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De-Ville, S., Menon, M. orcid.org/0000-0001-5665-7464 and Stovin, V. orcid.org/0000-0001-9444-5251 (2018) Temporal variations in the potential hydrological performance of extensive green roof systems. Journal of Hydrology, 558. pp. 564-578. ISSN 0022-1694

https://doi.org/10.1016/j.jhydrol.2018.01.055

Temporal variations in the potential hydrological performance of extensive green roof systems

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Abstract

Existing literature provides contradictory information about variation in potential green roof hydrological performance over time. This study has evaluated a long-term hydrological monitoring record from a series of extensive green roof test beds to identify long-term evolutions and sub-annual (seasonal) variations in potential hydrological performance. Monitoring of nine differently-configured extensive green roof test beds took place over a period of 6 years in Sheffield, UK.

Long-term evolutions and sub-annual trends in maximum potential retention performance were identified through physical monitoring of substrate field capacity over time. An independent evaluation of temporal variations in detention performance was undertaken through the fitting of reservoir-routing model parameters. Aggregation of the resulting retention and detention variations permitted the prediction of extensive green roof hydrological

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performance in response to a 1-in-30-year 1-hour summer design storm for Sheffield, UK, which facilitated the comparison of multi and sub-annual hydrological performance variations.

Sub-annual (seasonal) variation was found to be significantly greater than long-term evolution. Potential retention performance increased by up to 12% after 5-years, whilst the maximum sub-annual variation in potential retention was 27%. For vegetated roof configurations, a 4% long-term improvement was observed for detention performance, compared to a maximum 63% sub-annual variation. Consistent long-term reductions in detention performance were observed in unvegetated roof configurations, with a non-standard expanded-clay substrate experiencing a 45% reduction in peak attenuation over 5-years. Conventional roof configurations exhibit stable long-term hydrological performance, but are nonetheless subject to sub-annual variation.
Keywords: Green Roof, Seasonal, Annual, Retention, Detention, Hydrological Performance

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Highlights

- Temporal changes in potential performance evaluated over 6 years for 9 test beds
- Potential retention performance identified via monitored field capacity
- Detention performance explored via the fitting of simple hydrological models
- Long-term performance evolutions are small in traditional green roof configurations

- Sub-annual (seasonal) variations are dominant over long-term evolutions

1. Introduction

1.1. Background

It has been widely demonstrated that extensive green roof systems offer stormwater management capabilities through two hydrological processes, the retention of rainfall (which subsequently is lost via evapotranspiration and does not become runoff), and the detention of runoff (the transient storage of rainfall as it passes through the roof layers). Stormwater managers typically assume that a green roof's physical characteristics — such as its hydraulic conductivity (which influences detention) and field capacity (which influences retention) — are constant over time, and therefore that the roof's potential to retain and detain runoff are also constant over time. However, these properties may change in response to seasonal factors (vegetation growth cycles, substrate wetting/drying regimes) and/or due to longer-term processes such as compaction (De-Ville et al., 2017). There is therefore a need to determine whether there is evidence of such seasonal or longer-term changes in the underlying potential performance characteristics.

The most frequently reported indicator of green roof hydrological performance is the percentage retention, reported as either a 'mean per-event' or 'total volumetric' retention. Many green roof monitoring programmes have highlighted seasonal trends in observed retention performance, particularly in temperate climates of the northern hemisphere, where there are distinct seasonal variations in temperature, rainfall patterns, and other climatic variables. Retention performance is consistently higher in the warmer summer months of the year (Mentens et al., 2006; Uhl and Schiedt, 2008; Poë et al., 2015; Elliott et al., 2016). This is widely attributed to the increased levels of evapotranspiration, resulting in greater recovery of storage capacities between rainfall events. Beyond temperate conditions, however, Voyde et al. (2010) did not observe any seasonal trends in retention performance for a 12-month study conducted in Auckland, New Zealand, owing to the small seasonal meteorological differences in Auckland's climate. In the humid-subtropical climate of Hong Kong, Wong and Jim (2014) identified the weakest retention performance in summer months (over a 12-month period) due to increased levels of rainfall, which prevented sufficient recovery of the green roofs storage capacity between events. Therefore, whilst seasonal variations in observed retention performance are expected and observed in temperate climates, the challenge is to identify whether these variations are wholly due to climate or whether changes also occur in the underlying physical properties that affect the system's fundamental retention characteristics.

Fewer studies have focused on the longer-term (year-on-year) performance evolution of extensive green roof systems. Mentens et al. (2006) and Hill et al. (2016) widely sampled existing green roof systems in Germany and Canada respectively, with both finding no statistical correlation between roof age and hydrological performance. However, no systematic year-on-year comparisons have been published. Whilst this partly reflects the scarcity of long-term hydrological records, it should also be noted that the effect of natural climatic variation on observed hydrological performance is expected to mask any subtle changes in the underlying hydrological characteristics of the system (De-Ville et al., 2017). Observed retention performance is strongly influenced by storm event characteristics and tends to be greatest for small events, as green roofs only have a finite maximum retention capacity (e.g. 20 mm for an extensive system, Stovin et al. (2012)). It is not meaningful to compare annual retention performance (either volumetric or mean per-event retention), as rainfall patterns, temperatures, and other climate variables differ significantly from year-to-year. For example, the same roof configuration undergoing a high rainfall-low Antecedent Dry Weather Period (ADWP) year/season/storm event will have a lower retention performance than if exposed to a low rainfall-high ADWP year/season/storm event. However, the green roof's fundamental capacity for retention, as dictated by its physical characteristics, may be the same in both scenarios.

Similarly, observations of temporal changes in detention performance are typically confounded by the controlling effects of retention (Wong and Jim, 2014; Stovin et al., 2015b), and have therefore rarely been explored in isolation. In summary, the literature clearly identifies patterns in sub-annual hydrological performance, whilst findings on longer-term changes to either retention or detention capabilities are inconclusive. No previous studies have attempted to disaggregate storm event or climate-related forcing factors from potential seasonal or longer-term changes to the roof's underlying hydrological response.

1.2. Objectives

This study aims to test the null hypothesis that neither sub-annual nor long-term temporal variations exist in the potential hydrological performance of green roof systems that have been monitored in Sheffield, UK. This is to be achieved through: 1) the identification of approaches that permit temporal variations in the physical properties that control retention and detention to be quantified; 2) the exploration of a long-term hydrological record of a series of extensive green roof test beds to identify temporal variations in both potential retention (5-year record) and detention performance (6-year record); and 3) an evaluation of the consequences of any predicted changes through the prediction of hydrological performance in response to design storms.

2. Literature Review

2.1. Physical controls on potential hydrological performance

A green roof's maximum retention capacity is widely attributed to be approximately equal to the substrate's Plant Available Water (PAW, mm), which is itself a function of the substrate's Field Capacity (Θ_{FC}, %v/v), Permanent Wilting Point (Θ_{PWP}, %v/v), and depth (d, mm):

$$PAW = (\Theta_{FC} - \Theta_{PWP}) \cdot d \quad (1)$$

It is proposed that tracking of these physical properties over time should provide a climatically independent temporal evaluation of the Absolute Retention Capacity (ARC) of the green roof system (equivalent to the maximum potential soil moisture deficit). These independent ARC evaluations may be combined with the observed effects of rainfall, ADWP, and PET in appropriate hydrological models to identify the Potential Retention Capacity (PRC) and Potential Retention Performance (PRP) of the green roof system in response to a specific climate/weather/storm event scenario. Section 3.3

outlines a novel approach to tracking field capacity using in-situ moisture content sensors.

As with retention, the system's detention characteristics may also be monitored through the identification of relevant physical properties. Detention processes may be modelled via the application of appropriate unsaturated media flow relationships. However, the governing equations for predicting unsaturated-media flow are complex, require numerous physical characteristics (Palla et al., 2012), and there is therefore scope for large compound errors. Alternatively, semi-empirical descriptions of the fundamental detention characteristics can be achieved with simple hydrological models, whilst maintaining suitable levels of predictive accuracy. Stovin et al. (2015a) proposed the use of a reservoir routing model to describe detention processes, and this approach was successfully deployed to identify differences in detention characteristics between various roof configurations independently of climate.

In summary, conventional retention and detention performance metrics derived from monitored data are poorly suited to the identification of temporal trends in underlying hydrological function. It is therefore proposed that a coupled physical property monitoring programme and validated hydrological modelling approach will better identify changes to the underlying green roof physical characteristics and their impacts on potential hydrological performance over time.

2.2. Temporal trends in green roof physical characteristics

Whilst yearly evaluations of hydrological performance may not exist in the literature, there have been some attempts to characterise temporal changes in green roof physical properties. Exploration of properties thought to directly influence hydrological performance has identified potential for improved hydrological performance in the long-term. Getter et al. (2007) found that pore volume doubled over a 5-year period, and hypothesised that this would lead to improvements in retention performance due to an increase in microporosity ($\leq 50\ \mu$m). However, Getter et al. (2007) also noted that these improvements may come at the expense of worsened detention performance due to an increased presence of macropore ($> 50\ \mu$m) channels. De-Ville et al. (2017) explored the physical properties of virgin and aged (5-years) green roof substrate, where observed structural differences were inferred to lead to improved retention performance with age. Inconclusive results prevented the identification of any trends in detention performance, but it was highlighted that — due to the controlling nature of retention performance — overall hydrological performance is likely to remain consistent, if not improve, with increasing system age.

