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Experimental Analysis of Green Roof Substrate Detention Characteristics

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ABSTRACT

Green roofs may make an important contribution to urban stormwater management. Rainfall-runoff models are required to evaluate green roof responses to specific rainfall inputs. The roof's hydrological response is a function of its configuration, with the substrate – or growing media – providing both retention and detention of rainfall. The objective of the research described here is to quantify the detention effects due to green roof substrates, and to propose a suitable hydrological modelling approach.

Laboratory results from experimental detention tests on green roof substrates are presented. It is shown that detention increases with substrate depth and as a result of increasing substrate organic content. Model structures based on reservoir routing are evaluated, and it is found that a one-parameter reservoir routing model coupled with a parameter that describes the delay to start of runoff best fits the observed data. Preliminary findings support the hypothesis that the reservoir routing parameter values can be defined from the substrate's physical characteristics.

KEYWORDS

Detention, green roof, modelling, substrate, SUDS, Urban drainage

1 INTRODUCTION

Green roofs typically comprise vegetation planted in substrate, or growing media, which overlies a drainage layer. Most green roof systems are less than 150 mm deep; these are termed *extensive* green roofs. Green roofs provide two key hydrological functions. As the plants evapotranspire, they remove moisture from the underlying substrate. This moisture deficit provides the roof with the capacity to ***retain*** rainfall and prevent it from ever becoming runoff. Any rainfall that cannot be retained will be ***detained*** (delayed) prior to becoming runoff. There are many different choices for plants, substrates and drainage layers, and they will all respond differently to rainfall events. If green roofs are to be widely deployed as part of stormwater management strategies, it is vital to understand how specific roof systems will respond to specific (design) rainfall events. This requires modelling tools that can relate hydrological performance to the physical characteristics of the different system components. Most previous studies of green roof hydrological performance have considered the system as a whole.

Worldwide, many local studies on test beds and full scale green roof installations have been undertaken. With real field data it can be difficult to separate out retention and detention effects. However, it is clear that the detention effect is a significant aspect of the green roof system's potential contribution to stormwater management. Many authors have reported peak attenuation of 60% or more, even for significant storm events (see, for example, Voyde *et al.*, 2010 and Stovin *et al.*, 2012).

The aim of this work is to quantify and model the detention performance of the substrate. Green roof substrates tend to be highly permeable and do not reach saturation or allow surface runoff to occur. Once field capacity is reached, the runoff exits the bottom of the substrate layer and enters the drainage layer. The drainage layer and moisture mat (if present) below may provide additional detention (Vesuviano and Stovin, 2012). When a hydrograph is routed through a detention facility, the reduction in peak discharge is referred to as *attenuation*, and the increase in the time to peak is referred to as the *lag*. Peak-to-peak lag times can be difficult to define, and a more robust estimate of the mean detention time is obtained from the difference between mean (centroid) or median times associated with the inflow and outflow hydrographs. The Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidance (FLL, 2008) requires that a *runoff coefficient* is calculated. This is defined (Deutsches Institut für Normung (DIN) 4095) as the ratio between the cumulative outflow and inflow volumes measured after 15 minutes of constant intensity rain, corrected for the flow length of the test apparatus.

Laboratory studies enable storm inputs to be controlled and for selected components of the green roof system to be considered in isolation. Villarreal (2007) applied both variable and constant intensity synthetic rainfall events to a shallow (40 mm) sedum vegetated green roof plot without a drainage layer. Experiments were carried out at different slopes with the substrate initially at field capacity. His results suggested that detention parameters were affected by rainfall profile, but were inconclusive regarding the effects of slope. Alfredo *et al.* (2010) focused on the effect of substrate depth. Their study, which included a drainage layer, provides some evidence that detention increased with increased depth of substrate. Buccola and Spolek (2010) have reported similar findings for green roof systems that included plants and drainage layers. 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. Although these studies have suggested that detention effects may be dependent on rainfall intensity and substrate physical characteristics (depth, porosity), only one (Villarreal, 2007) has considered the substrate layer in isolation. None has attempted to link the detention characteristics of different substrates to their (measureable) physical characteristics.

Detention modelling is typically addressed using reservoir routing concepts, although Villarreal and Bengstsson (2005) demonstrated that an approach based on Unit Hydrograph theory might also be valid in this context. She and Pang (2010) have confirmed that conventional infiltration modelling approaches, in which all rain water is used to advance the wetting front, are inapplicable in the context of green roof runoff modelling. Kasmin *et al.* (2010) demonstrated that, if the retention effect is properly accounted for, it is feasible to back-calibrate a reservoir routing model to characterise the detention performance of a specific system. However, for such a model to have generic predictive capability, it is necessary to understand how the individual components (vegetation, substrate, drainage layer) impact upon detention. This paper presents preliminary results from a laboratory-based study aimed at measuring and modelling the detention characteristics of selected green roof substrates.

