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The influence of substrate and vegetation configuration on green roof hydrological performance

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ABSTRACT

A four-year record of rainfall and runoff data from nine different extensive (80 mm substrate) green roof test beds has been analysed to establish the extent to which the substrate composition and vegetation treatment affect hydrological performance. The test beds incorporated three different substrate components with different porosity and moisture retention characteristics, and three different vegetation treatments (Sedum, Meadow Flower and unvegetated).

Consistent differences were observed, with the vegetated beds showing higher levels of rainfall retention and better detention compared with unvegetated beds. The seasonal Meadow Flower beds had similar hydrological performance to Sedum-vegetated beds. There was a 27% performance reduction in annual volumetric retention attributable to differences in substrate and vegetation. The beds with the most porous/permeable substrates showed the lowest levels of both retention and detention.

As with previous studies, retention efficiency in all nine beds showed a strong dependency on rainfall depth (P), with retention typically >80% for events where $P < 10$ mm, but significantly lower when $P > 10$ mm. The effects of vegetation and substrate were most evident for rainfall events where $P > 10$ mm, with the mean per-event retention varying between beds from 26.8% to 61.8%. On average, the test beds were able to retain the first 5 mm of rainfall in 65% of events where $P > 5$ mm, although this ranged from 29.4% to 70.6% of events depending on configuration. In terms of detention, all but one of the test beds could achieve runoff control to a green field runoff equivalent of 2 l/s/ha for more than 75% of events.

Detention was also characterised via the calibration of a reservoir-routing model that linked net rainfall to the measured runoff response. The parameter values identified here – when combined with a suitable evapotranspiration/retention model – provide a generic mechanism for predicting the runoff response to a time-series or design rainfall for any unmonitored system with comparable components, permitting comparison against local regulatory requirements.

1. Introduction

1.1. Background

Green roofs are widely understood to offer stormwater management capabilities via the retention of rainfall and the detention of runoff. In this context, retention refers to rainfall that is held within the roof system and does not leave the roof as runoff (i.e. initial losses). Retained rainfall may subsequently leave the roof as evapotranspiration. Detention refers to the temporal delay that occurs between rainfall that is not retained hitting the roof and emerging as runoff.

Stormwater management regulations vary across jurisdictions, but most include requirements for both volumetric control (retention) and for detention. Volumetric control requirements are intended to protect the water quality in receiving watercourses, mitigate flood risk, and minimise the volumes unnecessarily treated in, or intermittently spilled from, combined sewers. Detention control is required to reduce the risks associated with pluvial flooding and/or intermittent combined sewer overflows. In England and Wales, for example, developers are encouraged (but not required) to use Sustainable Drainage Systems (SuDS). Current SuDS guidance (Woods-Ballard et al., 2007) includes requirements to prevent runoff from (i.e. retain) the first 5 mm of rainfall, and to attenuate the 6 h duration 100 year return period event to a

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greenfield runoff rate equivalent to 2 l/s/ha. Drainage systems specifically need to be designed to avoid causing site flooding in the event of a 1 in 30 year event. This guidance relates to site runoff, and a complete SuDS system may incorporate a green roof upstream of a number of other SuDS devices to form a site-scale treatment train. Within this context, it is clear that a proper understanding of green roof hydrological performance underpins SuDS design to meet regulatory requirements for stormwater management.

Many pilot and full scale monitoring studies have been undertaken (see e.g. Palla et al. (2010) or Li and Babcock (2014) for an overview). Although many authors have provided generalised metrics – such as mean per-event retention – to characterise performance, it is widely acknowledged that runoff responses to specific events depend upon a complex set of processes and interactions involving roof configuration (slope, aspect, drainage layer, substrate type and depth, and vegetation), rainfall characteristics (duration, depth, intensity) and antecedent conditions (in particular the role of evapotranspiration in restoring the substrate's retention capacity).

For test beds located together and subjected to the same climatic influences, it is feasible to identify trends in retention performance related to the specific roof configuration, and in particular to substrate and vegetation characteristics. For shallow systems (25–60 mm substrate) VanWoert et al. (2005) found that beds planted with Sedum species provided marginally greater volumetric retention compared with unvegetated systems, but suggested overall that the substrate physical properties and depth would have greater influence than vegetation. Monterusso et al. (2004) also concluded that the substrate has a greater influence than the vegetation on retention performance. Wolf and Lundholm (2008) found that vegetation enhanced moisture loss in green roof microcosms subjected to controlled irrigation regimes, but only when water availability was very low. Similarly, Nagase and Dunnett (2012) used controlled rainfall experiments to test 12 different plant species, and found that greater plant mass had a positive influence on runoff reduction. However, the effects are likely to have been exaggerated compared with complete green roof systems due to the use of a minimal substrate depth and some fairly substantial plants. Graceson et al. (2013) also demonstrated that the volumetric retention associated with different configurations of green roof test beds was more significantly affected by the physical properties of the growing media, particularly its pore size distribution and the maximum water holding capacity, than by either the vegetation treatment (Sedum or Meadow Flowers) or the growing media depth.

Detention comparisons are less regularly reported. Detention processes are difficult to characterise because many of the reported observable detention effects – such as the time to start of runoff – include the effects of retention at the start of the storm event (Stovin et al., 2015). For example, Whittinghill et al. (2015) compared the runoff profiles from Sedum, native prairie and vegetable-producing green roofs, suggesting that detention effects were more evident with Sedum and prairie grass compared with the vegetables. However, it is unclear exactly how detention was determined in this case.

Green roof detention combines the effects of many elements, including: detention due to plants; delays experienced as the runoff flows vertically downwards through the substrate (dependent on substrate depth and physical characteristics); and interactions between plant roots and the substrate.

In full-scale systems detention effects will also include delays experienced as the runoff drains through the drainage layer (which will be affected by the roof length and drainage layer configuration); and delays occurring in the guttering and downspout (affected by flow path length) upstream of the measurement location. Vesuviano et al. (2014) proposed a two-stage (substrate plus drainage layer) detention modelling approach, but this ignored any effects due to the collection system downstream of the roof. Fassman-Beck et al. (2013) observed that the downstream collection system may have contributed to differences in the 5-min Peak Attenuation observations for four different extensive living roofs in Auckland, New Zealand.

Laboratory studies enable rainfall inputs to be controlled, and for selected components of the green roof system to be considered in isolation. In reality green roofs will generally provide some retention at the start of a rainfall event, which will mean that observed attenuation effects will exceed the benefits due to physical detention processes alone. Where detention performance is the focus of the study, the substrate should initially be brought to field capacity to eliminate retention effects (Villarreal, 2007; Alfredo et al., 2010; Yio et al., 2013). The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidance (FLL, 2008) outlines a standard test to determine the coefficient of discharge, C, based on the ratio of cumulative runoff to cumulative rainfall at the end of a 15-min constant intensity rainfall of 27 mm. The test is undertaken in a 5 m laboratory rainfall simulator, with the substrate pre-wetted to ensure that it is at field capacity. Field capacity corresponds to the moisture that is held within the soil matrix against the force of gravity; in the FLL tests this corresponds to two hours' free drainage following saturation. The resultant value of C can be used to determine worst-case drainage requirements for the roof, and to compare the relative detention performance of different green roof systems. Colli et al. (2010) found that the FLL runoff coefficient increased (i.e. detention was reduced) with increased rainfall intensity, increased slope and decreased substrate depth.

These laboratory studies suggest that detention effects may be dependent on rainfall intensity and substrate physical characteristics (depth, porosity). However, these controlled studies were mainly undertaken with a single vegetation type or on unvegetated substrates, and therefore do not provide significant insights into the detention effects of different vegetation treatments. Buccola and Spolek (2010) varied vegetation treatments, but reported that their findings were inconclusive. There is therefore a requirement for improved understanding of the combined effects of vegetation and substrate configuration on green roof detention performance.

Comparative studies based on field or laboratory monitoring programmes provide useful data on the relative benefits of different configuration options, but they do not directly permit the prediction of runoff responses to arbitrary rainfall events, in particular to the design (extreme) rainfall events that are considered relevant for urban flood mitigation. Stovin et al. (2013) and Locatelli et al. (2014) inter alia have emphasised the value of using empirical data to develop, calibrate and validate modelling tools to enable quantitative runoff prediction and attenuation evaluation. Key to this model development is the need to represent the initial losses (retention) processes and the delay (detention) processes independently. The complex interactions between plant roots and the substrate imply that detention effects are unlikely to be accurately predicted from knowledge of the substrate's physical characteristics alone, so an empirical approach to the identification of suitable model coefficients may be required. Stovin et al. (2015) argued that empirically-calibrated detention modelling parameters provide a unique and fundamental description of a system's detention characteristics, which is independent of retention effects.