In a study of green roof establishment, Emilsson and Rolf (2005) observed a net loss of organic matter (unspecified origin) from 3 to 1% of the total substrate volume over a single year. Bouzouidja et al. (2016) identified similar falls in organic content (1:1 peat dust and pine bark) over a 4 year-period and reported a reduction in the mass of particles smaller than 2 mm in diameter. The impact that organic matter fluctuations can have on green roof hydrological performance is demonstrated by the laboratory experiments of Yio et al. (2013), where a threefold increase in organic content (coir) was associated with a peak attenuation (detention performance) increase from 15 to >50%.

The changes in physical characteristics noted above will influence the substrate's field capacity and/or its detention response. The present study focuses on the use of long-term hydrological monitoring data from green roof test beds to identify sub-annual (seasonal) and longer-term changes in these underlying system characteristics.

3. Methodology

3.1. Introduction to the Hadfield Test Beds

The Hadfield Test Beds comprise 9 differently-configured green roof test beds located at the University of Sheffield's Green Roof Centre on a third-floor terrace of the Sir Robert Hadfield Building (Grid Reference 53.3816, -1.4773). Each test bed (TB) configuration has a different substrate composition and vegetation treatment pairing (Figure 1). The test beds are 1 m wide by 3 m long and are installed at a 1.5° slope. Each test bed physically comprises, from base to surface, a hard plastic tray, a drainage layer (ZinCo Floradrain FD 25-E), a filter sheet (ZinCo Systemfilter SF), one of three substrates to a depth of 80 mm, and one of three vegetation treatments.

[**Approximate location of Figure 1**]

The first two substrates are commercially available substrates manufactured by Alumasc ZinCo, Heather with Lavender (HLS) and Sedum Carpet Substrate (SCS). HLS is installed in TB1, TB4 and TB7, with SCS being installed in TB2, TB5 and TB8. The third substrate is a bespoke mix based on Lightweight Expanded Clay Aggregate (LECA) and is installed in TB3, TB6 and TB9. HLS is a semi-intensive commercial substrate consisting of crushed brick and pumice (ZincolitPlus), enriched with organic matter including com-

Property	Units	HLS	SCS	LECA
Particle size < 0.063 mm	% (m/m)	2.1±1.4	1.4±0.3	0.4±0.0
Median particle diameter, d_50	mm	4.7±0.7	5.2±0.3	5.0±0.1
Dry density	g/cm^3	0.95±0.04	1.06±0.05	0.41±0.00
Wet density	g/cm^3	1.36±0.02	1.45±0.07	0.76±0.02
Total pore volume	% (v/v)	63.8±1.6	59.8±2.0	84.8±0.0
Field Capacity, Θ_{FC}	% (v/v)	41.2±2.3	39.1±2.1	35±1.6
Air content at Θ_{FC}	% (v/v)	22.6±0.8	20.7±4.1	49.8±1.5
Permanent Wilting Point, Θ_{PWP}	% (v/v)	6.6	2.9	2.1
Hydraulic Conductivity, K_{sat}	mm/min	1-15	10-35	≥35
Organic content	% (m/m)	3.8±0.1	2.3±0.5	6.0±0.3

Table 1: Substrate physical characteristics as derived according to FLL (2008) test methods, Mean ± Standard deviation (Stovin et al., 2015b).

post with fibre and clay materials (Zincohum). SCS is a typical extensive green roof substrate consisting of crushed bricks (ZincoLit), enriched with Zincohum. The LECA-based substrate contains LECA as the sole mineral component, with loam and compost. The physical characteristics of these substrates are presented in Table 1.

The three vegetation treatments comprise two planted test groups and a single un-vegetated group. TB1, TB2 and TB3 were vegetated with Alumasc Blackdown Sedum Mat, TB4, TB5 and TB6 were vegetated with a Meadow Flower mix, whilst TB7, TB8 and TB9 were unvegetated. The sedum vegetation was chosen as it is a commonly adopted species for extensive green roof applications due to its tolerance of drought, extreme temperatures and high wind speeds (VanWoert et al., 2005). The Meadow Flower treatment comprises a mix of flowers, grasses and succulents. These species exhibit a lower drought tolerance (Lu et al., 2014) but greatly increase the biodiversity potential compared to Sedum (Benvenuti, 2014). The unvegetated test bed configurations were created to provide a control against which the contribution of vegetation could be evaluated.

Data collected from the Hadfield Test Beds has been previously reported by Berretta et al. (2014) and Stovin et al. (2015a), where the influence of vegetation and substrate characteristics on moisture content behaviour and overall hydrological performance were explored respectively. The findings of Stovin et al. (2015a) are particularly relevant to this study, although only aggregated hydrological performance statistics over their entire 4-year study period were presented.

3.2. Monitoring Study Data Collection

The experimental setup included a Campbell Scientific weather station that recorded hourly wind speed, temperature, solar radiation, relative humidity and barometric pressure. Rainfall depth was measured at one minute intervals using three 0.2 mm resolution ARG-100 tipping bucket rain gauges manufactured by Environmental Measures Ltd. The rain gauges were located at the same height as the test beds, between TB1 and TB2, TB5 and TB6, and beside TB9 (Figure 1). Runoff was measured volumetrically in 25 l collection tanks equipped with Druck Inc. PDCR 1830 pressure transducers. The collection tank located under each test bed was designed for increased measurement sensitivity at the beginning of each rainfall event and to avoid direct discharge onto the sensor. The pressure transducers were calibrated against collected volumes on site. An electronic solenoid valve emptied the tank when maximum capacity was reached (8.3 mm runoff depth) and every day at 14:00. Runoff was recorded at one minute intervals. Data were recorded using a Campbell Scientific CR3000 data logger.

Water content reflectometers were located at three soil depths to measure the soil moisture profile and behaviour in four of the nine test beds (TB1, TB2, TB3 and TB7). The sensors used were Campbell Scientific CS616 Water Content Reflectometers. The probes were installed horizontally at the centre of each test bed and the rods were located at 20 mm (bottom), 40 mm (mid) and 60 mm (top) above the drainage layer and filter sheet. Considering the proximity of the probes in each test bed, the rods of the mid and top probes were installed at 90° and 180° respectively from the lower one, in order to avoid distortion of the measurement reading taken by the enabled probe. The orientation of each probe was pre-determined to ensure that the wires did not interfere with the accuracy of the measurements from nearby probes. Furthermore, to avoid inter-probe interference, the probes were differentially-enabled, with each of the four sub-scans measuring three probes in different test beds. Moisture content measurements were recorded at 5 min intervals. Moisture probes were calibrated in the laboratory before being installed into the test beds (as described in Berretta et al. (2014)).

The Hadfield test beds have been in place since late June 2009. After a commissioning period, rainfall and runoff data collection began in February 2010. Climate data were collected from June 2010 and moisture data from January 2011. This study uses data collected from all sources between February 2010 and February 2016. Throughout the monitoring period the runoff collection system experienced some failures. The failures were caused by clogging of the automatic barrel-emptying valves with fine particulate material washed out from the test beds. Even with regular maintenance the collected rainfall/runoff dataset is not complete; this prevents the reporting of annual volumetric retention metrics and requires the adoption of 'per-event' analysis. The 6-year data record is made up of 503 individual rainfall events where total precipitation exceeded 2 mm and the inter-event period exceeded 6-hours. An inter-event period of 6-hours was chosen to allow comparability with previous studies (Stovin et al., 2012), whilst a 2 mm minimum rainfall depth is considered to be the amount of rainfall typically retained by a non-green roof (Voyde et al., 2010).

3.3. Identifying & Modelling Potential Retention Performance

3.3.1. Identifying temporal changes in field capacity

The ageing study utilised all three data types collected from the Hadfield beds: climate; rainfall/runoff; and moisture content. Each rainfall event where rainfall (P) and runoff (R) were greater than 2 mm was identified from the 6-year data record (between 98 and 198 events depending on the test bed).

As previously outlined, the identification of any year-on-year trends in retention performance using monitored rainfall and runoff data is of limited value due to the dominant effects of climatic factors. Therefore, a physical property monitoring approach was adopted to assess how the *potential maximum retention depth* of the green roof varied over time. The moisture content (Θ) of the substrate was monitored continuously using the moisture content probes installed into TB1, TB2, TB3 and TB7. Theoretically, runoff only occurs from a green roof once the substrate has reached field capacity (Θ_{FC}). Therefore, after the point of runoff initiation, the substrate should be at/around Θ_{FC}. Due to the highly permeable nature of green roof substrates, any significant saturation above Θ_{FC} is unexpected. The substrate's field capacity was therefore defined as the moisture content of the substrate 2 hours after the cessation of rainfall. Only events that generated >2 mm runoff were considered.

The observed field capacity values were analysed over two temporal scales, by study-year, and continuously over a Julian year. Categorical evaluations were undertaken statistically using the non-parametric Kruskall-Wallis Test method for identifying significant differences in distribution and to explore the presence of trends over time.

Continuous evaluations were undertaken by fitting a Fourier series model to the data to identify sub-annual trends in Θ_{FC}. The Fourier series model takes the form:

$$\Theta_{FC} = a + b \cdot cos(D \cdot p) + c \cdot sin(D \cdot p) \tag{2}$$

where a, b, and c are optimised parameters, p was set equal to $2\pi/365$, Θ_{FC} is the monitored field capacity and D is day of the year (where January 1^{st} is 1 and December 31^{st} is 365, 366 in a leap year). Model fit was evaluated with the R^2 goodness of fit statistic and a bisquare weighting of residuals.