2 METHODOLOGY

2.1 Laboratory Data Collection

The custom-developed laboratory rainfall simulator (Figure 1) comprises a raindrop former panel, a substrate holder and a runoff-collecting system. The rain intensity is controlled by the pumping rate of a peristaltic pump, whilst the runoff from the substrate is monitored continuously using a pressure transducer in a straight-sided runoff-collecting barrel. The substrate holder consists of a wire grid and a filter sheet to hold the substrate in place.

The simulator was constructed from pipework available in the laboratory, and has a constant internal diameter of 360 mm. This size was chosen to be sufficiently large to ensure that any effects of substrate heterogeneity would be minimised, whilst still being practical for experimental handling. Note that the simulator’s cross-sectional area is nearly six times larger than the standard test vessel (150 mm diameter) recommended by the FLL guidance for green roof substrate physical characterisations. The filter sheet was a commercial green roof product, Alumasc SF, which is a geotextile filter sheet, manufactured from thermally strengthened polypropylene, with a reported effective pore size of 110 µm. The permeability of the filter sheet is given as 155 litres/m^2.sec (9300 mm/min) under a 100 mm water column. The substrate depth tested was chosen to be representative of typical extensive green roof system build-ups. Whilst the substrate fills the full diameter of the simulator, the placement of the dripper needles ensures that there is a minimum distance of 30 mm between the wall and the nearest dripper, which minimises the possibility of preferential pathways developing at the side-walls. Observations during laboratory tests have confirmed that there is no evidence of preferential pathways and that runoff exits evenly from below the filter sheet.

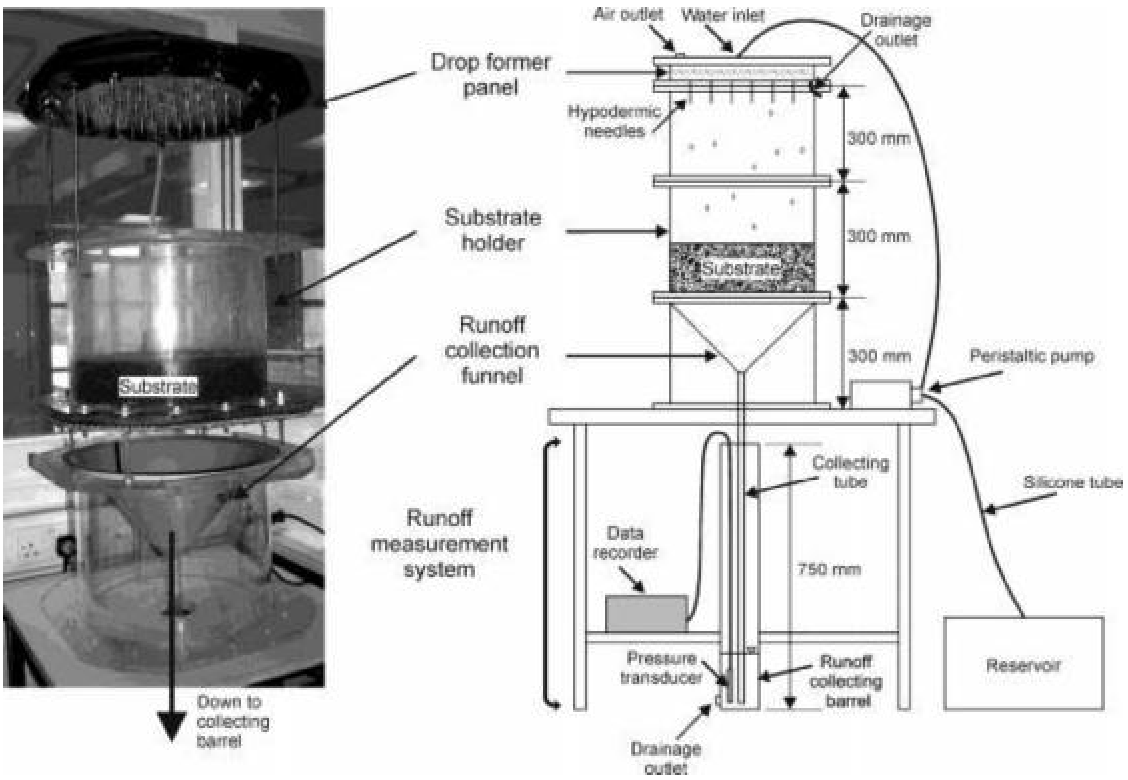


Figure 1. Photograph and schematic drawing of the rainfall simulator

The tested substrates consisted of a Mineral Substrate (MS) (a lightweight mineral aggregate mixture comprising crushed bricks and pumice in the volumetric ratio 11:6) and different quantities of organic matter (coir and/or composted bark). Two separate investigations were undertaken to evaluate:

