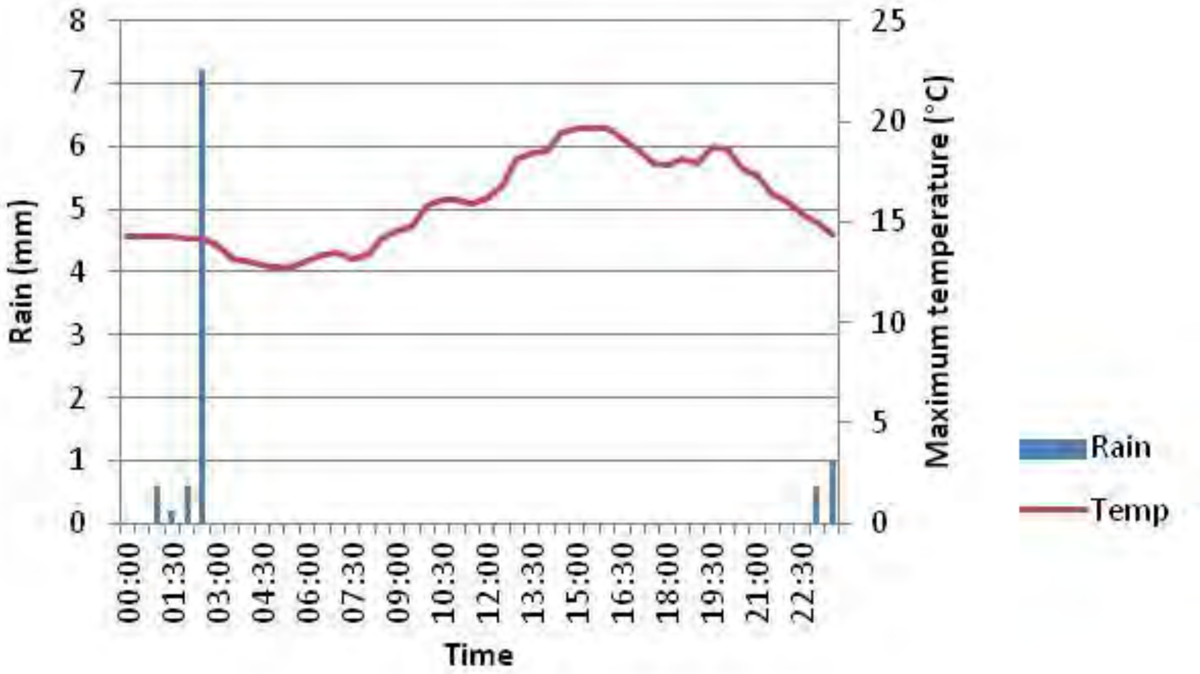


Figure 16. Rain event on the 17th June 2016 at Richard Knight House, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes.

The highest volume and intensity of rainfall during this event fell between 02:00 and 02:30, with the highest rain volume of 7.2 mm in an hour and the highest rain rate recorded as 182.8 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

Despite this intense and substantial nature of the rainfall over a short period, the time-lapse camera images revealed no evidence of excessive filling of the Richard Knight House rain garden (Figure 17).

Figure 17. Time-lapse camera images from Richard Knight House rain garden (FPC5). Images show i) rain garden during the period of rain building up to the highest rain intensity and ii) following the period of highest intensity.

Queen Caroline Estate on the 23rd June 2016

On the 23rd June 2016 a 39 mm rain event occurred at Henrietta House with a rainfall intensity of 73 mm/hr. The pattern of this rainfall event is represented in Figure 18. The time lapse-cameras were taking images every 15 minutes so a comprehensive catalogue of images during the rain event was captured. Two images of several of the SuDS components are presented in Figures 19 to 22, one during and one after the peak rainfall during this event.

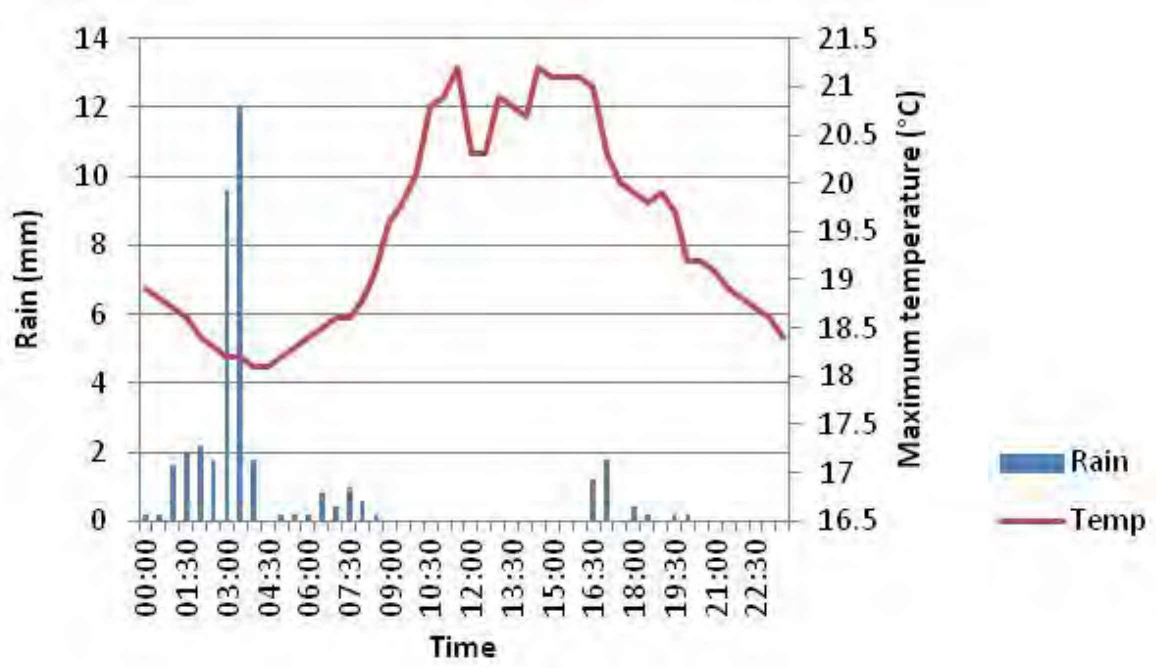


Figure 18. Rain event on the 23rd June 2016 at Henrietta House, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes.

The highest volume and intensity of rainfall during this event fell between 02:30 and 03:30, with the highest rain volume of 21.6 mm in an hour and the highest rain rate recorded as 73 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

Selected fixed point photos for this rain event from Queen Caroline Estate are displayed in Figures 19 to 22.

i)

ii)

Figure 19. Time-lapse camera images from Beatrice House swale (FPC4). Images show no sign of excessive pooling in the swale i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 20. Time-lapse camera images from Adella House basin (FPC2). Images show no sign of excessive pooling in the basin i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 21. Time-lapse camera images from Adella House basin (FPC3). Images show no sign of excessive pooling in the basin i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 22. Time-lapse camera images from Alexandra House swale (FPC1). Images show no sign of excessive pooling in the swale i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

Queen Caroline Estate on the 8th June 2016

On the 8th June 2016 an 8.2 mm rain event occurred at Henrietta House with a rainfall intensity of 167 mm/hr. The pattern of this rainfall event is represented in Figure 23. The time lapse-cameras were taking images every 15 minutes so a comprehensive catalogue of images during the rain event was captured. Two images are presented of several SuDS components in Figures 24 to 27 , one during and one after the peak rainfall during this event.

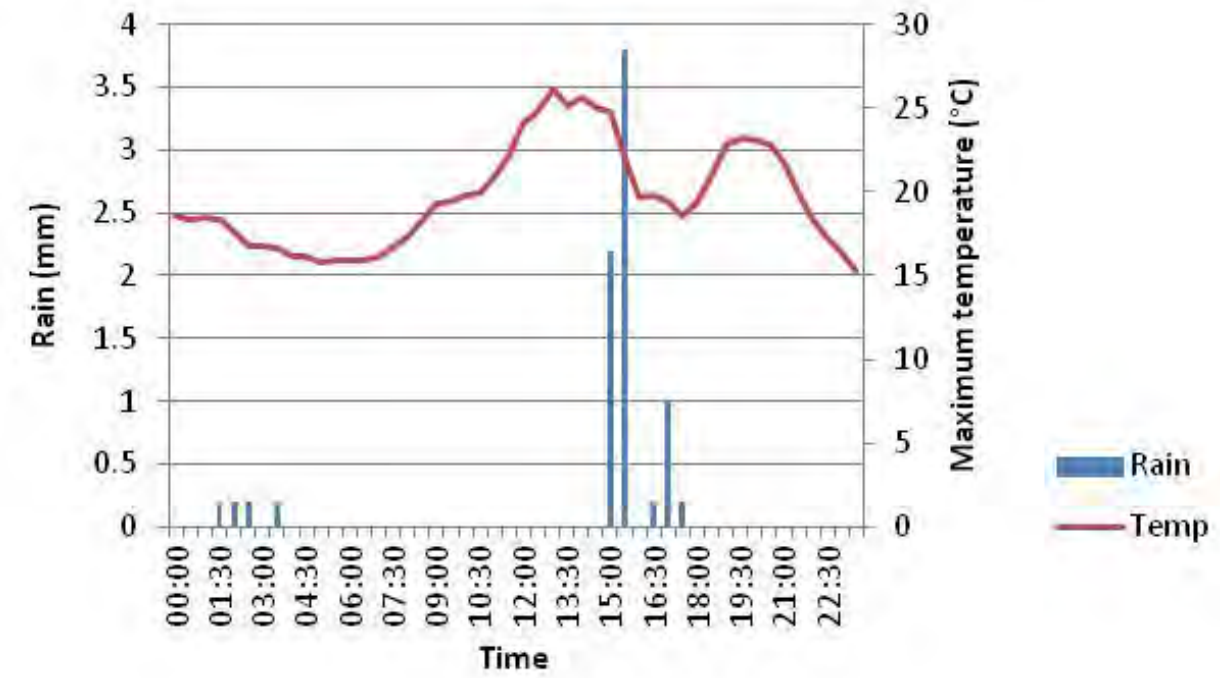


Figure 23. Rain event on the 8th June 2016 at Henrietta House, London Borough of Hammersmith and Fulham. Bars represent the total rainfall every 30 minutes.

The highest volume and intensity of rainfall during this event fell between 14:30 and 15:30, with the highest rain volume of 6 mm in an hour and the highest rain rate recorded as 167 mm/hr. To put this event in context, the Met Office classifies rain (other than showers) as 'slight', 'moderate' or 'heavy' for rates of accumulation less than 0.5 mmhr-1, 0.5 to 4 mmhr-1 and greater than 4 mm-hr respectively. Showers are classified as ‘slight’, ‘moderate’, ‘heavy’, or ‘violent’ for rates of accumulation of about 0 to 2 mm h–1, 2 to 10 mm h–1, 10 to 50 mm h–1, or greater than 50 mm h–1, respectively (Met Office 2007).

Selected fixed point photos for this rain event from Queen Caroline Estate are displayed in Figures 24 to 27.

i)

ii)

Figure 24. Time-lapse camera images from Beatrice House swale (FPC4). Images show no sign of excessive pooling in the swale i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 25. Time-lapse camera images from Adella House basin (FPC2). Images show no sign of excessive pooling in the basin i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 26. Time-lapse camera images from Adella House basin (FPC3). Images show no sign of excessive pooling in the basin i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

i)

ii)

Figure 27. Time-lapse camera images from Alexandra House swale (FPC1). Images show no sign of excessive pooling in the swale i) during the period of intense rainfall or ii) following the cessation of the most intense period of the rain event.

Queen Caroline Estate on the 16th June 2016

In addition to the fixed-point time-lapse camera data from the 37.2 mm rain event on the 16th June 2016, SRI staff were on site downloading data from the cameras and in-line flowmeter dataloggers when one of this day's downpours occurred. Whilst not during the highest intensity rainfall during the day, the SRI researchers were present for a period when 2 mm of rain fell within the space of 30 minutes with an intensity of 36.8 mm/hr. The SRI researchers were able to take photographs (Figure 28) and videos to record this event. A video showing the outflow from one of the pramshed roofs without a green roof and another with a green roof during the intense period of this rainfall is available on YouTube on the UEL SRI channel (https://www.youtube.com/watch?v=srAZW5v-_WA). It must be noted that the areas of the roofs draining into each downpipe were not exactly equal. Nevertheless, both were fairly large catchments and the stark difference in terms of the rate of runoff from each roof is demonstrative of the effect that installation of green roofs can have on stormwater runoff. Stills taken from this video are presented as Figure 29.

Figure 28. Beatrice House downpipe outflow. Image shows runoff from downpipe to ground level swale during a storm event on the 16th June 2016.

i)  ii) 

Figure 29. Queen Caroline Estate pramshed roof downpipe outflows. Images show runoff from downpipe to ground level drainage during a storm event on the 16th June 2016 for i) a pramshed with a green roof installed, and ii) a pramshed with no green roof installed.

3.3 Storm event simulations

Beatrice House Swale

On the 29th July 2016, SRI researchers ran a storm simulation at the Beatrice House swale at Queen Caroline Estate. Beatrice House swale was designed to retain and attenuate a 1 in 100 year storm event for a 250 m² catchment area. Based on calculations for the London area, a 1 in 100 rain event would correspond to a 40 mm rain event falling over the period of an hour (Alves et al. 2014).

In order to create a simulation of a 1 in 100 year event it was therefore necessary to pump 10,000 L of water into the swale over the course of an hour. In order to achieve this it was necessary (with the support of Thames Water Ltd) to hire a tanker capable of transporting and delivering such a quantity of water (Figure 30).

Figure 30. Water tanker delivering 10,000 Litres of non-potable water for the storm simulation event at Beatrice House swale. Storm simulation was carried out over the course of an hour on the 29th July 2016.

The tanker water level was calibrated into 1,000 litre divisions and one of these divisions was released into the swale every six minutes over the course of an hour. As much as possible, this release was controlled to be spread across the six minute period, but with no control rate on the water release it was impossible to be entirely accurate with this. Nevertheless, real storms would not be expected to have exactly even rainfall over a storm event, so it was determined that the method adopted would be sufficiently accurate to test the performance of the swale during a 1 in 100 year rain event. Figure 31 represents the prevailing weather in the 6 days preceding the storm simulation event. Whilst there were rain events recorded in the two days preceding the rain simulation, these events were small (<2 mm) with warm daily temperatures so are unlikely to have affected the water retention and attenuation performance of the swale during the test. As such, the swale was considered to be in a dry state with a low groundwater table at the time of the storm simulation.

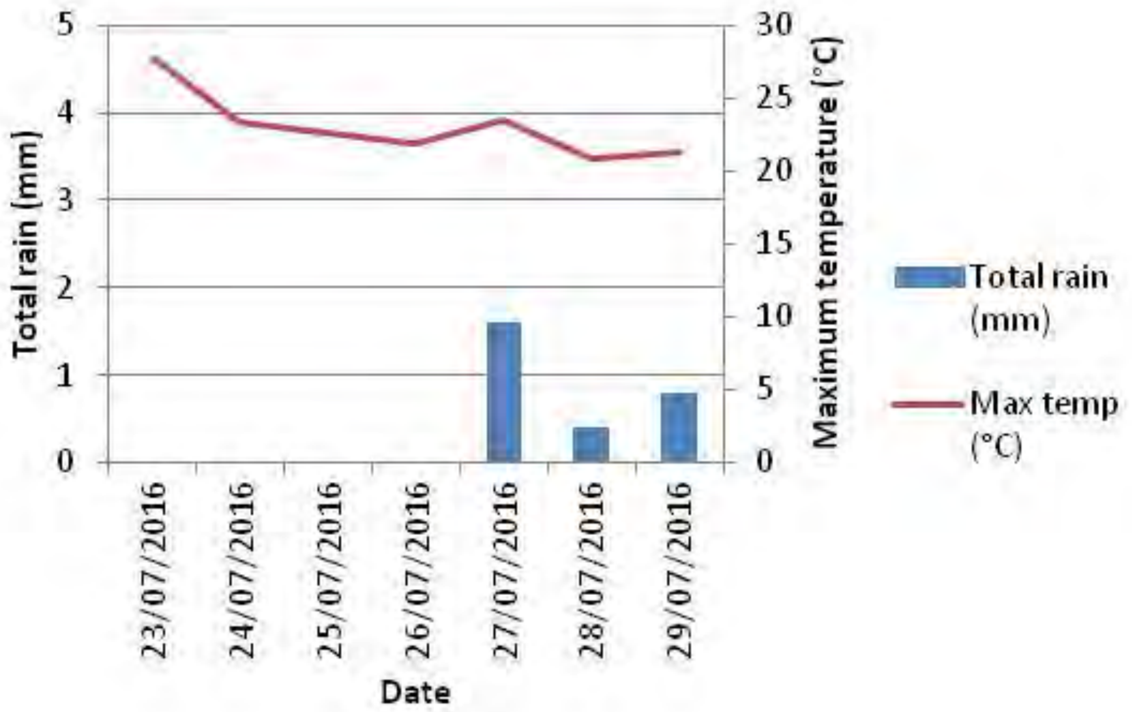


Figure 31. Weather conditions at Queen Caroline Estate, London Borough of Hammersmith and Fulham, preceding the storm event simulation at Beatrice House swale.

In order to monitor the performance of the swale under the storm simulation conditions, several monitoring techniques were utilised. This included:

- Photographic documentation to show how the basin filled;
- Visual monitoring of the control flow chamber to check for overflow from the swale;
- Pressure sensor data to monitor water infill and infiltration from the swale to assess emptying times following the storm.

Photographs documenting the storm simulation process are presented in Figures 32 to 34.

Figure 32. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 29th July 2016. Images show i) water release from tanker being timed to release 1000 Litres every six minutes; ii) 1000 Litres entering the centre of the swale; iii) condition of the swale after the first 1000 Litres; iv) condition of the swale as it starts to fill after several 1000 Litres releases.

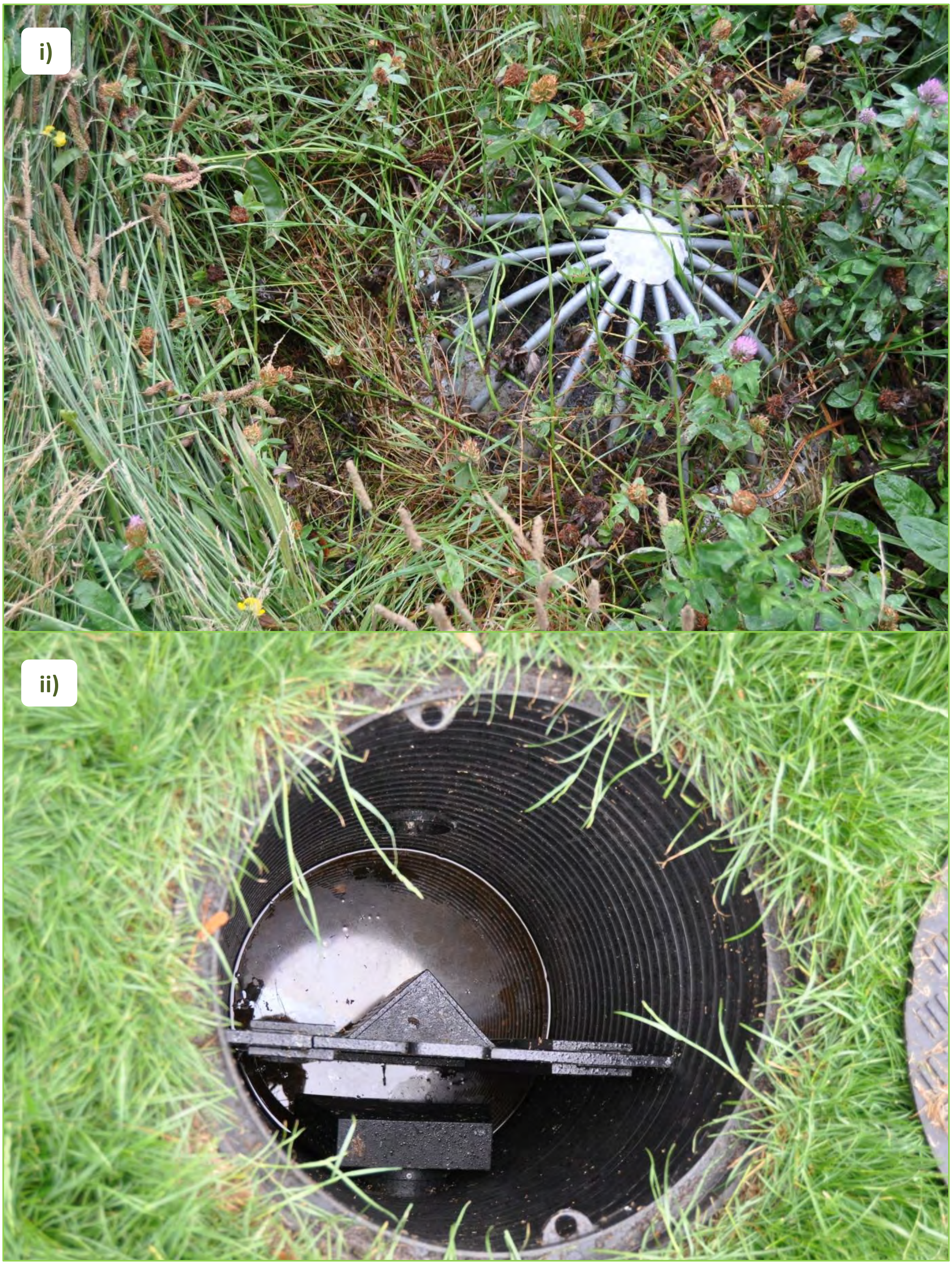


Figure 33. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 29th July 2016. Images show that no water was released to the i) swale overflow or ii) the control flow chamber, after the 10,000 Litres of water were pumped into the swale to simulate a 1 in 100 year storm event.

Figure 34. Images from the storm simulation event at Beatrice House swale, Queen Caroline Estate, 29th July 2016. Images show i) the Beatrice House swale immediately after the last of the 10,000 Litres of water was released and ii) the centre of the swale where the water was pumped in 15 minutes after the last of the water was released.

Using visual monitoring of the swale during the storm simulation event, it was possible to confirm that the Beatrice House swale was able to retain all of the 10,000 Litres of stormwater that was pumped into the basin. Moreover, at no point during the storm simulation did water pooling in the swale reach the swale's stormwater overflow. This was evidenced with the photographs taken during the simulation. This result indicated that, during dry summer periods, the swale had additional storage capacity that could be used. That could include additional capacity so that a storm greater than a 1 in 100 year event could be retained, or that additional catchment area could be diverted into the existing swale for retention of a 1 in 100 year 1 hour rain event.

In addition to retaining all of the 10,000 Litres of the storm simulation, it is also important to assess how long the water sat in the swale after the event and thus how long until the swale was empty again and the recharge volume available for another storm event. It has been suggested that London soils may be inappropriate for infiltration SuDS components as London soils are generally designated as being heavy impermeable clay and thus do not allow infiltration (Alvez et al 2014). Monitoring how long it takes for any standing water to disappear from the swale after the testing provided a good assessment of infiltration times during the event (although it is not possible to establish whether this was due to basal infiltration or lateral infiltration). Visual assessment of the swale following the study indicated that no standing water was visible within the swale 15 minutes after the storm event. This visual evidence was supported by data obtained from the pressure sensor buried at the base of Beatrice House swale (Figure 35).

Following the initiation of the storm event, the levelogger recorded no additional pressure above the baseline level. This may have been indicative of a delay between the infilling of the swale and the water infiltrating to the levelogger, or may have indicated that all of the initial storm simulation water infiltrated very quickly before saturation resulted in pooling. By the time that 2000 L of water had been pumped into the swale the water level had increased indicating that pooling/soil saturation was occurring. Following the cessation of the storm simulation (i.e. after all 10,000L had been pumped into the swale), the levelogger indicated that pooling disappeared very rapidly - within 10 minutes of the end of pumping the pressure readings had returned to the pre-testing baseline level. This data supported observations made on site and indicated that infiltration rates were fast. This provided evidence that recharge volumes would be available very quickly following a 1 in 100 year storm event during dry summer conditions. It would be interesting to repeat this test again in winter when the groundwater table would be expected to be higher and the soil more saturated to assess any effect of this on storage and recharge durations.

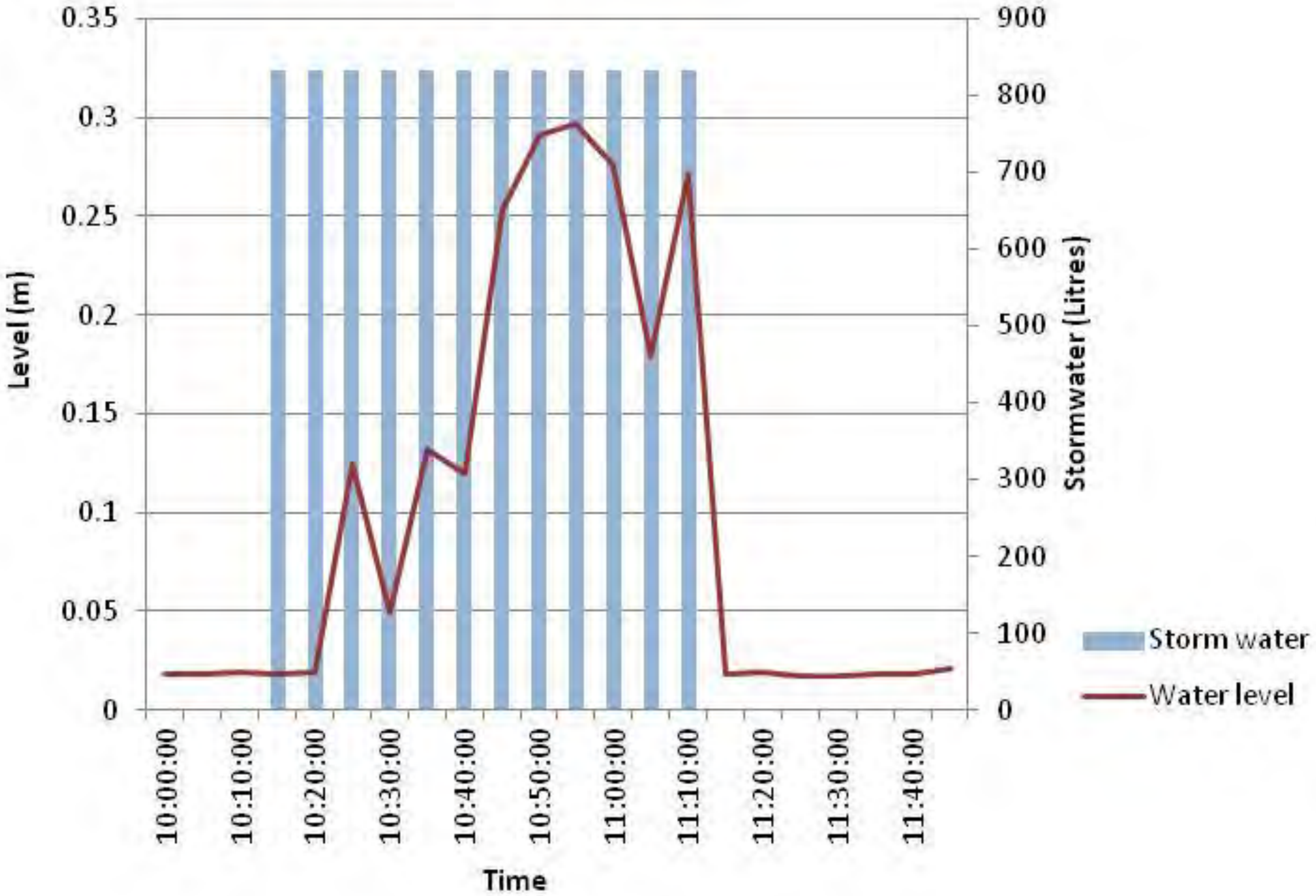


Figure 35. Pressure sensor data from 1 in 100 year storm simulation event at Beatrice House swale, Queen Caroline Estate, London Borough of Hammersmith and Fulham. Blue bars represent the times when stormwater was pumped into the swale, the red line represents the readings of a pressure sensor buried beneath the swale to monitor pooling water.

Cheeseman Terrace Estate Rain Gardens

On the 23rd September 2016, SRI researchers ran a storm simulation at the Sun Road rain gardens at the Cheeseman Terrace Estate. The rain gardens were designed to retain and attenuate a 1 in 2 year storm event for a 310 m^2 catchment area. Due to the success of the Beatrice swale test and the design of the rain gardens permitting excess stormwater to overflow to storm drains, it was decided that the rain garden would be tested under 1 in 5 year storm conditions. Based on calculations for the London area, a 1 in 5 rain event would correspond to a 18 mm rain event falling over the period of an hour.

In order to create a simulation of a 1 in 5 year event it was therefore necessary to pump 5580 L of water into the swale over the course of an hour. In order to achieve this it was necessary to hire a tanker capable of transporting and delivering such a quantity of water (Figure 36).

Figure 36. Water tanker delivering 6000 Litres of non-potable water for the storm simulation event at Cheeseman Terrace Estate. Storm simulation was carried out over the course of an hour on the 23rd September 2016.

The tanker water level was calibrated into 1,000 litre divisions and one of these divisions was released into the rain gardens every ten minutes over the course of an hour. Each 1000 Litres was approximately divided between the inlet chambers of the first and third rain gardens to mimic as closely as possible a natural storm event. With no control over the rate of flow, it was not possible to release any of the water directly onto the surface of the rain garden as the power of the water may have washed the newly installed substrate away. As much as possible, the release was controlled to be spread across the ten minute period, but with no control rate on the water release it was impossible to be entirely accurate with this. Nevertheless, real storms would not be expected to have exactly even rainfall over an entire storm event, so it was determined that the method adopted would be sufficiently accurate to test the performance of the swale during a 1 in 5 year rain event. Figure 37 represents the prevailing weather in the 6 days preceding the storm simulation event. Whilst there were rain events recorded on five of the days preceding the rain simulation, these events were small (<1 mm) with warm daily temperatures so were unlikely to have affected the water retention and attenuation performance of the swale during the test. As such, the swale was considered to be in a dry state with a low groundwater table at the time of the storm simulation.