3.3.2. Modelling potential retention performance

The identified values of Θ_{FC} allow for temporal evaluations of the maximum retention capacities of the green roof systems. Retention performance, as previously established, depends upon Θ_{FC}, but is also a function of rainfall patterns, ADWP, and PET values. These additional factors can be incorporated as part of a conceptual hydrological flux model to better identify potential retention performance, whereby:

$$S_{max} = PAW = (\Theta_{FC} - \Theta_{PWP}) \cdot d \tag{3}$$

S_{max} is the maximum storage capacity of the substrate in mm, taken here to be equal to PAW and determined from the difference in Θ_{FC} and the Permanent Wilting Point (Θ_{PWP}, Table 1) multiplied by the substrate depth (d) in mm, 80 mm in this study. S_{max} is used to define the storage through time (S_t). The stored water depth at time t (S_t, mm) is calculated as the stored water depth from the previous time step (S_{t-1}, mm) minus the expected evapotranspiration (ET, mm). Expected ET is estimated by scaling Potential ET (PET_t, mm) with a moisture limited Soil Moisture Extraction Function (SMEF) based upon an effective substrate saturation between Θ_{PWP} and Θ_{FC} (Stovin et al., 2013). PET is calculated using the Hargreaves method and long-term climate averages for Sheffield, UK (Figure 2).

$$S_t = S_{t-1} - (PET_t \cdot \frac{S_{t-1}}{S_{max}}) \tag{4}$$

The Potential Retention Capacity at time t (PRC_t, mm) is defined as the cumulative losses from the inital storage level, in this study set as S_{max}.

$$PRC_t = S_{max} - S_t \tag{5}$$

The Potential Retention Performance (PRP, %) in response to a 1-in-30-year 1-hour Summer design storm event for Sheffield, UK, was determined via:

$$PRP = \frac{PRC}{P} \cdot 100 \tag{6}$$

where P is total rainfall depth (in this case 30 mm). An Antecedent Dry Weather Period (ADWP) from 0 to 28-days in duration was investigated to explore PRP under varying climatic conditions.

3.4. Identifying & Modelling Detention Performance

The same monitored rainfall events used for retention performance evaluation were also utilised for identifying detention characteristics. As highlighted above, conventional detention metrics derived from monitored field data (e.g. Peak Delay, Peak Attenuation) are often confounded by the controlling effects of retention. Stovin et al. (2015b) proposed the use of a fitted reservoir routing model to act as a descriptor of the physical detention processes occurring within an extensive green roof system. This approach provides a descriptor of detention that is independent of retention and climatic effects.

Kasmin et al. (2010) suggested that the detention performance of a green roof test bed could be modelled using reservoir routing concepts, whereby:

$$h_t = h_{t-1} + Qin_t - Qout_t \quad (7)$$

in which Qin and $Qout$ represent the flow rates into and out of the substrate layer respectively (mm/min), h represents the depth of water temporarily stored within the substrate (mm), and t represents the discretisation time step. $Qout$ is given by:

$$Qout_t = D_S \cdot h_{t-1}^{D_E} \quad (8)$$

in which D_S and D_E are the reservoir routing parameters (scale and exponent respectively). For h in mm and $Qout$ in mm/min, D_S has the units $\mathrm{mm}^{(1-D_E)}$/min, whilst D_E is dimensionless. Note: in previous literature, the scale and exponent of the reservoir routing equation were referred to as k and n respectively; they have been altered in this study to avoid confusion with other physical properties and model parameters.

Yio et al. (2013) demonstrated that a model based on a fixed value of D_E was capable of predicting observed runoff profiles with almost no loss of accuracy when compared with a model for which both parameters had been optimised. With a fixed value of $D_E = 2$, values of D_S were optimised for each identified rainfall event by fitting the predicted runoff, in response to net rainfall profiles, to monitored runoff profiles. Model fit was evaluated using the R_t^2 goodness of fit statistic.

As with retention, the resultant D_S values were analysed at two temporal scales, categorically by study-year, and continuously over a Julian year. Categorical evaluations were undertaken statistically using the non-parametric Kruskall-Wallis Test for identifying significant differences in distribution and to explore the presence of trends over time. Continuous evaluations were undertaken by fitting a Fourier series model to the data to identify sub-annual trends in D_S.

3.5. Predicting Overall Hydrological Performance

Identified retention and detention physical characteristics were combined to predict the runoff of the green roof systems in response to a 1-in-30-year 1-hour Summer design storm event — as per the CIRIA SuDS Manual (Woods Ballard et al., 2015) — for Sheffield, UK, to assess the impact of the identified sub-annual and long-term parameter variations. A net-rainfall profile was generated by subtracting total retention losses (PRC) from the beginning of the rainfall event, and this was then routed using the detention model outlined in Section 3.4 combined with appropriate model parameters. A range of ADWP durations, from 0 to 28-days, was investigated to explore any influence on runoff response.

4. Results

4.1. Study Period Climate

The monthly rainfall depths (Figure 2) highlight the typically high levels of variability associated with a temperate climate. Figure 2 also aids in understanding the difficulty of observing similar rainfall characteristics over time; with the exception of June, almost all other months receive vastly different levels of rainfall from year to year. Cumulative rainfall for the 503 identified rainfall events totalled 4224 mm, out of a total recorded 4670 mm, representing 90.5% of all rainfall. Characterisation of storm return periods indicated that the vast majority of storms could be classified as having a return period of less than 2 years (for their respective durations). Only 4 of the 503 events were classified as having a return period in excess of 2 years, as defined by the Flood Estimation Handbook (CEH and NERC, 2008).

[**Approximate location of Figure 2**]

4.2. Moisture Content

Figure 3 presents rainfall, runoff and moisture content data for TB1 for six contrasting rainfall events. The events have been selected to illustrate typical responses in summer and winter conditions. The first four events, 09/Jun/14, 27/Jul/13, 10/Feb/13 and 26/Dec/14, all relate to conditions where the substrate was either at, or near to, field capacity at the onset of rainfall. Whilst there is some evidence of temporarily raised moisture content levels around the time of the onset of runoff, the important point is that the moisture content is relatively stable and constant following the initiation of runoff. The plots confirm that the moisture content levels recorded 120 minutes after the end of an event provide a good estimate of the effective field capacity during the event. The summer events (upper row) show consistently lower effective field capacity values compared with the winter events (middle row).

The final two plots illustrate cases where the moisture content prior to the rainfall event was low, close to the permanent wilting point. Whilst these also demonstrate increasing moisture content in response to the rainfall, the patterns are less consistent. For example, there is a far greater difference between moisture content at different depths in the 25/Aug/11 event compared with the first four events, and the top probe appears to be registering rising moisture levels after the event ceased on 08/Aug/14. In both of these cases runoff was measured at very low levels of moisture content. These plots suggest that under conditions of extreme dryness the wetting process is uneven and preferential flow paths may lead to runoff before all the substrate has been wetted to field capacity. There is clearly scope for more detailed research on this topic. However, for the purposes of the present study, this dry condition data has been omitted from calculations of seasonal variations in maximum moisture holding capacity. A systematic approach was adopted for the removal of outliers, in which all monitored field capacities lying below 1.5 x the interquartile range of a specific test bed's observed field capacity range were excluded. In practice, this resulted in lower cut-off Θ_{FC} values of 28.2, 29.2, 12.9, and 24.9% for TB1, TB2, TB3 and TB7 respectively. For the three brick based substrates there were considerably fewer outlier events than for the LECA test bed: 2 events was omitted from TB1; 4 events from TB2; 7with depth of from TB3; and 3 from TB7. There was some commonality between rainfall event exclusion between test beds. This small number of excluded events represents only 1-6% of the monitored data, dependent on test bed configuration.

[Approximate location of Figure 3]

4.3. Retention performance

Figure 4 presents the monitored post runoff event field capacity of TB1, TB2, TB3, and TB7 over the study period. Moisture probe data was not available for the first year of the study, and so a 5-year period is used for the evaluation of any trends in Θ_{FC} over time. The bottom of the substrate consistently exhibits a higher moisture content than either the middle or top. The presence of a vertical moisture profile is exaggerated in the vegetated test beds (TB1-3) compared with the unvegetated TB7. This suggests that plant and root activity contribute to the development of the vertical profile. Comparisons between TB1 (Sedum vegetation) and TB7 (Unvegetated), which share the same substrate, reveal that moisture levels are consistently elevated in TB1 over TB7. Berretta et al. (2014) suggested that this phenomenon was due to the moisture retention effects of plants and roots, a result of greater entrained organic content. However, Figure 4 also reveals the presence of a sub-annual cycle in which monitored field capacities were highest in the winter months — vertical dotted lines indicate 1^{st} January of each study year — and lowest in the summer. If differences were solely due to vegetative processes, sub-annual trends would be unexpected in the unvegetated TB7.

[Approximate location of Figure 4]

4.3.1. Long-term performance evolutions

Categorising the monitored field capacity values by study year (Figure 5) clearly reveals significant differences (Kruskal-Wallis, $p \leq 0.05$) in the distributions of monitored field capacity over time for the full depth of TB1 and TB7; TB2 and TB3 show less variation over time. There is spread on all of the distributions, some of which is due to systematic sub-annual variations which will be discussed later. Supplementary Dunn's pairwise comparisons revealed a significant difference between Year-2 monitored field capacity values and all other years. From Year-3 onward there is no significant statistical difference in the value of monitored field capacity for any test bed.