- **The effect of substrate depth on detention**. In the depth tests, one substrate mix was evaluated at three different substrate depths, 50, 100 and 150 mm. The 'Basic' substrate mix comprised 55% crushed brick, 30% pumice, 10% coir and 5% compost (by volume). Its physical characteristics are as follows: particle size <= 0.063 mm, 2.2%; median particle size = 3 mm, maximum particle size approximately 10 mm, wet density 1520 kg/m^3; total pore volume 56.9%.
- **The effect of organic matter on detention**. In the second set of tests the type and proportion of organic matter was varied. Coir and composted bark were incorporated with the MS component to create substrate mixes with 0, 5 and 15% organic content. These substrates were tested at a constant depth of 100 mm.

To understand whether detention is affected by rainfall intensity, two design rainfall intensities were chosen, based on rainfall depths for Sheffield (UK) with return periods of 1 and 10 years and duration 60 minutes. The one hour rainfall depths of 5.92 and 21.94 mm respectively equate to mean rainfall intensities (*i*) of 0.10 and 0.37 mm/min. These rainfall intensities were applied as 15-minute constant intensity events, which is comparable with FLL guidance (FLL, 2008) for detention measurements.

The substrate was placed in the test rig and leveled off without mechanical compaction. The substrate was initially saturated under constantly-applied heavy rainfall (i = 0.50 mm/min) for two hours, such that a constant runoff rate (equal to the inflow rate) was observed. It was then allowed to drain under gravity for a further two hours, to ensure that it was at field capacity (FLL, 2008). Tests were then begun, with rainfall applied at a constant rate for 15 minutes. The substrate was allowed to drain for two hours before repeat tests commenced. Each test was repeated three times. A high degree of consistency was observed between repeat tests; therefore only mean results will be presented here.

Control tests were undertaken to assess the detention of the non-substrate components of the test apparatus. The substrate holder contained only the filter sheet (Alumasc SF). Both the performance analysis and the model development treated the runoff measured from this configuration as the input to the system, with the additional detention due specifically to substrate being evaluated. A *Substrate Runoff Delay* (SRD) parameter was defined as the difference between the centroids of the outflow hydrograph from the tests with and without substrate (i.e. filter sheet only).

2.2 Model Development

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

$$h_t = h_{t-1} + Qin_t \Delta t - Qout_t \Delta t \qquad (1)$$

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 stored within the substrate, in mm. Δt represents the discretisation time step, which in this case was one minute. *Qout* is given by:

$$Qout_t = kh_{t-1}^n \qquad (2)$$

in which *k* and *n* are the reservoir routing parameters. For *h* in mm and *Q* in mm/min, *k* has the units mm$^{(1-n)}$/min, whilst *n* is dimensionless.

The *lsqcurvefit* function (which is a nonlinear curve-fitting algorithm based on least-squares optimisation) (MATLAB, 2007) was utilised to identify the best-fit parameter values from the monitored runoff data. Three variants on the basic *k-n* reservoir routing model were evaluated. For Model 1, k and n were both determined by optimisation for each specific configuration. In Models 2 and 3, n and k respectively were fixed to evaluate whether it might be feasible to reduce the required number of model parameters to one. The values used were $n = 1.5$ for Model 2 and $k = 0.1$ mm$^{(1-n)}$/min for Model 3, based approximately on the median of the complete set of derived values for n and k for Model 1.

The reservoir routing model inherently generates runoff immediately as rainfall commences. However, significant time delays were observed in the laboratory for some of the tested configurations. Therefore, in addition to the two-parameter reservoir routing model, a second model framework was also proposed, in which a delay parameter was introduced (Model 4). This may be visualised as the time taken for the rainfall to flow into the reservoir. n was fixed at 1.5 for Model 4; k and *Delay* (in minutes) were estimated via optimisation.

For the model to have generic value, it should be feasible to predict the required parameter values from the physical characteristics of the substrate. In the case of the green roof's substrate layer, it may be hypothesised that detention characteristics should be dependent upon substrate depth and permeability. An indication of permeability for the substrates considered here has been obtained using the FLL (2008) methodology, and preliminary comparisons between substrate depth, permeability and the derived reservoir routing parameter values will be presented.