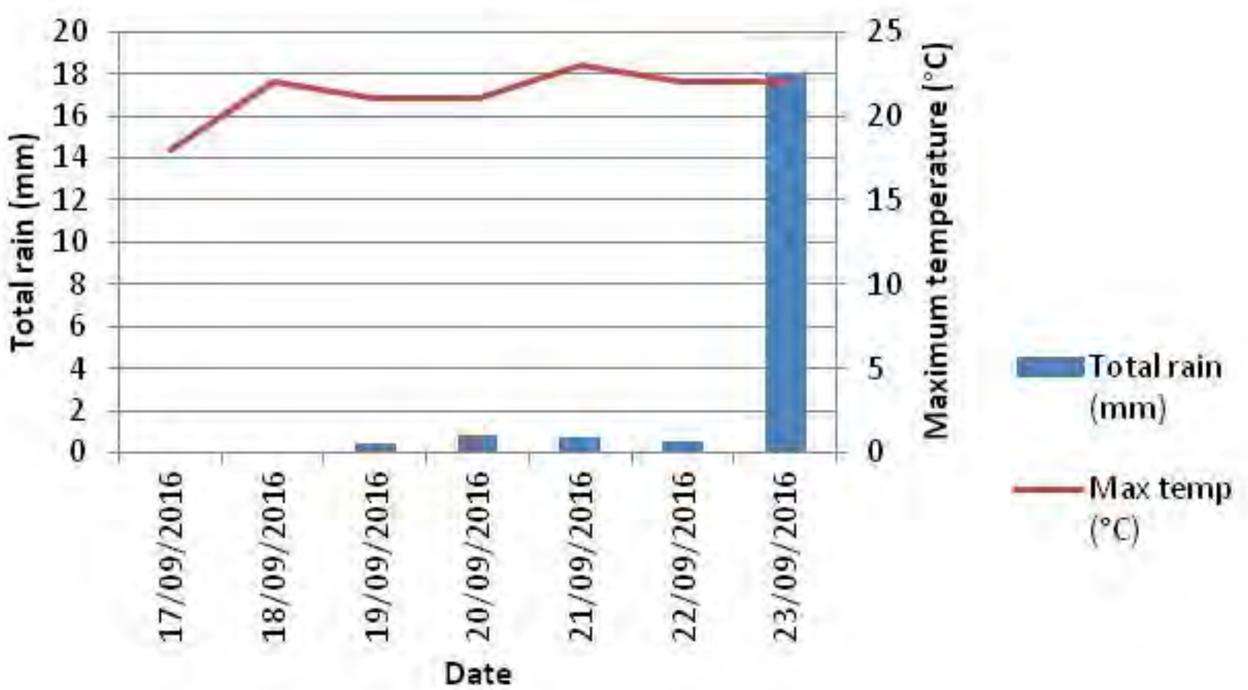


Figure 37. Weather conditions in Hammersmith preceding the storm event simulation at the Cheeseman Terrace Estate rain gardens. At the time of preparing this report no download had been carried out of the RKH or Henrietta House weather stations. As such, data for the preceding weather was taken from World-wide Weather Online (2016). Rain on the 23rd represents that for the rain simulation event. No other rain fell on this day at Hammersmith.

In order to monitor the performance of the swale under the storm simulation conditions, several monitoring techniques were utilised. This included:

- Photographic documentation to show how the rain gardens filled;
- Visual monitoring of the control flow chamber to check for overflow from the rain gardens;
- Pressure sensor data to monitor water infill and infiltration from the rain gardens to assess emptying times following the storm;
- Soil moisture sensor to detect changes in surface level moisture.

Photographs documenting the storm simulation process are presented in Figures 38 to 41.

Figure 38. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 23rd September 2016. Images show i) Cheeseman Terrace Estate rain gardens before rain simulation; ii) pressure sensor installed in the corner of one of the rain gardens; iii) pressure sensor installed in the control flow chamber in the outlet from the rain garden.

Figure 39. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 23rd September 2016. Images show i) water being pumped into the inspection chamber of the rain garden; ii) inlet chamber full after the stormwater was pumped in.

Figure 40. Images from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 23rd September 2016. Images show i) the rain garden inspection chamber 30 minutes after the last of the 6,000 Litres of water was released and ii) the control flow chamber showing no release of water from the rain gardens following the 1 in 5 year storm event simulation.

Figure 41. Image from the storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, 23rd September 2016. Image shows the rain gardens after the end of the stormwater simulation test with no signs of water pooling on any of the rain gardens.

Using visual monitoring of the rain gardens during the storm simulation event, it was possible to confirm that the Cheeseman Terrace rain gardens were able to retain all of the 6,000 Litres of stormwater that was pumped into the inspection chambers. Moreover, at no point during the storm simulation did water pumped into the rain gardens reach the stormwater control flow chamber within the rain garden outlet. This was evidenced with the photographs taken during the simulation. This result indicated that, during dry summer periods, the rain gardens had additional storage capacity that could be used. That could include additional capacity so that a storm greater than a 1 in 5 year event could be retained, or that additional catchment area could be diverted into the existing rain gardens for retention of a 1 in 5 year 1 hour rain event.

In addition to retaining all of the 6000 Litres of the storm simulation, it is also important to assess how long this water sits in the rain gardens after the event and thus how long until the rain gardens are empty again and the recharge volume is available for another storm event. It has been suggested that London soils may be inappropriate for infiltration SuDS components as London soils are generally designated as being heavy impermeable clay and thus do not allow infiltration (Alvez et al 2014). Monitoring how long it takes for any standing water to disappear from the rain garden after the testing provided a good assessment of infiltration times during the event (although it is not possible to establish whether this was due to basal infiltration or lateral infiltration). Visual assessment of the rain gardens following the study indicated that no standing water was visible within the rain garden inspection chambers 30 minutes after the storm event. In addition, no data was obtained from the pressure sensors buried in each of the rain gardens indicating that the rain garden soil did not become saturated and that there was additional capacity that could be filled (Figure 42).

Following the initiation of the storm event, the leveloggers recorded no additional pressure above the baseline level. It is likely that the main reason for this pattern was due to the stormwater being introduced to the rain gardens through the inspection chambers (as would occur from roadside run off), rather than some also being introduced on top of the rain garden to mimic rainfall patterns that would occur during a natural storm event. As such, all infiltration would have occurred below the level of the pressure gauges. Nevertheless, no evidence of backing up of the rain gardens was provided by the pressure sensors. This indicated that the rain gardens were able to retain and infiltrate all of the stormwater introduced below the height of the gauges and thus additional storage capacity would have been available at the top of the rain gardens were a natural rain event to have occurred with larger rain volumes than that simulated in this rain event. This finding was also supported by the lack of any significant increases recorded by the soil moisture sensors during or after the rain simulation (Figure 43).

It would be interesting to repeat this simulation again in winter when the groundwater table would be expected to be higher and the soil more saturated to assess any effect of this on storage and recharge durations. If such a test were carried out, it would be worthwhile moving at least one of the pressure sensors to an inspection chamber to monitor how quickly water levels in these chambers rise and fall in relation to filling and subsequent infiltration.

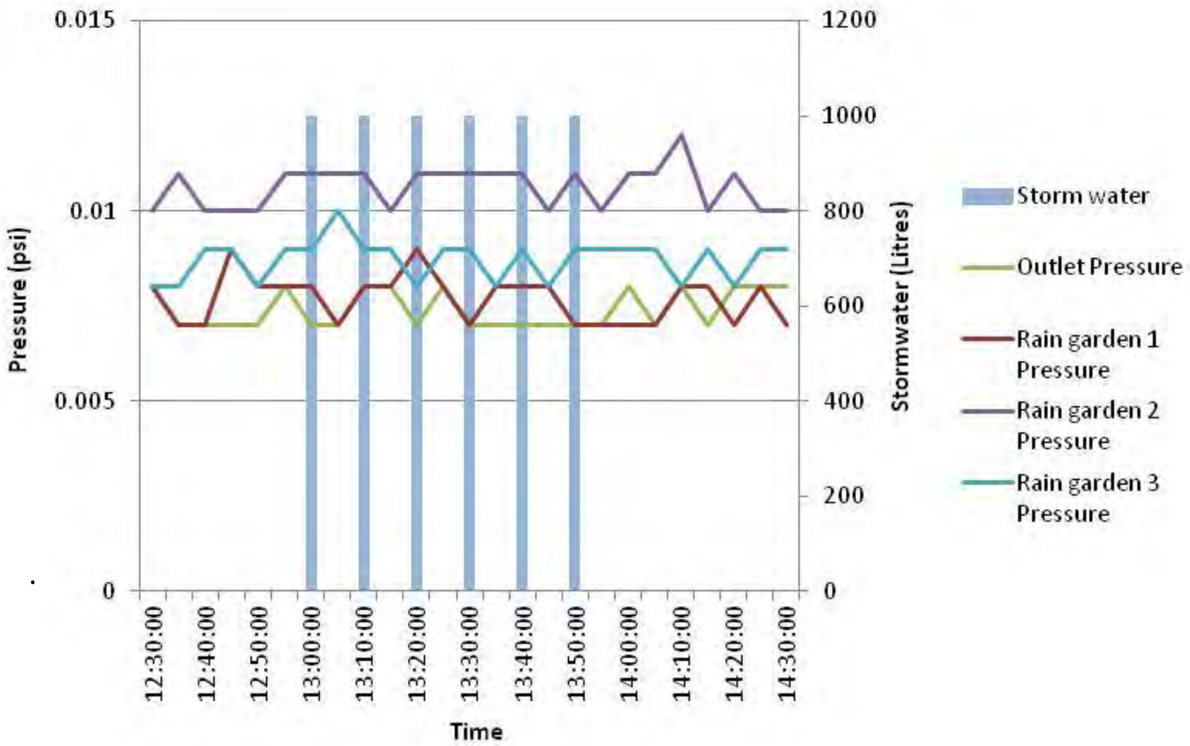


Figure 42. Pressure sensor data from 1 in 5 year storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, London Borough of Hammersmith and Fulham. Blue bars represent the times when 1000L of water were pumped into the swale, the red, green, purple and light blue lines represent the readings of pressure sensors buried within each rain garden and in the control flow outlet chamber to measure changes in the water table.

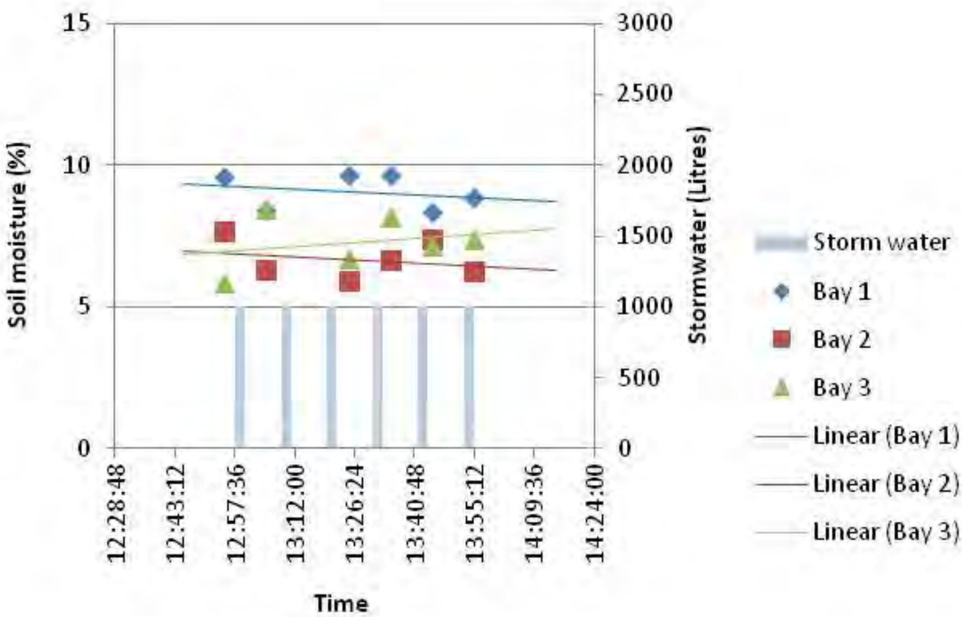


Figure 43. Surface soil moisture data from 1 in 5 year storm simulation event at the Sun Road rain gardens, Cheeseman Terrace Estate, London Borough of Hammersmith and Fulham. Blue bars represent the times when 1000L of water were pumped into the swale. The scatterplot data represents the average of five soil moisture readings taken within each of the three rain gardens before, during and after each 1000 L of stormwater was introduced.

3.4 Thermal monitoring

Thermal camera images taken using a FLIR B335 thermal imaging camera were analysed using FLIR Quickreport 1.2© software to assess temperature differences between green infrastructure retrofit features, pre-existing green infrastructure features and hardstanding areas across Queen Caroline Estate and Richard Knight House and surrounding areas.

Visits were made on several hot days during the second monitoring period. This included the 19th July, 27th July and 24th August 2016. Maximum temperatures recorded at the Queen Caroline Estate weather station on these days were 32.6 °C, 23.5 °C and 33.5 °C respectively. Maximum temperatures recorded at the Richard Knight House weather station were 33.3 °C, 24.3 °C and 32.2 °C respectively.

Results for these hot days when site visits were made with the thermal imaging camera are presented below. Results are broken down by date.

Thermal imaging 19th July 2016

On this visit it was not possible to get access to the roof levels of Richard Knight House and Henrietta House. As such photographs are limited to those areas that were accessible from ground level. Nevertheless, with maximum temperatures of 32.6 °C at Queen Caroline Estate and 33.3 °C at Richard Knight House, this represented an unusually hot day and was thus ideal for thermal image capture of green infrastructure retrofit features.

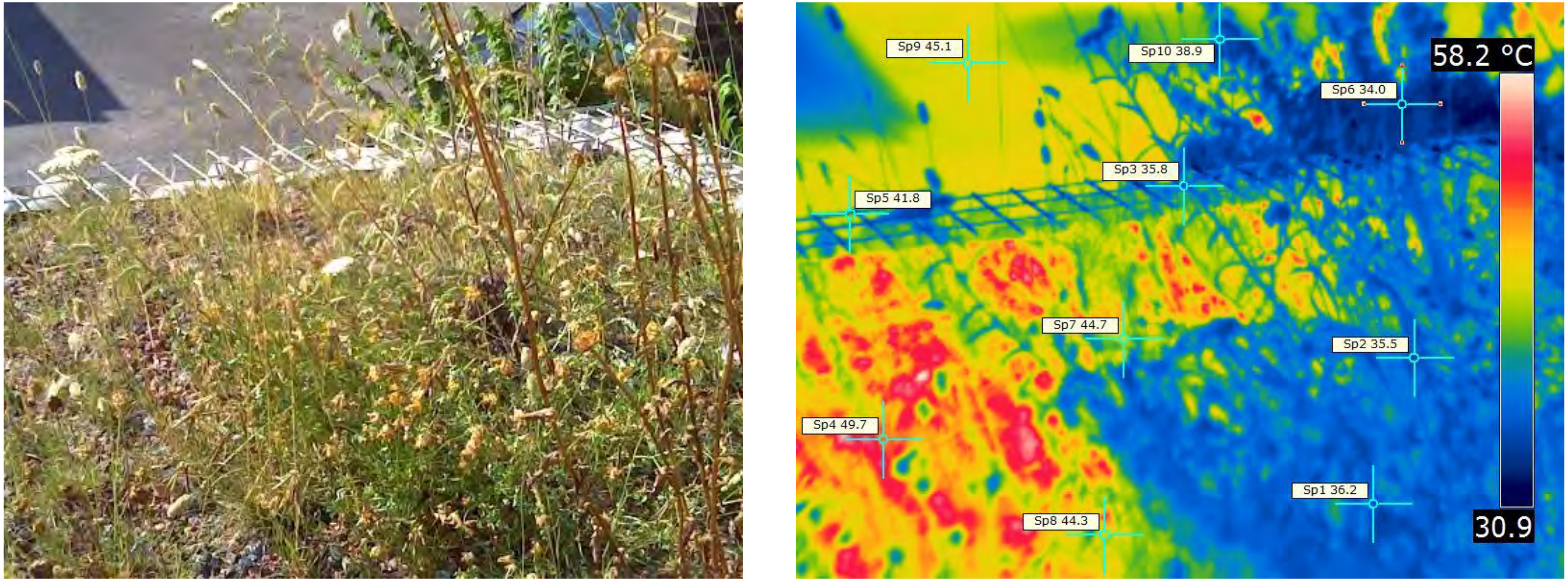


Figure 44. Photo and infrared image of pramshed green roof and surrounding grey infrastructure on the 19th July 2016. Infrared image reveals a temperature difference of 27.3 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>45 °C) were associated with the surrounding tarmac and some areas of bare substrate on the green roof. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (33.3 °C). Coolest temperatures were associated with vegetated areas of the green roof (with temperatures from 35.5 °C to 36.2 °C) and surrounding vegetation (34.0 °C).

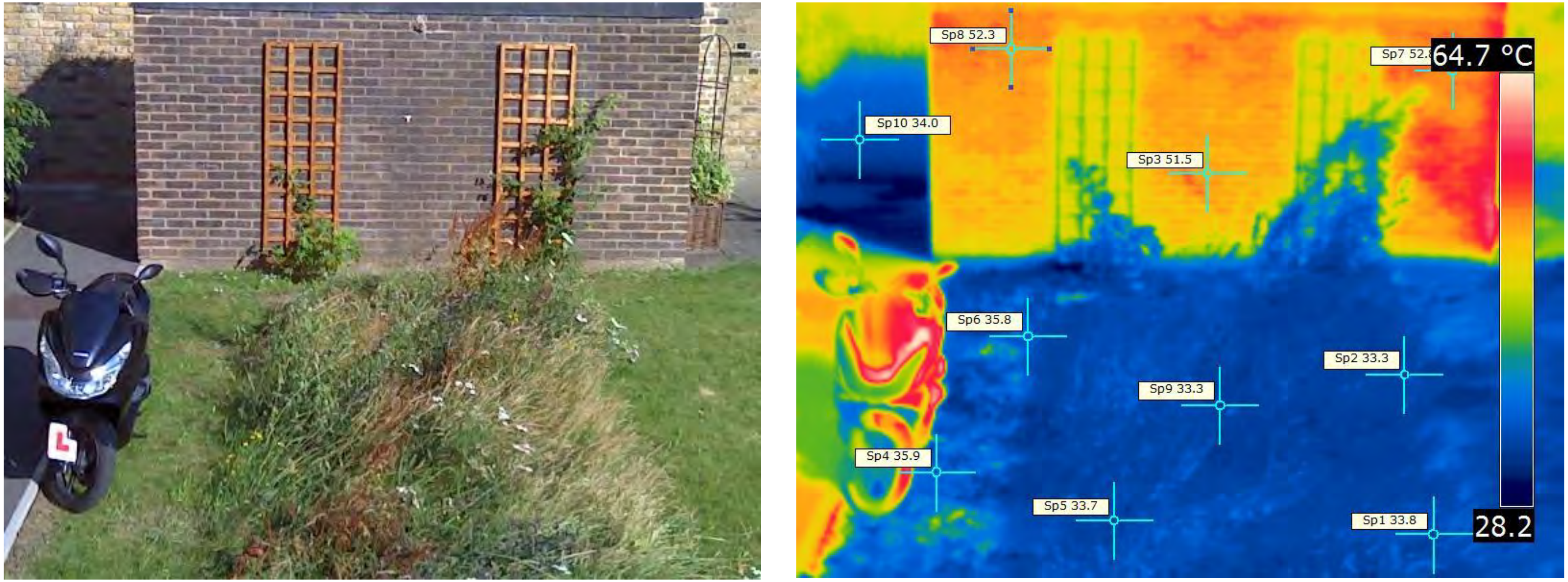


Figure 45. Photo and infrared image of the Richard Knight House swale and surrounding grey infrastructure, 19th July 2016. Infrared image reveals a temperature difference of 36.5 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>51 °C) were associated with the neighbouring pramshed wall. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (33.3 °C). Coolest temperatures were associated with the tall vegetated areas of the swale (with temperatures from 33.3 °C to 33.8 °C). Surrounding areas of amenity turf vegetation were warmer than those in the swale (35.8 °C).

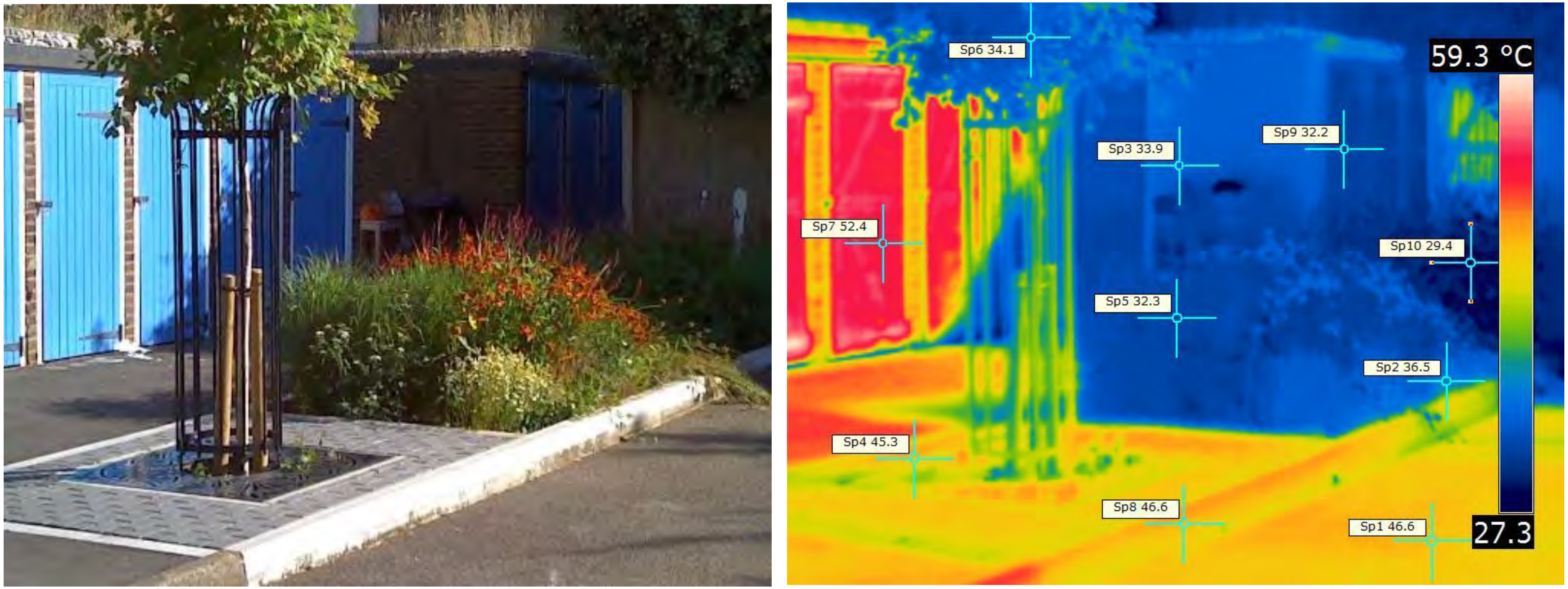


Figure 46. Photo and infrared image of the Richard Knight House rain garden and surrounding grey infrastructure on the 19th July 2016. Infrared image reveals a temperature difference of 32.3 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>45 °C) were associated with the neighbouring pramshed doors and surrounding tarmac areas. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (33.3 °C). Coolest temperatures were associated with the tall vegetated areas of the rain garden (with temperatures from 29.4 °C to 36.5 °C). The tree canopy as part of the SuDS feature also showed cooling potential with a temperature of 34.1 °C.

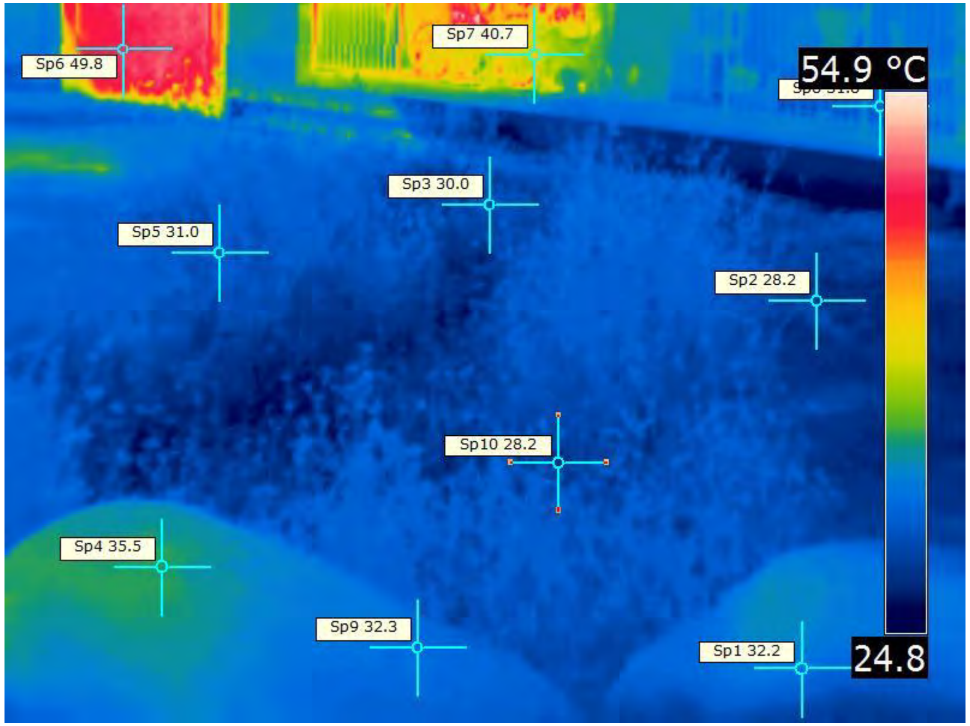


Figure 47. Photo and infrared image of Adella rain basin at Queen Caroline Estate 19th July 2016. Infrared image reveals a temperature difference of 30.1 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>40 °C) were associated with the neighbouring walls. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the rain garden (with temperatures from 28.2 °C to 31.0 °C) although these areas were in the shade compared to surrounding walls. Nevertheless, boulders at the edge of the rain basin were warmer than the vegetation in the basin (32.2 °C to 35.5 °C).

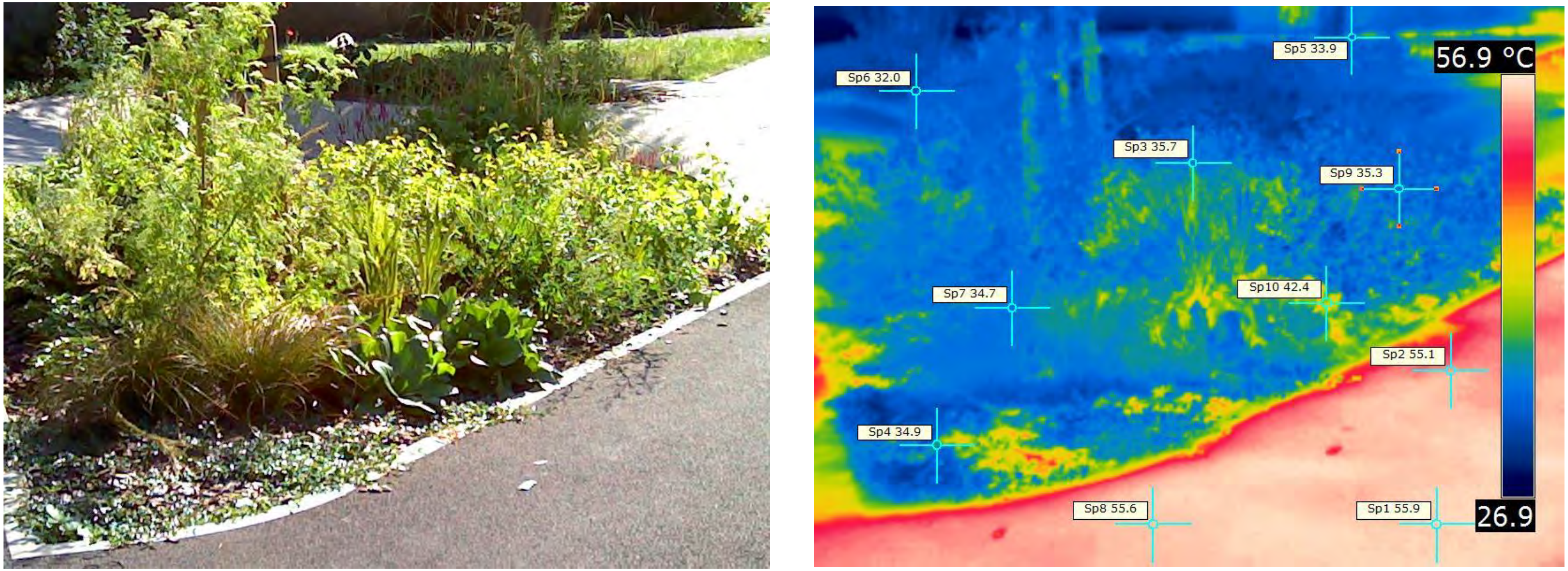


Figure 48. Photo and infrared image of SuDS planting features at Queen Caroline Estate, 19th July 2016. Infrared image reveals a temperature difference of 30.0 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>55 °C) were associated with the neighbouring tarmac paths. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the SuDS feature (with temperatures from 33.9 °C to 35.7 °C).

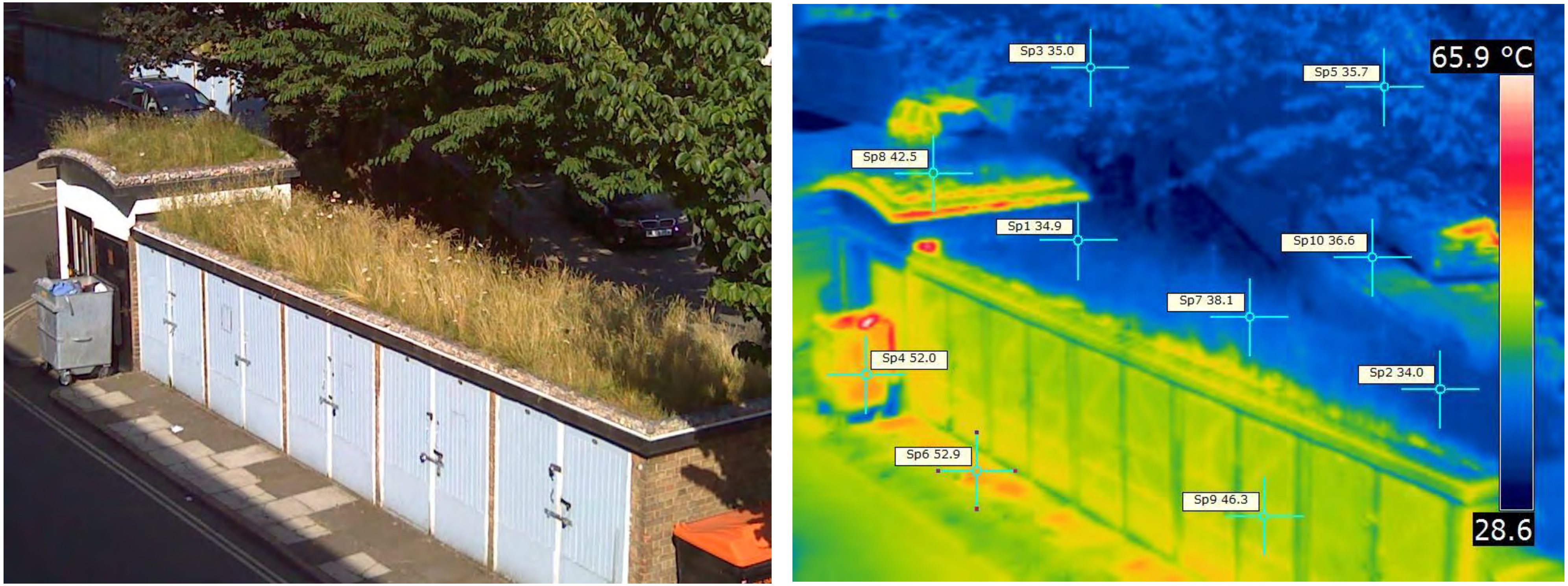


Figure 49. Photo and infrared image of pram shed roofs at Queen Caroline Estate 19th July 2016. Infrared image reveals a temperature difference of 37.3 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>52 °C) were associated with the neighbouring paving and bins. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the pramshed green roofs (with temperatures from 34.0 °C to 38.1 °C). The surrounding tree canopy was also cooler than paved areas (35.0 °C to 35.7 °C).