[**Approximate location of Figure 5**]

4.3.2. Sub-annual performance variations

The compiled annual monitored field capacity values of the four test beds fitted with moisture content probes are presented in Figure 6. Whilst scatter in the data is evident, as for Figure 4, there is a visible sinusoidal trend in Θ_{FC} over the year. Fourier series models describe this relationship with an acceptable degree of model fit ($R^2 \geq 0.7$). As previously identified, there is considerably less variation in the moisture levels with depth in the unvegetated TB7 compared to the same, but vegetated, substrate of TB1. All test beds, and all layers, exhibited a minimum Θ_{FC} in July or August, and a maximum around February. Taking the worst-case (i.e. lowest) value of Θ_{FC} from the top layer of each test bed and applying a substrate-specific constant PWP value (Table 1) suggests that the PAW of brick-based substrate configurations fluctuates by approximately 5 mm within a year. The LECA-based substrate exhibited a much greater variation of 9.6 mm or 62% (about the mean), which is more than 40 times the long-term change.

[**Approximate location of Figure 6**]

Figure 7 presents the potential retention capacities of each of the four test bed configurations for varying levels of ADWP. The PRC on any day of the year and for an ADWP of up to 28-days can be identified from each plot. PRC is always greatest for the highest ADWP (28-days) as the regeneration of storage capacity by ET is cumulative. Without a variable PAW and at an infinite ADWP the PRC curves shown in Figure 7 would follow a similar relationship to the PET curve of Figure 2, with lower levels of PRC in the winter months and higher levels in the summer months. The effect of a reduced PAW in the summer months is a corresponding reduction in the level of PRC *(compared to a theoretical maximum)*; this reduction is most evident at high levels of ADWP. The greatest levels of PRC for all configurations at the highest ADWPs (≥21-days) can be observed to occur in late spring (May). For low levels of ADWP (≤7-days) in the brick-based substrate configurations (TB1, TB3, & TB7), PRP follows a relationship more similar to that of PET, maintaining the highest levels of PRC in summer months.

[**Approximate location of Figure 7**]

The reduced levels of PAW in the LECA-based substrate of TB3 compared to its brick-based counterparts result in lower overall estimates of PRP. When the greater sub-annual variation in PAW of the LECA-based substrates is also considered, PRP is heavily reduced in the summer months for any ADWP $\geq$ 3-days and does not exhibit the same plateau in performance as the brick-based substrates.

4.3.3. Summary

By monitoring Θ_{FC} over a period of five years, it was found that sub-annual variations in maximum potential retention are more significant than those identified year-on-year. From Year-1 to Year-5, the greatest change in Θ_{FC} was 12.6% in the unvegetated HLS test bed (TB7), whilst the greatest sub-annual (seasonal) variation (62%) was observed in the sedum vegetated LECA test bed (TB3). Sub-annual variations were found to be up to 40 times greater than long-term evolutions (TB3).

4.4. Detention performance

Figure 8 presents a scatter plot of the fitted detention model parameter D_S over time and highlights considerable variation in the data. Sub-annual trends are less apparent than those seen for the retention analysis. Note: higher values of D_S indicate more rapid runoff and so represent reduced detention performance.

4.4.1. Long-term performance evolutions

The grouping of D_S values by study year reveals the long-term trends in median D_S over time (Figure 9). Vegetated test beds (TB1-6) exhibit little or no change in detention performance (as inferred from D_S values) over the six-year study period when compared to unvegetated systems. The vegetated systems also exhibit reduced interquartile ranges compared to the corresponding unvegetated systems. The unvegetated test beds (TB7-9) experience large variations in the yearly-median value of D_S, with TB9 showing a steady year-on-year increase (+151% Year-1 to Year-6). The unvegetated beds have a statistically significant difference in D_S between Year-1 and Year-

6. For all three vegetation treatments, LECA test beds generally exhibit the greatest range of D_S values for each year compared to their brick-based counterparts.

[Approximate location of Figure 8]

[Approximate location of Figure 9]

4.4.2. Sub-annual performance variations

Figure 10 reveals that there is a sub-annual pattern to detention performance. The scatter plot highlights significant variation in D_S over the year, making trends more difficult to identify visibly compared with retention. The monthly median values of D_S and the applied Fourier series models reveal the presence of an inverted sub-annual relationship compared with Θ_{FC}, with elevated D_S values (i.e. reduced detention) in summer months. However, particularly for TB1, there is a lack of data during the summer months. This low number of data points is unsurprising as retention performance has been demonstrated to be higher in summer months, preventing the generation of sufficient runoff volumes for detention analysis ($R \geq 2$ mm).

The installed vegetation of each configuration plays a significant role in dictating the median annual D_S value (Table 2), with the unvegetated test beds (TB7-9) exhibiting higher annual median values of D_S compared to vegetated configurations. However, for the vegetated test beds the vegetation type (Sedum or Meadow-Flower) does not lead to any clear differences in sub-annual variability.

[Approximate location of Figure 10]

Application of the Fourier series model values of D_S for a *detention performance only* (0-day ADWP) runoff response highlights that the greater values

Test Bed	Model Fit (R^2)	Median D_S	Max. Variation (%)	Peak Attenuation (%)	
				Jan	Jul
1	0.75	0.0073	±25.6	59.5	47.8
2	0.86	0.0061	±41.7	68.7	49.18
3	0.79	0.0084	±44.6	63.2	40.5
4	0.82	0.0070	±47.1	68.1	45.2
5	0.86	0.0079	±34.6	60.9	44.2
6	0.86	0.0094	±36.2	57.3	38.9
7	0.74	0.0139	±31.5	47.2	29.9
8	0.80	0.0105	±36.5	54.9	36.0
9	0.65	0.0144	±15.2	38.6	33.5

Table 2: Summary of detention Fourier series model fit, annual median D_S values, the maximum variation from this median value, and peak attenuation values for a 1-in-30-year design storm with 0-days ADWP.

of D_S in summer months lead to a reduced peak attenuation (reduced performance, see the last two columns of Table 2). The vegetated brick-based test beds (TB1 & TB2) exhibit the smallest levels of peak attenuation variation over the course of the year, whilst the unvegetated brick based configuration (TB7) and the vegetated LECA configuration (TB3) both experience significantly greater sub-annual variation in peak attenuation. The greater magnitude of variation in TB3 for detention is also present for retention, suggesting that the LECA-based substrate is more susceptible to sub-annual variations in performance than its brick-based counterparts.

4.4.3. Summary

The fitting of the D_S parameter to observed net rainfall/runoff profiles permits the temporal monitoring of detention processes independently of climate and retention effects. For an unvegetated system, long-term evolutions in detention performance (as inferred from D_S values) are significant, with up to 10 times greater increases than those observed sub-annually (e.g. 151% vs. 15% respectively for TB9). However, vegetated configurations generally exhibit greater sub-annual (seasonal) variation compared with long-term evolutions (e.g. 42% vs. 12% respectively for TB2). This, in conjunction with the retention findings, suggests that sub-annual variations are more critical than long-term evolutions.

4.5. Overall hydrological performance

4.5.1. Long-term performance evolutions

Figure 11 demonstrates the differences in overall performance for two test beds installed with the HLS brick-based substrate (TB1 and TB7) alongside a single test bed with a LECA-based substrate (TB9). The model predictions incorporate Year-1 to Year-6 changes in the detention model parameter D_S and also apply the relevant monitored field capacity. For TB1, the small increase in Θ_{FC} and small decrease in D_S result in no clearly observable difference in runoff profile from Year-1 to Year-6 at any ADWP, with peak attenuation decreasing by just 4.2% for a 0-day ADWP. The result of a greater change in Θ_{FC} for TB7 is masked by the considerable difference in Year-1 to Year-6 D_S value, which results in a visually distinct 0-day ADWP runoff response from Year-1 to Year-6, with peak attenuation reducing by 30.2%. The LECA substrate of TB9 exhibited the greatest change in D_S

value from Year-1 to Year-6 and this results in a 45.2% reduction in peak attenuation. The predicted runoff responses of all 3 test beds confirm the stabilising effect that vegetation can have on long-term hydrological performance, as previously seen in Figures 5 and 9.

[**Approximate location of Figure 11**]

4.5.2. Sub-annual performance variations

The predicted runoff responses shown in Figure 12 represent the minimum and maximum detention performances of TB1, TB2, TB3 and TB7, and their associated maximum retention potential at these times. All instances of minimum detention performance are during the warmer summer months, whilst the maximum detention performance is seen in the winter months. The differences in D_S are significant and evident in the differences between minimum and maximum D_S 0-day ADWP responses; peak attenuation improved by 63.1% for TB3 between August and February.

The best runoff responses are always achieved at the 28-day ADWP duration due to the additional retention performance, with a maximum peak attenuation of 90.4% for TB1 in July. Under minimum detention performance conditions (summer months) there is considerably more variation between the 0-day and 28-day ADWP responses (56.1%, TB1) than under maximum detention performance (winter months, 15.2%, TB1). This is due to the elevated levels of PET in the summer months which permit the faster recovery of retention storage, and thus greater potential retention performance.

[**Approximate location of Figure 12**]

4.5.3. Summary

The modelling exercise has clearly demonstrated that retention effects dominate over detention effects, with increased ADWP durations resulting in significantly greater improvements in peak attenuation compared with those due to either sub-annual, or long-term changes in detention charateristics. Similarly, for sub-annual variations, PET rates strongly dictate the levels of achievable performance in the cooler winter months.