In this paper detention model parameter identification will be applied to data from a four-year field monitoring experiment to quantify the combined effects of both substrate and vegetation treatments on green roof runoff detention performance. This approach permits an assessment of the relative performance benefits of alternative vegetation/substrate combinations, and also provides a calibrated set of model parameters to enable each of these system's responses to unseen rainfall events to be predicted.

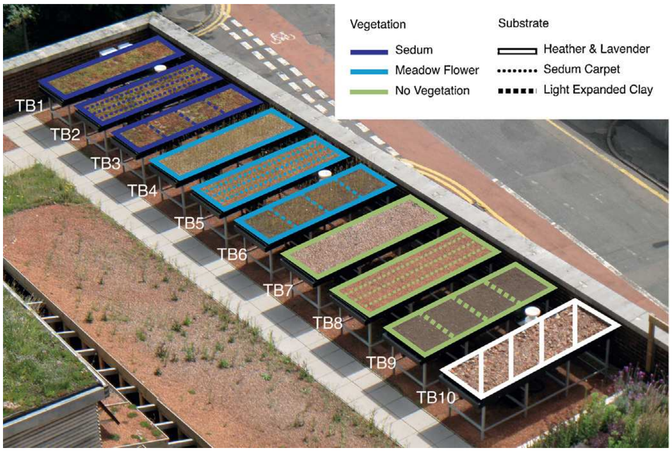


Fig. 1. The Hadfield Test Beds at The University of Sheffield. The nine test beds incorporate three different vegetation treatments (arranged in groups of three, colour coded) and three different substrates (repeating order within each vegetation treatment group, indicated by shading). Note that TB10 is not relevant to the present study. Photograph taken 16 July 2009. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.2. *Objectives*

The objectives of the present paper are: to establish whether the previous findings relating to the effects of substrate and vegetation on retention performance are reflected in the hydrological data from previously-unreported four-year pilot-scale trials; to provide new insights into the effects of configuration on detention performance; and to comment on the implications of any systematic differences for stormwater management.

2. Material and methods

2.1. *The experimental setup*

The research was conducted at the University of Sheffield's Green Roof Centre. The test site is located on a fifth-floor terrace of the Sir Robert Hadfield building (Grid Reference 53.3816, −1.4773) and comprises 9 green roof test beds (TB) which vary systematically in their substrate composition and vegetation treatments (Fig. 1). This experiment was established in summer 2009 and data have been collected since February 2010 to assess the extent to which substrate type and vegetation treatment affect runoff retention and detention performance. Each test bed is 3 m long × 1 m wide, installed to a 1.5° slope. The test beds consist of an impervious hard plastic tray base, a drainage layer (ZinCo Floradrain FD 25-E), a filter sheet (ZinCo Systemfilter SF), and one of three substrates (80 mm deep). With the intention of providing universally-applicable findings, two commercially-available substrates manufactured by Alumasc ZinCo – Heather with Lavender Substrate (HLS) (TB1, TB4 and TB7, Fig. 1) and Sedum Carpet Substrate (SCS) (TB2, TB5 and TB8) – were considered, alongside a bespoke substrate based on the widely used Lightweight Expanded Clay Aggregate (LECA) (TB3, TB6 and TB9). HLS is a semi-intensive commercial substrate which consists of crushed bricks and pumice (ZincolitPlus), enriched with organic matter including compost with fibre and clay materials (Zincohum) (ZinCo GmbH). The SCS substrate is a typical extensive green roof substrate consisting of crushed bricks (Zincolit), enriched with Zincohum. The LECA-based substrate contains 80% LECA, 10% loam (John Innes No. 1) and 10% compost by volume.

Laboratory tests on these substrates were carried out according to the Guidelines for the Planning, Construction and Maintenance of Green Roofing of the German Landscape Development and Landscaping Research Society (FLL, 2008). The tests included Particle Size Distribution (PSD), apparent density (dry condition (105 °C for >24 h) and at maximum water capacity), total pore volume, maximum water holding capacity (MWHC), permeability and organic content (Table 1). To address the uncertainty associated with sub-sampling heterogeneous mixtures, a sample splitter was used and 3–6 replicate samples were tested, depending on the analysis.

Considerable uncertainty surrounds the permeability data presented in Table 1, as the relatively small sample size (150 mm diameter cylinder 100 mm deep) and small head drop assessed (10 mm only) lead to considerable variation in repeat and replicate determinations. Some LECA samples could not be characterised due to the rapidity of the drop, with permeabilities in excess of 150 mm/min being estimated. The FLL test is primarily intended as a check against performance thresholds rather than an accurate physical characterisation, and Fassman and Simcock (2012) have also commented that additional work is required to define a meaningful standard permeability test for green roofs. For this reason the data are presented as a range of typically observed values. The three substrates generally comply with the FLL permeability requirements for vegetated extensive systems (0.6–70 mm/min), although some LECA samples may exceed the guideline. It is evident that the HLS substrate is the least permeable and that the permeability of LECA is one order of magnitude greater.

Berretta et al. (2014a) presented soil moisture release curves obtained using a Pressure Plate Extractor, which suggested lower values for the field capacity of both HLS and SCS at 25.0% and 22.4% (v/v) respectively. However, the test did not produce reliable values for the LECA-based substrate. De-Ville et al. (2015) used X-Ray microtomography to provide preliminary comparisons between the LECA-based substrate and a brick-based substrate comparable to the two considered here. From these images, total porosity was estimated to be higher for the LECA-based substrate (approximately 55%, v/v) compared with the brick-based substrates (40%, v/v). However, it is important to note that much of the pore space in the LECA-based substrate (as with other volcanically-derived aggregates such as pumice) is occupied by large pores and/or closed pores (i.e. internal to the expanded clay particles) rather than the smaller pores that actively contribute to water retention at field capacity. It is therefore expected that the LECA-based substrate will provide less retention and less detention when compared with brick-based substrates.

Possible effects due to substrate ageing have not been considered in the current analysis. However, there is an ongoing study specifically focusing on this aspect. De-Ville et al. (2015) also used the X-Ray microtomography data to comment on some possible substrate ageing effects, and these comments will be revisited as part of Section 4.

Recent photographs of the three substrates are provided in Fig. 2. No visible differences due to ageing are evident when comparing these images with photographs taken at the start of the trial. It may be seen that HLS appears to be contain a good mix of coarse and fine particles, with few unfilled large pore spaces. The SCS is more dominated by coarse aggregate particles, with some larger pore spaces evident. The LECA-based substrate is dominated by near-spherical uniformed sized particles, again with large pore spaces visible.

Three test beds were vegetated with Alumasc Blackdown Sedum Mat (TB1, TB2 and TB3), three with Meadow Flower (TB4, TB5 and TB6) and the final three have no vegetation (TB7, TB8 and TB9). Sedum was chosen because it is the most commonly adopted plant in green roof applications due to its tolerance of drought, extreme temperatures and high wind speeds, (VanWoert et al., 2005). Note that whilst some of the green roof literature asserts that Sedum species exhibit CAM (Crassulacean acid metabolism) physiology,

Table 1
Substrate characteristics according to FLL (2008) test methods.

		HLS (brick-based)		SCS (brick-based)		LECA	
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Particle size < 0.063 mm	(% w/w)	2.1	1.4	1.4	0.3	0.4	0.0
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
MWHC (field capacity)	(% v/v)	41.2	2.3	39.1	2.1	35.0	1.6
Air content at MWHC	(% v/v)	22.6	0.8	20.7	4.1	49.8	1.5
Permeability	(mm/min)	1–15		10–35		>30	
Organic content	(% w/w)	3.8	0.1	2.3	0.5	6.0	0.3

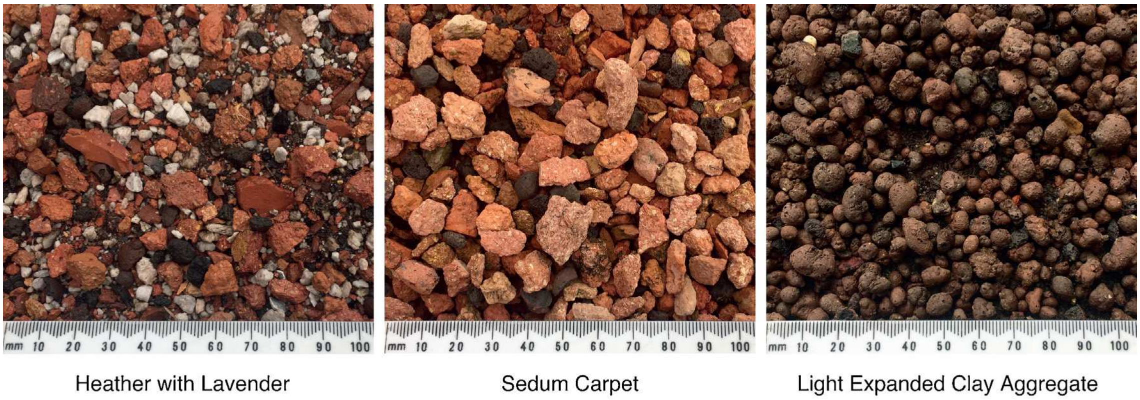

Heather with Lavender
Sedum Carpet
Light Expanded Clay Aggregate

Fig. 2. The three trial substrates. Photographs taken from TB7, TB8 and TB9 respectively in July 2015.

the consensus now is that this is probably not the case. Sedum species show good adaptation to drought conditions, reducing their moisture requirements in line with moisture availability. However, there is no evidence that this is achieved through switching to night-time transpiration. The Meadow Flower treatment comprises a mix of flowers, grasses and succulents that display poorer drought tolerance (Lu et al., 2014) but increase biodiversity potential (Benvenuti, 2014). Unvegetated configurations provide a basis against which the contribution of vegetation can be evaluated.