3 RESULTS AND DISCUSSION

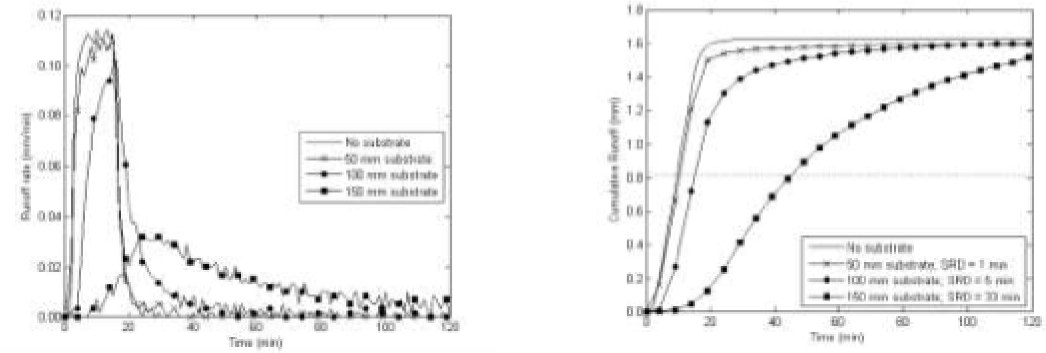
3.1 Laboratory Performance Evaluation

Figs. 2 and 3 present the complete set of data from the substrate detention experiments, in hydrograph form in the left column and cumulative form in the right column. The cumulative plots include a horizontal dotted line that indicates the 50th percentile. This was used to determine the SRD values, which are presented in the key to each plot. In all cases the recorded runoff is compared to the runoff observed in the system without the substrate present.

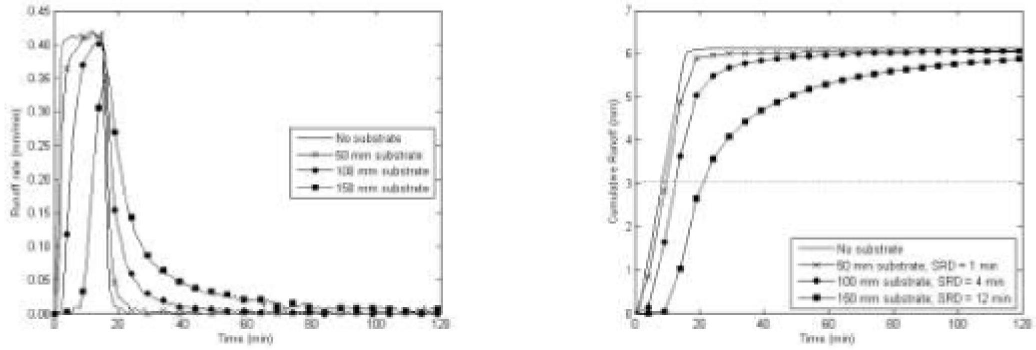
It is clear that detention times increase with substrate depth (Figs. 2a to d), although the relationship is not linear. At the higher rainfall intensity (Figs. 2c and d) the delay times are reduced, but, at both rainfall intensities, the proportional increase in detention time is significantly greater as the substrate depth is increased from 100-150 mm compared with 50-100 mm. The deepest substrate indicates a delay to the start of runoff of around 10 minutes, independent of rainfall intensity.

For the 50 mm substrate depth it can be seen that runoff rate almost equilibrates with the 'no substrate' response within the test duration (Figs. 2a and c); for the two greater depths of substrate it does not. Fig. 2a suggests that significant runoff attenuation is achieved with the 150 mm substrate depth, with the peak runoff rate being approximately 70% lower than for the 'no substrate' condition. However, it is also evident that the storm duration is a critical factor in determining attenuation, as peak attenuation will tend to reduce as storm duration increases, and ultimately rainfall and runoff reach equilibrium. For this reason percentage attenuation will not be discussed further.

The results of the organic matter tests at the lower rainfall intensity are shown in Figs. 3a and b. For the compost, even 5% appears to make a very significant difference, increasing the SRD time from 4 minutes (MS only) to 20 minutes. Adding 15% of either organic component results in SRD times of at least 26 minutes and delays to the start of runoff of at least 15 minutes.