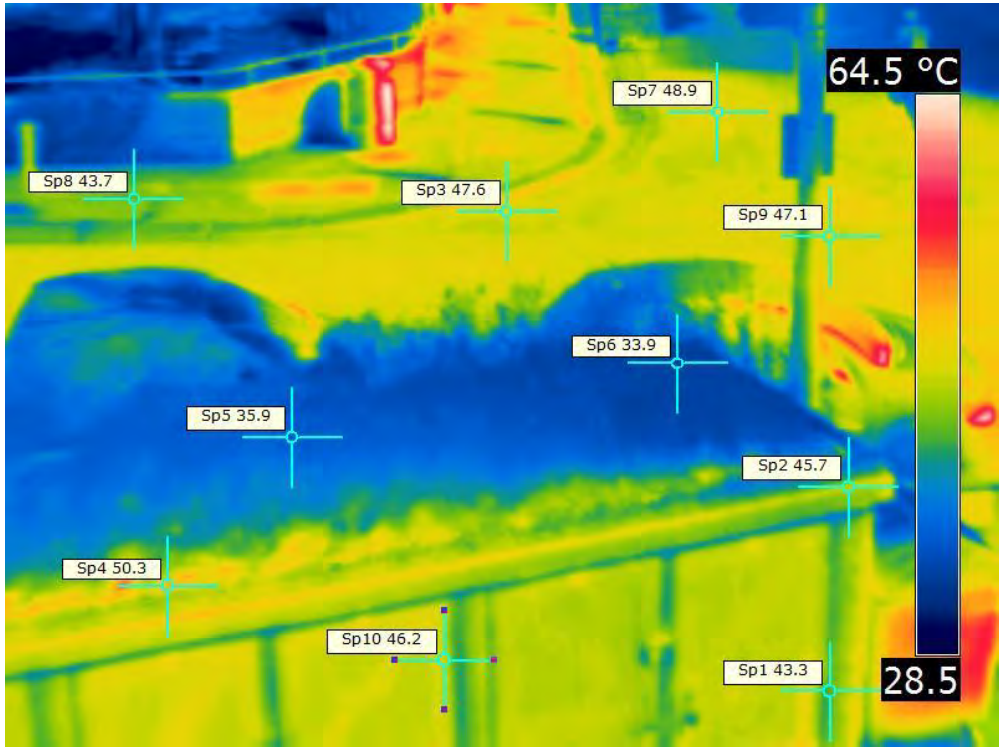


Figure 50. Photo and infrared image of pram shed roofs at Queen Caroline Estate 19th July 2016. Infrared image reveals a temperature difference of 36.0 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>47 °C) were associated with the road and neighbouring paving areas. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the pramshed green roofs (with temperatures from 33.9 °C to 35.9 °C). The roof edges were also hot (45.7 °C and 50.3 °C).

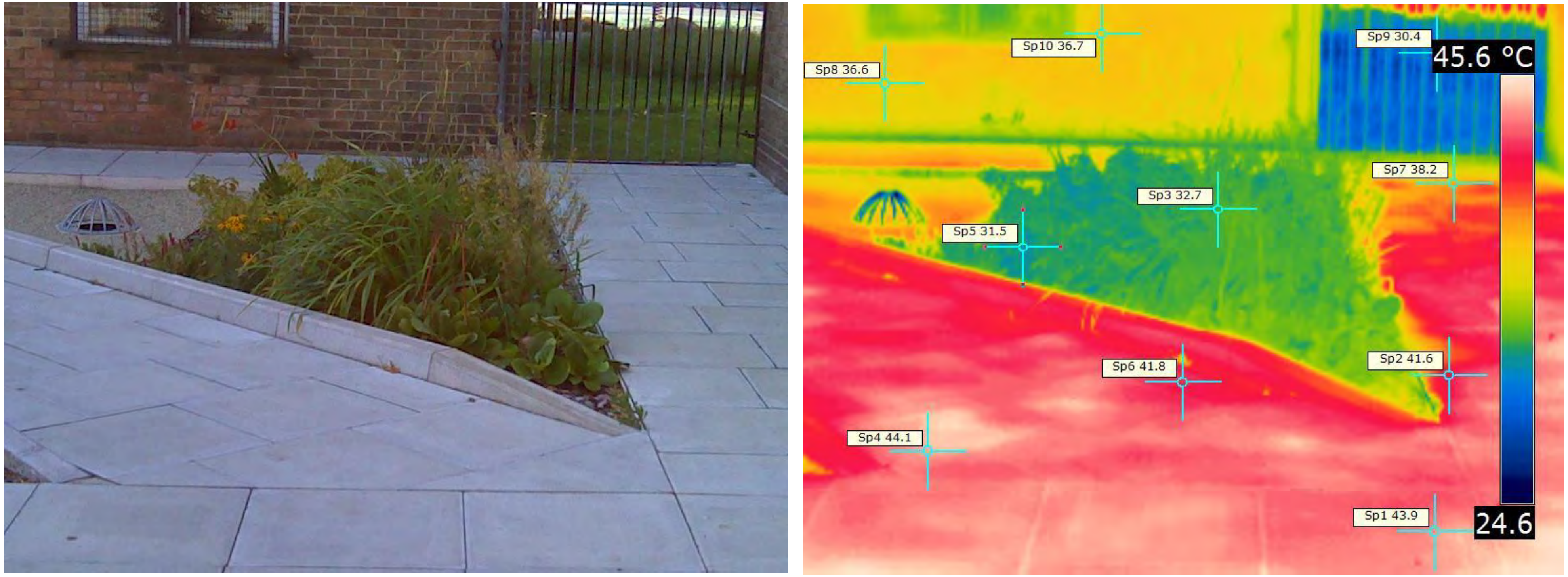


Figure 51. Photo and infrared image of rain garden at Queen Caroline Estate 19th September 2016. Infrared image reveals a temperature difference of 21.0 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>40 °C) were associated with the paved areas surrounding the rain garden. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the rain garden (with temperatures from 31.5 °C to 32.7 °C). The surrounding walls were also hot (36.6 °C and 36.7 °C).

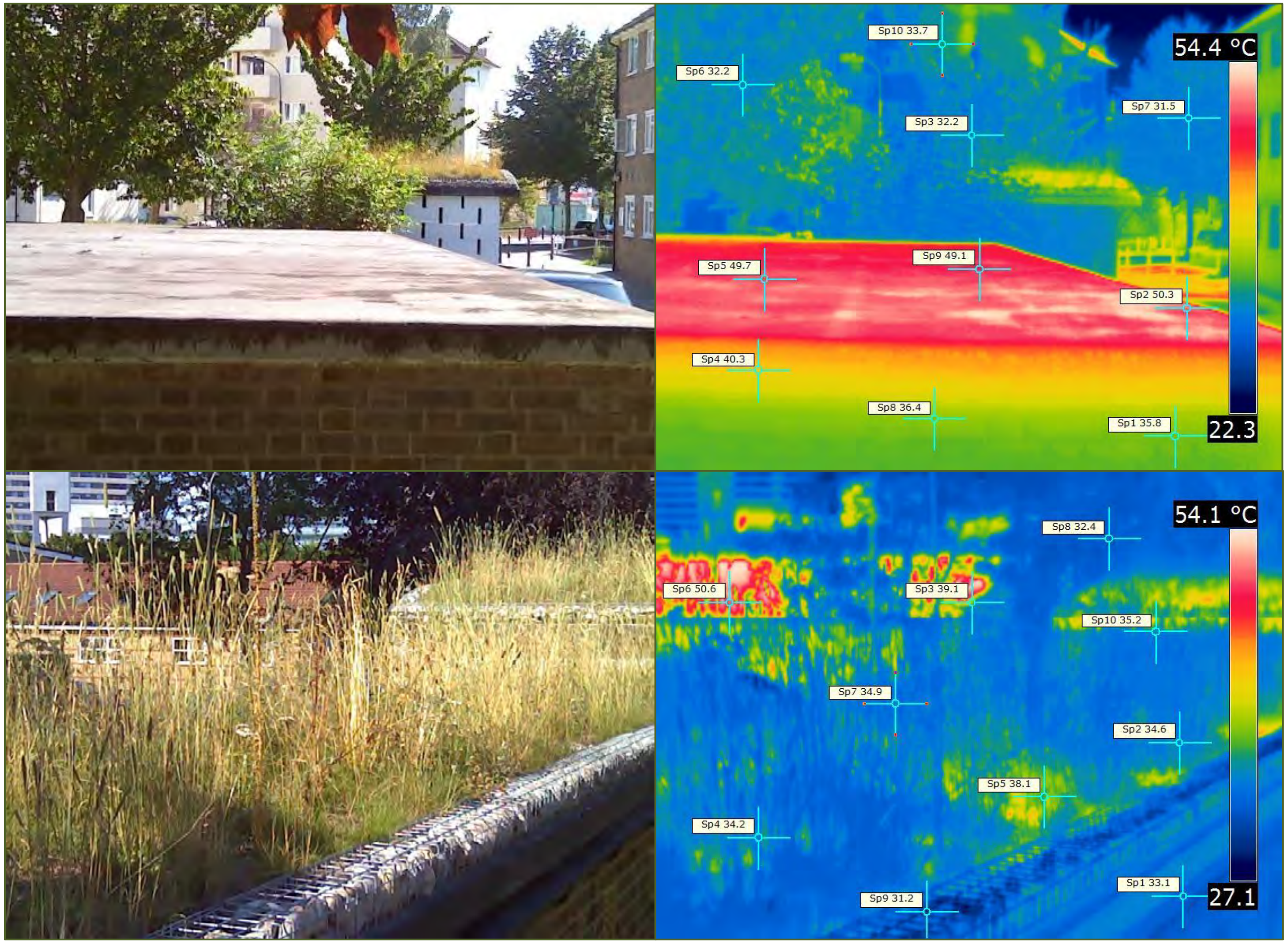


Figure 52. Photo and infrared image of standard and greened pramshed roofs, 19th July 2016. Infrared image reveals a temperature difference of 32.1 °C between the hottest and coolest areas within the fields of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the fields of view. Hottest temperatures (>49 °C) were associated with the standard pramshed roof areas. These areas were recorded as being substantially hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the greened pramshed roofs (with temperatures from 34.2 °C to 34.9 °C).

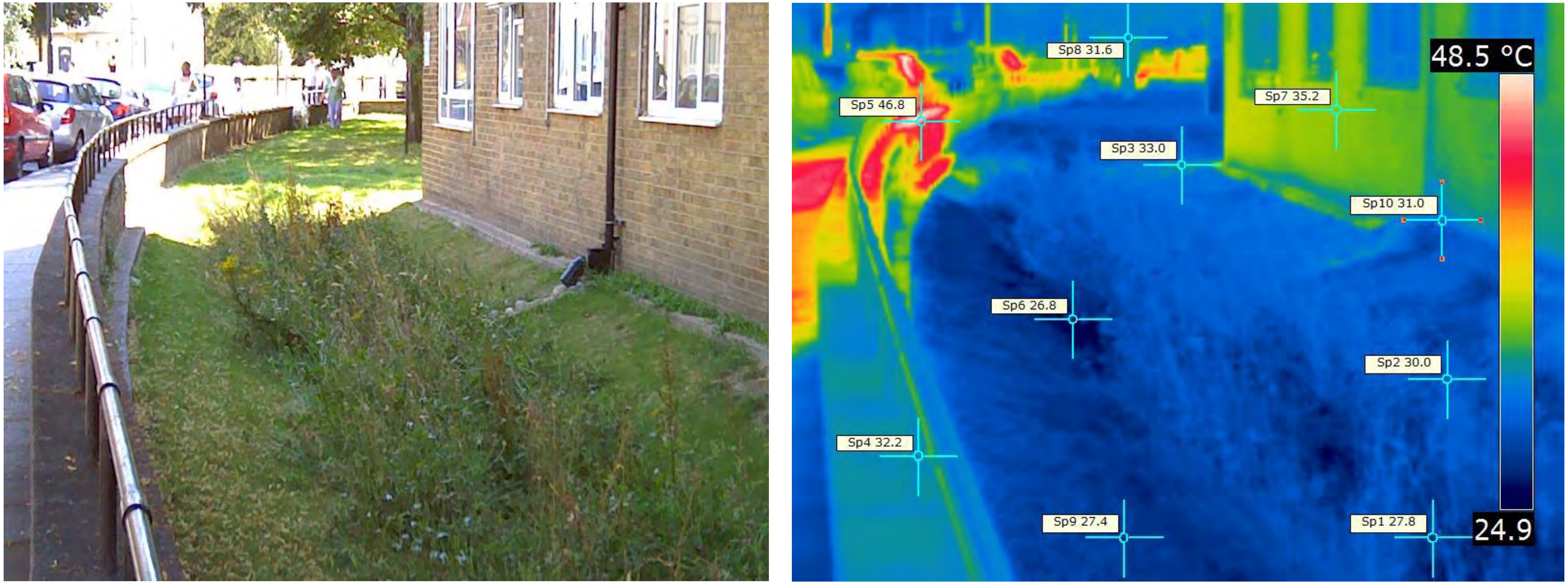


Figure 53. Photo and infrared image of Beatrice House Swale, 19th July 2016. Infrared image reveals a temperature difference of 23.6 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>35 °C) were associated with the walls of Beatrice House surrounding the rain garden. These areas were recorded as being hotter than the maximum daily temperature recorded by the nearby weather station (32.6 °C). Coolest temperatures were associated with the tall vegetated areas of the swale (with temperatures from 26.8 °C to 30.0 °C).

Thermal imaging 27th July 2016

On this visit it was possible to get access to the roof levels of Richard Knight House and Henrietta House. As such photographs are focused on those areas that were not accessible during the previous visit. With maximum temperatures of 23.5 °C at Queen Caroline Estate and 24.3 °C at Richard Knight House, this represented a typical warm summers day and was thus ideal for thermal image capture of green infrastructure retrofit features.

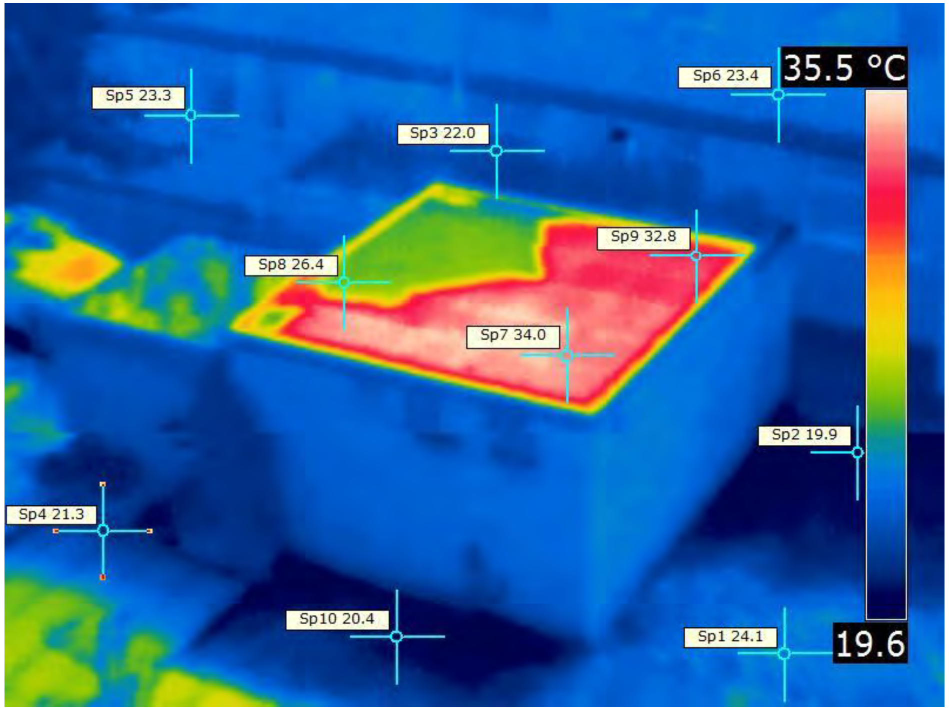


Figure 54. Photo and infrared image of Pramshed standard and green roofs at Richard Knight House, 27th July 2016. Infrared image reveals a temperature difference of 15.9 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>32 °C) were associated with the standard flat pramshed roofs. These areas were recorded as being hotter than the maximum daily temperature recorded by the nearby weather station (24.3 °C). Temperatures on the greened roofs were substantially lower (22.0 °C).These temperatures were even lower than those associated with pooled water on the standard flat roof (26.4 °C).

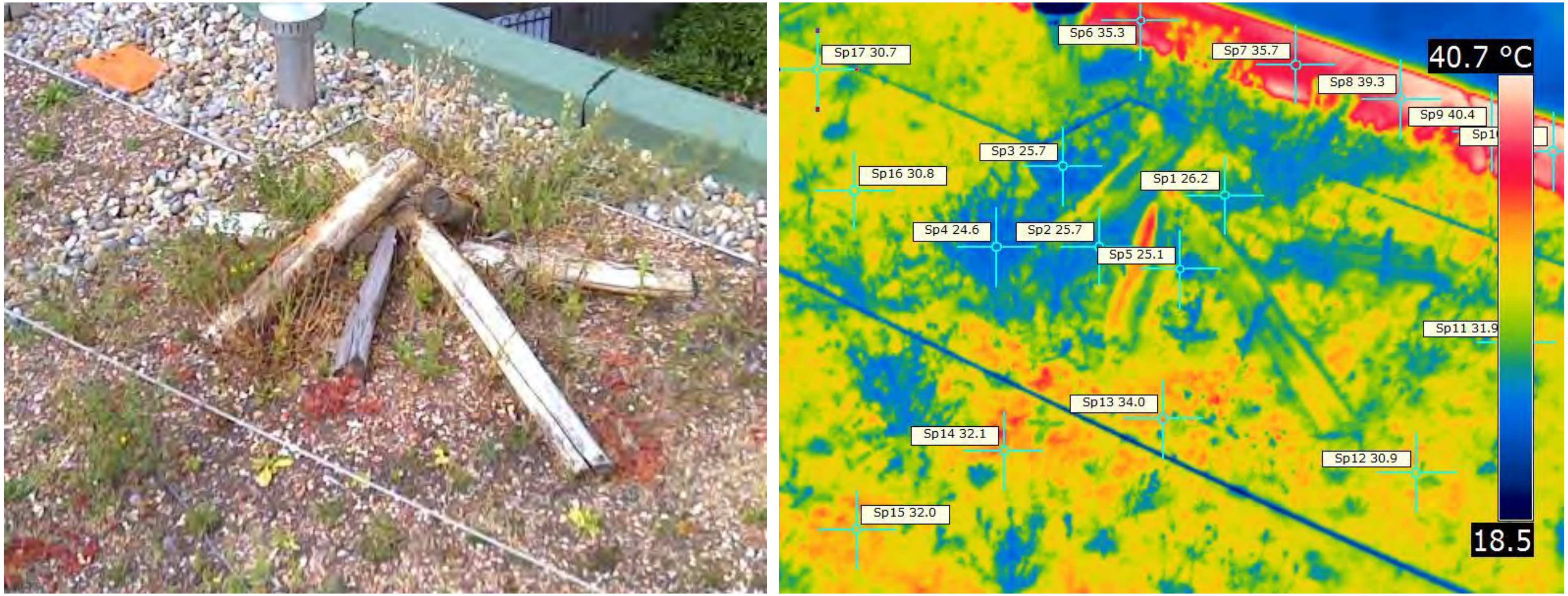


Figure 55. Photo and infrared image of habitat pile on the Richard Knight House green roof 27th July 2016. Infrared image reveals a temperature difference of 22.2 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>35 °C) were associated with the non-greened edges of the flat roof. These areas were recorded as being hotter than the maximum daily temperature recorded by the nearby weather station (24.3 °C). Temperatures on sparsely vegetated areas of the greened roof were substantially lower than the roof edges (30.9 to 34.0 °C). The coolest areas were associated with the log habitat pile, this area appeared to provide refuge for the wildflowers and shading on the substrate. Temperatures around the log pile were between 24.6 to 26.2 °C providing evidence for the additional benefits of habitat piles on green roofs.

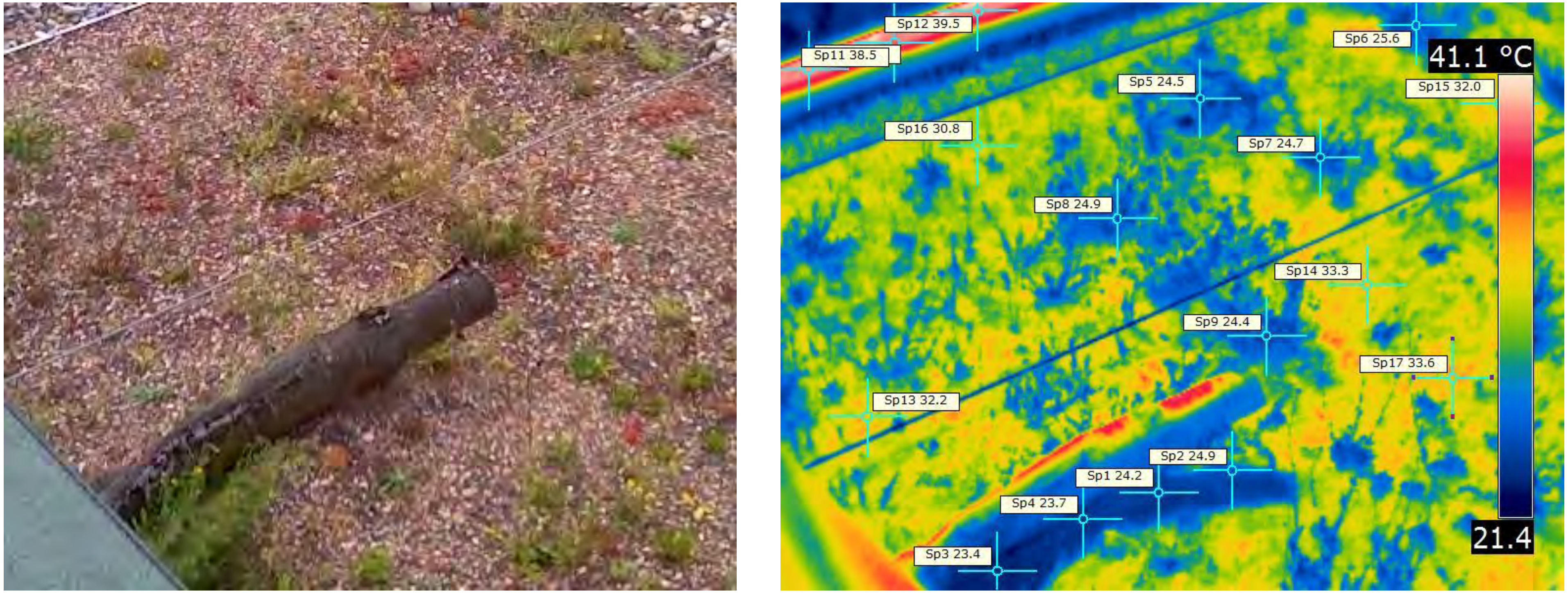


Figure 56. Photo and infrared image of habitat pile on the Richard Knight House green roof 27th July 2016. Infrared image reveals a temperature difference of 19.7 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>38 °C) were associated with the non-greened edges of the flat roof. These areas were recorded as being hotter than the maximum daily temperature recorded by the nearby weather station (24.3 °C). Temperatures on sparsely vegetated areas of the greened roof were substantially lower than the roof edges (30.8 to 33.6 °C). The coolest areas were associated with the log habitat pile (23.4 °C to 24.9 °C) and the vegetated areas of the green roof (24.4 to 25.6 °C). This provided additional evidence that habitat piles can provide refugia on green roofs and cooling benefits when other areas of the roof are drought stressed and thus have sparse vegetation.

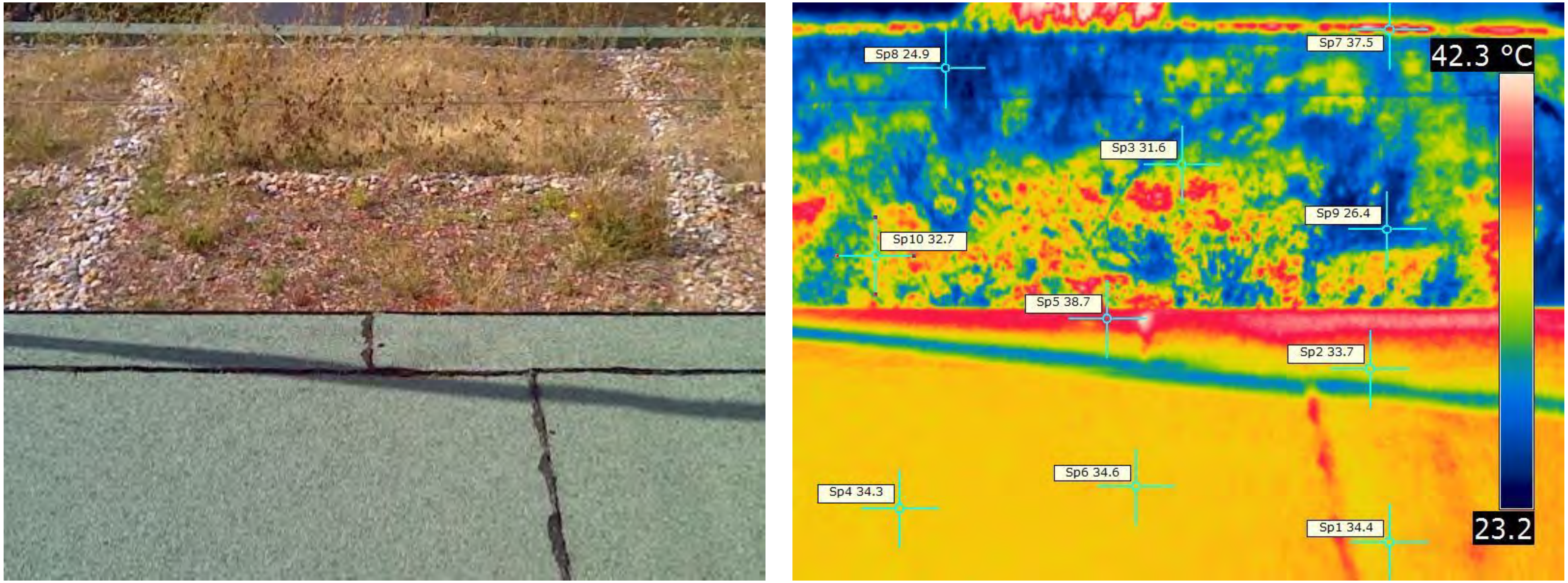


Figure 57. Photo and infrared image of green roof and neighbouring standard roof on Richard Knight House 27th July 2016. Infrared image reveals a temperature difference of 19.1 °C between the hottest and coolest areas within the field of view. A FLIR QuickReport spotmeter was used to identify individual temperatures within the field of view. Hottest temperatures (>33 °C) were associated with the non-greened areas of the flat roof. These areas were recorded as being hotter than the maximum daily temperature recorded by the nearby weather station (24.3 °C). Temperatures on sparsely vegetated areas of the greened roof were slightly lower than the non-greened roof area (31.6 to 32.7 °C). The coolest areas were associated with the vegetated areas of the green roof (24.9 to 26.4 °C).

Richard Knight House experimental plots

Thermal images were also taken of each of the experimental plots on the Richard Knight House green roof. This was carried out to assess whether there were consistent differences in the thermal performance in relation to the experimental design of each plot. Results for the 27th July and 24th August are presented in Table 1 along with values for the standard flat roof on the neighbouring building.

Table 1. Average temperatures recorded on the green roof experimental plots of Richard Knight House and neighbouring standard flat roof. Temperatures calculated using a FLIR B335 thermal imaging camera. Images were analysed using FLIR QuickReport 1.2 software. Ten spots were placed on the image of each green roof test plot and the standard roof using stratified randomisation. An average of the temperatures within each of these test plots was calculated.

	Experimental design of area			27/07/2015		24/08/2015	
Expt. area	**Substrate depth (mm)**	**Planting**	**Aquaten**	**Average temp (°C)**	**S.E.**	**Average temp (°C)**	**S.E.**
1	100	Plug	No	26.04	0.41	41.48	0.66
2	50	Plug	No	29.91	1.08	40.63	0.72
3	130	Plug	No	30.14	0.45	41.64	1.01
4	100	Seed	No	33.34	0.65	45.13	1.22
5	50	Seed	No	34.41	1.76	48.38	1.25
6	130	Seed	No	31.22	0.97	45.29	1.40
7	100	Seed	Yes	30.75	0.56	46.48	0.91
8	50	Seed	Yes	37.65	1.00	52.58	0.84
9	130	Seed	Yes	32.51	0.82	44.31	0.46
10	100	Plug	Yes	32.23	0.79	47.4	0.63
11	50	Plug	Yes	34.67	0.72	51.49	1.05
12	130	Plug	Yes	30.02	1.23	47.69	0.15
Control	**X**	**X**	**X**	**40.61**	**0.35**	**54.86**	**0.15**

A Kruskal-Wallace non-parametric test was carried out on the data to assess whether there was a significant difference between the temperatures recorded across the test plots. Non-parametric testing was used due to the low sample number (*n*=10). For both thermal imaging dates (the 27th July and the 24th August) a significant difference was found between the test plots ($p<0.001$).

Following the positive results for significance obtained by the Kruskal-Wallace test, Mann-Whitney U exact tests were performed to identify where significant thermal differences were recorded.

Selected Mann-Whitney results from the thermal images taken on the 27th July 2015 and 24th August are presented in Tables 2 and 3.

Table 2. Mann-Whitney U exact test on the difference between thermal properties of the experimental green roof plots on Richard Knight House, 27th July 2016. Significance levels are given for those comparisons that were significant in relation to a $p < 0.05$ significance level. For non-significant comparisons N/S is listed. The direction of significance is also presented.

Test	Significance	Warmest roof experiment
Green roof vs control roof	**p < 0.001**	Control roof
Aquaten vs no Aquaten	**p = 0.003**	Aquaten
No Aquaten plug planted vs no Aquaten seeded	**p < 0.001**	Plug planted
Aquaten plug planted vs Aquaten seeded	N/S	N/A
50 mm substrate vs 100 mm substrate	**p < 0.001**	50 mm substrate
50 mm substrate vs 130 mm substrate	**p = 0.001**	50 mm substrate
100 mm substrate vs 130 mm substrate	N/S	N/A

Key result from this study was that, even on a typical summers day, the green roof plots were significantly cooler than those on the neighbouring non-greened flat roof. This demonstrated the beneficial effect that green roofs could have on the urban heat island effect and thermal stress.