During this monitoring programme the vegetation was well established with surface coverage >85%. As would be expected, the vegetation changed seasonally and over time. In particular, the Meadow Flower coverage reduced in winter time and increased in spring.

The experimental setup includes a Campbell Scientific weather station that records 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 TB9 and TB10 (Fig. 1 (Note that TB10 was not part of the comparative experiment reported here)). Runoff was measured volumetrically in 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 on the sensor. The pressure transducers were calibrated against collected volumes on site. An electronic solenoid valve empties the tank when maximum capacity is reached and every day at 14:00. Runoff is recorded at one minute intervals. Data are recorded through a Campbell Scientific CR3000 data logger. Provisional findings from the beds have been reported by Poë et al. (2011) and Berretta et al. (2014b), whereas Berretta et al. (2014a) presented a detailed discussion of moisture content fluctuations that were monitored concurrently in four of the test beds, focusing specifically on evapotranspiration (ET). Poë et al. (2015) reported on detailed climate chamber tests aimed at quantifying ET rates for the same nine configurations.

2.2. Data analysis

The data record spans the period 2 Feb 2010–2 Feb 2014. The rainfall record was divided into individual storm events assuming a minimum inter-event dry period of 6 h (Stovin et al., 2012). Rainfall events with depths $P < 2$ mm were excluded from the analysis, as it is commonly assumed that normal impervious roof surfaces will retain up to 2 mm in initial losses (Voyde et al., 2010b). There were 324 individual storm events with $P > 2$ mm. This database of storm event responses is referred to as the AE (All Events) dataset.

2.2.1. Retention analysis

Inevitably there are gaps in the data record. These are predominantly associated with blockages in the valves used to empty the runoff collection barrels, which occurred more frequently than previous experience would have foreseen. The lowest number of valid runoff responses is 165 (TB9) and the highest is 258 (TB6). The gaps mean that concurrent data is only available for all nine beds for a subset of 49 events, approximately 15% of the AE dataset. This dataset is referred to as AE9. For retention analysis it should be recognised that any comparisons between test beds will be strongly influenced by the event rainfall characteristics, so the absence of one or more events from an individual test bed record could severely skew the results. Therefore all retention comparisons are made using only the AE9 dataset. Box plots were generated to allow an initial comparison of retention performance across the nine beds. However, as retention performance is heavily influenced by rainfall depth, log plotted probability density functions (pdfs) were also used to qualitatively compare the observed retention distributions. Retention comparisons were also made for a sub-set of the data with $P > 10$ mm.

Independent-samples Kruskal–Wallis tests with Dunn's pairwise comparisons were used to assess whether any observed differences due to either vegetation or substrate were statistically significant.

2.2.2. Detention analysis

For comparability with other published studies, Peak Attenuation values for the AE data with $P > 10$ mm were calculated. Peak Attenuation was defined as the percentage reduction in the peak 5-min runoff compared with the peak 5-min rainfall depth. It should be noted that this method does not distinguish between detention effects resulting from initial losses (retention) and actual physical delays inherent in the system.

Stovin et al. (2015) highlighted the fact that most of the parameters typically used to describe detention performance (e.g. Peak Attenuation, centroid-to-centroid delay) fail to provide a good indication of actual detention processes, due to the influence of retention effects (initial losses) on real monitored runoff data. Only when a system is at field capacity at the onset of a storm event will detention metrics reflect the effects of detention alone. Stovin et al. (2015) proposed an alternative approach which assumes that the roof's detention characteristics are properties of the physical system and therefore independent of rainfall event characteristics. Assuming that a suitable hydrological model for the detention process can be identified, the observed rainfall-runoff data may be used to identify the model parameter(s) that uniquely define each individual system's detention characteristics.

Several different approaches to modelling green roof detention processes have been presented in the literature, including finite element (Hilten et al., 2008; Palla et al., 2012) and unit hydrograph-based (Villarreal and Bengtsson, 2005) approaches. However, many authors have shown that simple reservoir routing approaches are suitable for modelling green roof detention processes (Kasmin et al., 2010; Yio et al., 2013).

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

$$h_t = h_{t-1} + Qin_t \Delta t - Qout_t \Delta t \tag{1}$$

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

$$Qout_t = kh_{t-1}^n \tag{2}$$

in which k and n are the reservoir routing parameters (scale and exponent respectively). For h in mm and Q in mm/min, k has the units $\text{mm}^{(1-n)}$/min, whilst n is dimensionless. Based on a typical extensive green roof test bed, values of 0.03 and 2.0 for k and n respectively were identified. (Note that the originally reported k value of 0.15 corresponded to a 5-min time step).

These initial estimates of k and n represent the combined detention effects due to the roof's vegetation, substrate and drainage layer. When considering only the influence of the substrate layer, Yio et al. (2013) demonstrated that a model based on a fixed value of n 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.

In the present study n was fixed at 2.0, and the best-fit value of the reservoir routing parameter k was identified for each of the nine test beds. Initial losses (or retention, defined simply as Rainfall (P) minus Runoff (R) in mm) were removed from the start of the monitored rainfall data to generate the net rainfall profile prior to reservoir routing. The *lsqcurvefit* function in MATLAB (2007) was utilised to identify the best-fit value of k for each individual event based on maximising the value of R_t^2 (Young et al., 1980) between the routed and monitored runoff profiles. The routing employed a 5-min time-step.

As the value of k is considered to be a system property, and therefore should not be affected by rainfall characteristics, the full AE dataset was used for this analysis. However, as it is not meaningful to assess detention for rainfall events that do not generate runoff, a minimum runoff threshold of 2 mm was applied. This resulted in between 71 and 136 events being used to identify the best-fit k value for each test bed. For each test bed the individual event-based calibrated k values were combined to determine the test bed's median k value. The derived values of k were compared both on a configuration-by-configuration basis, and by combining beds into groups of three to compare the effects due to substrate and vegetation. Independent-samples Kruskal–Wallis tests with Dunn's pairwise comparisons were carried out to determine whether the identified k values were statistically independent.

3. Results

3.1. Storm events

Fig. 3 shows the monthly rainfall depths throughout the study period. The totals highlight the typically high levels of variability associated with temperate climates, but also confirm that the mean depths are reasonably consistent with the location's long-term mean (UK Met Office, 2015). Spring/summer 2012 was unusually wet, whilst an unusually dry period occurred in Feb/Mar 2012.

Fig. 4 shows the probability distribution of the monitored rainfall event depths for both the AE and the AE9 data sets. It may be seen that the AE9 dataset includes only one of the largest (>30 mm) events present in the AE data, but that otherwise the sampled events are very representative. The largest events will tend to have the greatest impact on retention performance metrics, so it is important to ensure that only the AE9 data is used when direct comparisons are made across the nine beds.

The relevant historical intensity-duration-frequency data for Sheffield (NERC, 1999) suggests that the analysed data includes a number of events that might be considered significant, i.e. with return periods of 1–5 years. Three events in the AE9 dataset have return periods of greater than one year. There are 19 events in the AE dataset and 1 in the AE9 dataset exceeding 25 mm, which is the 1 in 2 year return period depth for a 6-h duration event. Ten events in AE9 have more than 10 mm rainfall, whilst over 70% of the events have rainfall depths of less than 10 mm; many of these result in little or no runoff.

Prior to considering the detailed statistical analysis of retention and detention performance, it is useful to qualitatively consider the way in which the individual beds respond to comparable rainfall inputs.

Fig. 5 presents cumulative runoff profiles for six storm events. These events have been selected as representing the range of storm events and responses observed. Except for EV314, they are all complete AE9 events, thereby allowing the nine test beds to be directly compared. The selected events include three from dry summer conditions and three from wetter winter conditions. The rainfall data for these events (ranging from 7.4 to 24.8 mm in depth), are presented in Table 2.

Several consistent behaviours can be observed in the runoff responses. In all cases except EV314 there is a marked delay between the onset of rainfall and the onset of runoff. This represents the period in which rainfall is subjected to initial losses, either intercepted by vegetation or retained within the substrate. The depth of rainfall that is retained depends on moisture losses due to ET in the antecedent period, and ranges here from 0 to 20 mm.