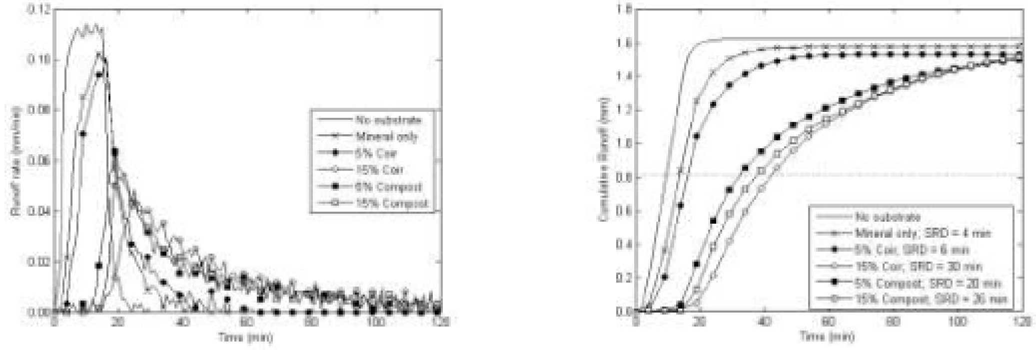


a) *i* = 0.10 mm/min b) *i* = 0.10 mm/min

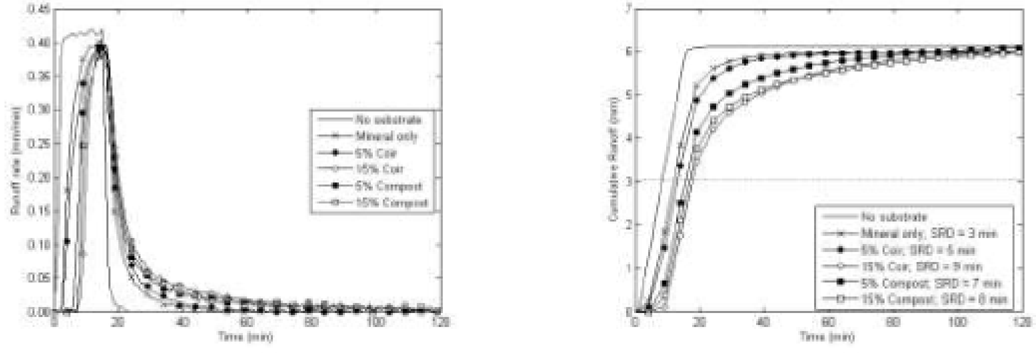


c) *i* = 0.37 mm/min d) *i* = 0.37 mm/min

Figure 2. Effect of substrate depth for the Basic substrate mix (MS + coir + compost)



a) *i* = 0.10 mm/min b) *i* = 0.10 mm/min



c) *i* = 0.37 mm/min d) *i* = 0.37 mm/min

Figure 3. Effect of organic content for constant depth of 100 mm

Similar trends with respect to composition are also evident at the higher rainfall intensity (Figs. 3c and 3d), although the delay times are shorter. This level of detention is significant when it is considered that critical storms for urban areas often have durations of one hour or less. It may also be seen that in all cases almost all the input rainfall has exited from the substrate within two hours (120 minutes).

3.2 Interpretation of Results

The observed detention response represents the combined effects of a range of interacting physical processes, and is influenced by the substrate's pore size distribution, its grain size distribution, the shape and texture of the particles, and the applied flow rate (or rainfall intensity). Green roof substrates, which are mixtures of relatively coarse mineral particles, organic matter and fines, are inherently heterogeneous, even when well-mixed. It is to be expected that detention will increase as substrate depth increases, and the geometric increase in SRD times observed here may reflect the fact that preferential flow paths are more likely to be interrupted by zones of slower flow in deeper substrates than in shallower ones. The presence of organic matter will tend to increase the proportion of fine particles in the mixture, leading to a consequential decrease in permeability. Coir is characterised by fibrous threads, whilst compost comprises more rounded particles (which will consequently have a greater surface area); these differences in shape/texture will influence the moisture-holding characteristics and vertical flow paths differently.

Although it may be feasible to adopt modelling concepts derived from geotechnical/soil science work on unsaturated flow (e.g. the Richards equation/HYDRUS-1D), this approach is arguably of limited practical value for stormwater management applications due to the need for 5 parameters per media layer, of which two must be empirically determined for each specific substrate. The following section therefore attempts to identify a simpler, semi-empirical, modelling approach, based on the identification of a limited number of reservoir routing parameters. A preliminary attempt to link the identified parameter values to a key physical property (i.e. permeability) is presented in section 3.3.2.