5. Discussion

5.1. Retention

Long-term performance evolutions

In most cases, the presented data suggest that something occurred late in Year-2/early in Year-3 resulting in increases to field capacity, particularly in the lower substrate layers. Such a clear divide between Year-2 and Year-3 could indicate the end of the primary consolidation process of the substrate. Whilst substrate levels were not measured, significant substrate consolidation was not visually observed in Year-3 to Year-6, with substrate levels maintaining approximate design depths. Hill et al. (2016) identified that substrate depth was not significantly reduced from *original design depth*, even for systems with up to 17-years of maturation. This observation is consistent with data from Year-3 onwards where field capacity – and inferred consolidation – is not significantly different from year-to-year. Consolidation reduces pore sizes, leading to more pores being capable of holding water against gravity, thus improving field capacity (Menon et al., 2015). The HLS and SCS substrates are supplied with compaction factors from the manufacturer of

1.25 and 1.12 respectively. FLL characterisation of substrate field capacity is undertaken on compacted substrate samples to replicate established roof conditions. A compaction factor of approximately 1.2 is used, whereby 120 mm of substrate is compacted to a 100 mm depth for testing. The similarity of monitored field capacity values (Figure 4) and FLL-derived values (Table 1) from Year-3 onward could indicate a similar level of compaction in the in-situ substrates to the FLL test samples. This further suggests that prior to Year-3 the in-situ substrates were not fully consolidated.

In the upper substrate layers the differences between median monitored field capacity in Year-2 and Year-3 are reduced for vegetated substrate configurations compared to lower layers and unvegetated configurations. This suggests that the vegetation is playing a role in moderating substrate consolidation, an observation that has also been made in bio-filter media (Virahsawmy et al., 2014).

Whilst substrate consolidation may have led to the observed increased values of Θ_{FC}, the absolute retention storage capacity of the roof may not have increased as predicted. As Θ_{FC} is measured as a percentage, reducing substrate depths (consolidation) will mean that retention capacity will decrease if Θ_{FC} is constant. The substrate depths of the Hadfield Test Beds were not monitored over the course of the monitoring programme and so it cannot be definitively said that the identified increases to Θ_{FC} have led to corresponding increases in retention capacities. Assuming the following: consolidation in line with the manufacturer's recommendations for HLS; PWP values equal to those identified by Poë et al. (2015); an initial substrate depth of 100 mm; a final substrate depth of 80 mm; and utilising the median values of monitored field capacity for TB1, potential retention capacity (PRC) in an unaged TB1 would have been approximately 28 mm compared to 26 mm in an aged TB1. This example highlights the importance of understanding the relationships between substrate physical properties and hydrological performance.

Ultimately, from the analysis of long-term retention performance, there is evidence of an increase in Θ_{FC} between Year-2 and Year-3, but there is little significant change after this point. If these increases in Θ_{FC} are a result of consolidation, then substrate depths are required to assess changes in the absolute potential retention capacity of the system.

Sub-annual temporal variations

Seasonal trends within the monitored field capacity data closely follow expectations of seasonal vegetation behaviour, with greater foliage extent and higher water use in summer months. However, the presence of seasonal changes also in TB7, which is unvegetated, indicate that this is unlikely to be the sole cause. An alternative hypothesis is that a seasonal variation in the substrate's wetting and drying response — as a result of variable water repellency — is being observed. As a substrate dries, just like an ordinary soil, the organic secretions of roots and soil microorganisms become more concentrated. In doing so, these secretions become increasingly hydrophobic, actively repelling water (Doerr et al., 2000). During winter months, frequent rainfall events and low levels of ET prohibit the substrate from drying excessively (Berretta et al., 2014), preventing the formation of strongly hydrophobic films on substrate particles. Low levels of hydrophobicity allow water to adhere to substrate surfaces, increasing the moisture content.

Contrastingly, in summer, there are fewer rainfall events and higher temperatures, allowing for greater depletion of substrate moisture through ET. These conditions allow for the generation of a hydrophobic environment, such that at the onset of the next rainfall event water is repelled from substrate particles (Doerr et al., 2000). This causes rainfall to leave the green roof more quickly and prevents the ingress of water to smaller pores, resulting in lower substrate moisture levels than may otherwise be theorised.

5.2. Detention

Annual temporal variations

Conventional detention metrics derived from observed runoff are not independent of retention effects and are poor descriptors of differences in temporal changes in actual detention processes. The application of a hydrological model to simulate detention processes, and the fitting of its parameters, provides an independent and more descriptive overview of potential variation in detention performance in the long-term. The steady year-on-year increase in the value of D_S observed in the unvegetated test beds implies that the driver of this change is a continuously occurring process. The more consistent values of D_S over time for vegetated beds suggest that vegetation helps mitigate against the negative effects of this unidentified process on detention performance. A reduction in detention performance (implied by increased D_S values) is perhaps unexpected, if substrate consolidation is occurring — as hypothesised from monitored field capacity observations — then detention performance may be expected to increase. Consolidation reduces substrate pore sizes, potentially reducing the cross-sectional area for water flow, thus resulting in a reduced hydraulic conductivity and a theorised improved detention performance (De-Ville et al., 2017).

The steady increases in D_S in the unvegetated beds could indicate the steady decay of the initial organic matter content over time. This loss of organic content has been observed in the literature, with Bouzouidja et al. (2016) observing a net loss of organic matter (peat dust and pine bark) from 5.0 to 2.1% v/v over 4 years in a vegetated system. Therefore, greater organic losses may be expected in the unvegetated test beds as no new organic matter is entrained through vegetative processes. The long-term stability of different organic matter types within extensive green roof systems remains largely unexplored. However, the use of partially decomposed organic matter (such as peat, and/or peat dust) in new systems may result in greater decomposition than other sources (Ampim et al., 2010). The unvegetated LECA substrate (TB9) experiences the greatest increase in median D_S over the study period, its compost only organic material may have decayed faster than the compost and fibre mix of HLS and SCS. For the unvegetated LECA substrate (TB9), the trend seen in the first 5 years of the study would support this hypothesis of organic content decay, with detention performance deterioration slowing until a steady level is reached around Year-4 to Year-5. This hypothesis could have been confirmed through the repeated sampling and analysis of substrate samples for organic content. The impact that organic matter changes can have on green roof hydrological performance was demonstrated by Yio et al. (2013), where a threefold reduction in organic content (coir) caused peak attenuation to fall from >50 to 15%.

Sub-annual temporal variations

Seasonal trends in D_S are the result of many co-active processes, the most visible cause being vegetation growth phases, evidenced by the generally reduced variation seen for unvegetated test beds (Table 2). It may have been expected that the Meadow-Flower vegetation (TB4-6) would experience the greatest levels of variation, due to the deciduous nature of many of the species, which greatly reduces vegetation coverage in winter months. However, Sedum vegetated configurations experienced the greatest sub-annual variation for 2 of the 3 substrate types (SCS - TB2, and LECA - TB3, Table 2). This observation, coupled with the presence of sub-annual variation in unvegetated test beds, indicates the presence of additional drivers of variation.

The sub-annual variation in substrate water repellency, hypothesised for the retention analysis, also has the potential to influence detention performance. The greater substrate moisture during winter months and reduced hydrophobicity/repellency permits the movement of water through the small pore networks of the substrate. This leads to increased travel times and ultimately greater detention performance, whilst in summer, increased hydrophobicity/repellency prevent water ingress into smaller pores and directs it into preferential flow paths (Doerr et al., 2000), reducing travel times and thereby reducing detention performance. The reduced levels of seasonal variation in the unvegetated test beds are therefore believed to be associated with reduced levels of organic matter and the absence of roots. Without these, the generation of hydrophobic conditions is greatly reduced. Combining observations for TB9's year-on-year decline in detention performance

— hypothesised to be associated with reducing organic levels — with these seasonal trends, adds additional support to the hypothesis of substrate hydrophobicity/repellency being the main observable driver of seasonal performance variation.

5.3. Comparison of long-term evolutions and sub-annual performance variations

Whilst long-term evolutions in retention and detention performance were observable for vegetated configurations, they generally resulted in insignificant reductions to overall hydrological performance. This evidence of consistent long term potential hydrological performance is reassuring given the increasing deployment of extensive green roof systems globally. However, sub-annual changes in the value of D_S were an order of magnitude higher than long-term evolutions. As discussed previously, TB1 experienced a 4% reduction in peak attenuation from Year-1 to Year-6, but a 15% reduction from winter to summer. This provides further evidence that sub-annual trends are more important in predicting vegetated green roof hydrological performance than long-term trends. As green roof systems are predominantly vegetated, these findings may be of particular importance to stormwater engineers.

The inverse relationships of sub-annual retention and detention performance, are likely to result in a moderately consistent year-round runoff response. Reduced summer detention performance is negated by typically longer ADWPs (greater retention), and elevated winter detention benefits restricted by low levels of PET (reduced retention). Figure 12 highlights these effects whilst also exploring the role of storm duration and return period. It is seen that extended storm durations and increased return periods, both synonymous with higher rainfall, result in reduced peak attenuation performance in all cases. This further highlights the finite nature of retention capacities and the importance of ADWP duration for storage recovery.

6. Conclusions

This study has explored the temporal variations in potential hydrological performance of a series of extensive green roof test beds with varying configuration. Potential retention performance was identified through a novel approach of substrate moisture content monitoring. Detention performance was identified via descriptive hydrological model parameters. Together, these observations permitted the prediction of overall hydrological response variation at sub-annual and long-term temporal scales.