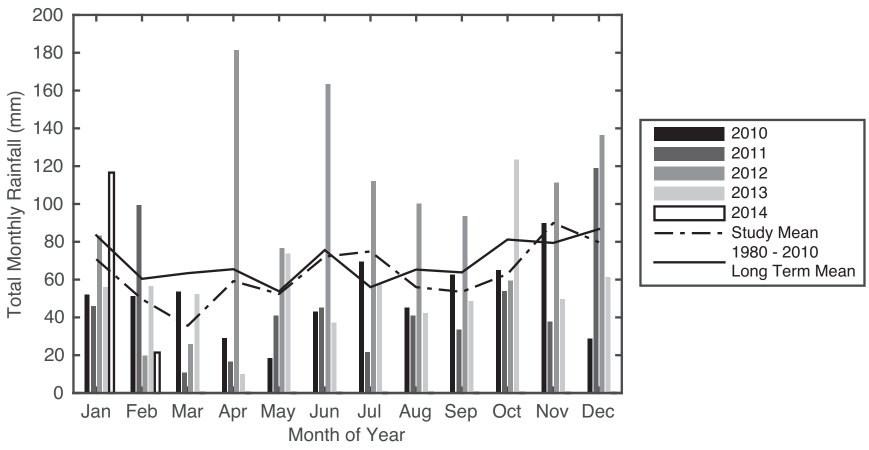


Fig. 3. Monthly rainfall totals for the study period compared with long term averages for Sheffield, UK.

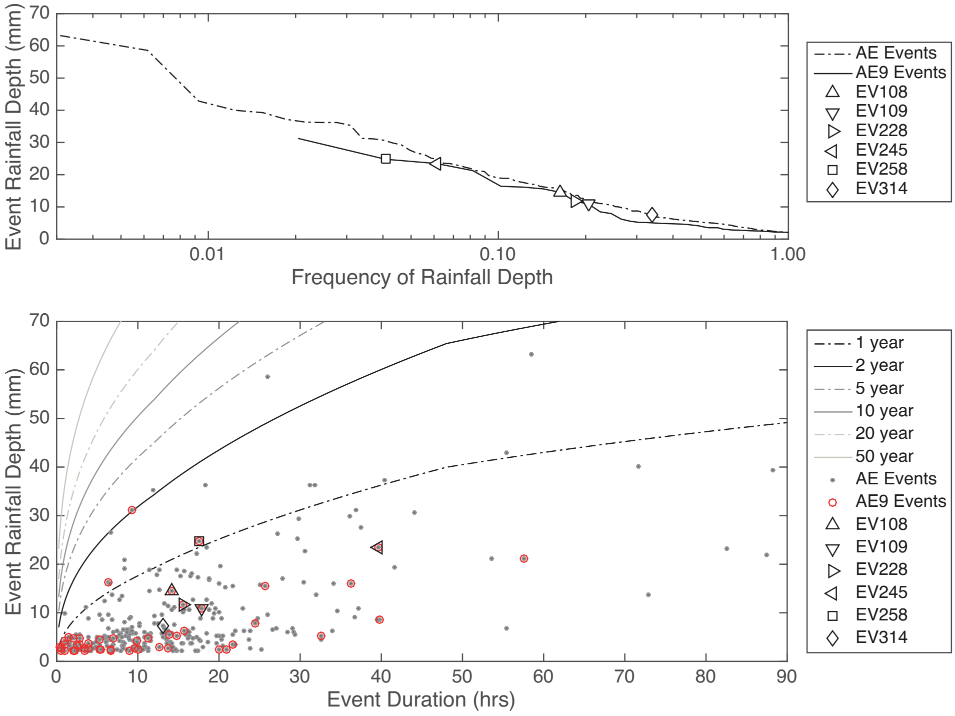
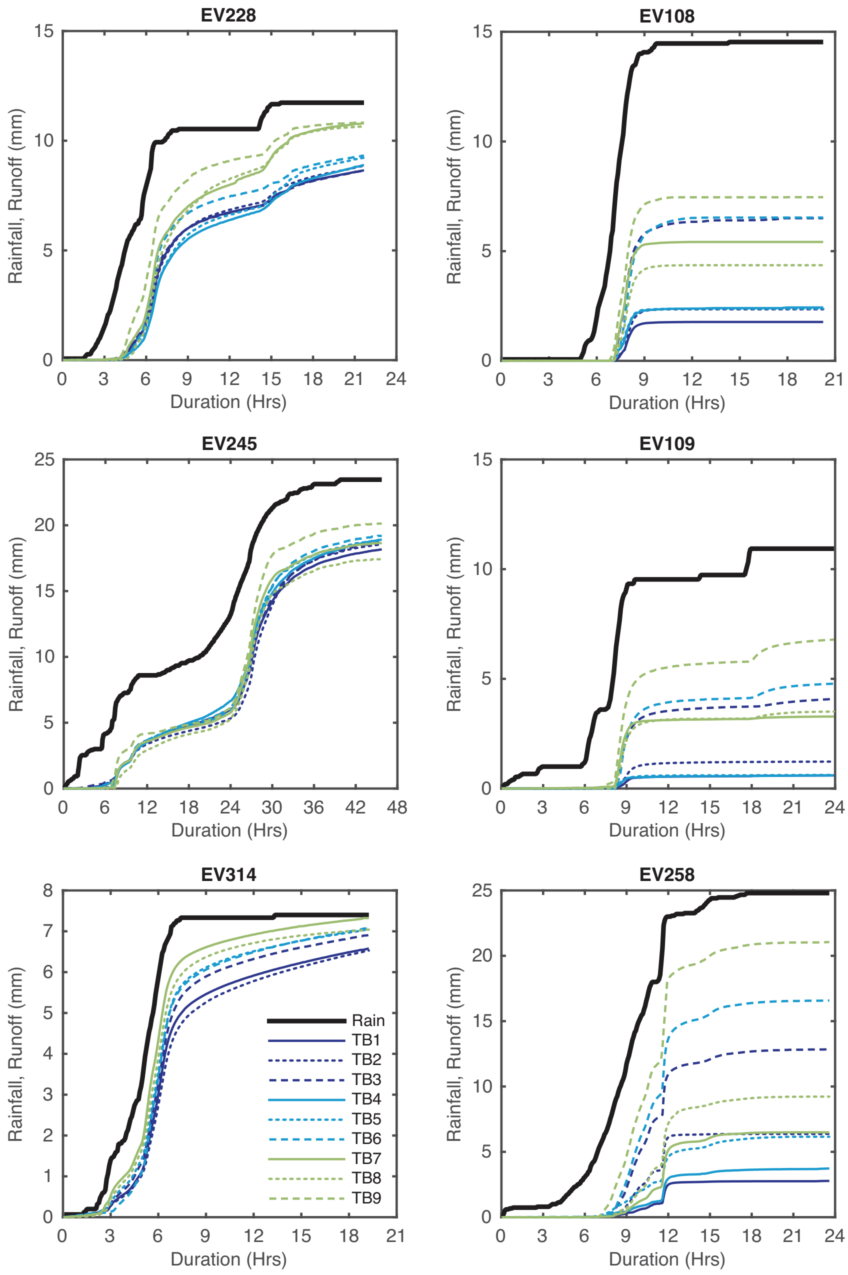


Fig. 4. Rainfall event distributions ($P > 2$ mm) (top), and intensity-duration-frequency plot for Sheffield (FEH CD-ROM) (bottom). Cumulative rainfall-runoff plots for the six highlighted events are shown in Fig. 5.

The three test beds with LECA substrate (TB3, TB6 and TB9; dashed lines in Fig. 5) generally show reduced initial losses compared with the two brick-based substrates. Several of the plots also suggest that the unvegetated test beds (TB7, TB8 and TB9; green lines in Fig. 5) typically generate more runoff than their vegetated counterparts. In EV258 the steep rise in cumulative runoff associated with the LECA beds after 6 h suggests that, once the available retention capacity has been utilised, these beds offer very limited detention. This is also evident in EV314, where only minimal retention losses are evident. The greatest differences in the responses of the configurations were apparent in summer and spring conditions (EV108, EV109 and EV258), rather than winter (EV228, EV245 and EV314).

Table 2
Summary of key event parameters for identified events.

Event	Start date	Rainfall depth (mm)	Rainfall duration (h)	ADWP duration (h)
108	24-Aug-2011 20:36	14.5	14.2	91.0
109	26-Aug-2011 05:59	10.9	17.8	19.2
228	06-Dec-2012 15:16	11.7	15.6	34.3
245	04-Feb-2013 15:10	23.5	39.7	10.9
258	14-May-2013 15:34	24.8	17.5	24.5
314	15-Jan-2014 18:30	7.4	13.2	6.8


EV228

EV108

EV245

EV109

EV314

EV258

Fig. 5. Cumulative runoff responses for the nine test-beds for six rainfall events that generated runoff. Winter events are presented in the left column, and spring/summer events are on the right.