3.3 Model Evaluation

3.3.1 Model Structure

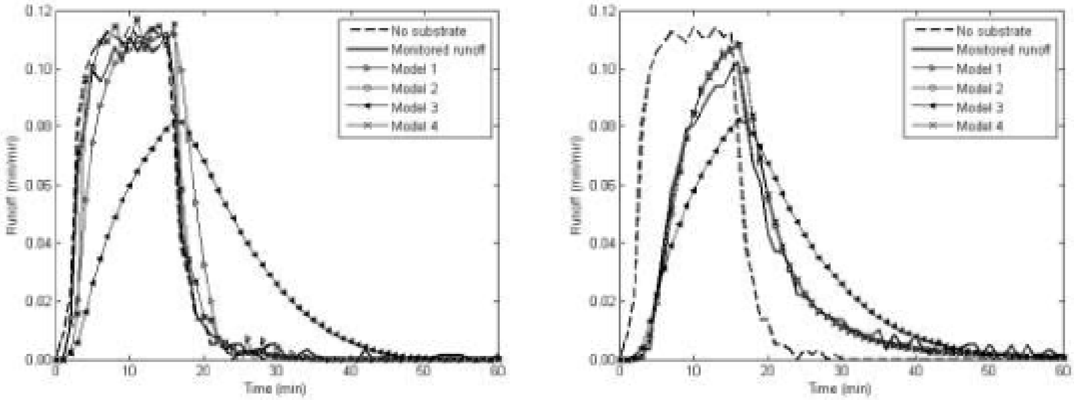
Table 1 presents the full set of identified model parameters. Fig. 4 illustrates the range of responses and model fits. Figs. 4a to c show the model fits for i = 0.10 mm/min for 50, 100 and 150 mm depth of Basic substrate respectively. Fig. 4d shows the data for i = 0.37 mm/min for the 150 mm deep Basic substrate. Model 3 performs consistently worse than any of the others. This suggests that it is inappropriate to use a fixed value of k. Model 4 – which uses a fixed value of n and introduces a new coefficient (*Delay*) to describe time to start of runoff – generally performs best of all, especially when there is a notable time delay between the start of rainfall and the onset of runoff, e.g. in Figs. 4c and d.

For the organic matter tests, model fits corresponding to high levels of organic matter in 100 mm deep substrate mixes perform similarly to the deeper substrate tests, with a notable delay, marked peak attenuation and a clearly better fit for Model 4. 15% coir or compost and the 5% compost results are comparable with Figs. 4c and d; the 5% coir is comparable with Fig. 4b. Across all test conditions, Model 4 could be calibrated to achieve a mean goodness of fit (as measured by R_t^2) of 0.97, with no configuration having an R_t^2 value below 0.93. In contrast, the mean R_t^2 values for models 1, 2 and 3 were 0.95, 0.94 and 0.52 respectively.

Table 1. Model parameters

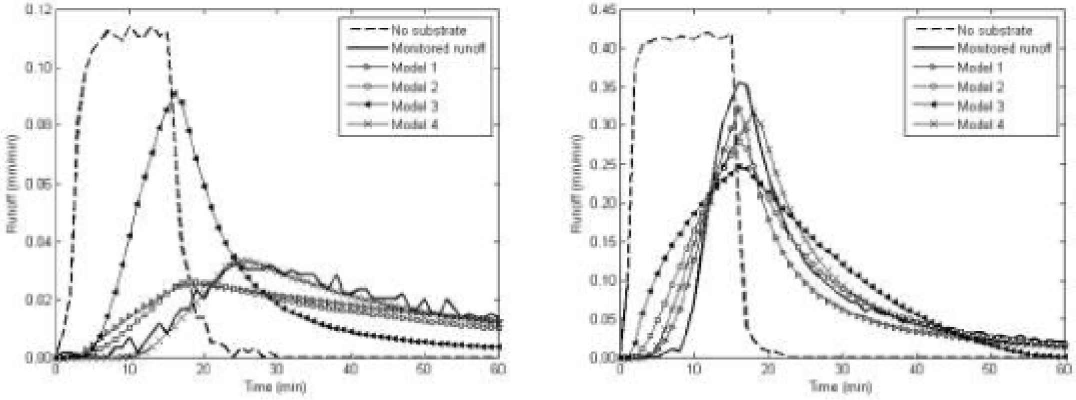
Substrate	**Depth**	***i***	**Model 1**			**Model 2**		**Model 3**		**Model 4**		
	(mm)	**(mm/min)**	***k***	***n***	**R_t^2**	***k***	**R_t^2**	***n***	**R_t^2**	***k***	***Delay***	**R_t^2**
Basic	50	0.10	0.317	0.692	0.97	3.426	0.97	0.797	0.56	3.426	0	0.97
Basic	50	0.37	0.380	0.808	0.93	1.108	0.98	5.194	0.89	1.109	0	0.98
Basic	100	0.10	0.256	1.621	0.98	0.241	0.98	0.899	0.90	0.241	0	0.98
Basic	100	0.37	0.152	1.809	1.00	0.184	1.00	2.275	0.99	0.184	0	1.00
Basic	150	0.10	0.019	0.915	0.90	0.016	0.88	2.218	-0.75	0.022	7	0.97
Basic	150	0.37	0.005	2.867	0.96	0.034	0.92	0.692	0.81	0.045	2	0.95
MS + 15% coir	100	0.10	0.020	0.959	0.78	0.017	0.77	1.955	-0.72	0.030	9	0.98
MS + 15% coir	100	0.37	0.005	3.283	0.97	0.054	0.92	1.155	0.87	0.066	1	0.93
MS + 5% coir	100	0.10	0.193	1.751	0.99	0.177	0.99	1.148	0.94	0.177	0	0.99
MS + 5% coir	100	0.37	0.136	1.594	1.00	0.146	1.00	1.897	0.99	0.146	0	1.00
MS + 15% bark	100	0.10	0.022	1.631	0.81	0.023	0.81	1.851	-0.15	0.036	6	0.95
MS + 15% bark	100	0.37	0.011	2.997	0.98	0.066	0.94	1.291	0.91	0.081	1	0.95
MS + 5% bark	100	0.10	0.027	2.161	0.90	0.031	0.89	2.024	0.35	0.040	3	0.96
MS + 5% bark	100	0.37	0.021	2.779	0.99	0.083	0.96	1.482	0.95	0.108	1	0.96
MS	100	0.10	0.273	1.213	0.99	0.336	0.99	0.746	0.88	0.336	0	0.99
MS	100	0.37	0.221	1.570	1.00	0.228	1.00	2.522	0.98	0.228	0	1.00