Other results from the 27th July 2016 study appeared to show more defined patterns than that recorded in the previous year. This may have been due to the increased development time of the roof and, thus, more established vegetation being more indicative of the environmental conditions on each roof plot. Of particular interest from these results were that the hottest plots were associated with the shallowest substrates. 50 mm substrate plot were significantly hotter than the 100 mm and 150 mm plots. Presumably this was due to the vegetation performing less well on shallower substrates, but this must be checked against vegetation surveys. Due to the non-randomised nature of the plots, however, there is also the possibility that the plots in the centre of the roof (the 50 mm plots) were hotter due to cooling at the roof edges. There was no significant difference between the 100 mm and 130 mm plots.

On the non-Aquaten half of the roof, plug planted plots were significantly hotter than the seeded plots. This was not the case on the Aquaten half, however, with no significant difference recorded. This difference between the Aquaten and non-Aquaten plots could be due to the plug plants performing better (relative to the seeded plots) on the Aquaten half of the roof, but care must again be taken in interpretation of the results due to the non-randomised nature of the plots.

As in the previous year's July survey, the Aquaten plots were significantly warmer than the non-Aquaten plots. Due to the design of the experiment, there is no way of knowing whether this is due to the Aquaten membranes or the position of all of the Aquaten plots on the southern end of the roof but it is a pattern that has continued following maturation of the vegetation.

Table 3. Mann-Whitney U exact test on the difference between thermal properties of the experimental green roof plots on Richard Knight House, 24th August 2016. Significance levels are given for those comparisons that were significant in relation to a $p < 0.05$ significance level. For non-significant comparisons N/S is listed. The direction of significance is also presented.

Test	Significance	Warmest roof experiment
Green roof vs control roof	**p < 0.001**	Control roof
Aquaten vs no Aquaten	**p < 0.001**	Aquaten
No Aquaten plug planted vs no Aquaten seeded	**p < 0.001**	Plug planted
Aquaten plug planted vs Aquaten seeded	N/S	N/A
50 mm substrate vs 100 mm substrate	**p = 0.002**	50 mm
50 mm substrate vs 130 mm substrate	**p = 0.003**	50 mm
100 mm substrate vs 130 mm substrate	N/S	N/A

Results from the 24th August 2016 survey were almost identical to those recorded during the 27th July 2016 visit:

- The non-greened roof was significantly hotter than the green roof;
- The area of the roof with Aquaten was significantly hotter than the area with no Aquaten;

- The plug planted plots of the non-Aquaten area were hotter than the seeded plots but there was no significant difference between the plug planted and seeded plots on the Aquaten half;
- The 50 mm substrate depth plots were significantly hotter than the 100 mm and 130 mm plots but there was no significant difference between the 100 mm and 130 mm plots.

It must be noted again, however, that the non-randomised nature of the trial make it difficult to draw definitive conclusions about the drivers behind these differences as location on roof (e.g. edge effect) could be at least partly responsible for some of the patterns recorded.

3.5 Biodiversity monitoring

Floral surveys were carried out at Richard Knight House on the green roof experimental plots. The first survey comprised an inventory list of all species that occurred on the roof. This survey was not a continuation of previous surveys but was part of a separate study investigating the benefit of addition pollinator nesting habitat to green roofs across central London. Results of this survey are displayed in Table 4.

Table 4. Floral inventory surveys on the Richard Knight House green roof, 8th June 2016.

Species	Common
Achillea millefolium	Yarrow
Agrostis stolonifera	Creeping bentgrass
Allium schoenoprasum	Chives
Anthemis arvensis	Corn chamomile
Anthyllis vulneraria	Kidney vetch
Armeria maritima	Thrift
Centaurea cyanus	Cornflower
Centaurea nigra	Knapweed
Cerastium fontanum	Mouse-ear chickweed
Conyza canadensis	Canadian fleabane
Daucus carota	Wild carrot
Dianthus carthusianorum	Carthusian pink
Dianthus deltoides	Maiden pink
Elytrigia repens	Couch grass
Epilobium parviflorum	Hoary willowherb
Epilobium tetragonum	Square-stalked willowherb
Festuca rubra	Red fescue
Galium palustre	Common marsh bedstraw
Galium verum	Lady's bedstraw
Geranium molle	Dove's-foot Crane's-bill

Species (continued)	Common (continued)
Geranium pusillum	Small-flowered crane's-bill
Helianthemum nummularium	Common rock-rose
Helminthotheca echioides	Bristly oxtongue
Holcus lanatus	Yorkshire fog
Knautia arvensis	Field scabious
Leucanthemum vulgare	Oxeye daisy
Lolium perenne	Perennial rye-grass
Lotus corniculatus	Birdsfoot trefoil
Lychnis flos-cuculi	Ragged-robin
Malva moschata	Musk mallow
Medicago lupulina	Black medick
Melilotus officinalis	Ribbed melilot
Mentha sp.	Mint sp.
Origanum vulgare	Oregano
Papaver rhoeas	Common poppy
Petrorhagia saxifraga	Tunic flower
Pilosella aurantiaca	Fox-and-cubs
Pilosella officinarum	Mouse-ear hawkweed
Plantago lanceolata	Ribwort plantain
Poa annua	Annual meadow grass
Polypogon viridis	Water bent
Poterium sanguisorba	Salad burnet
Primula veris	Common cowslip
Prunella vulgaris	Selfheal
Sagina filicaulis	Annual pearlwort
Salvia pratensis	Meadow clary
Scabiosa columbaria	Small scabious
Scorzoneroides autumnalis	Autumn hawkbit
Sedum acre	Biting stonecrop
Sedum album	White stonecrop
Sedum forsterianum	Rock stonecrop
Sedum rupestre	Reflexed stonecrop
Sedum sexangulare	Six-sided stonecrop
Sedum spurium	Two-row stonecrop
Silene dioica	Red campion
Silene latifolia	White campion
Sisymbrium officinale	Hedge mustard
Sonchus asper	Prickly sow-thistle
Sonchus oleraceus	Smooth sow-thistle
Stellaria media	Chickweed
Trifolium pratense	Red clover
Trifolium repens	White clover
Vulpia myuros	Annual fescue
Total	64

Floral diversity on the roofs was good with 64 species recorded with a diversity of flower types, flowering times and duration. As such this should provide a valuable resource for wildlife including pollinator groups. Floral species recorded included species that were plug planted, seeded and species that had colonised the roof naturally.

Comparative surveys were also carried out at Richard Knight House on 27th July, 24th August and the 22nd September 2015. Surveys here comprised of 50 cm x 50 cm quadrat surveys. Three quadrats were placed in each of the green roof experimental plots using a stratified random methodology. The quadrats were divided into 100 sub-units. The presence of each vegetation species present within the quadrat as a whole was recorded within each of the sub-units (i.e. a species present in all sub-units within the quadrat would score a total abundance of 100). Where possible, plants were identified to species. Presence of new shoots that were as yet unidentifiable to genus or species were also recorded, as was the presence of bare ground within each sub-unit.

27th July 2016 survey

By the time of this second year of surveys, vegetation on Richard Knight House green roof experimental plots was more established. This allowed more detailed analysis of the pattern of distribution in relation to the plot treatments. Lack of randomised replication of individual treatments made it difficult to draw detailed conclusions from the experiment. Nevertheless, it was possible to identify certain trends from the data that indicate areas for more detailed study.

Floral diversity

Overall, fifty-two floral species were recorded in the thirty-six 50 x 50 cm quadrats. Of these, five were species of grass and the rest were wildflowers. The was almost no difference in average floral diversity between seeded plots and plug planted plots (Figure 58). This was confirmed by a Mann-Whitney U Exact two-tailed test that demonstrated that there was no significant difference between the seeded and plug planted treatments in terms of floral diversity (p = 0.955). This was true both on the non-Aquaten areas of the roof (p = 0.166) and the Aquaten areas (p = 0.114). There was, however, a significant difference between the floral diversity on the seeded Aquaten and non-Aquaten areas (p= 0.001), with non-Aquaten areas having greater floral diversity. The same was not true for the plug planted plots (p = 0.947).

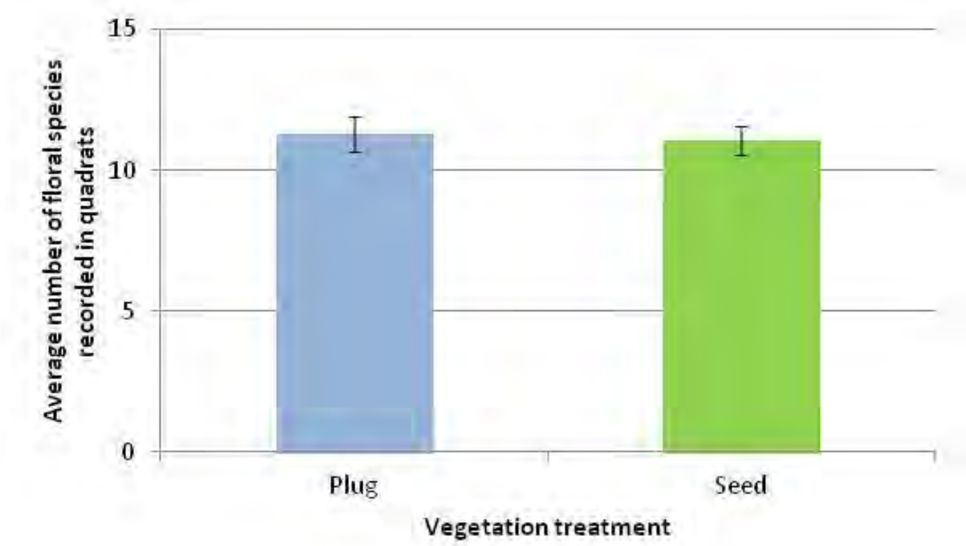


Figure 58. Average floral diversity on the Richard Knight House green roof, 27th July 2016. Averages are calculated on the number of floral species recorded in 18 quadrats for each of two treatment areas (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Vegetation cover

In terms of colonisation of the plots and vegetation cover, number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. Substantially more bare ground was recorded on the plug planted plots than the seeded plots (Figure 59). A Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was significant ($p = 0.003$). In contrast, no significant difference in vegetation cover was recorded between the seeded plots on the Aquaten and non-Aquaten areas of the roof ($p = 0.586$), or on the plug planted Aquaten and non-Aquaten areas ($p= 0.744$).

Similarly, no significant difference was recorded between substrate depths when comparing 50 mm plots with 100 mm plots ($p = 0.590$), 50 mm with 130 mm plots ($p = 0.898$), or 100 mm with 130 mm plots ($p = 0.459$).

Mann-Whitney U Exact two-tailed tests were also carried out to investigate whether there was a significant difference between vegetation cover on different substrate depths on the Aquaten and non-Aquaten areas. The only significant difference recorded was between 100 mm and 130 mm depths on the Aquaten area ($p = 0.02$). All other comparisons were not significant.

A Kruskal-Wallace non-parametric test was carried out comparing the vegetation cover on each test treatment to assess whether there was a significant difference. Non-parametric testing was used due to the low sample number (n=3). The test revealed that there was no significant difference between any of the test plots when compared individually ($p = 0.113$).

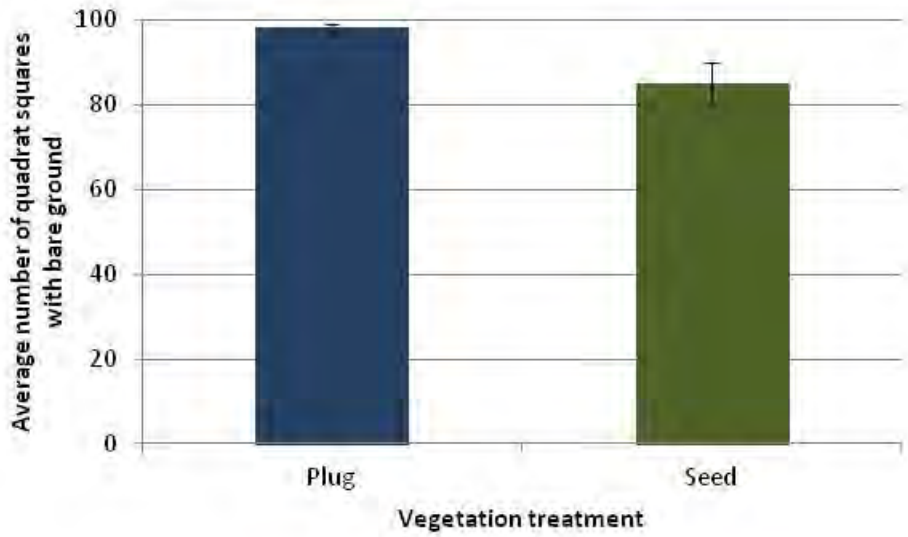


Figure 59. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 27th July 2016. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Grass cover

In addition to vegetation cover, grass cover within quadrats was also analysed. Some grass cover is considered to be desirable for green roofs. Both as a resource for biodiversity and in terms of providing cover and urban cooling benefits some grass is a positive feature. However, on biodiverse roofs, providing a floral resource for pollinators is considered to be a key target so dominant grass swards are undesirable. Moreover, typically grasses are less resilient to drought stress than wildflowers so green roofs dominated by grasses would be expected to provide less urban cooling benefits during prolonged hot periods than a corresponding cover of wildflowers. To assess the grass cover development on different green roof treatments on Richard Knight House, the number of quadrat sub-units in which grasses were counted was compared.

Results revealed that substantially more grass was recorded on the seeded plots than on the plug planted plots (Figure 60), indeed grass was the dominant vegetation on the seeded plots. A Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was significant ($p < 0.001$).

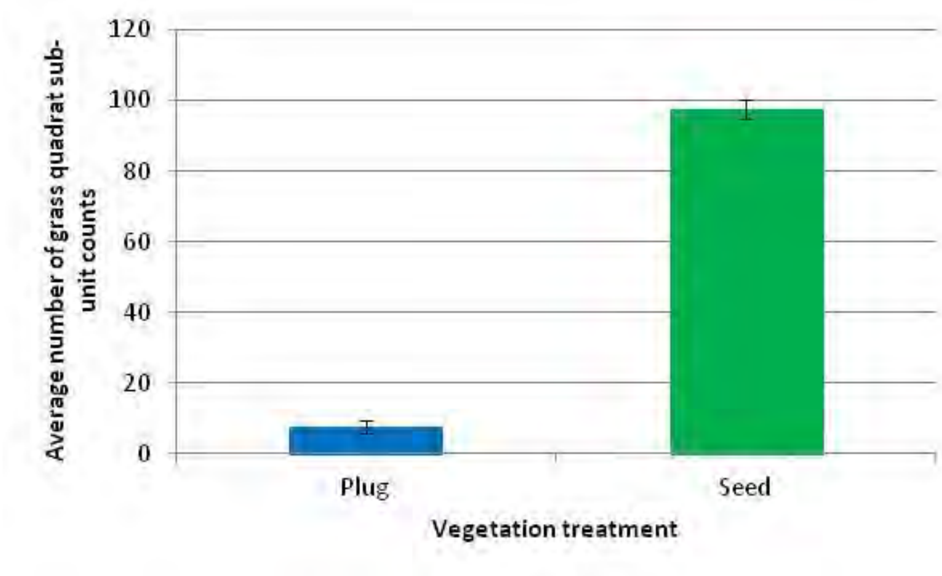


Figure 60. Average number of grass counts in quadrat sub-units on the Richard Knight House green roof experimental plots, 27th July 2016. Averages are calculated on the total number of records of all grass species within each quadrate within each experimental plot for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

24th August 2016 survey

By the time of this second survey in 2016, vegetation on Richard Knight House green roof experimental plots was much more drought-stressed due to a period of prolonged hot dry weather. This was reflected in the survey data.

Floral diversity

Floral diversity was lower than in the July survey with forty-five species being recorded in the thirty-six 50 x 50 cm quadrats. Of these, four were species of grass and the rest were wildflowers. In contrast to the previous survey there was a substantial difference in the average floral diversity between seeded plots and plug planted plots (Figure 61). This was confirmed by a Mann-Whitney U Exact two-tailed test that demonstrated that there was a significant difference between the seeded and plug planted treatments in terms of floral diversity ($p < 0.001$). This was true both on the non-Aquaten areas of the roof ($p = 0.01$) and the Aquaten areas ($p < 0.001$). There was, however, no significant difference between the floral diversity on the seeded Aquaten and non-Aquaten areas ($p = 0.472$), or on the plug planted Aquaten and non-Aquaten areas ($p = 0.967$). The contrasting nature of these results to the first survey in July 2016, provided some evidence that the plug planted plots were more resilient to drought conditions than the seeded plots. It is necessary to monitor these plots over a longer period, however, to see whether this pattern is reversible once the weather becomes more favourable to green roof growth.

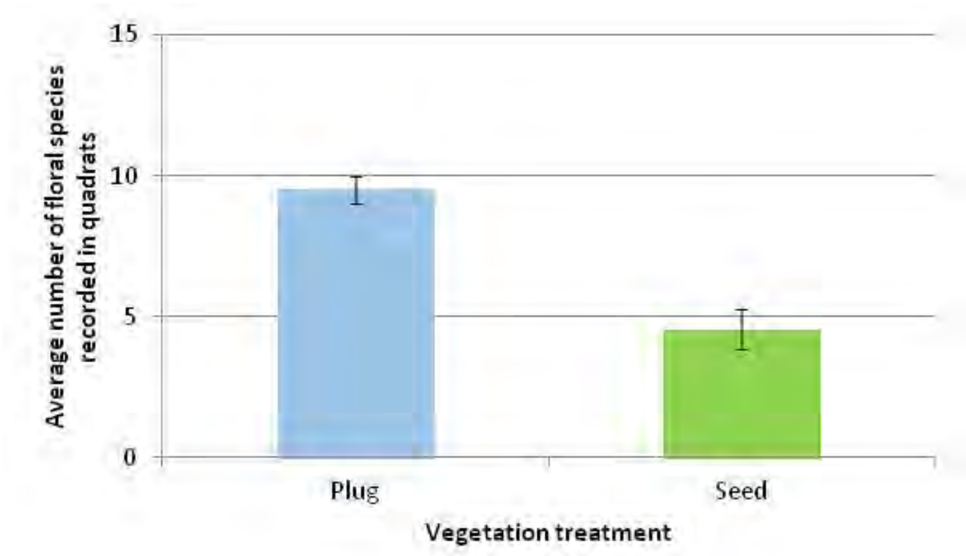


Figure 61. Average floral diversity on the Richard Knight House green roof, 24th August 2016. Averages are calculated on the number of floral species recorded in 18 quadrats for each of two treatment areas (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Vegetation cover

In terms of colonisation of the plots and vegetation cover, number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. Similarly to the previous survey, more bare ground was recorded on the plug planted plots than the seeded plots (Figure 62). However, a Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was no longer significant (p = 0.255). This change was presumably linked to the overall decline in diversity on the seeded plots relative to the plug planted plots. Similarly, no significant difference in vegetation cover was recorded between the seeded plots on the Aquaten and non-Aquaten areas of the roof (p = 0.205), or on the plug planted Aquaten and non-Aquaten areas (p= 0.834).

Similarly, no significant difference was recorded between substrate depths when comparing 50 mm plots with 100 mm plots (p = 0.08), 50 mm with 130 mm plots (p = 0.764). There was, however, a significant difference between 100 mm and 130 mm plots (p = 0.023). There is no obvious reason for this but may be due to their location on the roof (i.e. one side colonising better than the other due to, for example, less wind exposure).

Mann-Whitney U Exact two-tailed tests were also carried out to investigate whether there was a significant difference between vegetation cover on different substrate depths on the Aquaten and non-Aquaten areas. The only significant difference recorded was between 100 mm and 50 mm depths on the non-Aquaten area (p = 0.05), with the 50 mm plots having fewer bare areas, and between the 100 mm and 130 mm depths on the Aquaten area (p = 0.039), with the 130 mm plots having fewer bare areas. All other comparisons were not significant.

A Kruskal-Wallace non-parametric test was carried out comparing the vegetation cover on each test treatment to assess whether there was a significant difference. Non-parametric testing was used due to the low sample number (n=3). As in the previous survey, no significant difference was recorded between any of the test plots when compared individually (p = 0.108).

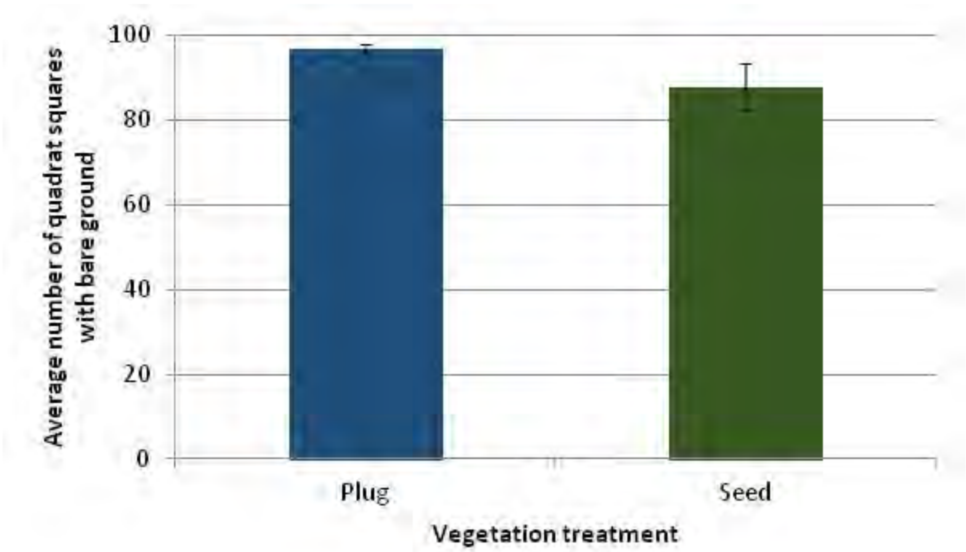


Figure 62. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 24th August 2016. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Grass cover

Similarly to the previous survey, a greater grass cover was recorded on the seeded plots than on the plug planted plots (Figure 63). However, grass cover on seeded plots had reduced substantially by the time of this second survey (from a 97.6 squares per quadrate average in July to 14.2 in August). This was indicative of how susceptible green roof grasses tend to be to the typical drought conditions experienced on green roofs in the UK during the summer months. A Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was no longer significant (p = 0.217).

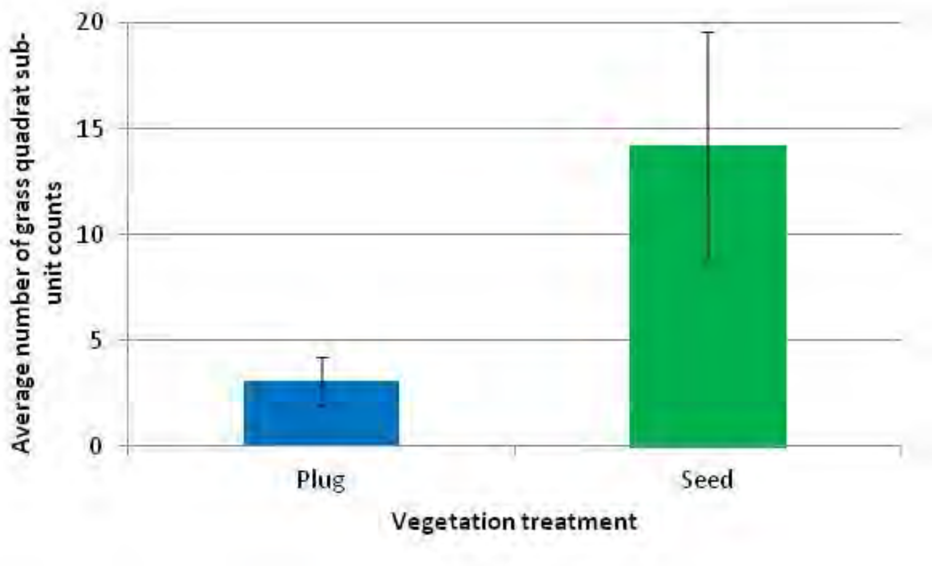


Figure 63. Average number of grass counts in quadrat sub-units on the Richard Knight House green roof experimental plots, 24th August 2016. Averages are calculated on the total number of records of all grass species within each quadrate within each experimental plot for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

22nd September 2016 survey

An additional vegetation survey was carried out at Richard Knight House on the 22nd September 2016. By the time of this third survey in 2016, vegetation on Richard Knight House green roof experimental plots remained drought-stressed as the prolonged spell of dry weather had persisted. This was reflected in the survey data.

Floral diversity

Floral diversity was lower than in the August survey with thirty-three species being recorded in the thirty-six 50 x 50 cm quadrats. Of these, three were species of grass and the rest were wildflowers. This provided further evidence of the decline in floristic diversity in relation to the dry spell and, in particular, the decline in number of grass species. Similarly to the previous survey, and in contrast to the July survey, there was substantially lower average floral diversity on the seeded plots than on the plug planted plots (Figure 64). This was confirmed by a Mann-Whitney U Exact two-tailed test that demonstrated that there was a significant difference between the seeded and plug planted treatments in terms of floral diversity (p = 0.009). This was true on the Aquaten areas (p = 0.005) of the roof, but there was no significant difference between the floral diversity on the seeded and plug planted areas of non-Aquaten areas of the roof (p = 0.474). Whilst there was no significant difference between the overall floral diversity on the Aquaten and non-Aquaten areas of the roof (p= 0.103), there was a significant differences between the floral diversity on the seeded Aquaten and non-Aquaten areas (p= 0.04), with the non-Aquaten plots being more diverse. There was, however, no significant difference in terms of floral diversity between the plug planted Aquaten and non-Aquaten areas (p = 0.978). This third survey provided further evidence that the plug planted plots were more resilient to drought conditions than the seeded plots. It is necessary to monitor these plots over a longer period, however, to see whether this pattern is reversible once the weather becomes more favourable to green roof growth.

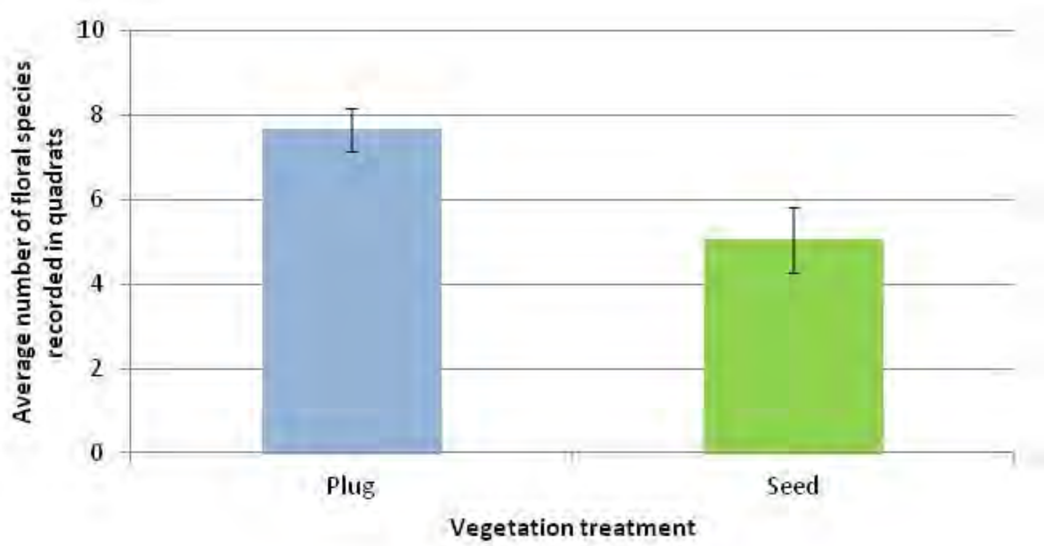


Figure 64. Average floral diversity on the Richard Knight House green roof, 22nd September 2016. Averages are calculated on the number of floral species recorded in 18 quadrats for each of two treatment areas (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Vegetation cover

In terms of colonisation of the plots and vegetation cover, number of quadrat sub-units containing bare ground was used as a proxy for vegetation cover. Similarly to the two previous surveys, more bare ground was recorded on the plug planted plots than the seeded plots (Figure 65). However, a Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments remained non-significant (*p* = 0.069). This again provided evidence that there was an overall decline in diversity on the seeded plots relative to the plug planted plots since the time of the first survey. Similarly, no significant difference in vegetation cover was recorded between the seeded plots on the Aquaten and non-Aquaten areas of the roof (*p* = 0.148), or on the plug planted Aquaten and non-Aquaten areas (*p*= 0.186).

There was also no significant difference recorded between substrate depths when comparing 50 mm plots with 100 mm plots (*p* = 0.405), 50 mm with 130 mm plots (*p* = 0.237), or 100 mm with 130 mm plots (*p* = 0.718).

Mann-Whitney U Exact two-tailed tests were also carried out to investigate whether there was a significant difference between vegetation cover on different substrate depths on the Aquaten and non-Aquaten areas. No significant difference recorded was for any of the depths on the non-Aquaten area or on the Aquaten area.

A Kruskal-Wallace non-parametric test was carried out comparing the vegetation cover on each test treatment to assess whether there was a significant difference. Non-parametric testing was used due to the low sample number (*n*=3). As in the previous survey, no significant difference was recorded between any of the test plots when compared individually (*p* = 0.055).

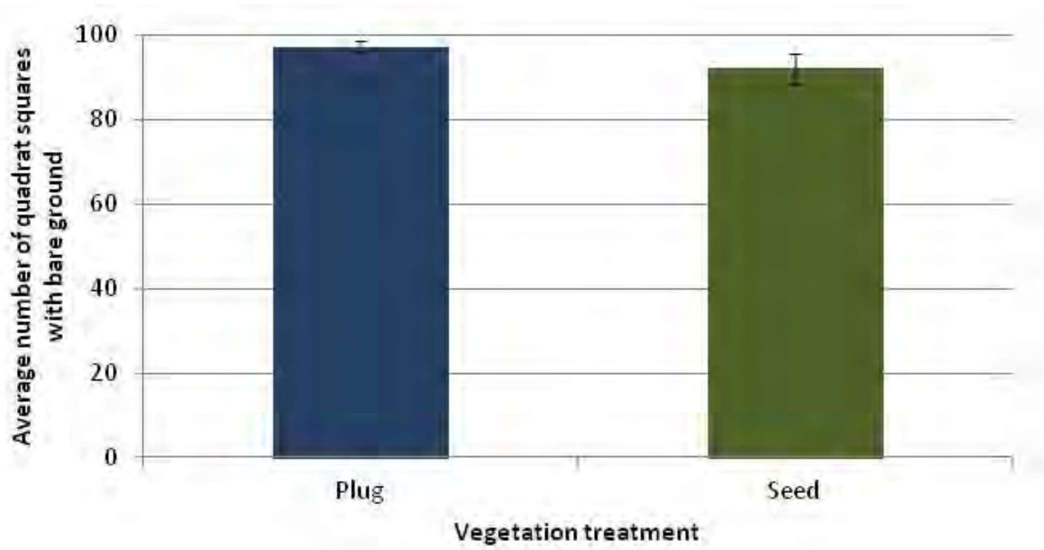


Figure 65. Average number of quadrat sub-units containing areas of bare ground on the Richard Knight House green roof, 22nd September 2016. Averages are calculated on the number of sub-units out of 100 sub-units within which bare ground was recorded for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

Grass cover

Similarly to the previous survey, a greater grass cover was recorded on the seeded plots than on the plug planted plots (Figure 66). Grass cover on seeded plots had increased slightly since the time of the second survey (from a 14.2 squares per quadrate average in August to 23.9 in September) but still remain substantially lower than the July average (97.6). Pressumably this slight increase was indicative of the slightly cooler and damper conditions in September meaning that the grasses were less drought-stressed and so able to recover slightly. A Mann-Whitney U Exact two-tailed test demonstrated that this difference between treatments was significant again (p = 0.012).