3.2. *Retention analysis*

Fig. 6 shows the distribution of per-event retention values for the 49 events in the AE9 dataset. The distributions are strongly influenced by the high retention performance associated with frequently occurring small rainfall events. The data do not reveal any systematic differences with respect to either substrate or vegetation configuration.

Fig. 7 presents the Fig. 6 data as probability density functions for the storm event rainfall depths and retention depths (total losses). For all three vegetation treatments, the effect of substrate choice is the same; the two brick-based substrates (solid and dotted lines) provide higher levels of retention for the low probability events compared with the LECA substrate (dashed lines). Similarly, the vegetated substrates (dark and light blue lines) offer the highest levels of retention and the unvegetated ones (green lines) perform less well. Substrate appears to have a greater influence than vegetation, with the three LECA-based beds (TB3, TB6 and TB9) performing least well during most of the larger events. The worst retention is observed for TB9, the unvegetated bed with LECA-based substrate. Some of the larger events (e.g. EV258 in Fig. 5) demonstrate differences in retention between the nine beds of more than 10 mm.

Considering only the 10 events with over 10 mm runoff (Fig. 8) the influences of substrate and vegetation are more evident. As highlighted above, the brick-based substrates provide greater retention compared with the LECA-based substrates (TB3, TB6 and TB9), and the vegetated systems generally offer improved performance over unvegetated systems (TB7, TB8 and TB9). The worst performance is associated with the unvegetated LECA-based system (TB9). However, due to the small sample size, these differences are not statistically significant.

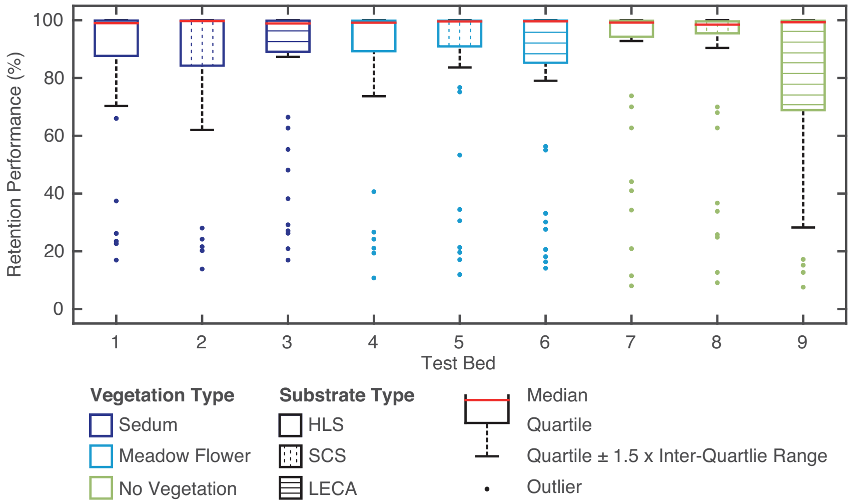


Fig. 6. Per-event retention performance (AE9 data).

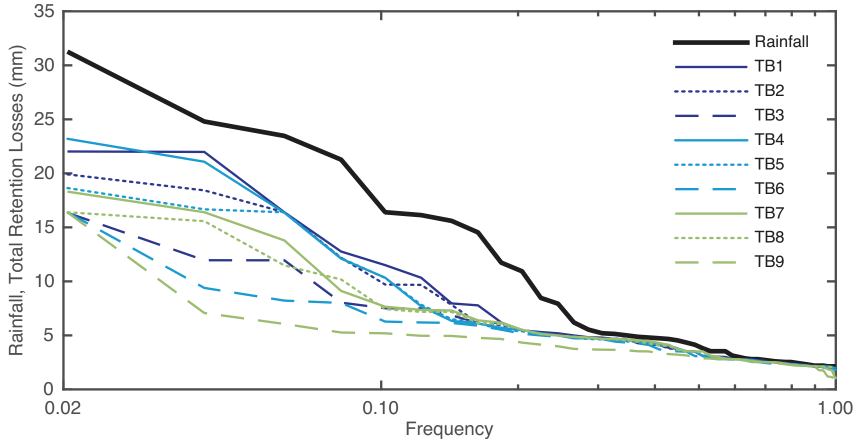


Fig. 7. Probability density functions for rainfall and retention (AE9 data).

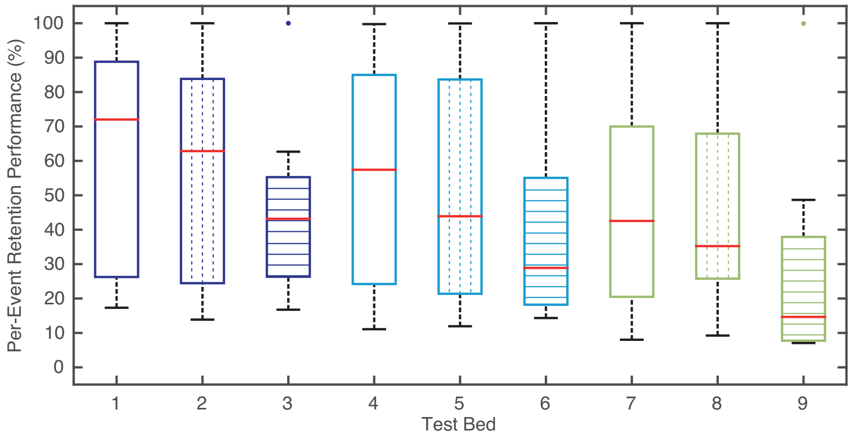


Fig. 8. Per-event retention performance for rainfall events $P > 10$ mm (AE9 data).

Fig. 9 confirms the influence of vegetation and substrate highlighted above. Unvegetated systems and LECA-based substrates lead to lower retention than those that are vegetated and/or brick-based. However, the differences are only evident in a small number of larger events, and the Independent-Samples Kruskal–Wallis test with Dunn's pairwise comparisons confirmed that the median retention values were not significantly affected by either substrate or vegetation.

3.3. Detention analysis

Considering the AE9 data, (i.e. events with >2 mm rainfall) all but one of the test beds (TB9) achieved runoff control to a green field runoff equivalent of 2 l/s/ha for more than 75% of events, demonstrating a good level of day-to-day attenuation performance. However, it is also important to understand how the different systems respond to larger rainfall events. Considering the sub-set of

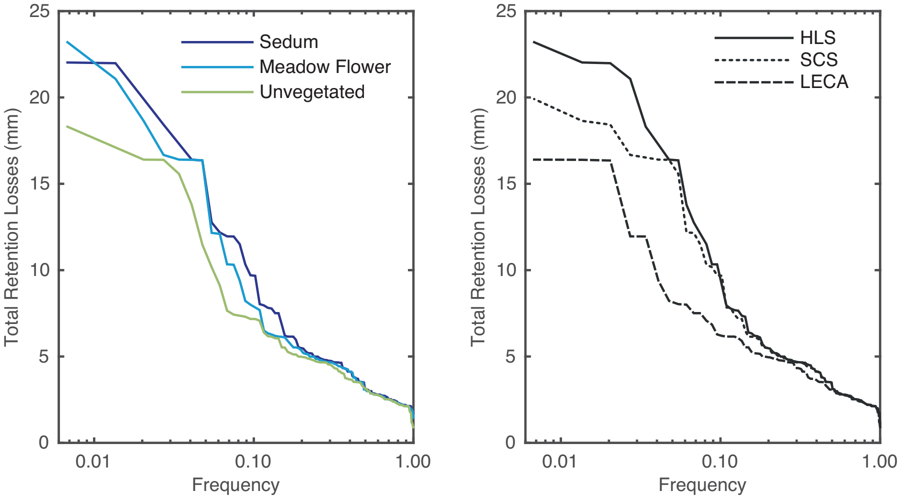


Fig. 9. Retention pdfs as a function of vegetation (left) and substrate (right) (AE9 data).

AE9 events with >10 mm rainfall, the percentage of events for which the runoff complied with the <2 l/s/ha standard fell to between 20% (TB1) and 10% (TB9).

Fig. 10 presents the Peak Attenuation performance data for the AE9 events with >10 mm rainfall. In each vegetation treatment group there is clear difference between the brick-based and LECA-based substrates, with the brick-based substrates offering consistently greater attenuation compared with the LECA-based substrate. Differences due to vegetation treatment are also evident; in every substrate, the vegetated systems offer higher attenuation than the unvegetated systems. A pairwise Dunn's test reveals the only statistically significant difference is between TB1 and TB9 ($P = 0.022$, $P < 0.05$ significance level). The best-case median 5-min attenuation (68%, TB1) is approximately twice the worst case (29%, TB9).