MS – Mineral Substrate; *k* [$mm^{[1-n]}$/min]; *n* [-]; *Delay* [min]



a) *i* = 0.10 mm/min, 50 mm substrate

b) *i* = 0.10 mm/min, 100 mm substrate



c) *i* = 0.10 mm/min, 150 mm substrate

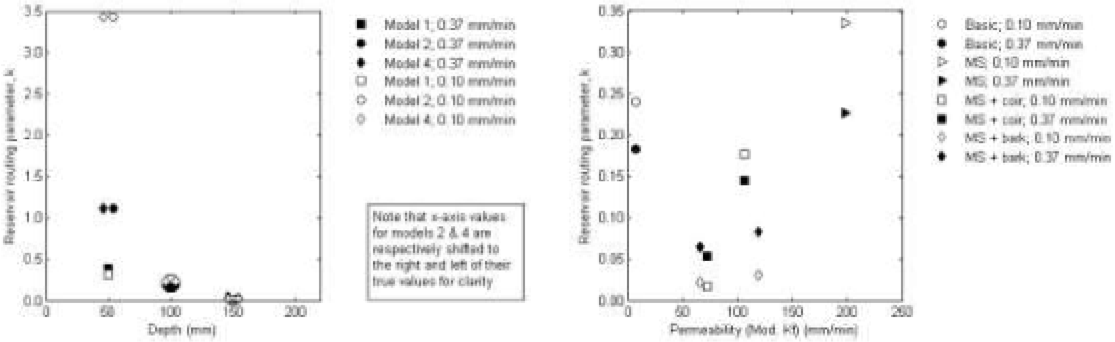
d) *i* = 0.37 mm/min, 150 mm substrate

Figure 4. Sample comparisons between modelled and observed runoff, Basic substrate

3.3.2 Parameter Identification

Permeability has been estimated using the FLL (2008) method. This method has certain limitations, and reproducibility between sample batches is not always high, so the data should be interpreted as providing a preliminary indication rather than an absolute value.

Fig. 5 presents scatter plots of k against depth and permeability for the two groups of tests. Each plot includes two data points for each configuration corresponding to the two different rainfall intensities. Note that permeability was constant in the depth tests (as a consistent substrate was used throughout) whereas depth was constant at 100 mm for the tests that varied % organic.