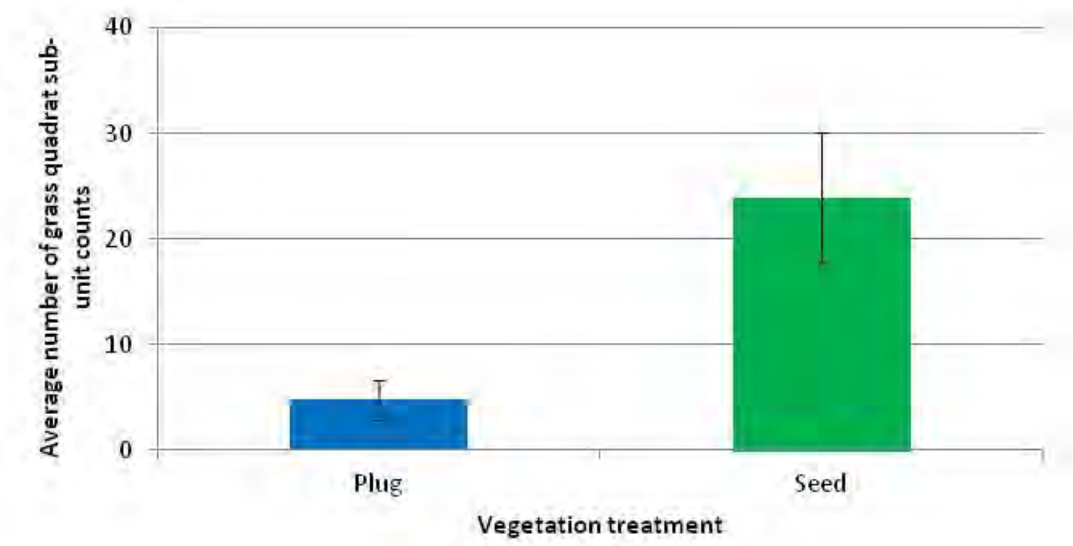


Figure 66. Average number of grass counts in quadrat sub-units on the Richard Knight House green roof experimental plots, 22nd September 2016. Averages are calculated on the total number of records of all grass species within each quadrate within each experimental plot for 18 quadrats for each of two treatments (plug planted vs seeded vegetation). Error bars represent standard error of the mean.

3.6 Photographic monitoring

In addition to the specific vegetation monitoring of the retrofitted green infrastructure, photos were taken to capture the development of the vegetation and wildlife visiting the sites. Below are a small selection of these images (Figures 67 and 68):

Figure 67. Images from green infrastructure retrofit project in Hammersmith. Clockwise from top left: cavity nesting bee habitat installed on Richard Knight House green roof; bird'sfoot trefoil (*Lotus corniculatus*) growing on pramshed green roof; The European garden spider (*Araneus diadematus*) making use of the habitat structure in the Beatrice House swale; and Pink (*Dianthus spp*) flower on the Richard Knight House green roof.

Figure 68. Images from green infrastructure retrofit project in Hammersmith. Clockwise from top left: Thanet sand habitat for ground nesting bees; experimental plots greening differently on the Richard Knight House green roof; Kidney vetch (*Anthyllis vulneraria*) sprawling across a green roof; Cornflower (*Centaurea cyanus*) providing a pollen resource for bees; Habitat pile and diverse wildflowers on the Richard Knight House green roof; a 'golden' green roof (drought stressed vegetation ready to burst in to life again once it rains).

3. 7 Flowmeter rainfall runoff monitoring

In addition to the rain simulation events, monitoring using the installed flowmeters continued during this second monitoring period from June to September 2016. Data monitoring was continuous on three pram shed roofs (Alexandra, Charlotte and Mary), two roof downpipes (Beatrice House left and right sides), a pressure sensor in the Beatrice House swale, and a barrologger located at the University of East London Docklands campus.

A graph of a sample of the raw data generated by one of these gauges is presented in Figure 69.

Figure 69. Raw rainfall runoff data collected from Alexandra House pram shed roof in-line flowmeter from the 8th July 2016 to 2nd August 2016.

Due to the continuous nature of the monitoring, substantial volumes of data were generated for all rain events. In order to present the most relevant of this data within this report, the five largest rain events during this monitoring period are presented in this report. The largest events were selected as they are those of most interest in terms of the potential to cause localised flooding and overload London's storm drain system.

Details of the six largest rain events are presented in Table 5. Six events are presented (rather than five as in the previous report) as data may have been missed from one of the largest five events due to a datalogger reset (details provided in rain data analysis).

Table 5. Top six largest rain events recorded at Queen Caroline Estate, Hammersmith during the initial monitoring period. Monitoring period was from June to September 2016. Data comes from a Vantage Vue weather station positioned on Henrietta House at Queen Caroline Estate.

Date	Max temp (°C)	Total rain (mm)	Maximum rain rate (mm/hr)
08/06/2016	26.1	8.2	167
12/06/2016	19.5	9	68.2
16/06/2016	19.7	37.2	188.8
20/06/2016	21.7	13.4	10.6
23/06/2016	21.2	39	73
16/09/2016			

In order to assess the performance of the green infrastructure features, two different analyses were carried out for each of the rain events. The first was an analysis of the proportion of the total rainfall that was attenuated by each of the pram shed green roofs. The second was a graphical representation of the timing and intensity of runoff from the green roofs, control roofs and the values from the pressure sensor at the base of Beatrice House swale.

Rain event 08/06/2016

Figure 70 shows the prevailing weather patterns preceding the rain event in the 8th June 2016.

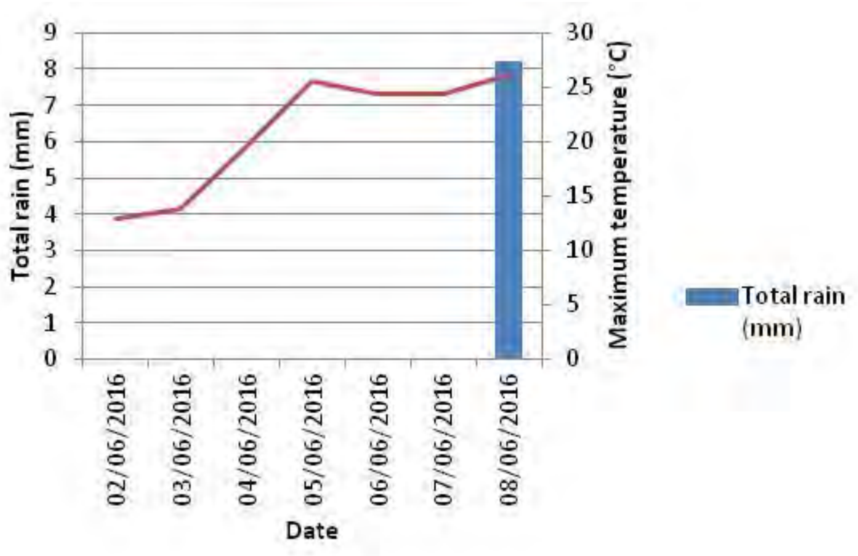


Figure 70. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 8.2 mm on 8th June 2016.

Table 6 presents the attenuation performance of the pramshed roofs during the rain event on the 8th June 2016.

Table 6. Pramshed green roof water attenuation performance during a rain event on the 8th June 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	8.2	22	180.4	95.02
Charlotte	8.2	32	262.4	96.08
Mary	8.2	33.25	272.65	85.21
Average				**92.10**

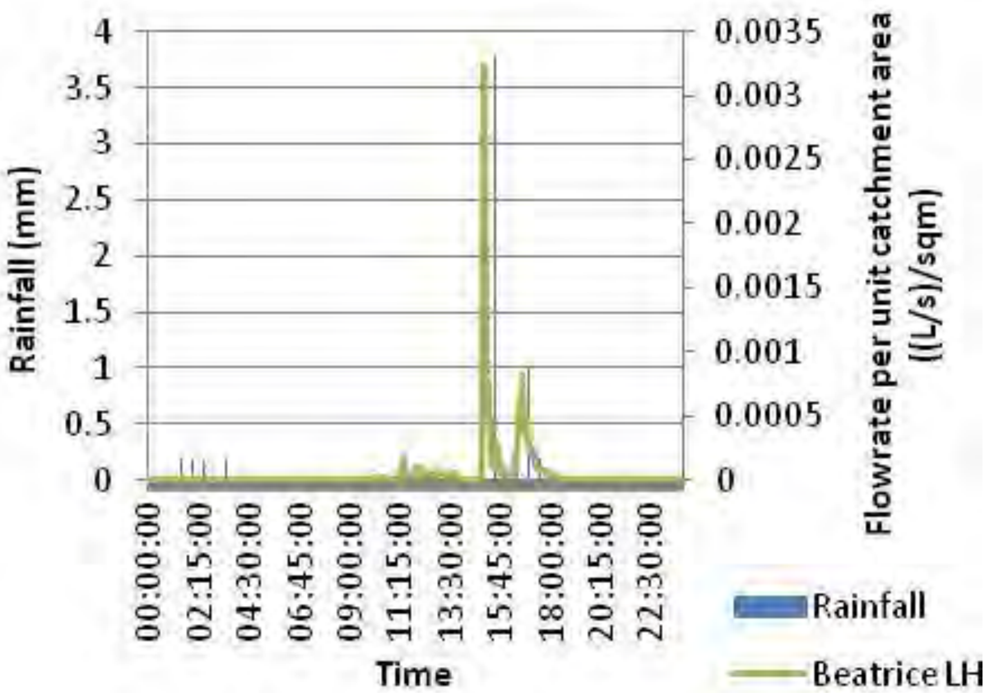
Figure 71 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 7.i). Maximum peak flow reduction recorded was 87%. However, peak flows were not delayed (Table 7.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

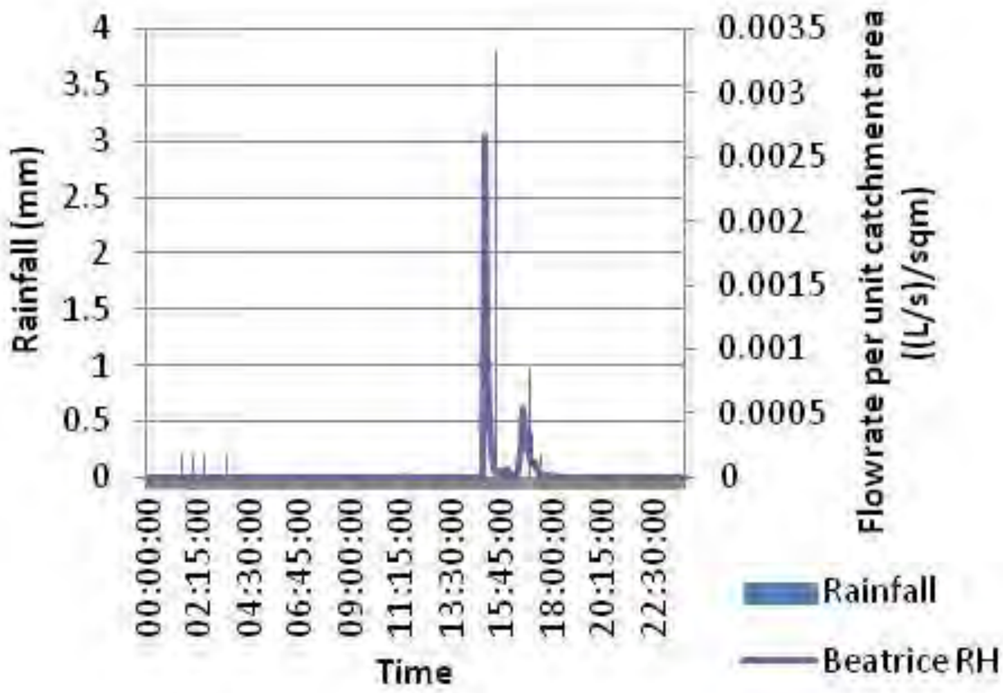
Table 7. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 8.2 mm rain event on the 8th June 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	75.30%	87.41%	53.33%
Beatrice RH	70.11%	84.77%	43.53%

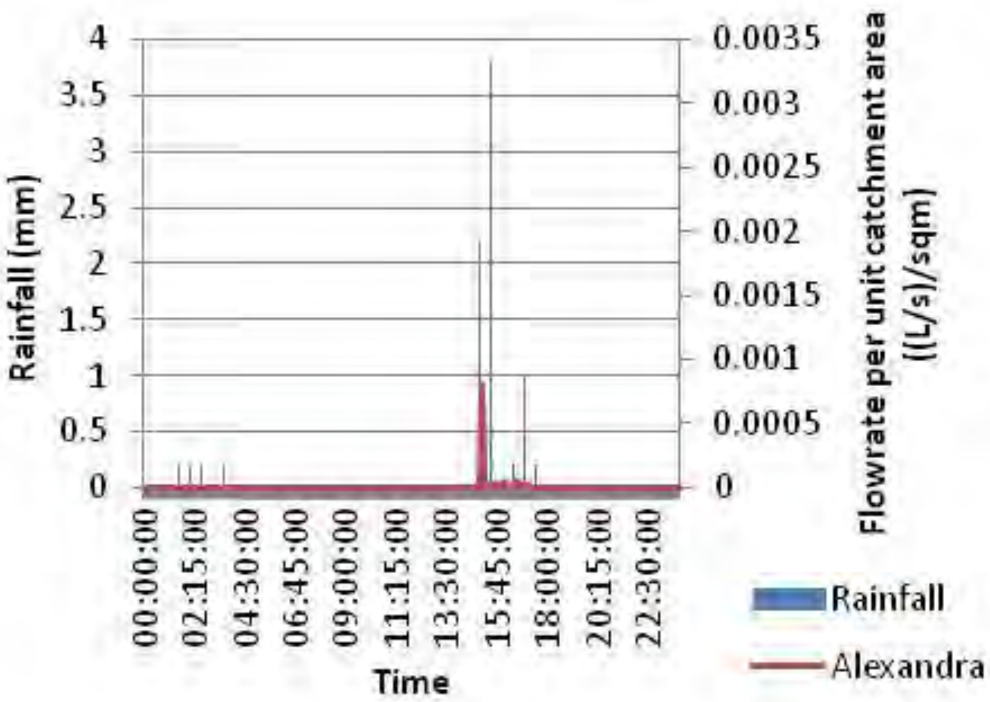
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:00:00	00:00:00	00:00:00
Beatrice RH	00:00:00	00:00:00	00:00:00


4
3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Beatrice LH

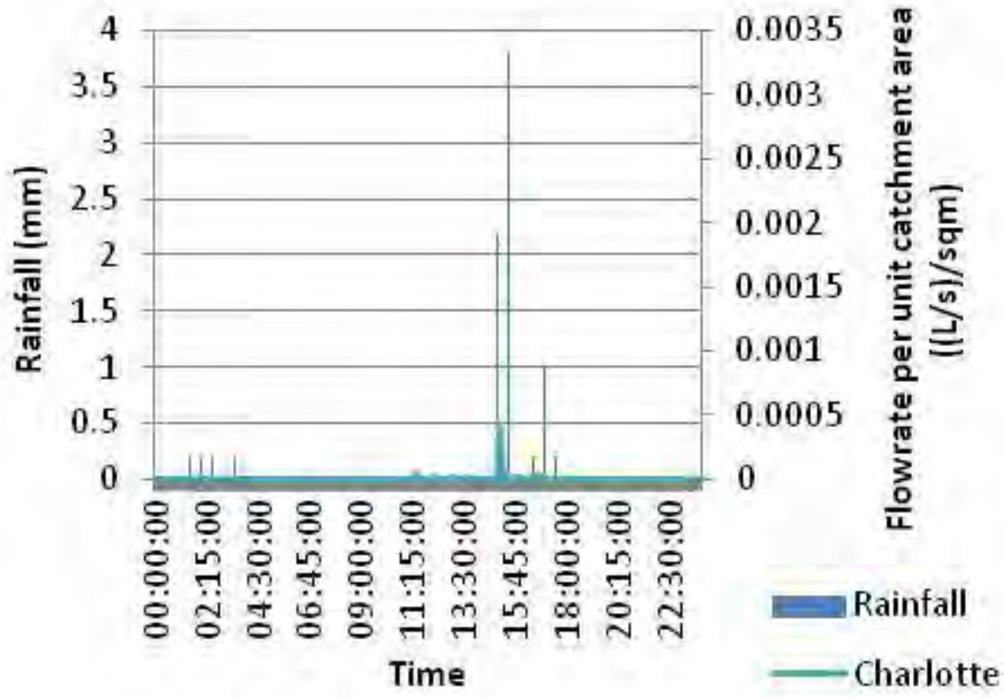
i)


4
3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Beatrice RH

ii)

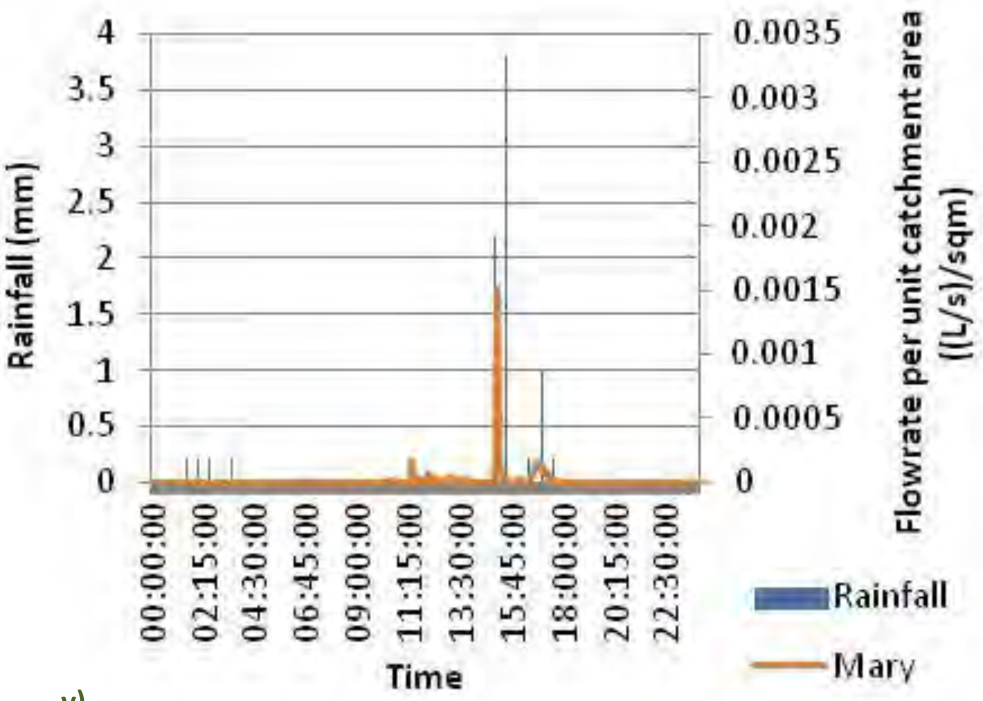


4
3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Alexandra

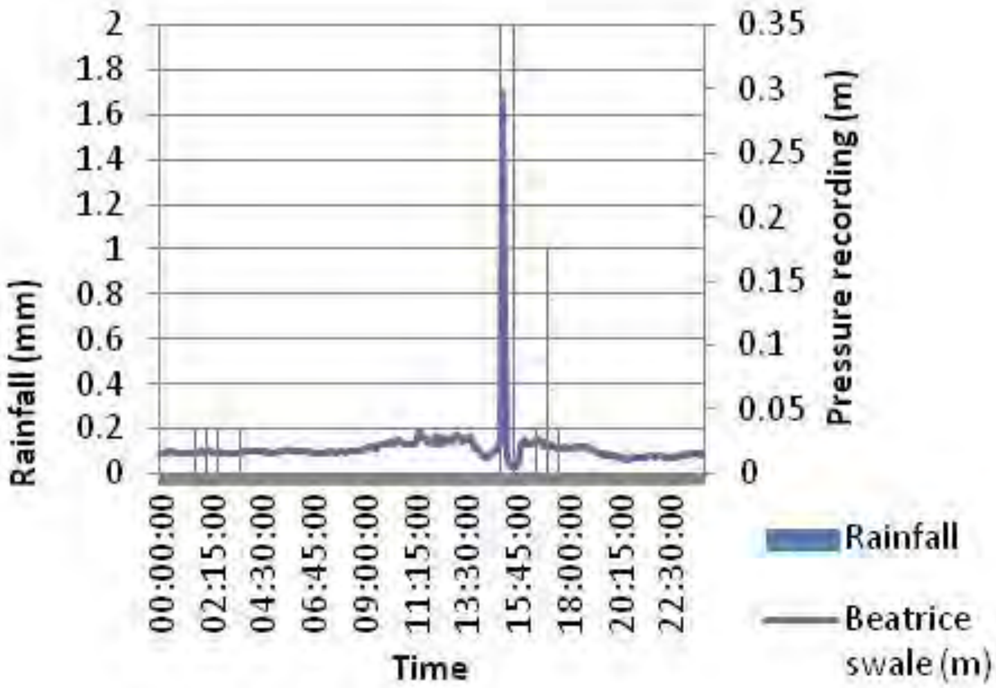


4
3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Charlotte

iii) **iv)**



v)



vi)

Figure 71. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 8th June 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 71.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

Rain event 12/06/2016

Figure 72 shows the prevailing weather patterns preceding the rain event in the 12th June 2016.

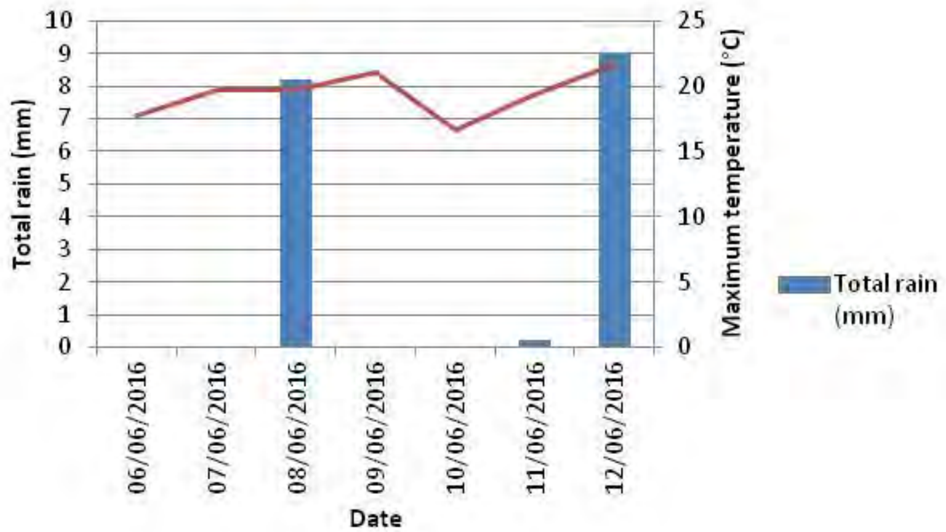


Figure 72. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 9 mm on 12th June 2016.

Table 8 presents the attenuation performance of the pramshed roofs during the rain event on the 12th June 2016.

Table 8. Pramshed green roof water attenuation performance during a rain event on the 12th June 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	9	22	198	98.80
Charlotte	9	32	288	98.43
Mary	9	33.25	299.25	96.30
Average				**97.84**

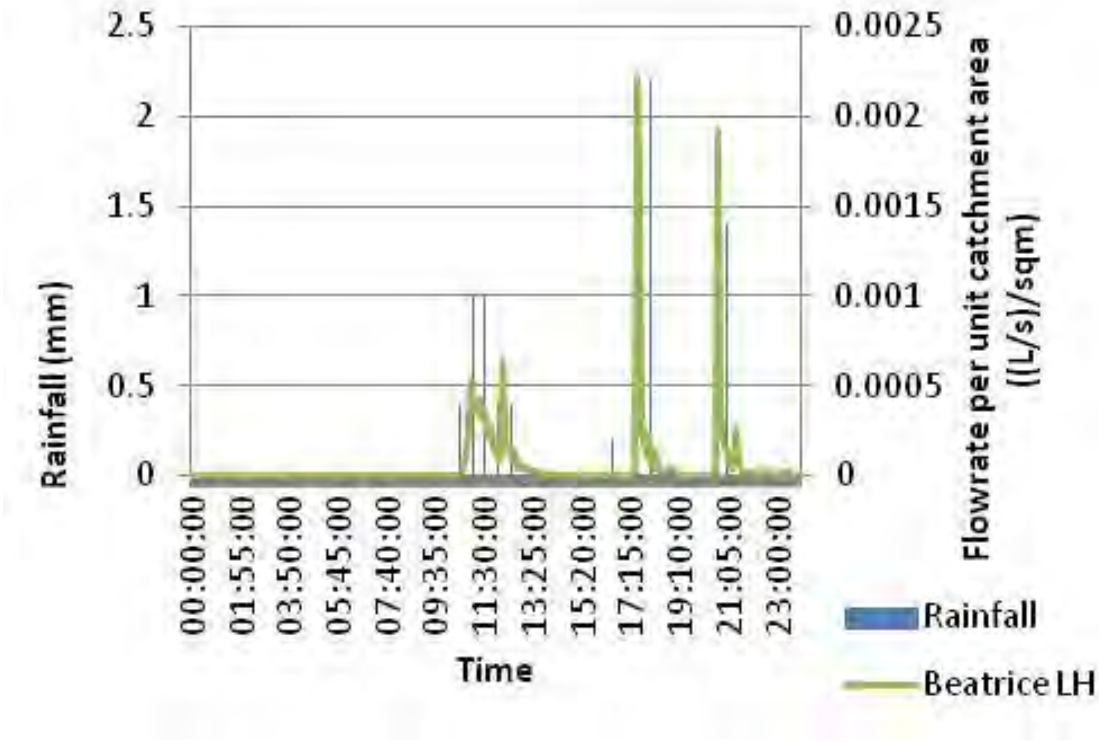
Figure 73 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 9.i). Maximum peak flow reduction recorded was 98%. Peak flows also showed some evidence of delay but only by a maximum of five minutes (Table 9.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

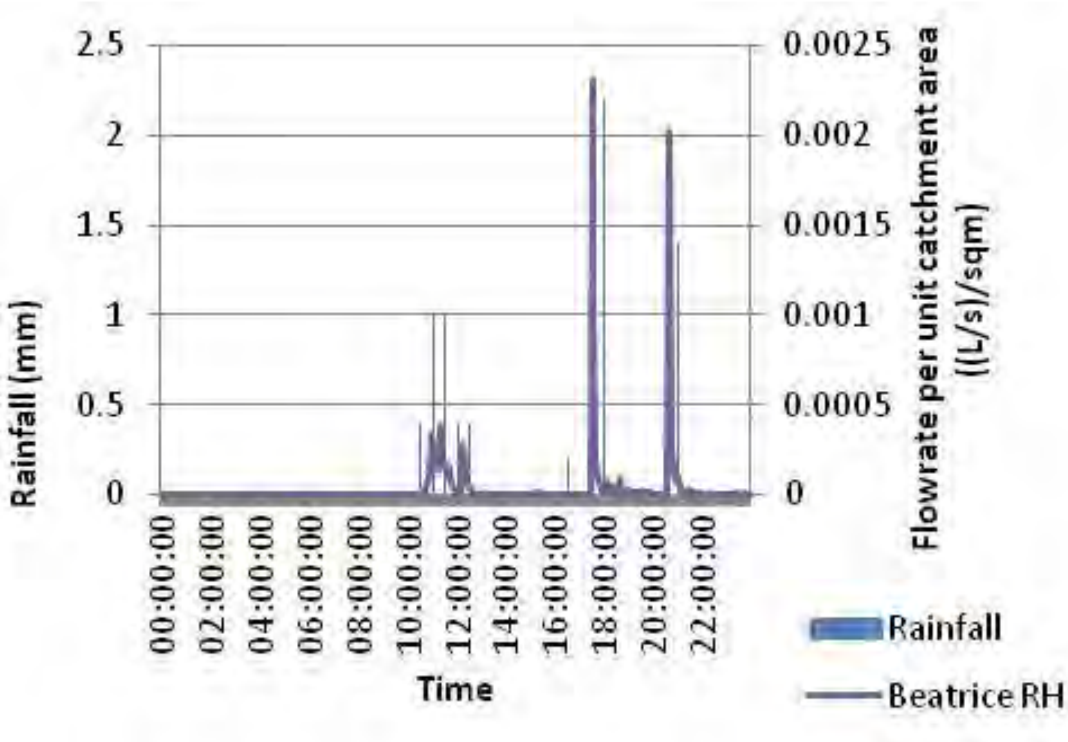
Table 9. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 9 mm rain event on the 12th June 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	97.09%	97.69%	88.06%
Beatrice RH	97.21%	97.78%	88.56%

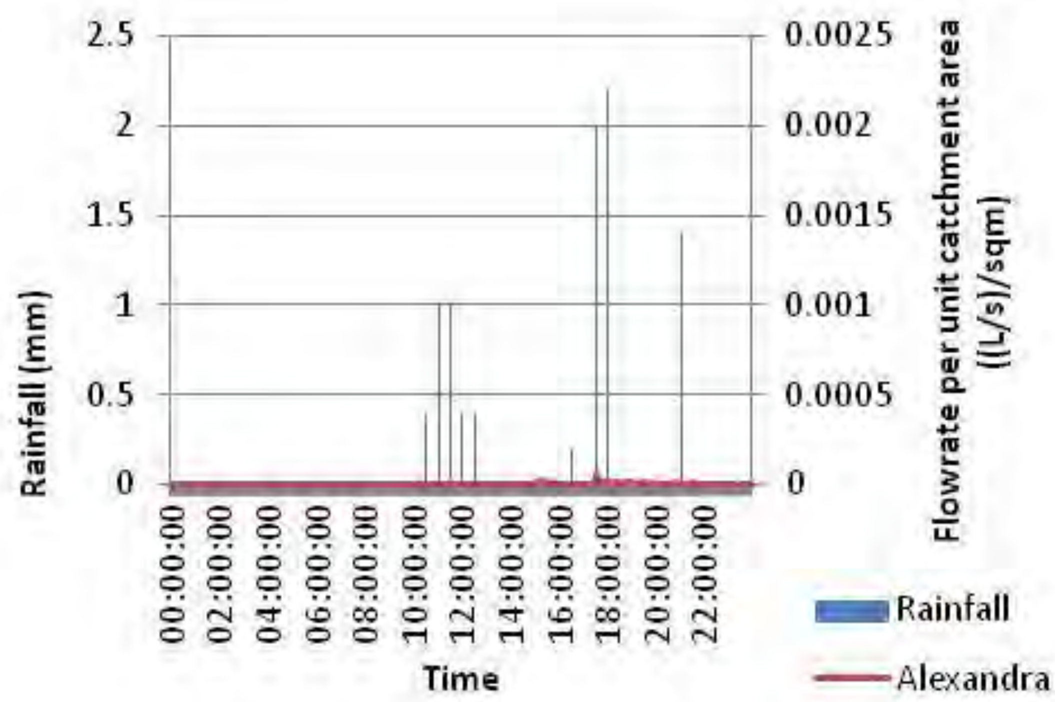
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:05:00	00:05:00	00:00:00
Beatrice RH	00:05:00	00:05:00	00:00:00