Monitored trends in substrate field capacity over time indicate an overall increase in potential retention performance over the study period. The small improvements in retention performance are likely to be the result of substrate consolidation generating more small substrate pores capable of holding water against gravity. Increased consolidation in the unvegetated test bed indicates that root action helps to stabilise retention performance over time. However, the magnitude of these improvements is exceeded by seasonal performance variations.

For detention performance, seasonal variation also proved to be more evident compared with annual trends. The steady year-on-year decline in detention performance for unvegetated test beds, compared to the relatively stable yearly performance of vegetated test beds, suggests that organic matter decay is the likely cause of long-term detention performance deterioration.

However, this hypothesis needs to be confirmed with monitoring of organic content evolution.

The identified sub-annual trends in retention and detention are hypothesised to be a result of temporally variable hydrophobicity/water repellency of the substrate. However, PET is also a controlling factor for potential retention performance. In the warmer summer months, water repellency is increased, limiting the elevated summer potential retention generated by greater PET, and directing flow into preferential flow paths thus reducing detention performance. In the cooler winter months, water repellency is low and so does not restrict potential retention performance which is then limited by low levels of PET. Detention performance is maximised under winter conditions as flow is more uniformly distributed throughout the substrate.

All of the above findings may help to explain why a Sedum vegetated green roof with a brick-based substrate has become a global industry standard. This configuration is capable of supporting strong levels of retention and detention, without significant long-term deteriorations in performance. However, what has been highlighted is the need for further understanding of the precise drivers of sub-annual variation. Multiple data sources and methods of analysis suggest that sub-annual water repellency cycles could be the driver, but further research is required.

Acknowledgements

Simon De-Ville was supported by an EPSRC DTA Award (EP/L505055/1).

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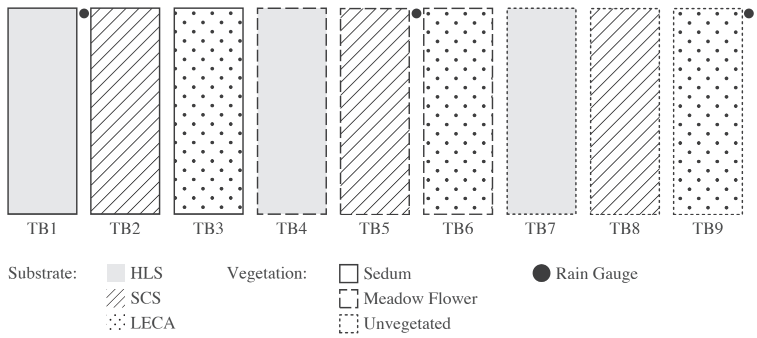

Figure 1: Test bed (TB) configuration layout. The nine test beds are grouped by the three vegetation treatments (indicated by exterior line style) with a repeating substrate order (indicated by shading style). HLS: Heather with Lavender Substrate, SCS: Sedum Carpet Substrate, LECA: Light Expanded Clay Aggregate Substrate. [190x70 mm]

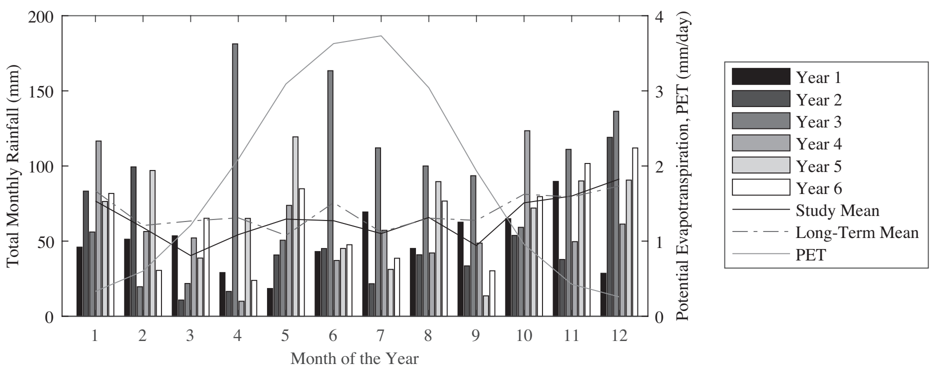

Figure 2: Monthly rainfall data for the 6 year study period compared to the long-term mean (1981-2010) for Sheffield, UK (UK METOffice, 2016), and Hargreaves PET values. [190x70 mm]

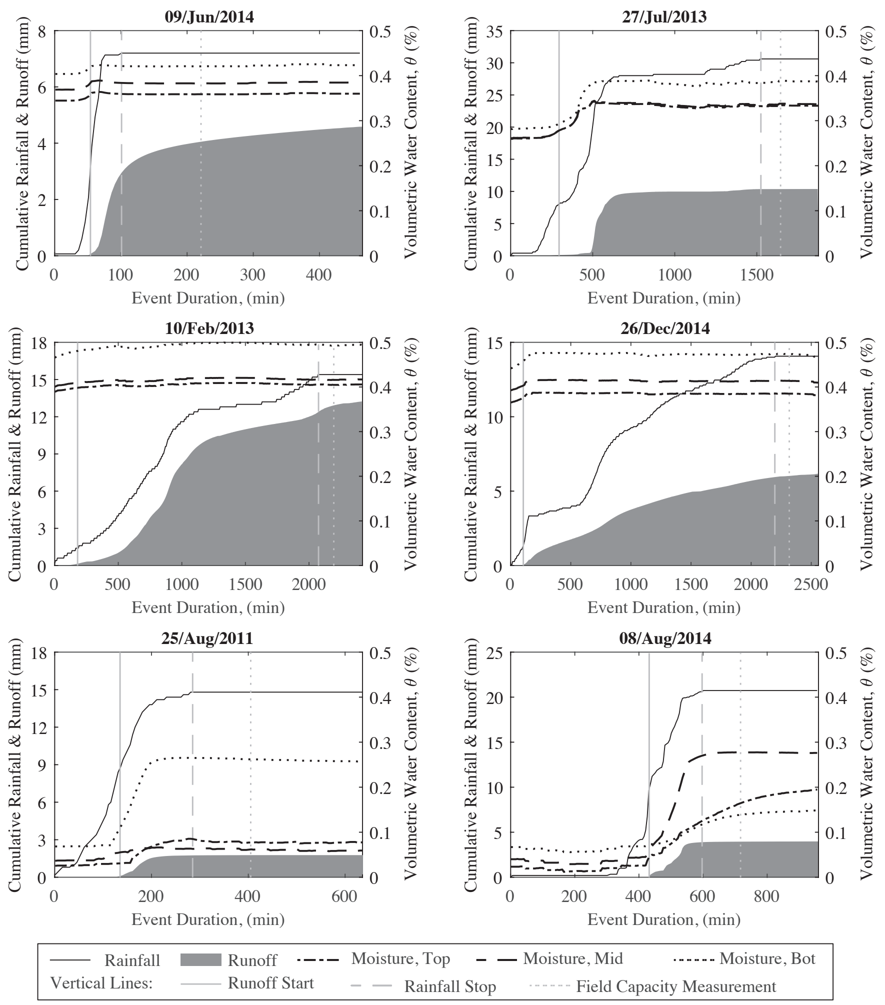

Figure 3: Moisture content profiles for TB1 for various storm events during the study period. [190x190 mm]

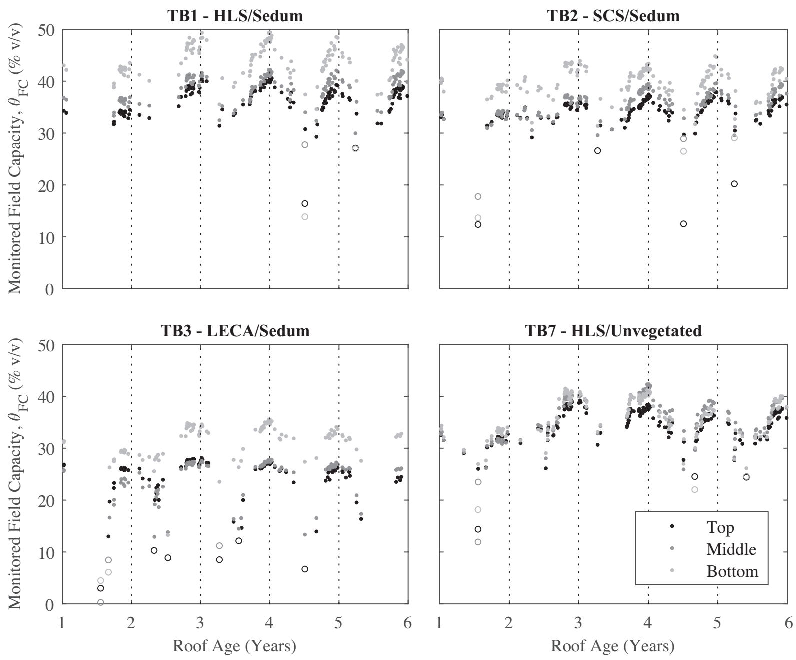

Figure 4: Observed temporal variation in monitored Field Capacity (outlier events included and shown as unfilled circles). [190x140 mm]