As previously explained, the Peak Attenuation data has some limitations as a detention metric: it is not necessarily independent from retention effects; it is dependent upon the specific set of observed rainfall events; it is sensitive to time-step; and it does not provide any mechanism for directly comparing performance against a target greenfield runoff rate for a design storm event.

To address these deficiencies, Stovin et al. (2015) suggested that a calibrated reservoir routing model may provide a more objective and independent mechanism for characterising detention, and for predicting detention effects in response to unseen (or design) rainfall profiles. The results of the reservoir routing coefficient k parameter identification based on the AE events with Runoff >2 mm will now be considered.

The optimised values for the reservoir routing coefficient k are presented in Fig. 11. The median value of k and the mean R_t^2 value per bed are presented in Table 3. The minimum mean R_t^2 value of 0.888 (TB6) confirms a good overall fit of the reservoir routing model to the observed data.

For each set of three consistently-vegetated beds it may be seen that the bed with the LECA-based substrate (i.e. TB3, TB6 and TB9) exhibits the highest value of k; i.e. the most rapid runoff or least effective detention performance. It may also be observed that the three unvegetated beds, TB7-9, have the highest k values, i.e. consistently the least effective detention, independent of substrate type. The LECA-based substrates consistently show greater variation in k compared with the brick-based substrates, and the unvegetated systems show higher variation compared with the vegetated systems.

Taking the median k value determined for each test bed to provide a bed-specific characterisation of the detention processes resulted in only a small deterioration in the goodness of model fit across all monitored events (as indicated by the R_t^2 values presented in the bottom line of Table 3). This implies that the median k values presented in Table 3 can be utilised to model the detention performance of unmonitored roofs providing that their vegetation and substrate characteristics are comparable to one of the beds characterised here.

Fig. 12 provides two examples of the range of predictive quality achieved by both the event-specific and the bed-specific k values. The selected test beds represent the configurations with the best and worst detention performance, based on their median k values.

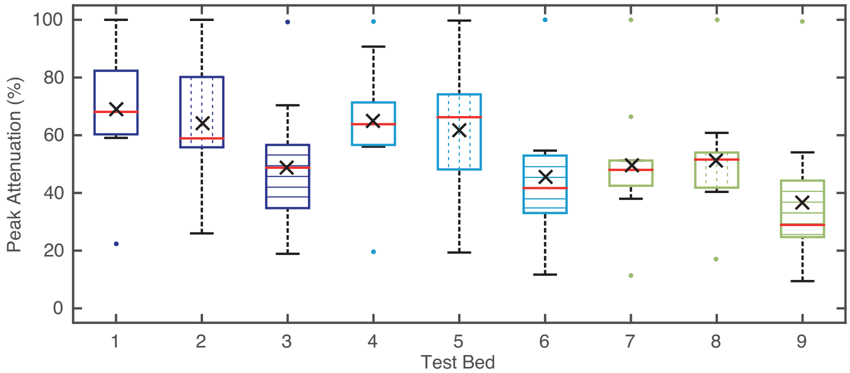


Fig. 10. Peak Attenuation for AE9 events with $P > 10$ mm. Peak Attenuation is based on a 5-min time-step.

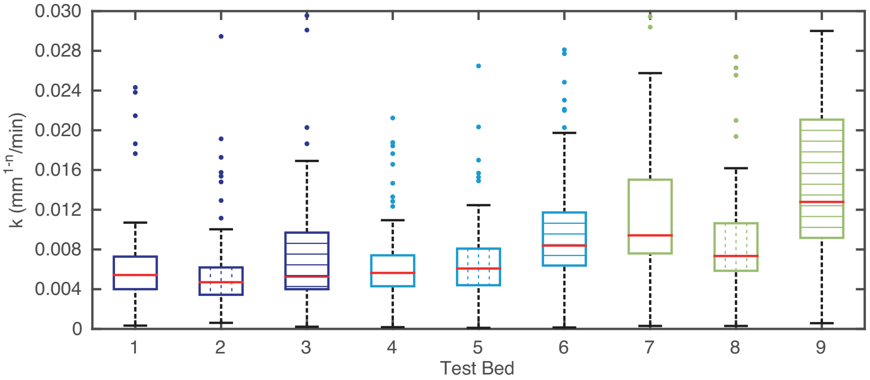


Fig. 11. Calibrated values for the reservoir routing coefficient k. This shows the distribution of k values derived from all valid events with $P > 2$ mm and $R > 2$ mm. Retained rainfall was removed from the start of the rainfall profile such that only net rainfall was routed into runoff.

Table 3
Configuration-specific k parameter values and goodness of fit statistics.

Test bed	1	2	3	4	5	6	7	8	9
Mean R_t^2	0.895	0.915	0.905	0.921	0.897	0.888	0.904	0.894	0.903
Median k	0.0054	0.0048	0.0052	0.0056	0.0060	0.0084	0.0094	0.0074	0.0128
Mean R_t^2 at median k	0.855	0.875	0.836	0.868	0.862	0.844	0.860	0.842	0.863

Both examples relate to EV228 (previously shown in cumulative form in Fig. 5). For TB2 (left) the R_t^2 value for the event-specific optimisation ($k = 0.0032$) was 0.945, while for the median value of k (0.0048) R_t^2 was 0.912. For TB9 (right) the R_t^2 value for the storm-specific optimisation ($k = 0.0038$) was 0.886, while for the median value of k (0.0128) R_t^2 was 0.793. For TB2 it is evident that both models provide a good description of the runoff response; for TB9 the differences are more apparent, though overall the model still provides a highly credible indication of runoff that is likely to be more than adequate for many stormwater management purposes. In the case of TB9, it appears that the observed runoff commenced later than the modelled runoff; possible explanations for this are provided in Section 4.

This comparison also highlights another key point; for routine, real (i.e. irregular in profile) rainfall events, the variations in detention performance across the configurations, although systematic, are relatively minor.

Fig. 13 shows the lumped effects of vegetation and substrate on k, confirming that the no vegetation and LECA cases offer the least effective detention control. An independent-samples Kruskal–Wallis test confirmed that the derived values of k for all categories of vegetation and substrate were statistically independent ($P = 0.000$, 0.05 significance level).

4. Discussion

This section discusses the physical mechanisms responsible for the observed differences in hydrological performance across the nine test bed configurations, before reflecting on their practical implications for stormwater management.

4.1. Physical controls on retention performance

The actual substrate moisture retention capacity at the start of a storm event is controlled by the difference between its field capacity and the residual moisture content, i.e. the moisture that remains within the substrate after losses due to evapotranspiration in the preceding dry period. The maximum possible moisture retention capacity is given by the difference between the substrate's field capacity and its permanent wilting point (Fassman and Simcock, 2012; Stovin et al., 2012, 2013; Berretta et al., 2014a).

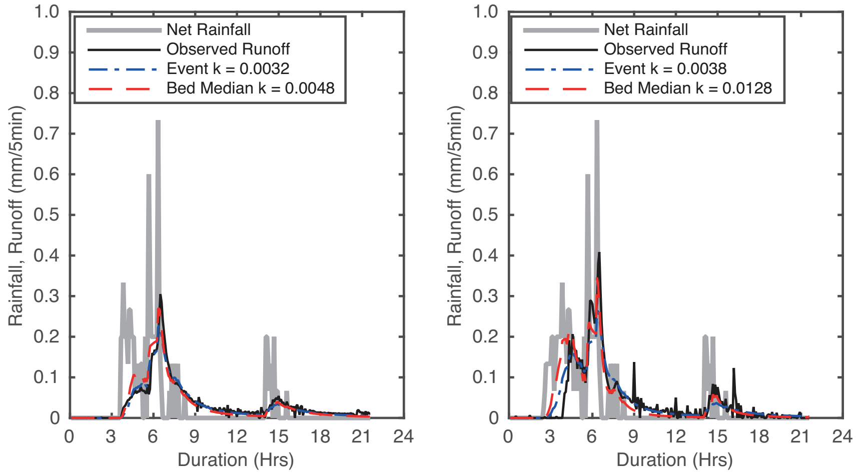


Fig. 12. Model fit examples for TB2 (Meadow Flower vegetation on SCS, left) and TB9 (unvegetated LECA, right).