2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
01:55:00
03:50:00
05:45:00
07:40:00
09:35:00
11:30:00
13:25:00
15:20:00
17:15:00
19:10:00
21:05:00
23:00:00
Time
Rainfall
Beatrice LH

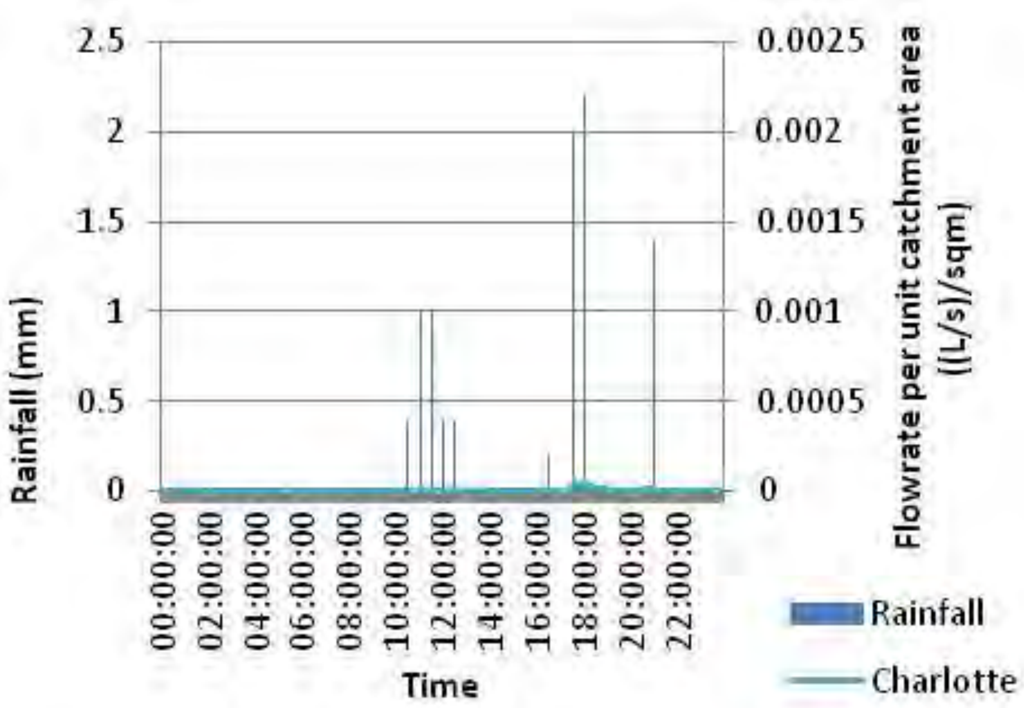
i)


2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Beatrice RH

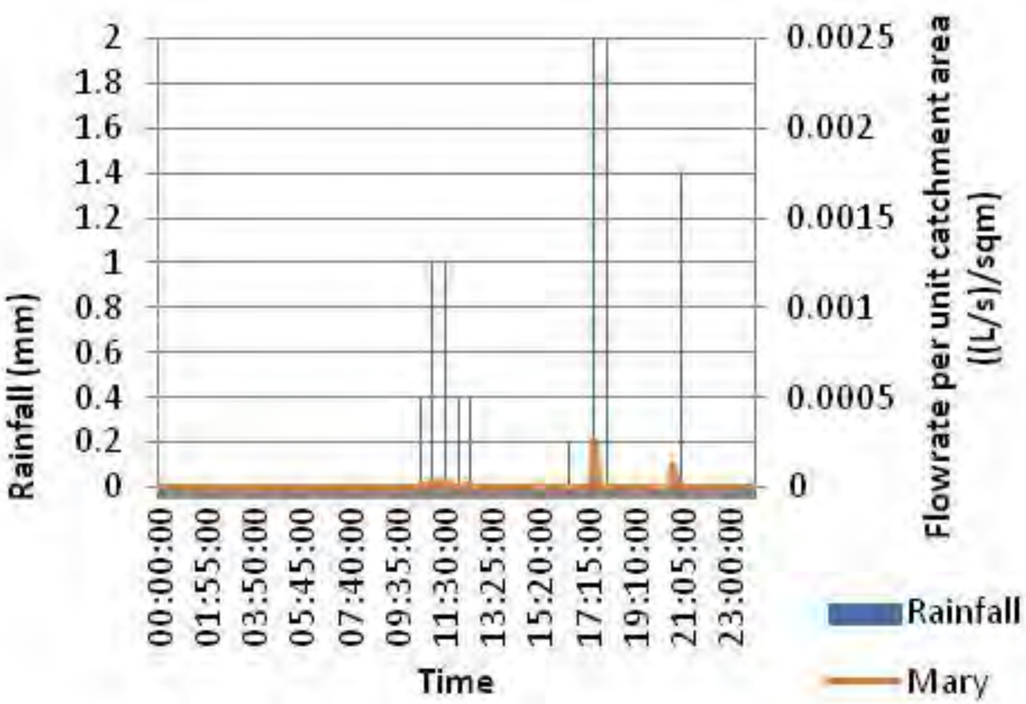
ii)


2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Alexandra

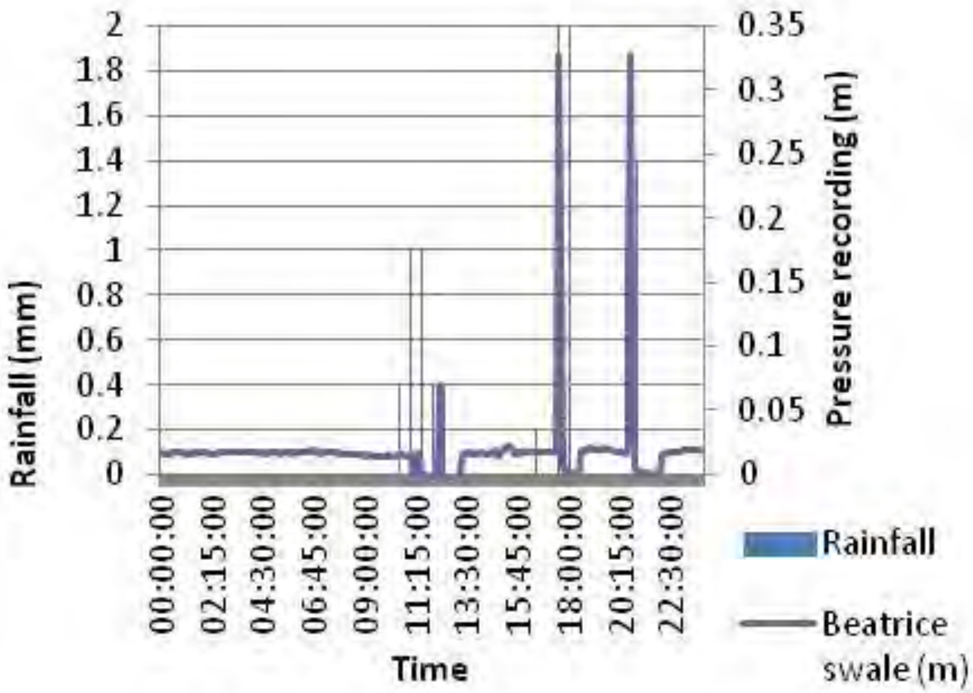
iii)


2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Charlotte

iv)



v)



vi)

Figure 73. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 12th June 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 73.vi) also supported the evidence captured by the time-lapse cameras. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in relatively short periods following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods.

Rain event 16/06/2016

Figure 74 shows the prevailing weather patterns preceding the rain event in the 16th June 2016.

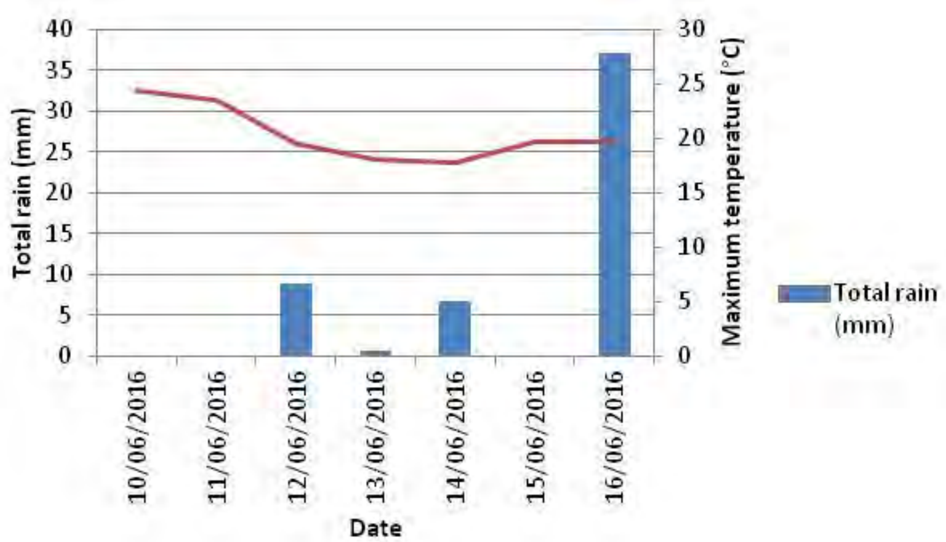


Figure 74. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 37.2 mm on 16th June 2016.

Table 10 presents the attenuation performance of the pramshed roofs during the rain event on the 16th June 2016. It should be noted that these values may be overestimations of the pramshed green roofs' performance. It is possible that some data from the rain event may have been lost due to a datalogger reset. Nevertheless, all loggers were running simultaneously, therefore data from quantifying performance can be directly compared.

Table 10. Pramshed green roof water attenuation performance during a rain event on the 16th June 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains. *N.B. Attenuation values may be over-estimations of the pramshed green roofs' performance. It is possible that some data from the rain event may have been lost due to a datalogger reset.*

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	37.2	22	818.4	95.28
Charlotte	37.2	32	1190.40	92.53
Mary	37.2	33.25	1236.9	93.26
Average				**93.69**

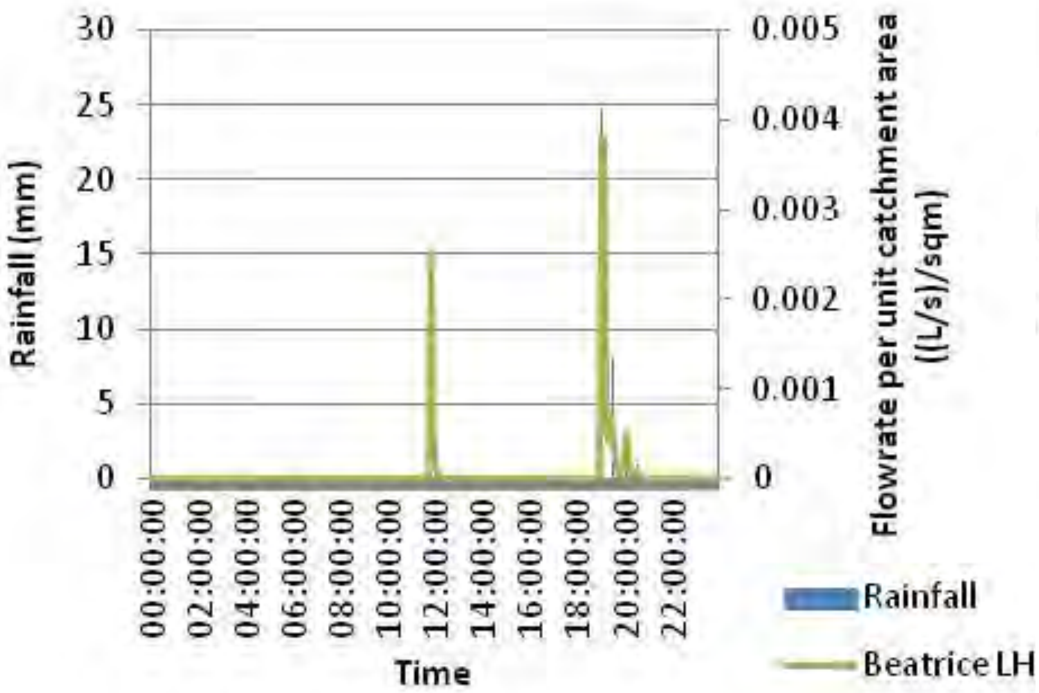
Figure 75 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 11.i). Maximum peak flow reduction recorded was 59%. Other values were lower and even negative for the Mary House pramshed green roof. It is likely that this was due to data loss caused by the datalogger reset meaning that peak flows from the control roofs were missed by the dataloggers as they were sooner after the rain event than the green roofs. This would artificially lower the recorded peak flows from these roofs. Peak flows showed evidence of a small delay relative to one control flowmeter (Table 11.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

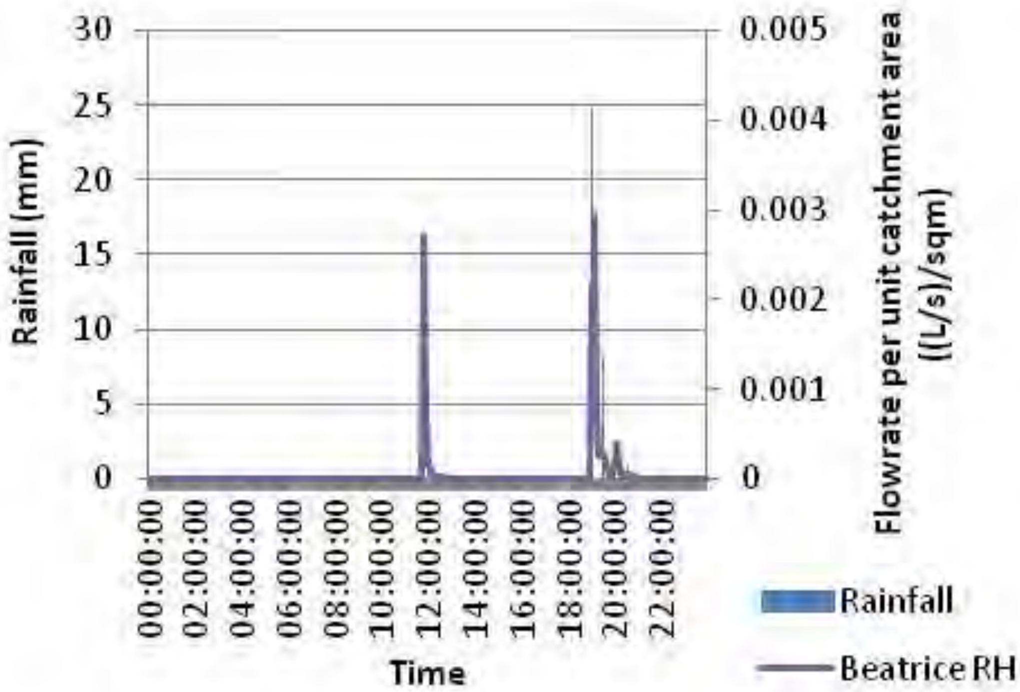
Table 11. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 9.8 mm rain event on the 16th June 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	59.25%	29.02%	-14.80%
Beatrice RH	47.48%	8.53%	-47.94%

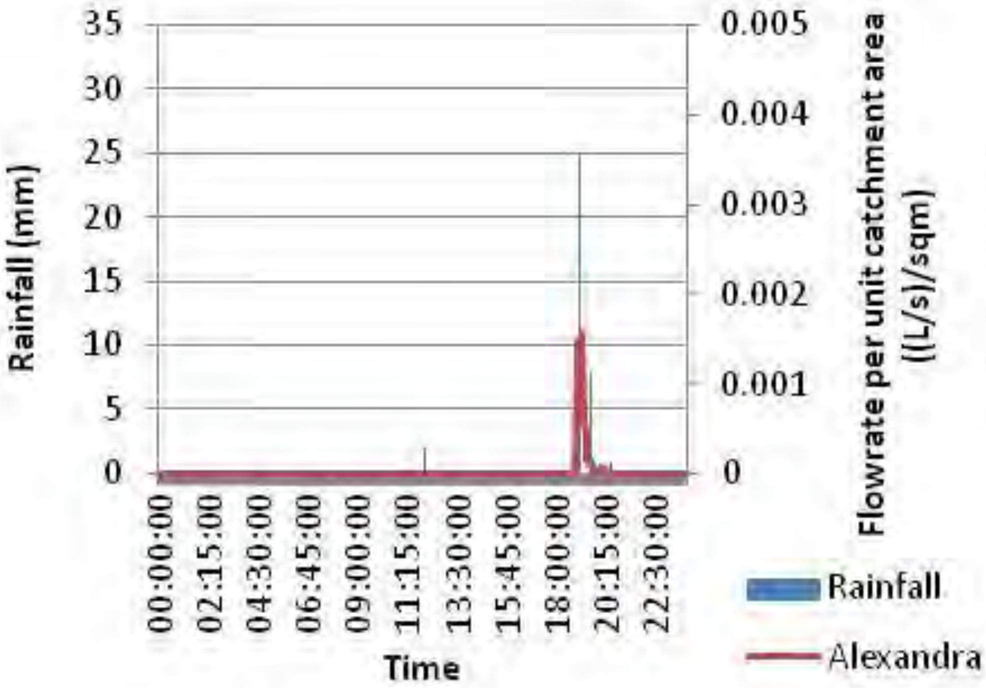
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:10:00	00:10:00	00:00:00
Beatrice RH	00:00:00	00:00:00	-00:10:00


Rainfall (mm)
30
25
20
15
10
5
0
0.005
0.004
0.003
0.002
0.001
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Beatrice LH

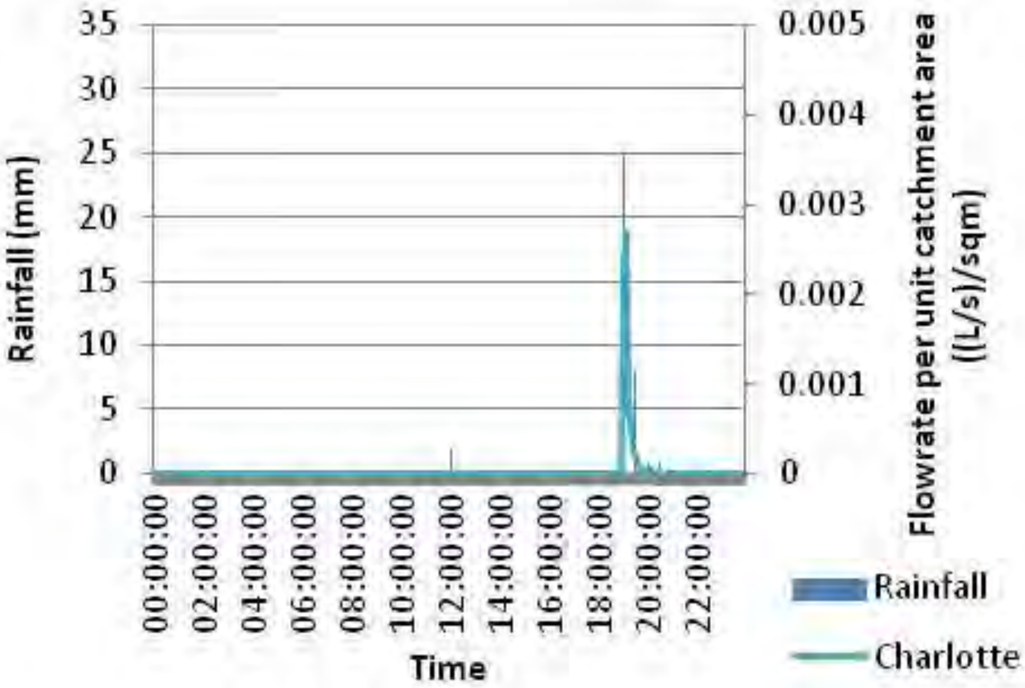
i)


Rainfall (mm)
30
25
20
15
10
5
0
0.005
0.004
0.003
0.002
0.001
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Beatrice RH

ii)



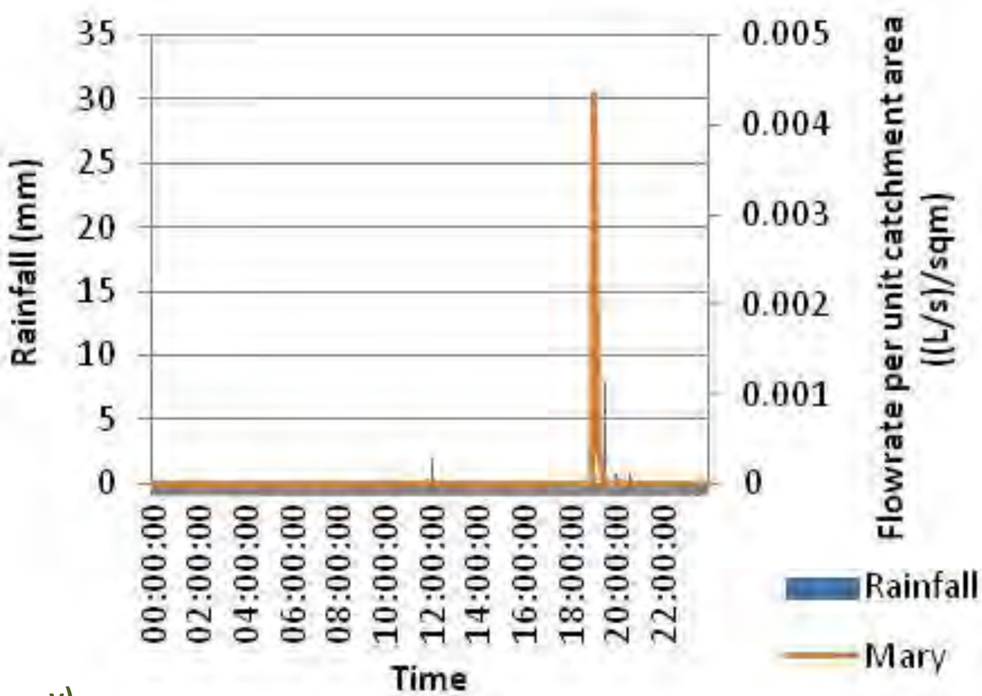
35
30
25
20
15
10
5
0
Rainfall (mm)
0.005
0.004
0.003
0.002
0.001
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Alexandra



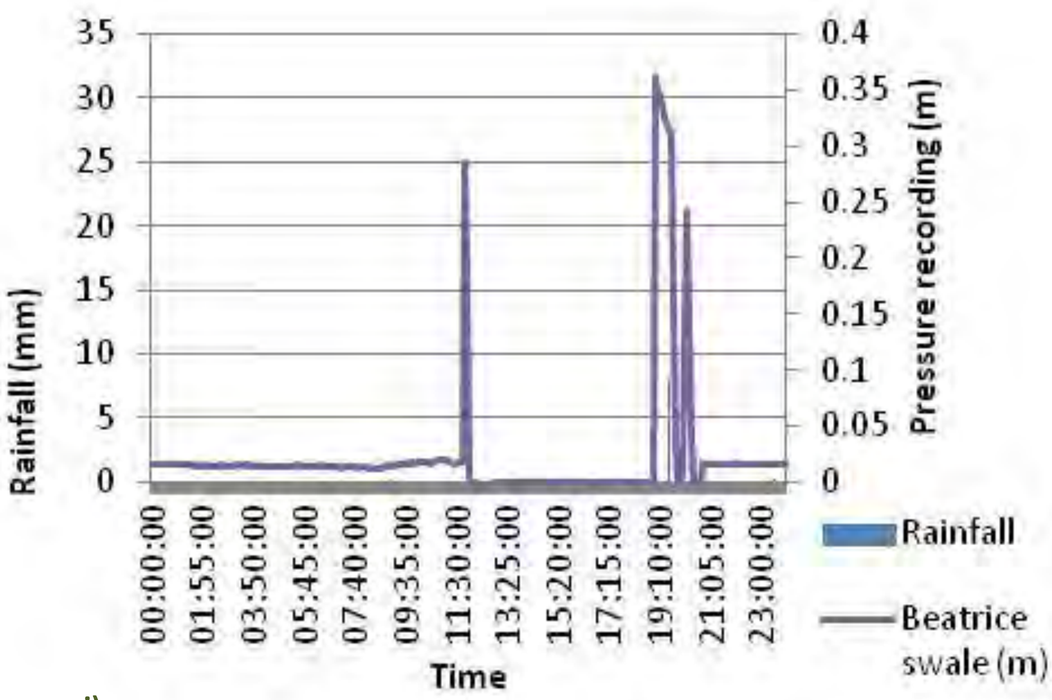
35
30
25
20
15
10
5
0
Rainfall (mm)
0.005
0.004
0.003
0.002
0.001
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:00:00
04:00:00
06:00:00
08:00:00
10:00:00
12:00:00
14:00:00
16:00:00
18:00:00
20:00:00
22:00:00
Time
Rainfall
Charlotte

iii)

iv)



v)



vi)

Figure 75. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 12th June 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction. Also attenuation values may be over-estimations of the pramshed green roofs' performance. It is possible that some data from the rain event may have been lost due to a datalogger reset.***

Data from the pressure sensor in the Beatrice swale (Figure 75 vi) also supported the evidence captured by the time-lapse cameras. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in relatively short periods following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods.

Rain event 20/06/2016

Figure 76 shows the prevailing weather patterns preceding the rain event in the 20th June 2016.

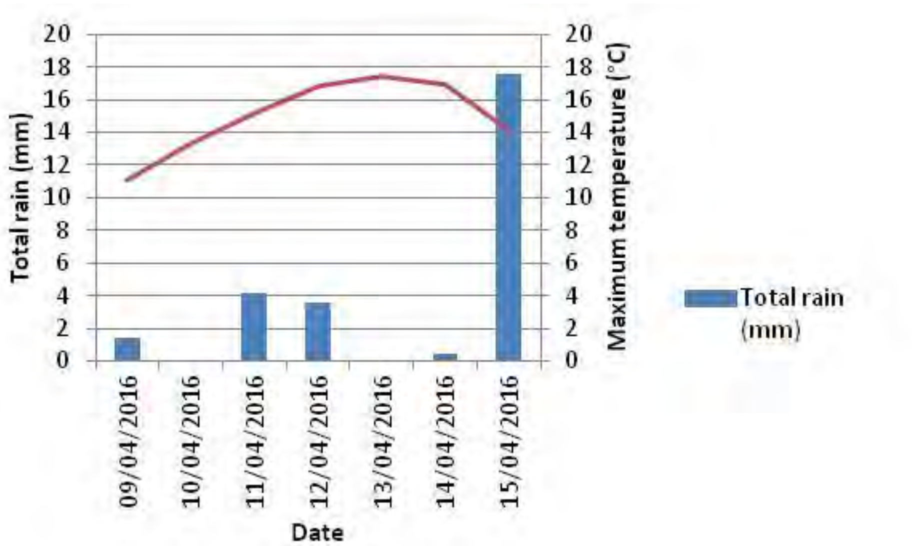


Figure 76. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 13.4 mm on 20th June 2016.

Table 12 presents the attenuation performance of the pramshed roofs during the rain event on the 20th June 2016.