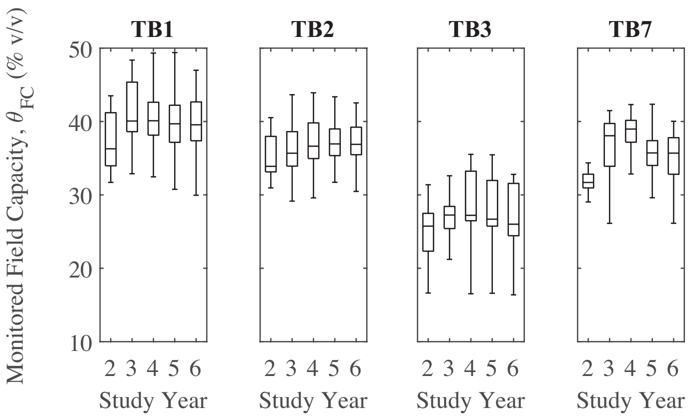

Figure 5: Categorised annual variation in monitored Field Capacity over full substrate depth. [140x60 mm]

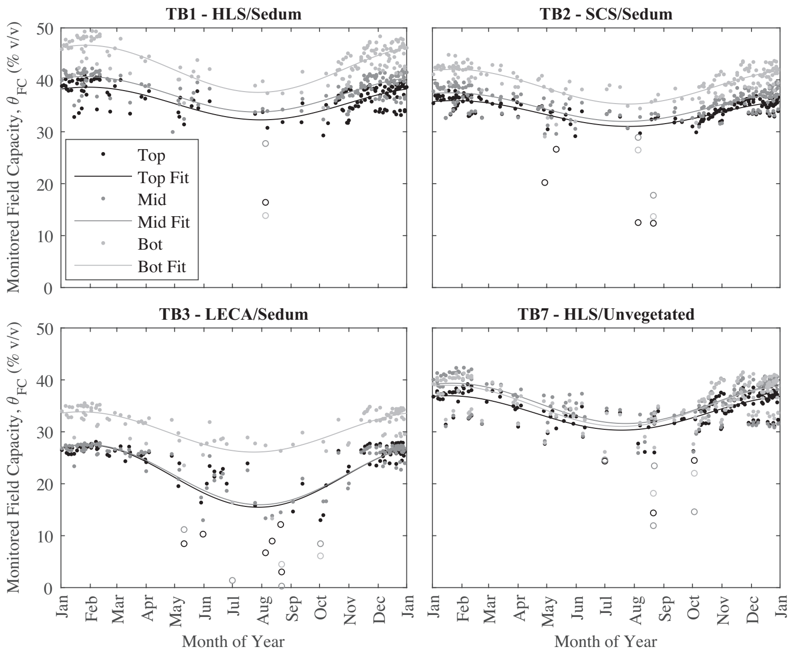

Figure 6: Monitored Θ_{FC} over time including Fourier series model fit (outlier events included and shown as unfilled circles). [190x140 mm]

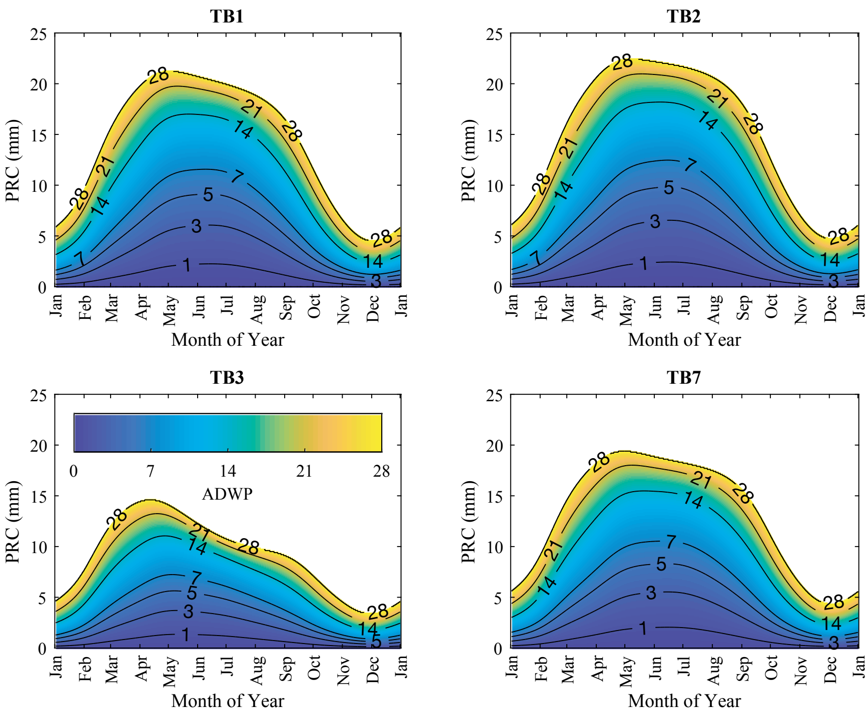

Figure 7: Potential retention capacities (PRC) of the four green roof test beds across a year for varying ADWP durations. Contours indicate ADWP in days.[190x140 mm]

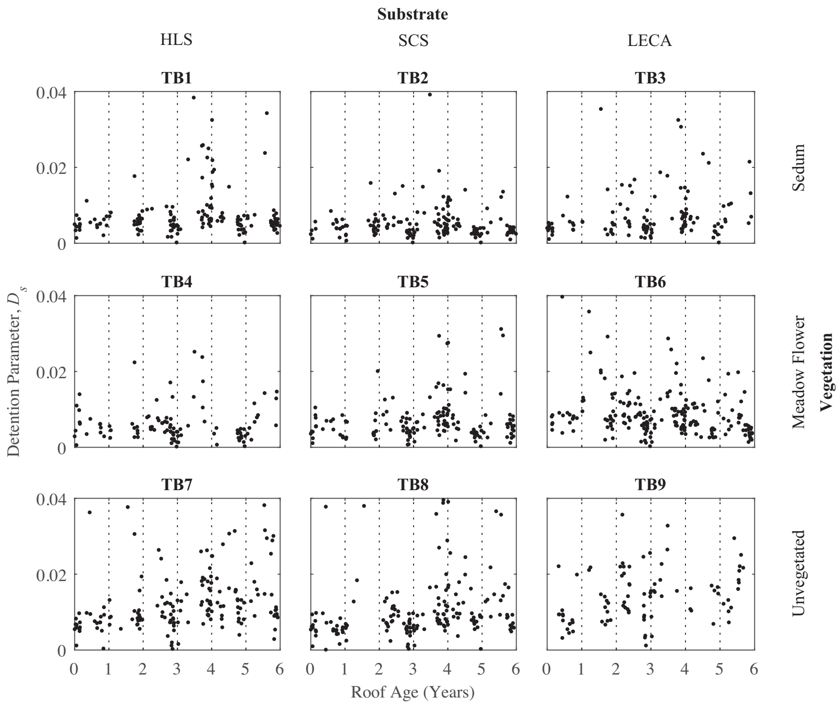

Figure 8: Temporal variation in detention model parameter D_s ($D_s > 0.04$ not shown). [190x140 mm]

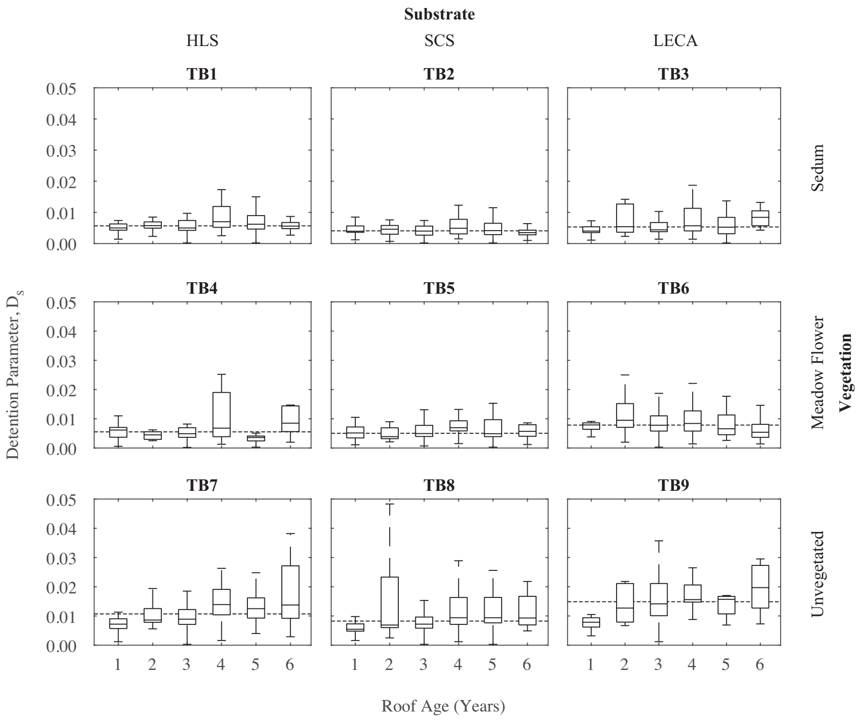

Figure 9: Median values of detention model parameter D_s for each test bed configuration. Dashed horizontal line indicates overall study median. [190x140 mm]