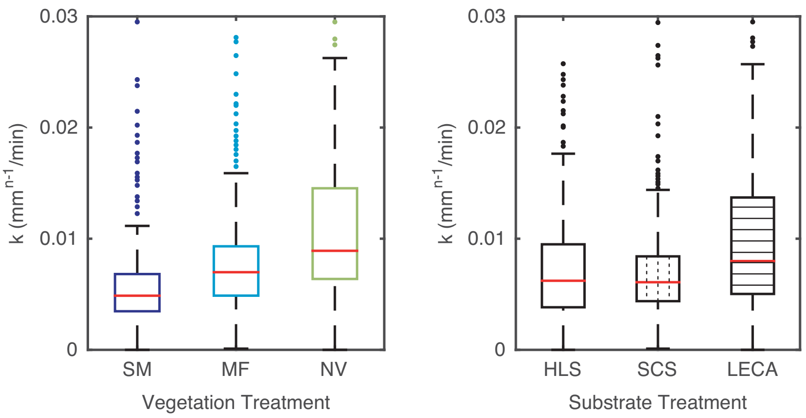


Fig. 13. Values of the detention parameter *k* as a function of vegetation treatment (left) and substrate (right).

However, the antecedent dry weather period needs to be sufficiently long, and ET rates sufficiently high, for this maximum possible retention capacity to be reached. In practice, particularly in temperate climates, the actual substrate moisture retention capacity may be closer to zero than to its maximum possible value for the majority of storm events. Even for relatively shallow extensive green roof systems such as these, Berretta et al. (2014a) and Poë et al. (2015) have presented moisture loss data suggesting that ADWPs in excess of a week are needed to obtain 50% of the maximum possible moisture retention capacity under summer conditions. Actual ET rates fall exponentially in proportion with the substrate's plant accessible moisture content (Berghage et al., 2007; Voyde et al., 2010a; Stovin et al., 2013; Berretta et al., 2014a; Poë et al., 2015). Therefore, it may be argued that the system's ET characteristics need to be considered alongside the substrate's moisture retention characteristics to fully explain the observations reported here.

Under controlled experimental conditions, using microcosms of the same green roof configurations as considered here, Poë et al. (2015) showed that during prolonged periods of dry weather (28-day tests) vegetated beds experienced significantly higher cumulative losses due to ET when compared with unvegetated beds with identical substrate and drainage layers. However, it was also noted that initial ET rates were typically higher for the unvegetated configurations. This applied for the first 7–10 days in spring but only for the first 1–2 days in summer conditions, suggesting that ET losses are enhanced by vegetation only when moisture starts to become restricted. Initial high rates of ET losses from bare substrates were also observed in glasshouse trials by Voyde et al. (2010a). In the current study, the greatest overall losses were associated with vegetated beds with brick-based substrates, and the lowest ET losses were consistently linked with the TB9 unvegetated LECA-based substrate. This was also observed in the field measurements of moisture content during dry periods (Berretta et al., 2014a). The previously-observed patterns of ET losses are entirely consistent with the differences in retention observed in the long-term field data record considered here.

Without vegetation (TB7, TB8 and TB9), retention was typically lower than for vegetated configurations (e.g. 21% lower versus Meadow Flower in EV258, 24.8 mm rainfall). In addition to ET effects, it may also be argued that the vegetated beds provide a greater surface area for the interception and evaporation of rainfall compared with the bare substrate (Koshimizu, 2008).

Berretta et al. (2014a) observed that vegetation, if well established and with good surface coverage (>85%), not only affected the rate of moisture decrease through transpiration, but also prevented wetting during minor rainfall events. Moisture content probes embedded within the substrate in March/April 2011 showed no alteration in moisture content within vegetated roofs in response to 11.4 mm rain over 7 minor events but did detect increases in the non-vegetated bed. However, the significance of interception in mitigating runoff from larger rainfall events is minor compared with the importance of evapotranspiration (ET).

The very different responses during EV245 (low retention) and EV258 (some beds showing high levels of retention) reflect previous findings (Rezaei and Jarrett, 2006; Koehler and Schmidt, 2008; Poë et al., 2015) that ET is higher in warmer conditions (as in EV258) than in lower temperatures (as in EV245).

Minor differences in the responses of Sedum and Meadow Flower were observed. These differences may be partly attributed to contrasts between the dense year-round coverage of low growing Sedum vegetation and the seasonally-influenced tall, thin leaf structures of Meadow Flower. In addition, Sedum may be better-adapted to regulate moisture consumption in line with availability (Berghage et al., 2007; Graceson et al., 2013).

The substrate's maximum storage capacity (or field capacity) is governed by its particle size and void size distributions (Beattie and Berghage, 2004). Moisture is attracted to small, dry pores where matric potential – the driving force for soil-water movements in unsaturated conditions (Manning, 1987) – is greatest (Hillel, 1998). Substrates with a higher proportion of small voids will therefore have greater field capacity. Table 1 highlighted that the LECA-based substrate has a lower field capacity (35.0%, based on the FLL tests) compared with the two brick-based substrates (HLS: 41.2%; SCS: 39.1%), which will, in part, contribute to the consistently lower retention associated with the LECA-based substrates. The air content at MWHC is almost 50% for LECA, but less than half that value for the two brick-based substrates. The higher field capacity of HLS can be attributed to the greater proportion of small pores within HLS, contrasting with the high number of large pores in LECA. The LECA's lower field capacity also reflects the fact that a significant portion of the pore volume is internal to the aggregate particles and therefore not likely to be plant available.

The present study has confirmed the well-understood inverse relationship between retention and rainfall depth (Rowe et al., 2003; Carter and Rasmussen, 2006; Stovin et al., 2012). Mean per-event retention was predictably high due to the large number of small rainfall events. However, a green roof has a finite retention capacity, and larger events (>10 mm) tended to result in a broader range of retention efficiencies across the nine beds (between 10% and 100%, Fig. 8). The greatest range was observed during the second-largest event (24.8 mm rain depth [EV258]). These differences reflect differences in plant-available moisture holding capacities and losses due to evapotranspiration between the configurations.

4.2. Physical controls on detention performance

Substrate composition has been observed to affect detention performance (Vesuviano and Stovin, 2013), with permeability being an important influence (Yio et al., 2013). The influence of substrate permeability on detention is apparent here, with the LECA (most permeable substrate) having the lowest Peak Attenuation and highest k values and HLS conversely exhibiting the best detention performance.

LECA has 58% of particles between 4 and 8 mm in diameter, compared with 35% for HLS and 40% for SCS. The high proportion of large, uniformly-sized and rounded LECA particles results in a substrate that has high porosity and high permeability. Although tortuosity was not measured directly, the graded distribution of particle sizes and shapes in HLS is likely to increase the number of tortuous paths through which gravitational water must pass; reducing permeability and increasing detention times (Miller, 2003).

Vegetation type also has a significant effect on detention. The vegetated test bed configurations exhibit lower values of k and greater Peak Attenuation compared with the unvegetated test beds. As no direct observations of soil/root/moisture interactions were made, it is only possible to speculate on exactly how the vegetation affects the system's detention characteristics. Several mechanisms have been highlighted in related literature, but these remain to be proved for green roof systems. The above-ground vegetation may introduce small delays to the runoff, and it is reasonable to assume that the dense year-round coverage of Sedum will be associated with greater delays that the less-dense seasonal Meadow Flower. The presence of roots is expected to change the size distribution and connectivity of pores compared with the bare/virgin substrate. Soil matrix porosity has been observed to fall by >20%, both in a conventional soil (Bruand et al., 1996) and – in a preliminary study – in green roof substrates (De-Ville et al., 2015). Any reduction in porosity is expected to be reflected in a reduction in permeability and consequently in increased detention. The differences in the detention performance between the two vegetated configurations may also reflect their contrasting rooting types. The mixed Meadow Flower vegetation contains species that have a deeper rooting system (Brickell, 2008) compared with the shallower fibrous rooting system of the Sedum vegetation (Snodgrass and Snodgrass, 2006). Root die-back may lead to the development of preferential flow paths and this effect would be expected to be more evident in the seasonal Meadow Flower. In a horticultural setting, particle travel speeds have been found to be 152 times faster than the measured soil matrix conductivity values due to the presence of dead root macropores (Schwen et al., 2011). Work is currently underway to better understand how these processes interact in the context of green roof systems, using X-ray microtomography to visualise and quantify the temporal changes due to soil/root interactions in vegetated systems with both the LECA-based substrates and a brick-based substrate (De-Ville et al., 2015).

The combined effects of Sedum vegetation with the well-graded brick-based substrates leads to notably better detention performance compared with the unvegetated open-textured LECA-based configuration.

4.3. Physical controls on the initialisation of runoff

Substrate moisture flux models typically assume that runoff occurs only once moisture content reaches field capacity (Bengtsson et al., 2005; Stovin et al., 2013), although the model proposed by Locatelli et al. (2014) reflected the fact that runoff can occur shortly before field capacity is reached. In the present data set the responses to EV108, EV109 and EV258 suggest that further retention occurred after runoff had been recorded (as seen by no runoff increase despite continuing precipitation). This may reflect one of several possible phenomena. Dry substrates may develop cracks or preferential paths that allow runoff to break through prior to field capacity. Time is required for wetting processes to overcome hydrophobicity and enable the organic matter to start to re-absorb water, and there is considerable uncertainty about moisture exchange processes between the external pore spaces and pore spaces internal to aggregate particles (e.g. pumice and LECA). Rainfall intensity can also influence the runoff response (Getter et al., 2007; Koshimizu, 2008; MacMillan, 2004) because saturated flow conditions develop near to the surface, creating localised gravitational forces that can temporarily exceed matric pressures in unsaturated conditions.