Table 12. Pramshed green roof water attenuation performance during a rain event on the 20th June 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	17.6	22	294.8	99.07
Charlotte	17.6	32	428.8	97.95
Mary	17.6	33.25	445.55	90.90
Average				**95.97**

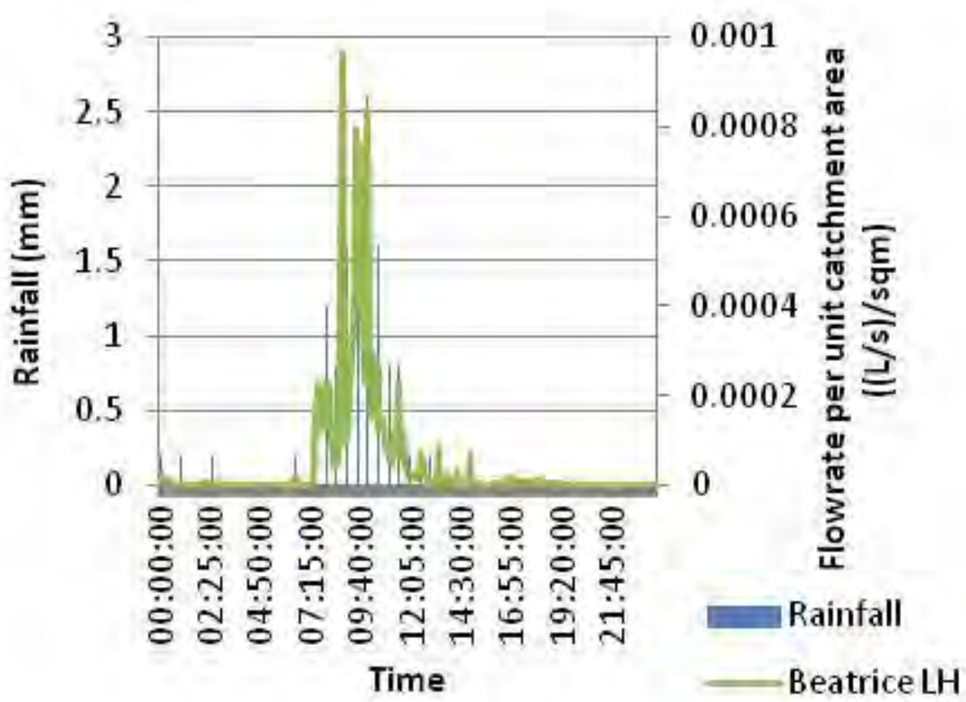
Figure 77 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 13.i). Maximum peak flow reduction recorded was 93%. Peak flows also showed substantial evidence of delay by as much as 6 hours (Table 13.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 13. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 13.4 mm rain event on the 20th June 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

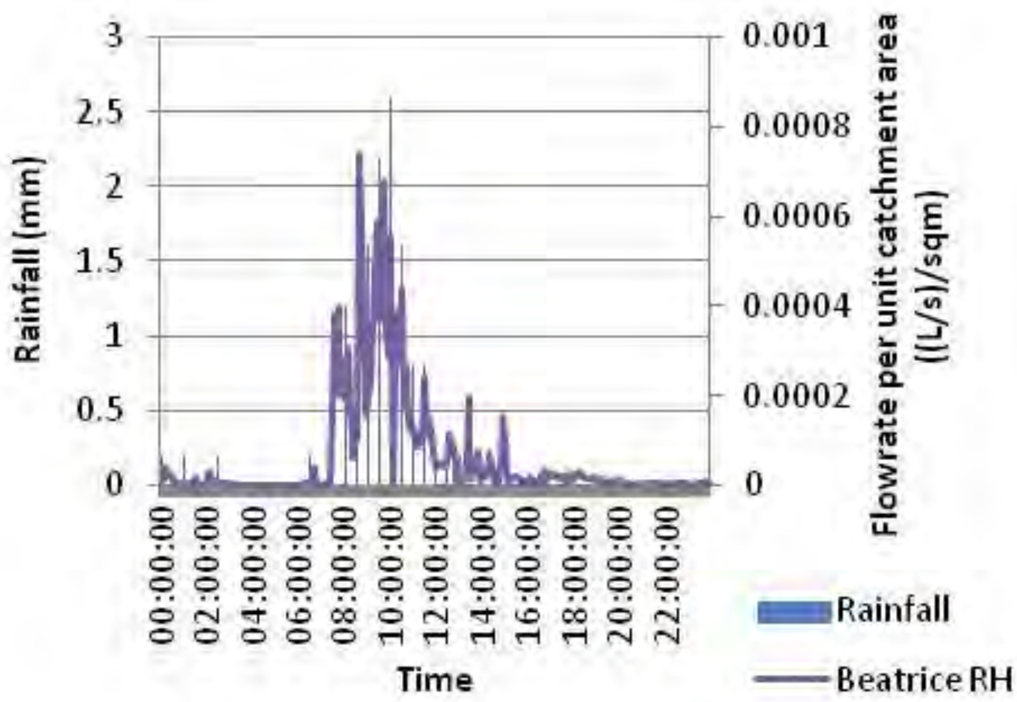
i)	Green roofs		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	92.54%	86.69%	79.30%
Beatrice RH	90.24%	82.58%	72.91%

ii)	Green roofs		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	06:05:00	06:05:00	00:30:00
Beatrice RH	06:15:00	06:15:00	00:40:00



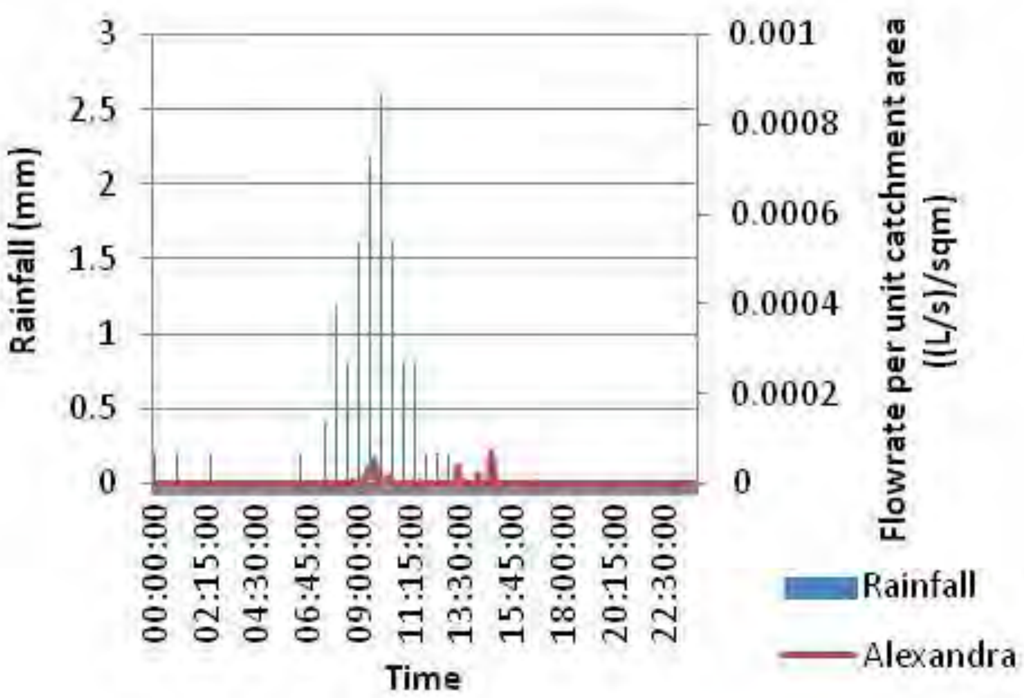
Rainfall (mm)
Flowrate per unit catchment area ((L/s)/sqm)
Time
Rainfall
Beatrice LH

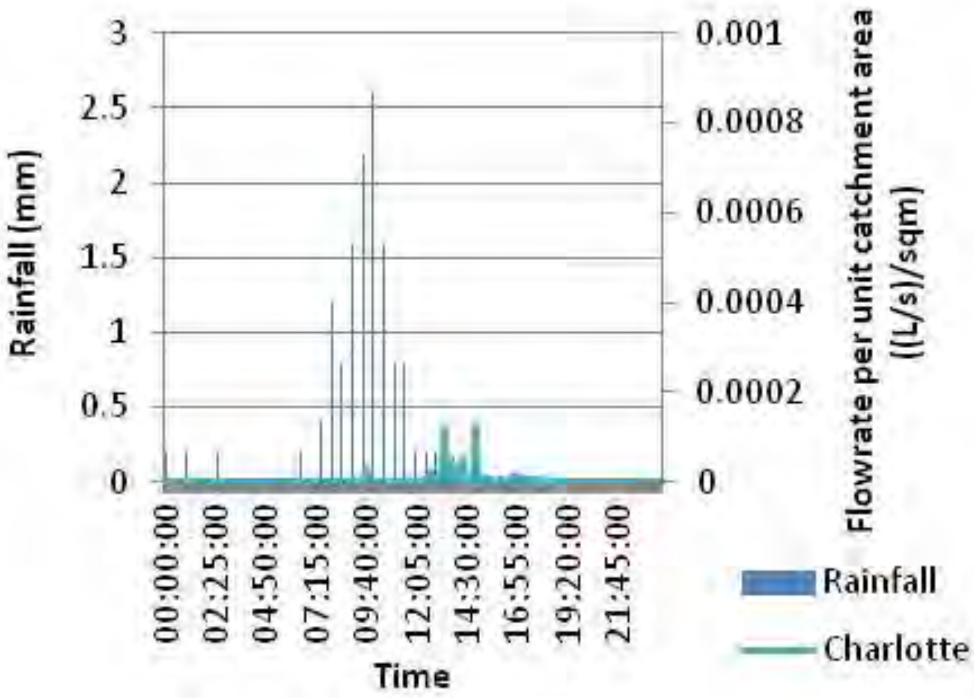
i)



Rainfall (mm)
Flowrate per unit catchment area ((L/s)/sqm)
Time
Rainfall
Beatrice RH

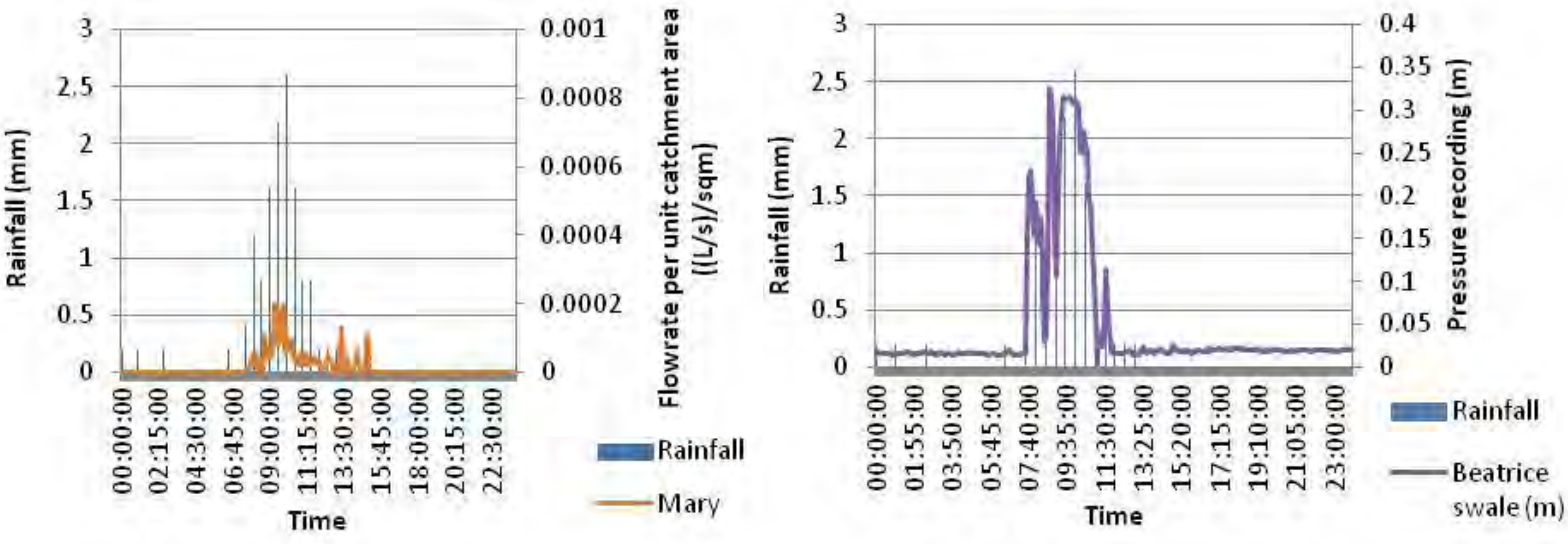
ii)


3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.001
0.0008
0.0006
0.0004
0.0002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Alexandra


3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.001
0.0008
0.0006
0.0004
0.0002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Charlotte

iii)

iv)



v) vi)

Figure 77. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 20th June 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 77 vi) also supported the evidence captured by the time-lapse cameras. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in relatively short periods following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods.

Rain event 23/06/2016

Figure 78 shows the prevailing weather patterns preceding the rain event in the 23rd June 2016.

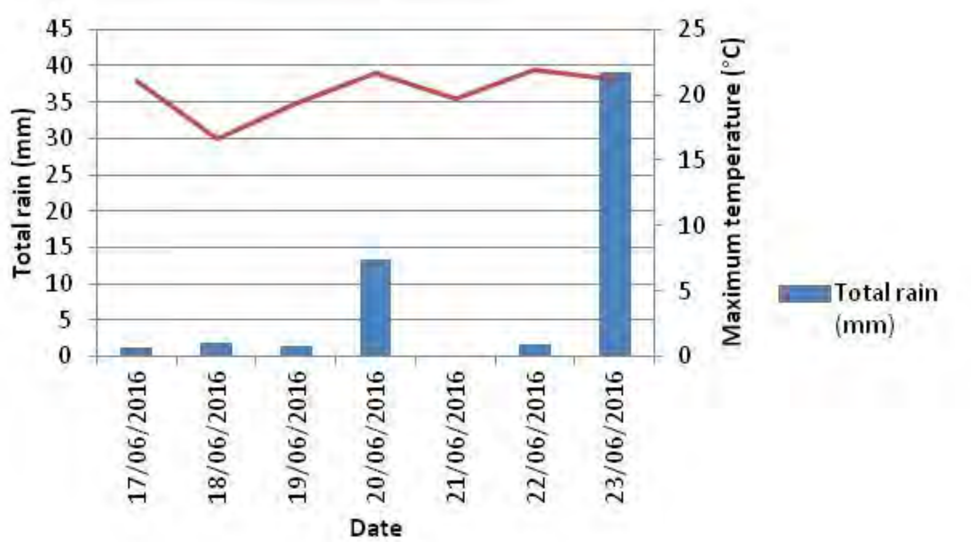


Figure 78. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 39 mm on 23rd June 2016.

Table 14 presents the attenuation performance of the pramshed roofs during the rain event on the 23rd June 2016.

Table 14. Pramshed green roof water attenuation performance during a rain event on the 23rd June 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	9.8	22	858	90.38
Charlotte	9.8	32	1248	88.20
Mary	9.8	33.25	1296.75	91.32
Average				**89.97**

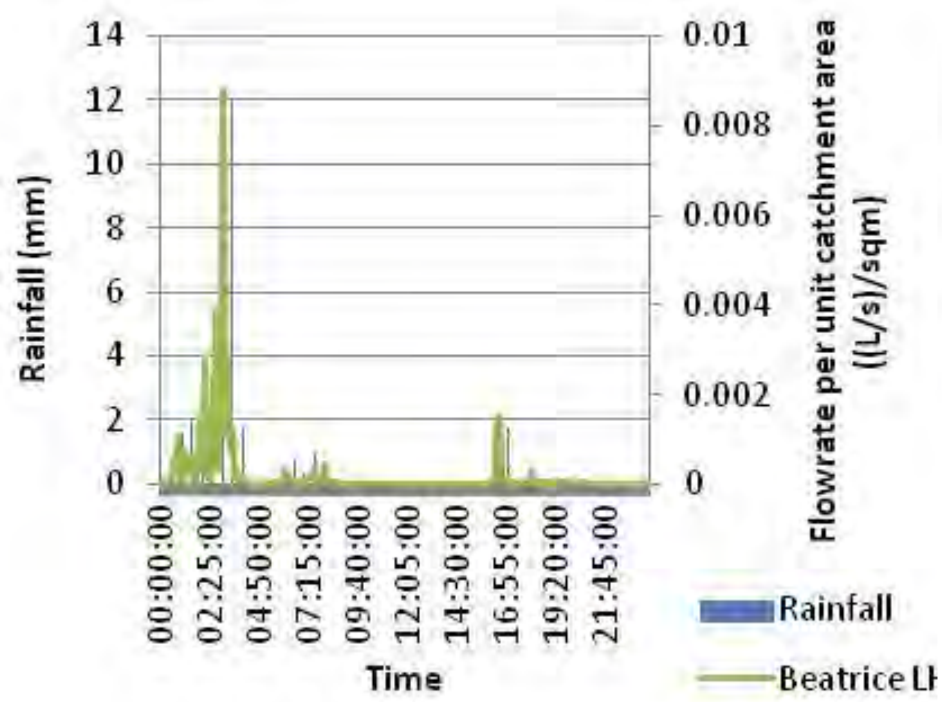
Figure 79 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 15.i). Maximum peak flow reduction recorded was 82%. Peak flows also showed evidence of delay (Table 15.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

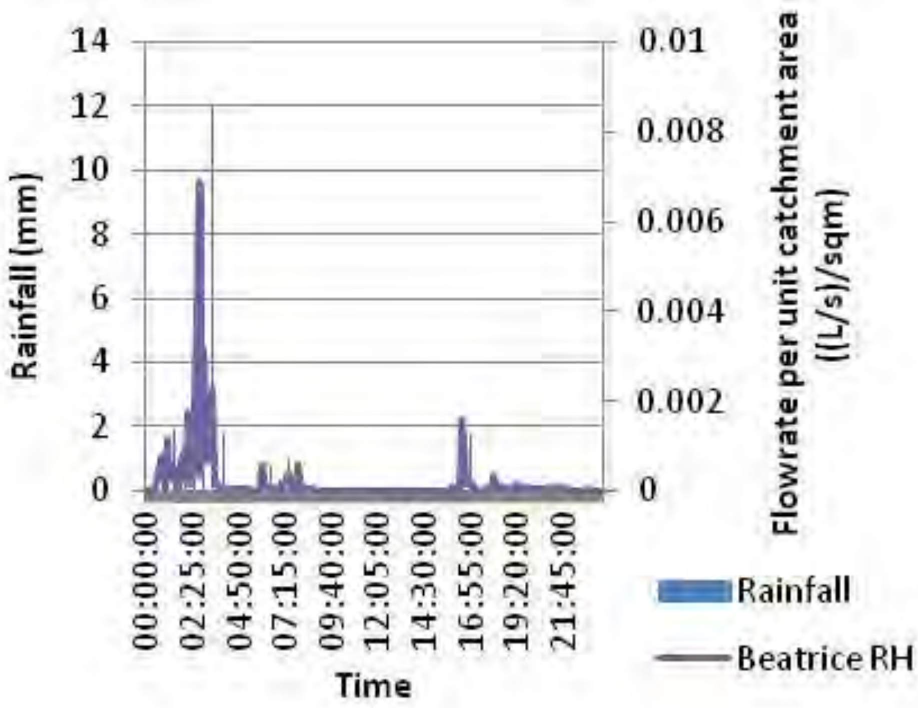
Table 15. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 27.2 mm rain event on the 11th May 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	81.68%	79.31%	80.59%
Beatrice RH	76.63%	73.61%	75.23%

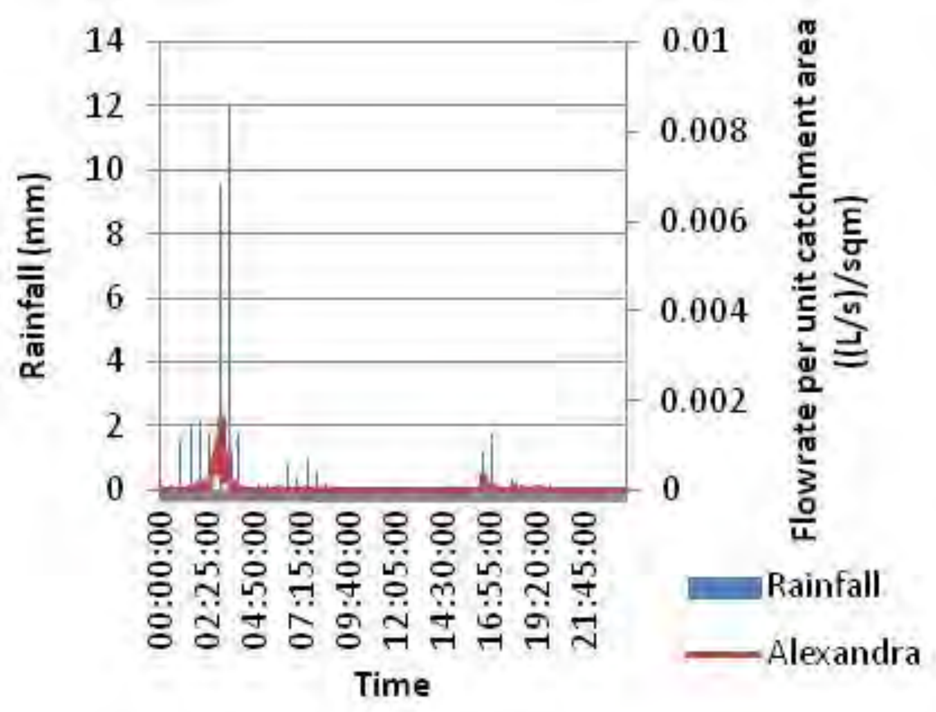
ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:05:00	00:00:00	00:00:00
Beatrice RH	00:25:00	00:20:00	00:20:00

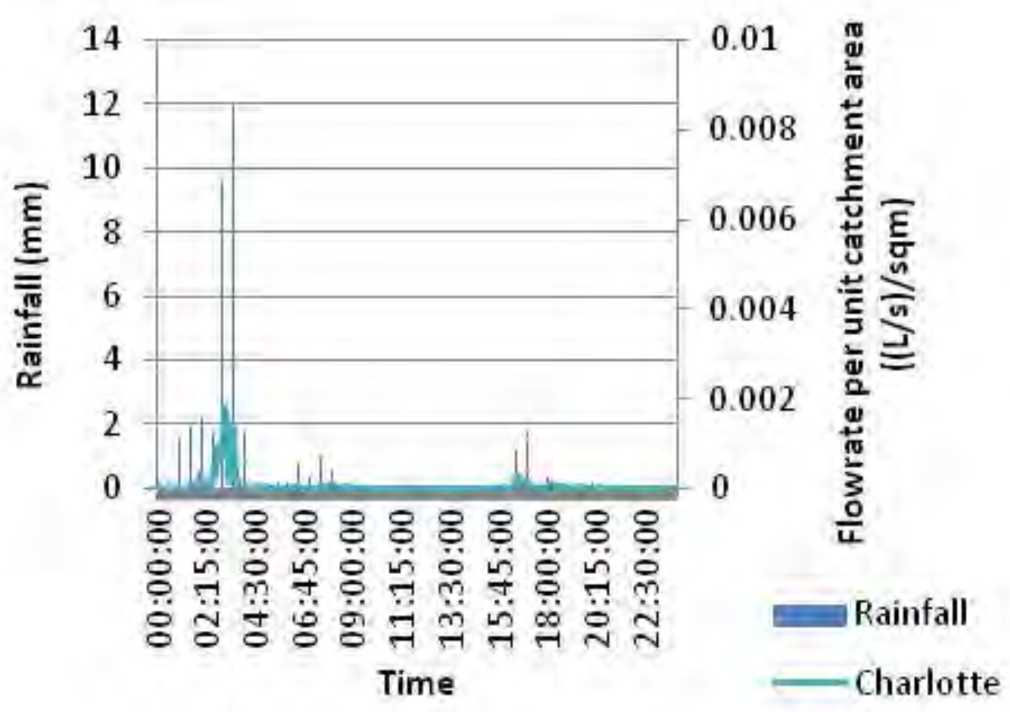

14
12
10
8
6
4
2
0
Rainfall (mm)
0.01
0.008
0.006
0.004
0.002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Beatrice LH

i)


14
12
10
8
6
4
2
0
Rainfall (mm)
0.01
0.008
0.006
0.004
0.002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Beatrice RH

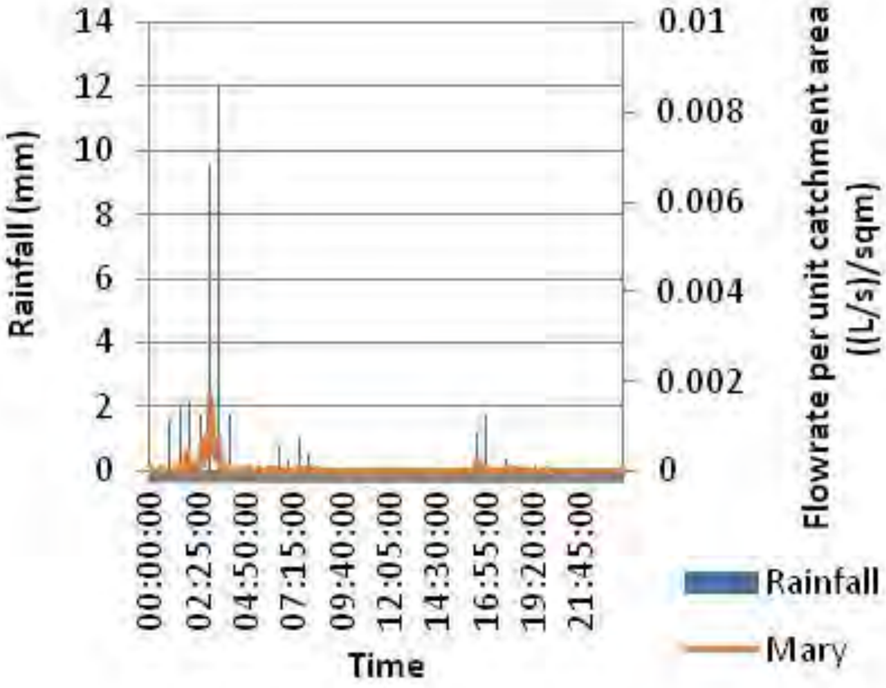
ii)


14
12
10
8
6
4
2
0
Rainfall (mm)
0.01
0.008
0.006
0.004
0.002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Alexandra

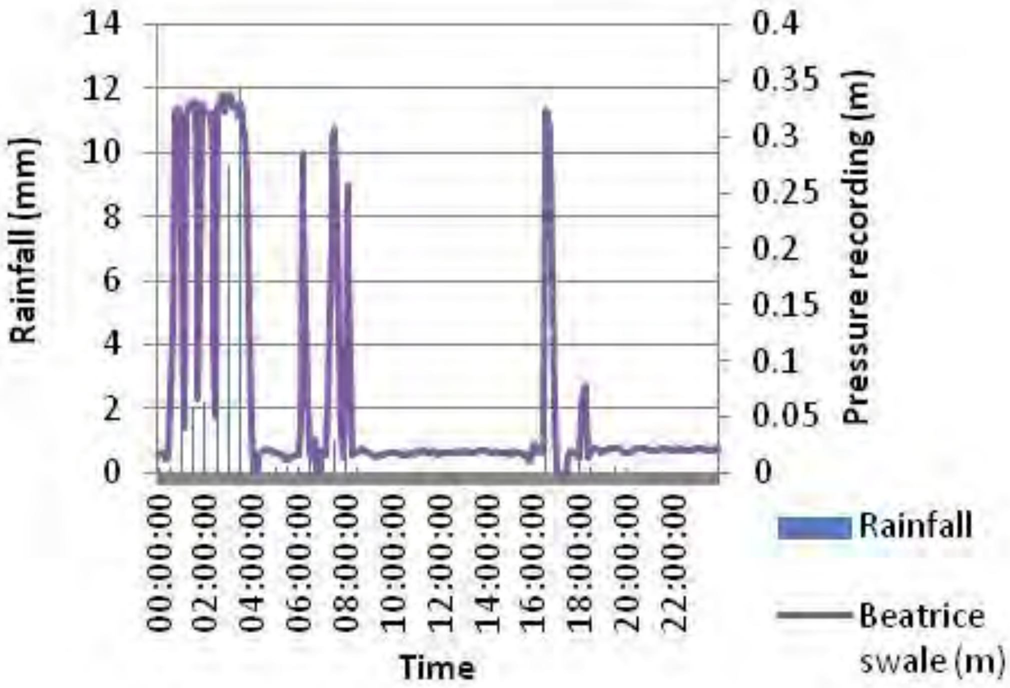

14
12
10
8
6
4
2
0
Rainfall (mm)
0.01
0.008
0.006
0.004
0.002
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Charlotte

iii)

iv)



v)



vi)

Figure 79. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 23rd June 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 79 vi) also supported the evidence captured by the time-lapse cameras. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in relatively short periods following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods.

Rain event 16/09/2016

Figure 80 shows the prevailing weather patterns preceding the rain event in the 16th September 2016.

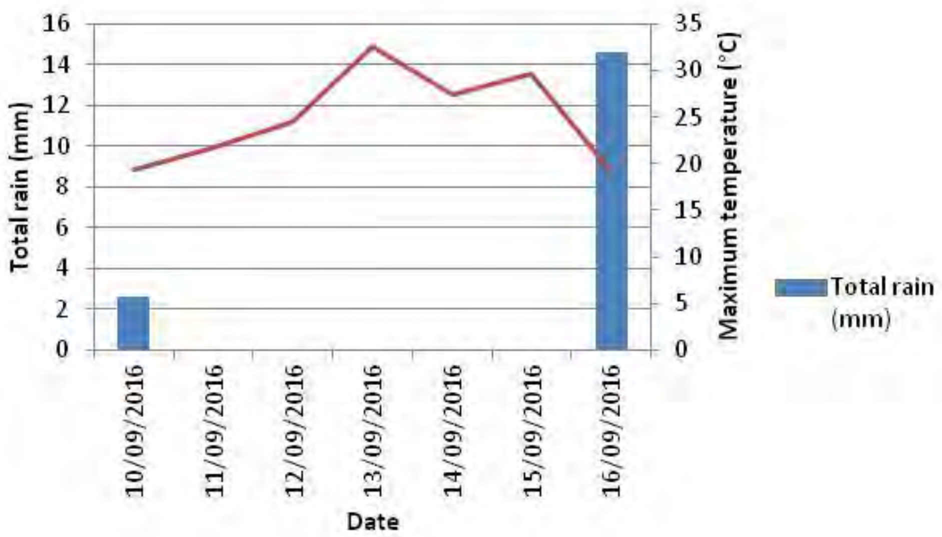


Figure 80. Prevailing weather conditions preceding one of the five largest rain events at Queen Caroline Estate, Hammersmith. Rain event was 14.6 mm on 16th September 2016.

Table 16 presents the attenuation performance of the pramshed roofs during the rain event on the 16th September 2016.

Table 16. Pramshed green roof water attenuation performance during a rain event on the 16th September 2016. Water attenuation calculated as the percentage of the total rainfall that fell on the roof held within the roof rather than being released to storm drains.

Green roof	Total rain (mm)	Catchment area (m)	Volume of rainfall in catchment area (L)	Attenuation (%)
Alexandra	14.6	22	321.2	98.39
Charlotte	14.6	32	467.2	92.35
Mary	14.6	33.25	485.45	91.13
Average				**93.96**

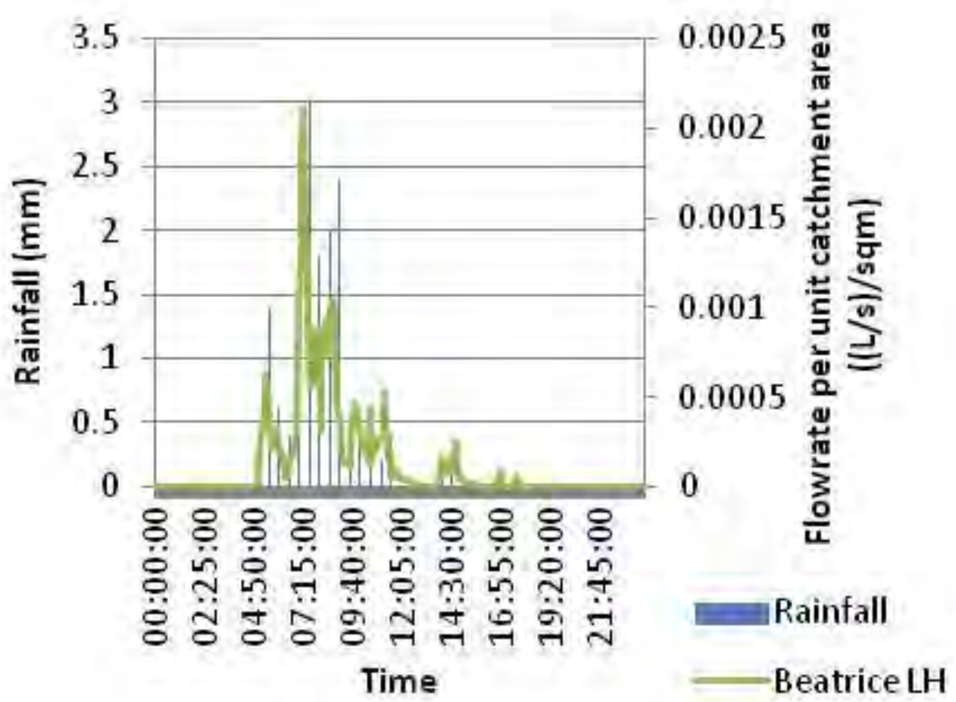
Figure 81 represents the water runoff from (i) and (ii) the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) the three pram shed roofs at Queen Caroline estate, and (vi) the pattern of the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event.

Evidence from the roof runoff monitoring was positive with substantial reductions in the peak flows from the green roofs compared to the control roofs (Table 17.i). Maximum peak flow reduction recorded was 92%. However, peak flows were not delayed and were slightly faster when compared to the Beatrice House RH gauge (Table 17.ii). Reduction and/or delay in peak flow of storm drain systems is vital in order to avoid system overloading.