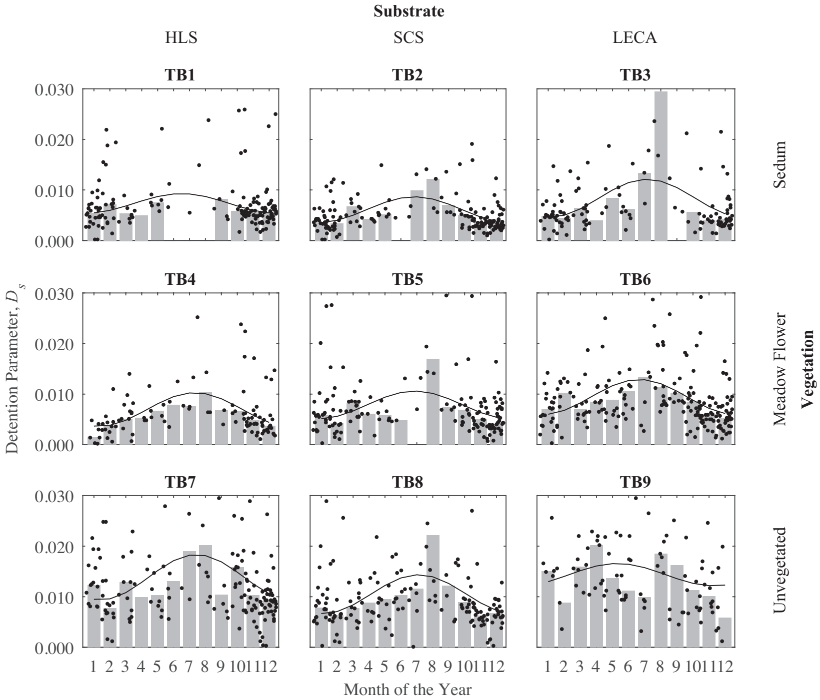

Figure 10: Scatter plot of identified detention model parameter D_S over time including monthly median values (bars) and best fit Fourier series model (line). [190x140 mm]

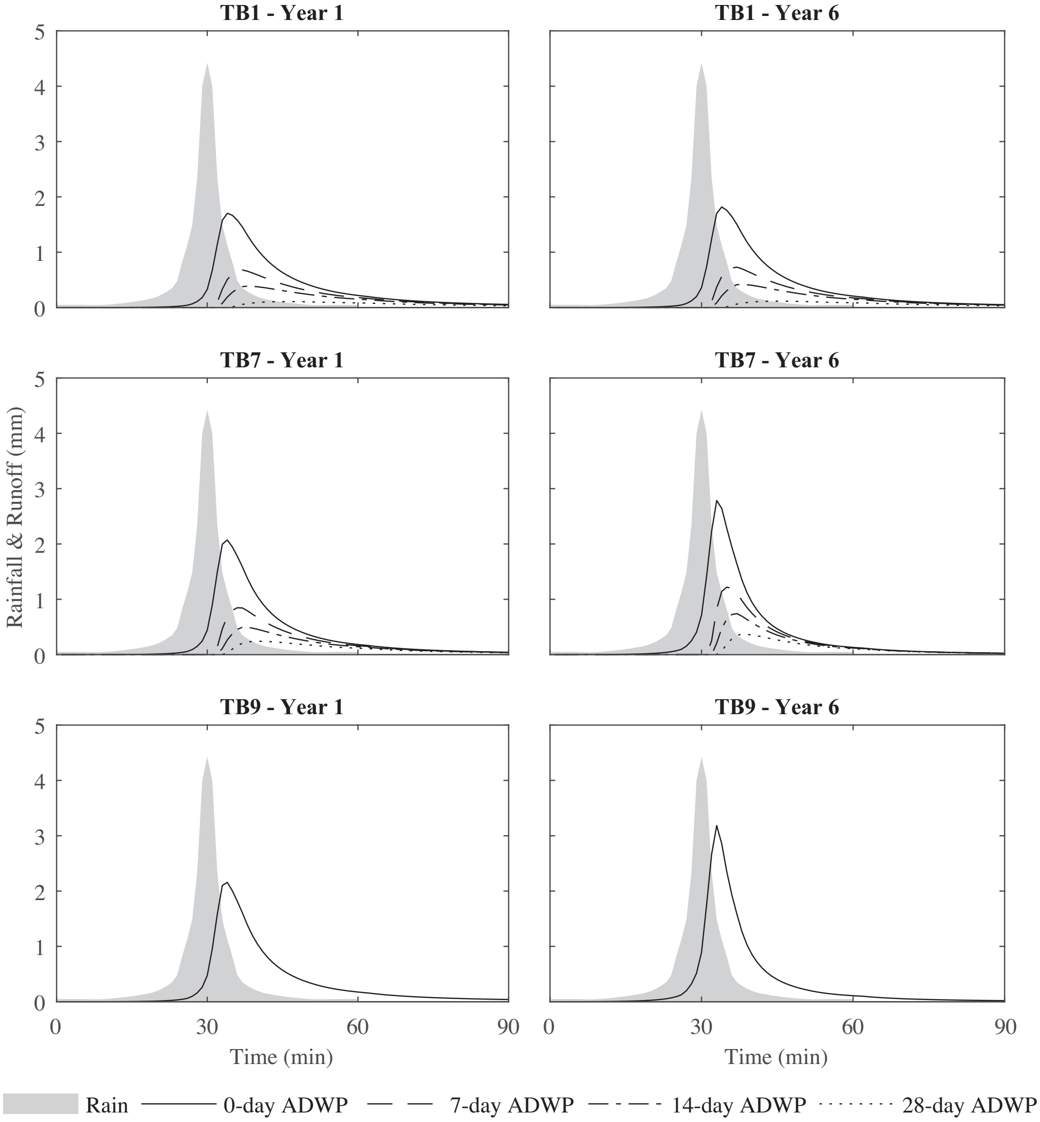

Figure 11: Modelled runoff profiles at Year-1 (left) and Year-6 (right) in response to a 1-in-30-year 1-hour Summer design storm for Sheffield, UK, for varying ADWP. Note: only 0-day ADWP for TB9 as moisture data/retention changes are not available. [190x180 mm]

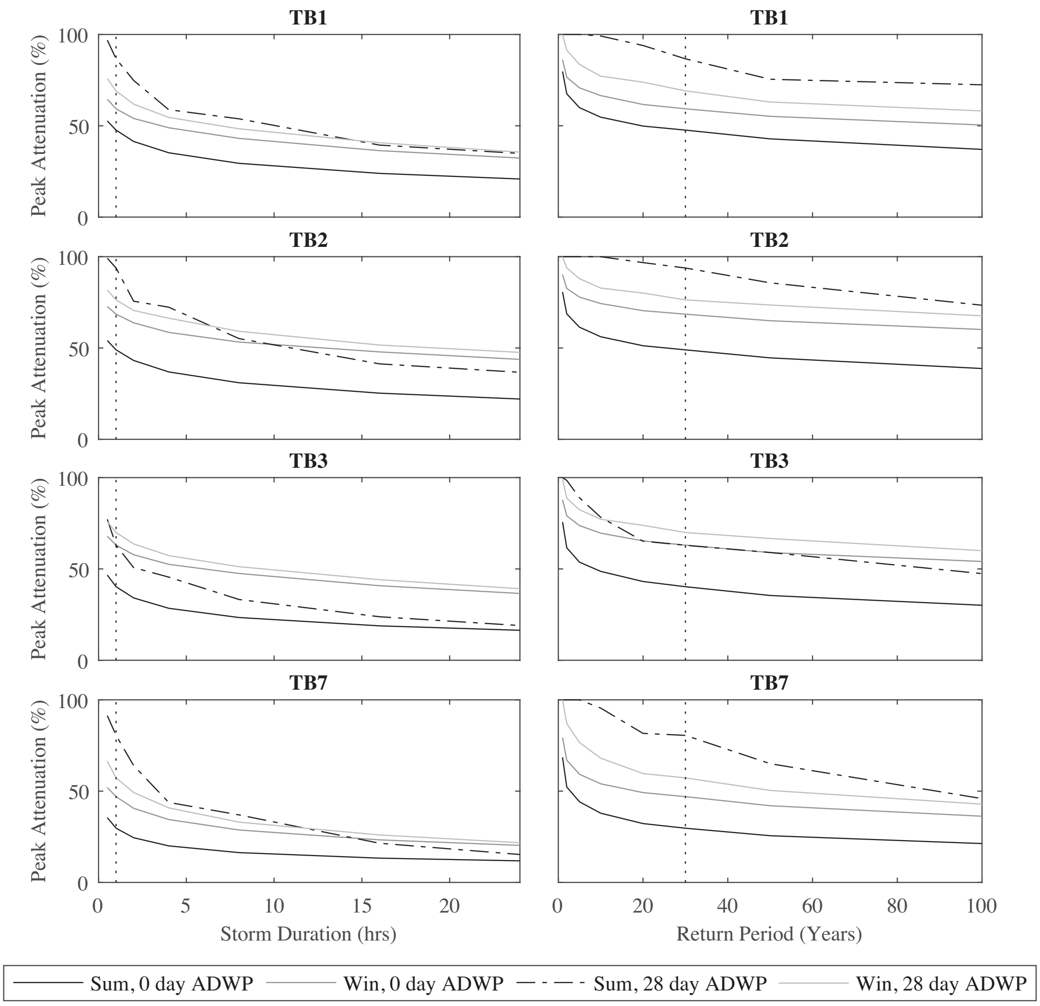

Figure 12: Peak Attenuation values of four test bed configurations for Summer and Winter conditions at 0 and 28-day ADWP durations, with varying Storm Duration (Left) and Storm Return Period (Right). Vertical dashed lines indicate the specific event considered in Figure 11. [190x160 mm]