Fig. 12 provided evidence of the reverse phenomenon, with runoff from TB9 commencing later than would be expected based on the field capacity threshold alone. Further work is required to fully explain why this occurs, but it is possibly a facet of the LECA-based substrate. Vertical leaching/sorting of the substrate has been observed to occur more readily than with the commercial brick-based substrates, leading to an accumulation of fine particles at the base of the substrate layer (Berretta et al., 2014a). This may locally increase the substrate's field capacity, leading to a delay in the initiation of runoff. In controlled laboratory experiments, Vesuviano (2014) also showed that runoff from LECA-based substrates may take longer to initiate than from a brick-based substrate. It should also be noted that the modelling approach adopted here assumes that no delays occur between the runoff leaving the substrate and arriving in the runoff collection barrel. In reality there are delays due to its passage through the drainage layer and drain pipes. In the present study all test beds are served by identical drainage layers and collection systems, so any differences in observed detention can be assumed to be due to differences in substrate and/or vegetation.

4.4. Implications for stormwater management

It is interesting to consider how well the roofs perform compared with regulatory requirements. The data have been analysed with reference to the UK requirement for SuDS to retain the first 5 mm of rainfall. The AE9 data set shows that most of the test beds were able to retain at least 5 mm of rainfall in 65% of events where $P > 5$ mm, although this ranged from 29.4% (TB9) to 70.6% (TB1) of events depending on configuration.

It is also possible to provide a coarse estimate of the overall annual retention of these systems, based on the observed retention efficiencies for different rainfall depth categories. For the complete record of rainfall, 9.1% of the annual rainfall occurred in 0–2 mm events, 15.4% in 2–5 mm events, 20.7% in 5–10 mm events and 54.8% in >10 mm events. For all events with $P < 2$ mm, it is reasonable to assume 100% retention. For the remaining three rainfall depth categories the mean AE9 retention efficiencies for TB1 are 97.0%, 85.7% and 61.8% respectively, whilst for TB9 the AE9 retention efficiencies are 91.3%, 80.4% and 26.8%. Apportioning the rainfall depth gives overall annual volumetric retention estimates of 75.1% for TB1 compared with 54.5% for TB9. It should be noted that these values systematically over-estimate actual retention for the following reasons: the AE9 $P > 10$ mm data set comprises only 10 events, and – as shown in Fig. 4 – it does not include some of the largest events for which reduced levels of retention would be expected to occur; Fig. 3 also indicates that the study period was drier than the long-term record. Indeed, these retention estimates are significantly higher than the 50.2% annual retention observed by Stovin et al. (2012) for a test bed that closely matched TB1 in configuration and location. Nonetheless, the relative differences due simply to substrate and vegetation are striking; the

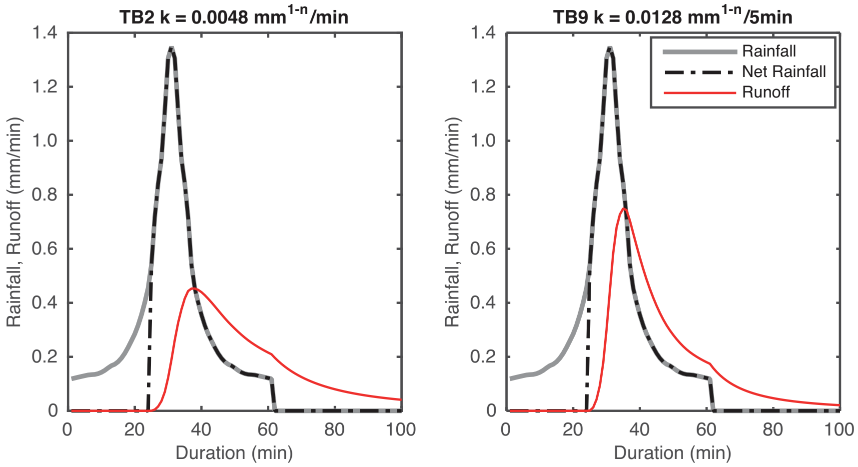


Fig. 14. Detention comparison between TB2 (highest observed detention) and TB9 (lowest observed detention) for a 1 in 30 year 1 h design storm for Sheffield (29.6 mm), UK assuming 10 mm initial losses.

worst-case configuration (TB9) offers a 27% reduction in annual retention performance compared with the best case (TB1).

Fig. 14 illustrates the effect of the observed differences in detention performance for a symmetrical 1-hour 30-year return period design storm, assuming a storm depth of 29.6 mm and initial losses of 10 mm. The reduced detention effect associated with the unvegetated LECA-based bed (TB9) leads to a peak runoff attenuation of 40%, compared with 60% for the best-performing TB2. Similarly, the duration of runoff is longer for TB2 compared with TB9. The absolute peak runoff values could obviously also be compared with local regulatory standards, such as the UK's 2 l/s/ha greenfield runoff objective. In this case, both TBs fail to meet the target by a considerable margin (2 l/s/ha equates to 0.06 mm/5 min).

In Fig. 14, both scenarios assumed initial losses of 10 mm. However, it has been shown within this paper and elsewhere that the different substrate and vegetation configurations influence retention performance (or initial losses). Figs. 7 and 8 showed that retention during large rainfall events was often 5–10 mm greater for TB1 and TB2 compared with TB9, which will tend to further enhance the overall hydrological performance of vegetated brick-based systems over unvegetated, LECA-based systems.

In addition to design storm analysis, Stovin et al. (2015) have demonstrated that an appropriately calibrated hydrological model can also be used with long time-series rainfall inputs to generate pdfs for a number of stormwater performance metrics, including the UK's 2 l/s/ha greenfield runoff threshold. Such a model-based approach provides a far more complete characterisation of performance than is feasible with, for example, the 49 events in the empirical AE9 data set considered here, and removes any bias introduced by the omission of high return period events from the monitoring record.

It should be noted that although these differences appear substantial when considering a smooth, highly peaked, short-duration event simulated at 1-min time-steps, the differences will reduce when considering more frequent, irregular, and natural events, especially if the model time-step is increased to 5-min or more.

Systems with deeper substrates and more vigorous vegetation are likely to offer improved performance and differences due to configuration are expected to be magnified (see e.g. Stovin et al., 2015). These differences may also be more evident under climatic conditions that are more extreme than in the UK. If significantly greater levels of detention are required, it may be necessary to consider the incorporation of additional storage (e.g. via a storage void located below the main green roof) with appropriate outlet controls. The present paper's focus on parameter identification should allow appropriate hydrological models to be developed and employed to characterise performance for unmonitored events and/or configurations, such that appropriate downstream controls can be selected.

5. Conclusions

The analysis of rainfall and runoff data from a set of nine parallel green roof test beds located in Sheffield, UK, has confirmed previously-reported findings related to runoff retention. Considering a subset of storm events that were sampled on all nine beds and for which rainfall exceeded 10 mm, systematic differences in retention were observed, although they were not found to be statistically significant. Unvegetated test beds provide lower retention than vegetated test beds and test beds with a large-pored and permeable substrate perform less well than well-graded, less permeable, substrates. These observations reflect the fact that in the long term vegetated systems will tend to offer higher moisture removal due to evapotranspiration, and that the large-pored substrate also has a lower maximum moisture holding capacity.

Alongside data on Peak Attenuation performance, a novel and robust method for describing the test beds' runoff detention characteristics has been demonstrated, in which the reservoir routing parameter k was calibrated from observed net rainfall and runoff data. In the case of detention, statistically significant differences were observed due to both substrate type and vegetation treatment. The highest values of k, implying the most rapid runoff response, were again associated with unvegetated, highly-permeable test beds.

Overall the study has demonstrated that the configurations most typical of commercial extensive green roof systems, i.e. Sedum vegetation on a brick-based substrate, will offer the best all-round performance in terms of both retention and detention. However, it should be noted that shallow, extensive, green roof systems need to be combined with downstream retention and detention measures to provide more holistic SuDS solutions that can mitigate flood risk for even the largest storm events. For example, whilst all configurations considered here offer good retention performance for routine storm events (e.g. 8 out of the 9 beds retained the first 5 mm rainfall for at least 64.5% of $P > 5$ mm events), none is reliably able to achieve the 2 l/s/ha peak runoff requirement for larger events (i.e. measured events where $P > 10$ mm or a simulated 1 in 30 year return period event).

The paper has highlighted the need for further research to better characterise the soil/root/moisture interactions occurring over time in the green roof's root zone, as these interactions provide critical controls on both retention and detention performance.

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