Table 17. i) Percentage reduction in peak flow and ii) delay in peak flow from green roofs compared to control roofs for the 14.6 mm rain event on the 16th September 2016 at Queen Caroline Estate, Hammersmith. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area.

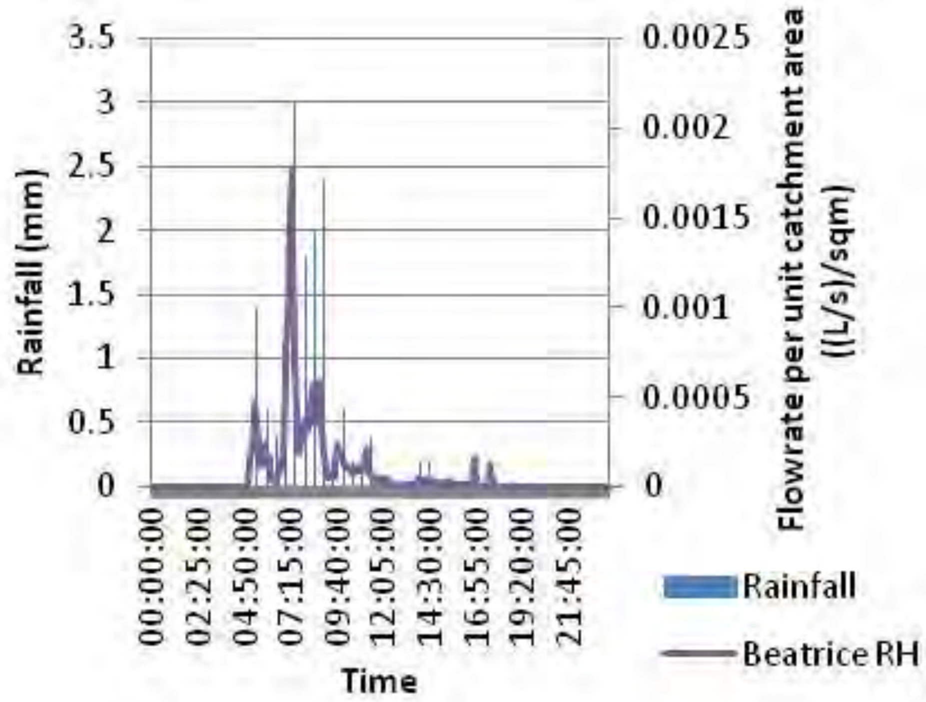
i)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	91.97%	88.74%	87.46%
Beatrice RH	90.45%	86.60%	85.04%

ii)	**Green roofs**		
Control roofs	**Alexandra**	**Charlotte**	**Mary**
Beatrice LH	00:00:00	00:00:00	00:00:00
Beatrice RH	-00:05:00	-00:05:00	-00:05:00



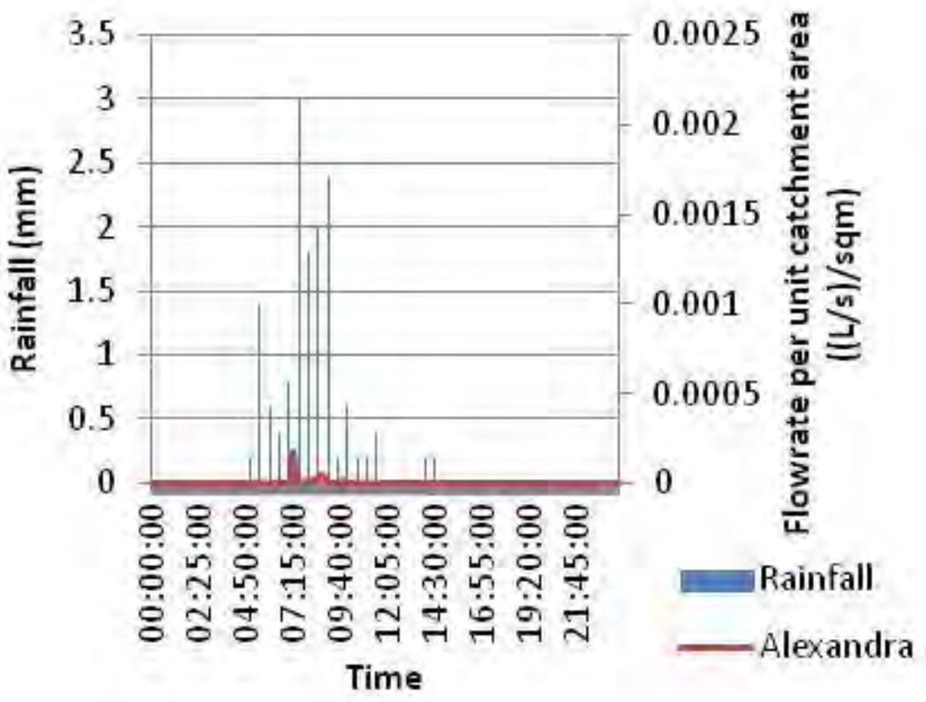
3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Beatrice LH

i)



3.5
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Beatrice RH

ii)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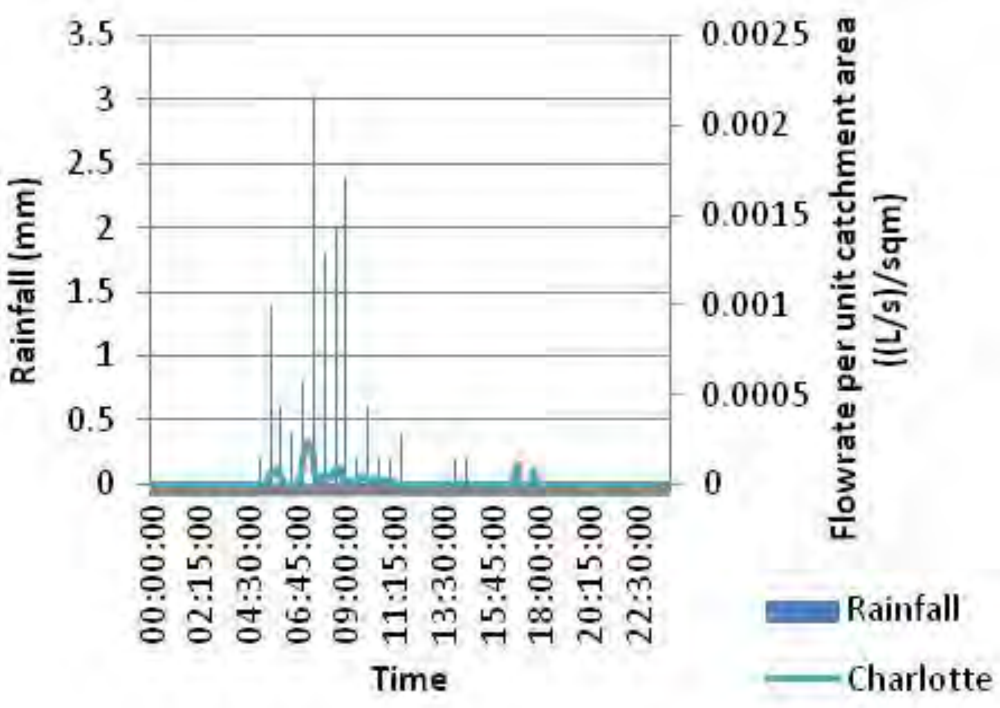
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:25:00
04:50:00
07:15:00
09:40:00
12:05:00
14:30:00
16:55:00
19:20:00
21:45:00
Time
Rainfall
Alexandra

iii)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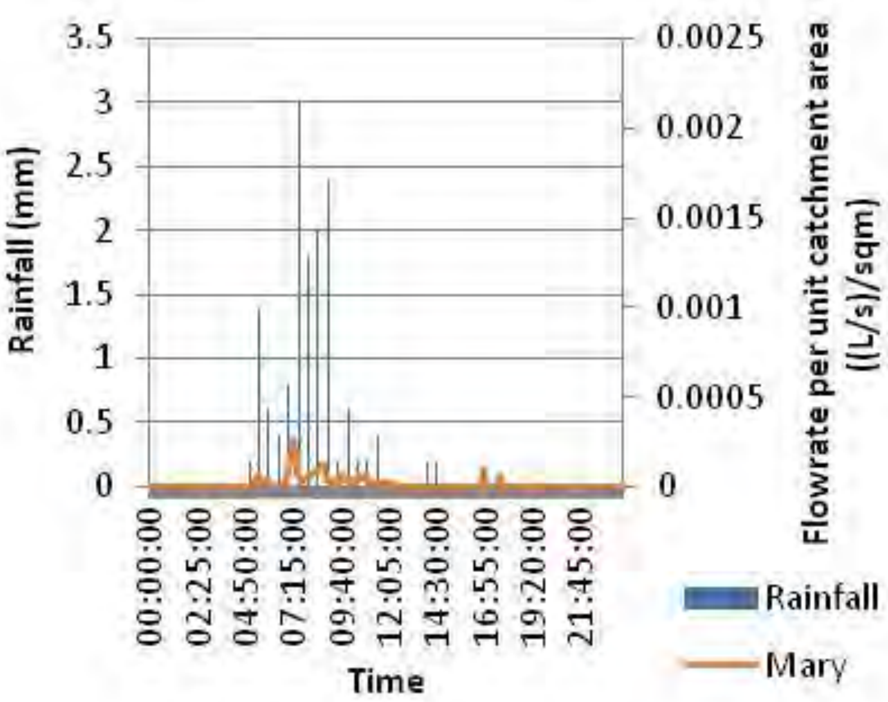
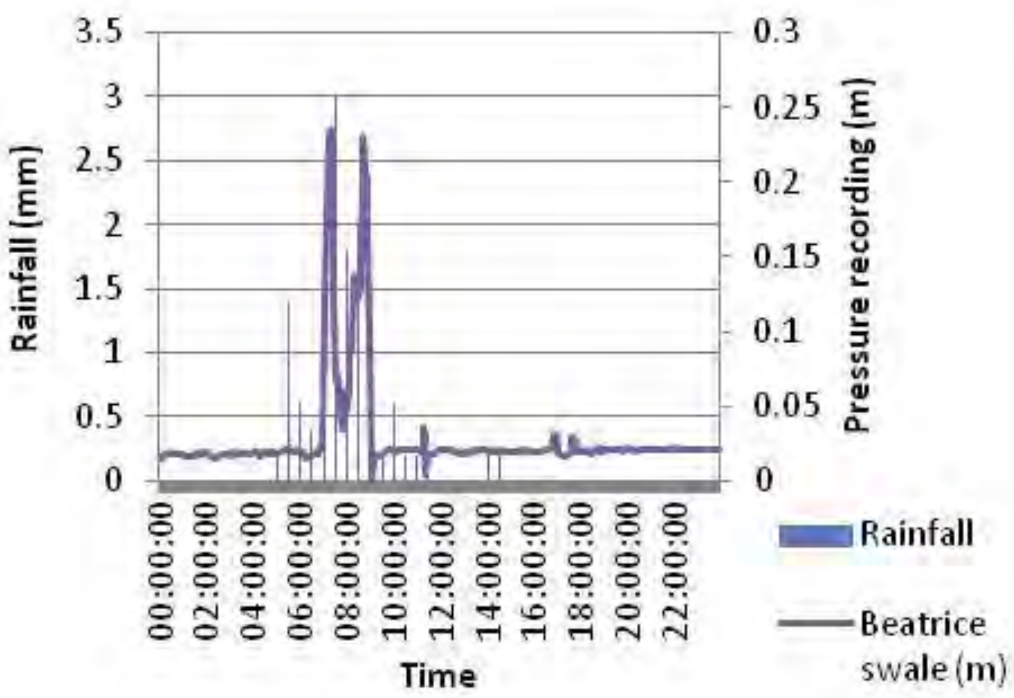
3
2.5
2
1.5
1
0.5
0
Rainfall (mm)
0.0025
0.002
0.0015
0.001
0.0005
0
Flowrate per unit catchment area ((L/s)/sqm)
00:00:00
02:15:00
04:30:00
06:45:00
09:00:00
11:15:00
13:30:00
15:45:00
18:00:00
20:15:00
22:30:00
Time
Rainfall
Charlotte

iv)



v)



vi)

Figure 81. Water attenuation patterns from Queen Caroline Estate, Hammersmith, 16th September 2016. Graphs represent individual storm management infrastructure components: (i) and (ii) represent the two control roof areas on Beatrice House (with no green roof), (iii), (iv) and (v) represent the three pram shed green roofs at Queen Caroline Estate, and (vi) the pressure sensor beneath Beatrice swale compared to rainfall patterns for the same rain event. Roof flow rates were measured using a pressure sensor combined with a v-notch weir. The swale was measured using a pressure sensor beneath the swale. All run off flow rates have been adjusted to a rate per metre square to compensate for difference in catchment area. ***N.B. It must be noted that the control roofs were pitched roofs and the catchment areas were based on the aerial view of the roof (i.e. a 2D 'vertical footprint'). Due to the pitch, the direction of rain for the rain event may have affected the volume of water recorded on the control roofs (i.e. the SE -facing pitched roofs would be expected to catch more rain from a SE wind direction rain event than a NE wind rain event). As such, the peak flows from the control roofs were likely to be a conservative estimate for all rain events other than those with wind from a SE direction.***

Data from the pressure sensor in the Beatrice swale (Figure 81.vi) supported the evidence captured by the time-lapse cameras for this event. The pressure sensor captured the swale reacting quickly to rainfall by recording an increase in pressure very quickly following rain (caused by water pooling above the sensor). This increase in pressure was short-lived however, with a reduction in pressure in a relatively short period following the cessation of the rain. This indicated that the swale was effectively conveying and infiltrating the stormwater, rather than the basin holding pooled water over long periods. This is important as it means that stormwater storage volumes are available for the next rain event.

3. 8 Monitoring in relation to performance indicators

Total evidenced surface water run-off & green roof run-off attenuation

Based on the data captured from the weather stations, the time-lapse cameras, the v-notch sensors and the pressure sensor, it is possible to calculate an approximate volume of rain that has been diverted from otherwise entering the storm drain system by the interventions installed across the estates during this initial monitoring period. This estimation was carried out by calculating the total rainfall that had fallen on each of the estates during the period 16th October 2015 to 30th September 2016:

- *Richard Knight House = 492.8 mm*
- *Queen Caroline Estate = 433 mm*

The total catchment areas of the SuDS interventions at each site:

- *Richard Knight House = 258.5 m^2 ground level SuDS and 244.5 m^2 of green roofs*
- *Queen Caroline Estate = 1305.5 m^2 ground level SuDS and 129.75 m^2 of green roofs*

Then multiplying the rainfall by the area of the SuDS interventions based on:

The evidence that the capacity of the ground level SuDS was never exceeded (and they therefore **diverted <u>100%</u> of the rainfall away from the storm drain system**);

and

That **green roofs absorbed an average of <u>89.48%</u> of rainfall** landing on them (a conservative estimate based on the average attenuation for the largest storm events analysed thus far).

This provided a total value of **850756 Litres of rainfall retained and thus diverted away from the storm drain system** by the interventions during the initial monitoring period.

In addition to the SuDS components that were monitored for a year at Queen Caroline Estate and Richard Knight House, the green roof at Cheesemans Terrace Estate was in place for the entire monitoring period and would have been expected to perform similarly to the pram shed roofs at Queen Caroline Estate. Thus, this roof should have **attenuated an additional 18073 L** (total Litres = 39 (m^2 catchment area) x 463.4 (mm average rainfall for the 12 month monitoring period from Henrietta and Richard Knight House weather station).

The Cheeseman Terrace Sun Road rain garden was also installed, functioning and tested during the last month of the monitoring. This component would have diverted away from the storm drain system an additional **6572 Litres of storm water** (total Litres = 310 (m^2 catchment area) x 30.7 (mm average rainfall for month of September from Henrietta and Richard Knight House weather station).

This provided **a total value of <u>875401 Litres</u> of rainfall retained and thus diverted away from the storm drain system** by the interventions during the initial monitoring period.

N.B. it must be noted that this is a rough estimate based on monitoring thus far and several caveats must be attached to this value. Firstly, values for the green roofs were based on the performance during the largest rain events and their performance during smaller events (that made up the majority of the events) would be expected to be better than the 89.48% threshold. Secondly, values for the Richard Knight House green roof used the same retention values as those for the pram shed roofs, although it is likely that the Richard Knight House green roof would have better retention potential (monitoring has not yet been possible due to lack of access to downpipes). The estimate also assumed that all rainfall falling within the catchment areas had been diverted to the SuDS features (and thus that all guttering was functioning correctly).

Total non-evidenced surface water run-off & green roof run-off attenuation

Whilst not directly monitored, other SuDS components were installed across the estates during the later stages of the first year of monitoring this project. These included the Orchard Square and Northern Car Park rain gardens at Cheeseman Estate and the Charlotte House and Community Centre rain gardens at Queen Caroline Estate. At the time of writing this report, no issues had been reported related to under performance of these new SuDS components. Assuming that they were performing similarly to the other monitored SuDS components, it is possible to calculate an additional volume of stormwater that would have been attenuated by these newer features that were not being directly monitored at the time of preparing this report:

- Charlotte House (installed 21st September 2016) - **1191 Litres**;
- Community Garden (installed 21st September 2016) - **460 Litres**;
- Orchard Square (installed 23rd August 2016) - **10041 Litres**;
- Northern Car Park (installed 22nd September 2016) - **1475 Litres**.

This would provide an additional volume **of <u>13167 Litres</u> of rainfall retained and thus diverted away from the storm drain system** by the non-monitored more recently installed SuDS components.

Reduction in ambient temperature

Calculation of the reduction in ambient temperatures across the entire estates due to green infrastructure interventions was not possible from the results of this study due to the scale of monitoring that would have been needed and the scope of the monitoring remit for delivering this study. Moreover, the majority of research associated with the effect of urban green infrastructure on the urban heat island effect and urban heat stress indicates that the effects of small-scale green interventions are typically quite localised (Eisenberg et al. 2015) with as little as two metres away from a green structure being enough distance for the cooling effects to be lost (Connp et al. 2016) and a substantial net increase of greenspace within a city being needed in order to reduce ambient temperatures across an area. For example, Gill et al. (2007) suggested that a 10% increase in the area of green infrastructure in Greater Manchester (in areas with little or no green cover) would be required for ambient temperatures to be cooled by up to 2.5°C under the high emissions scenarios based on UKCP02 predictions.

Nevertheless, some quantifiable benefits of the green infrastructure interventions were captured and would have been expected to provide benefits to local residents when in the vicinity of the green infrastructure interventions. This included temperature reductions recorded from thermal cameras of:

- **A maximum of a <u>35.73%</u> reduction in temperature on a vegetated green roof compared to surrounding grey infrastructure**
- **A maximum of a <u>35.87%</u> reduction in temperature on a vegetated green roof compared to surrounding flat roof areas**
- **A maximum of a <u>42.74%</u> reduction in temperature in a swale compared to surrounding grey infrastructure**
- **A maximum of a <u>37.92%</u> reduction in temperature between a rain garden and surrounding grey infrastructure**
- **A maximum of a <u>37.75%</u> reduction in temperature between and SuDS basin and surrounding grey infrastructure**

Reduction in surface water pollution

In addition to stormwater management benefits, there is evidence to suggest that the use of green infrastructure SuDS components can provide surface water pollution benefits in urban areas (Ellis et al. 2012). This comprises improving the water quality associated with urban pollutants such as hydrocarbons in road run-off. There is less consensus in published literature on the effects that green roofs can have on water quality (Berndtsson 2010), with research indicating that effects can vary dependent upon the age of the roof (i.e. newly installed versus established) and the water quality entering the roof (i.e. direct rainfall versus scrubbing of urban pollutants from rooftops).

In relation to this study, ground level SuDS systems created **a <u>100%</u> improvement in surface water pollution**, as no surface water was recorded leaving any of the designed elements and feeding into the combined sewer system.

No monitoring of water quality from green roofs was carried out as it was decided that water quality would reflect the newly-installed state of the roofs rather than a mature performance and would thus merely capture an initial flushing of nutrients from the roofs following installation (based on experience from the Barking Riverside green roof experiment, Connop et al. 2013). However, with an average reduction in runoff from the largest rain events of 89.48%, even if there was some initial nutrient flushing from the newly installed roofs, it would be expected that overall nutrient loading would be reduced compared to standard flat roofs due to the reduced run off from the green roofs.

Increase in biodiversity of selected groups when conventional amenity vegetation is compared with a biodiverse treatment (%)

In relation to quantifying the increase in biodiversity of selected groups when compared to amenity vegetation, an example of the biodiverse habitat created across the sites included the biodiverse green roof at Richard Knight House. In addition to creating habitat piles containing deadwood and sand mounds for ground nesting bees and wasps, 64 species of plant were recorded on the roof. Compared to a standard flat roof**, this comprised a net increase of <u>64 floral species</u>**. Compared to a typical amenity lawn area this comprised an **increase of <u>54 floral species</u> or a <u>525%</u> increase.** The figure for amenity lawn flora diversity was based on floral surveys carried out on typical amenity lawn areas as part of a Barking Riverside landscaping study (Connop et al 2014) and a UEL campus biodiversity study (Connop et al 2012) giving an average number of floral species as 10.24 (*n = 42*).

In addition to the floral increase, numerous invertebrate species, including species of bee, hoverfly, beetle and spider, were observed using both the structure and wildflower diversity of the ground level and roof level landscaping that were not observed using the surrounding amenity grass landscaping (see section 3.6 in this report and the first monitoring period report (Connop and Clough 2016).

4. References

Alves, L. Lundy, L., Ellis, J.B., Wilson, S. and Walters, D. (2014) The Design and Hydraulic Performance of a Raingarden for Control of Stormwater Runoff in a Highly Urbanised Area . Proceedings of the 13th International Conference on Urban Drainage, Sarawak, Malaysia, September 2014.

Atkins, Meterological Office & ADAS (1999) Rising to the challenge; Impacts of climate change in the South East in the 21st century. Kingston upon Thames: Surrey C.C.

Berndtsson, C.J. (2010) Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering, 36(4), 351-360.

Connop, S. and Clough, J. (2016) LIFE+ Climate Proofing Housing Landscapes: Interim Monitoring Report - August 2015 to May 2016. London: University of East London.

Connop, S., Clough, J., Lindsay, R. & Nash, C. (2012) University of East London: the 2012 biodiversity update. London: University of East London.

Connop, S. Lindsay, R., Freeman, J., Clough, J., Kadas, G. and Nash, C. (2014) TURAS multidisciplinary urban landscape design guidance: Design, incorporation and monitoring of Barking Riverside brownfield landscaping. University of East London, London, UK.

Connop, S., Nash, C., Gedge, D. Kadas, G, Owczarek, K and Newport, D. (2013) TURAS green roof design guidelines: Maximising ecosystem service provision through regional design for biodiversity. TURAS FP7 Milestone document for DG Research & Innovation.

Connop, S., Vandergert, P., Eisenberg, B., Collier, M., Nash, C., Clough, J. and Newport, D. (2016) Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure. Environmental Science & Policy 62, Pages 99–111.

Department of the Environment (1996) Review of the potential effects of climate change in the United Kingdon. London: DOE.

Eisenberg, B., Gölsdorf, K., Weidenbacher S., Schwarz-von Raumer, H.-G., (2015) Report on Urban Climate Comfort Zones and the Green Living Room Ludwigsburg, Stuttgart.

Ellis, J.B. , Revitt, M.D. and Lundy, L. (2012) An impact assessment methodology for urban surface runoff quality following best practice treatment. Science of The Total Environment

416, 172–179.

Gill, S.E., Handley, J.F., Ennos, A.R. and Pauleit, S. (2007) Adapting cities for climate change: the role of green infrastructure. Built Environment 33 (1), 115–133.

UKCIP (2001) Socio-economic scenarios for climate change impact assessment: A guide to their use in the UK. Available from http://www.ukcip.org.uk/wordpress/wp-content/PDFs/socioeconomic_sum.pdf

World-wide Weather Online (2016) Weather station data available from: http://www.worldweatheronline.com/v2/historical-weather.aspx?q=w6

Appendix A

A1 *Beatrice House swale performance during 37.2 mm rain event on 16th June 2016*


Ltl Acorn
062°F
017°C
06/16/2016 18:58:23


Ltl Acorn
060°F
016°C
06/16/2016 19:11:02


Ltl Acorn
059°F
015°C
06/16/2016 19:23:41


Ltl Acorn
059°F
015°C
06/16/2016 19:36:19


Ltl Acorn
059°F
015°C
06/16/2016 19:48:57


Ltl Acorn
059°F
015°C
06/16/2016 20:01:35

A2 *Alexandra House swale performance during 37.2 mm rain event on 16th June 2016*


Ltl Acorn
062°F
017°C
06/16/2016 19:01:48


Ltl Acorn
060°F
016°C
06/16/2016 19:14:38


Ltl Acorn
059°F
015°C
06/16/2016 19:27:27


Ltl Acorn
059°F
015°C
06/16/2016 19:40:17


Ltl Acorn
057°F
014°C
06/16/2016 19:53:04


Ltl Acorn
057°F
014°C
06/16/2016 20:05:52

A3 *Community Hall and Sofia House grass basin performance during 37.2 mm rain event on 16th June 2016 (FPC2)*


Ltl Acorn
066°F
019°C
06/16/2016 18:56:49


Ltl Acorn
062°F
017°C
06/16/2016 19:09:17


Ltl Acorn
062°F
017°C
06/16/2016 19:21:46


Ltl Acorn
060°F
016°C
06/16/2016 19:34:13


Ltl Acorn
060°F
016°C
06/16/2016 19:46:42


Ltl Acorn
060°F
016°C
06/16/2016 19:59:10

A4 *Adella House grass basin and Adella House stoney basin (FPC3) performance during 37.2 mm rain event on 16th June 2016*

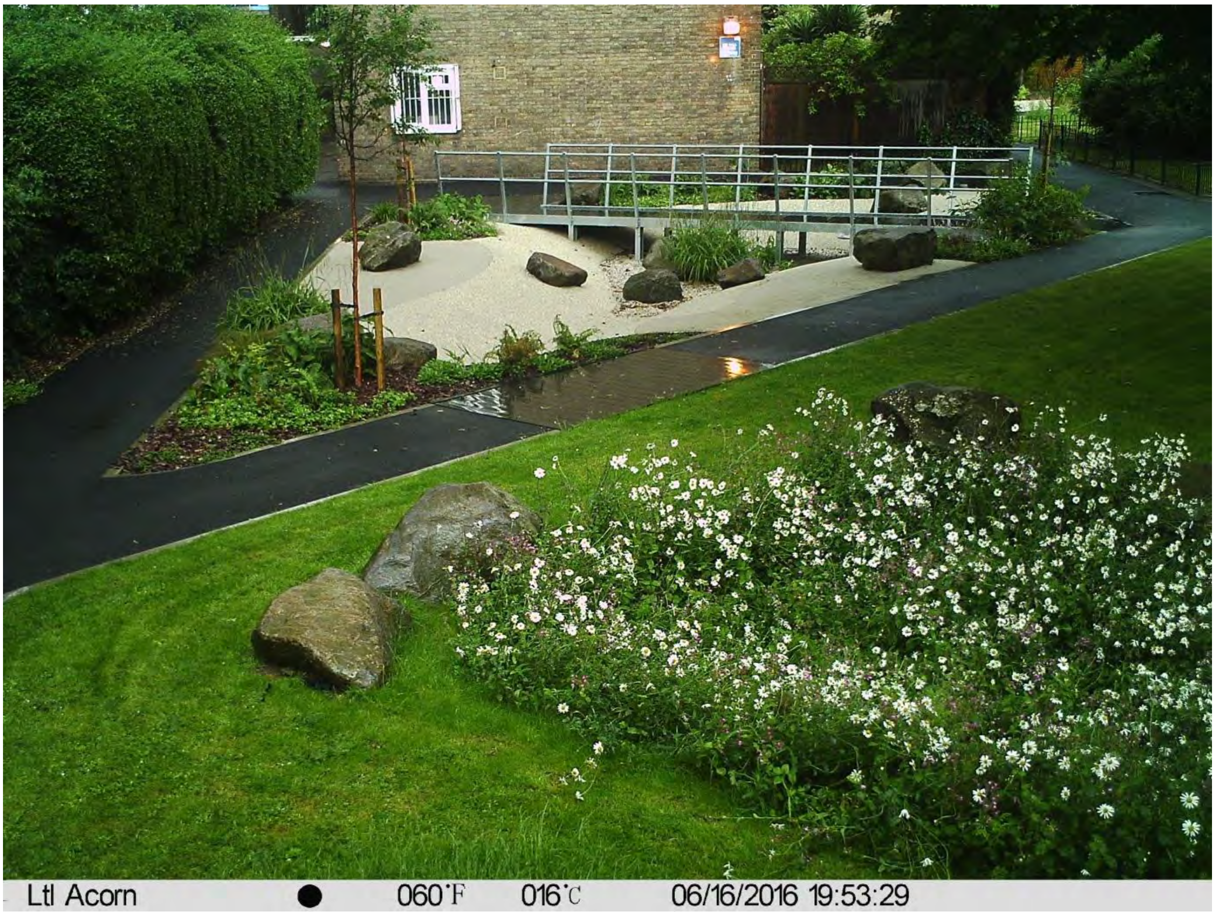
Ltl Acorn
066°F
019°C
06/16/2016 18:51:23

Ltl Acorn
064°F
018°C
06/16/2016 19:03:49


Ltl Acorn
062°F
017°C
06/16/2016 19:16:14


Ltl Acorn
062°F
017°C
06/16/2016 19:28:39


Ltl Acorn
060°F
016°C
06/16/2016 19:41:04


Ltl Acorn
060°F
016°C
06/16/2016 19:53:29

A5 *Richard Knight House rain garden performance during 48.8 mm rain event on 23rd June 2016 (FPC2)*


Ltl Acorn
066°F
019°C
06/23/2016 01:05:58


Ltl Acorn
064°F
018°C
06/23/2016 01:18:56


Ltl Acorn
064°F
018°C
06/23/2016 01:31:55


Ltl Acorn
064°F
018°C
06/23/2016 01:44:54


Ltl Acorn
064°F
018°C
06/23/2016 01:57:53


Ltl Acorn
064°F
018°C
06/23/2016 02:10:52


Ltl Acorn
064°F
018°C
06/23/2016 02:23:51


Ltl Acorn
064°F
018°C
06/23/2016 02:36:49


Ltl Acorn
064°F
018°C
06/23/2016 02:49:49


Ltl Acorn
064°F
018°C
06/23/2016 03:02:47


Ltl Acorn
064°F
018°C
06/23/2016 03:15:47


Ltl Acorn
064°F
018°C
06/23/2016 03:28:45


Ltl Acorn
064°F
018°C
06/23/2016 03:41:44


Ltl Acorn
064°F
018°C
06/23/2016 03:54:42


Ltl Acorn
064°F
018°C
06/23/2016 04:07:41


Ltl Acorn
064°F
018°C
06/23/2016 04:20:39