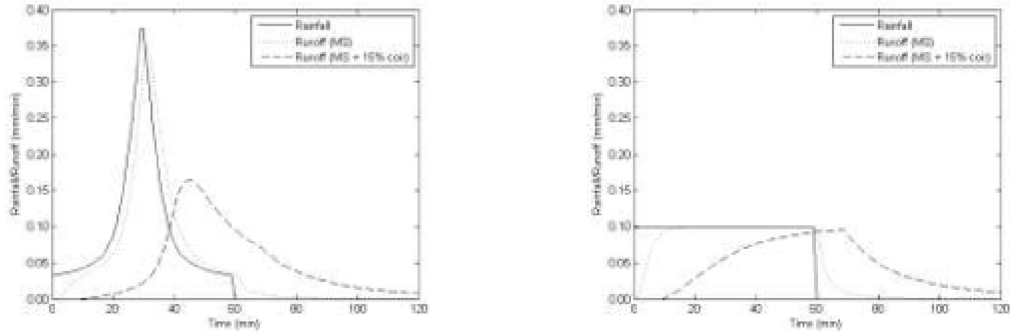
a) Depth variation tests; Basic substrate b) Organic content variation tests; Model 4 only

Figure 5. Relationships between reservoir routing coefficients and substrate physical characteristics

Fig. 5a suggests that the k values in Models 1, 2 and 4 are related to substrate depth. Fig. 5a and Table 1 confirm that k values were relatively consistent between the three models, so Fig. 5b only presents the Model 4 k values. In this case k appears to be related to permeability. It may also be seen that k is generally less sensitive to rainfall intensity than to either substrate depth or permeability. The relationships between k and permeability appear to be influenced by substrate composition, which suggests that the specific shape and nature of the organic components also warrants further investigation. The delay parameter in Model 4 ranged from 0-9 minutes. It appears to be related to substrate depth, organic content (i.e. permeability) and rainfall intensity. The highest delays are associated with lower intensity rainfalls, deep substrates and substrates with higher organic content.

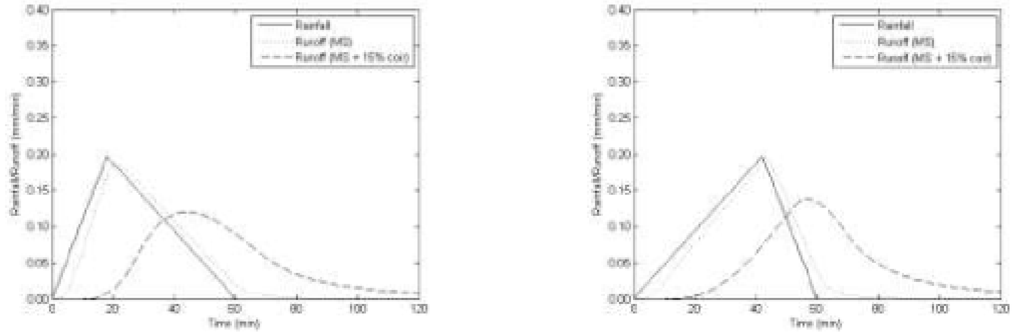
3.4 Model Application

The proposed model is intended to form part of a complete green roof system continuous simulation model, which will ultimately include both retention and detention processes for all system components. Although the model generated here relates only to the substrate detention function, some indication of the substrate's influence on detention performance can be derived from its application to design rainfall events (Calabrò, 2004). Fig. 6 shows runoff responses which have been simulated using Model 4 (constant n parameter, variable k and *Delay* parameters) for two contrasting substrates: 100 mm deep MS (low detention); 100 mm deep MS with 15% coir (high detention). Four alternative rainfall input profiles have been used: the symmetric 60-minute 1 year return period Sheffield rainfall profile (total depth 5.92 mm, mean intensity 0.10 mm/min, peak intensity 0.37 mm/min, Fig. 6a); a constant intensity profile with the same total depth and duration (Fig. 6b); and two triangular rainfall profiles with the same total depth and duration (Figs 6c and 6d), which peak at 30% and 70% of the storm duration respectively. Although not included in the figures for clarity, the 150 mm Basic substrate's parameter values (Table 1) imply that its performance is comparable with that of the 100 mm deep MS with 15% coir substrate. It may be seen that whilst the highest peak attenuation (56%) is associated with the higher detention substrate and the most peaked input profile (Fig. 6a), the constant intensity rainfall event almost reaches equilibrium state and the peak attenuation is practically zero.



a) Symmetrical design storm

b) Uniform rainfall intensity



c) Triangular rainfall profile with peak at 30% storm duration

d) Trinagular rainfall profile with peak at 70% storm duration

Figure 6. Responses of two contrasting substrate configurations to different rainfall profiles

For the triangular profiles, the detention effect lies between that associated with the highly-peaked symmetrical design event and the constant intensity profile. Of the two, the event with the earlier peak results in better peak attenuation (39% compared with 30%) and a longer peak-to-peak lag (26 minutes compared with 15 minutes) for the higher detention substrate. This decrease in performance arises because the amount of runoff in temporary storage is far higher by the time the peak rainfall occurs in the latter case.

It should be noted that these predictions correspond to the detention effect of the substrate only. In reality, any water passing through the bottom of the substrate layer will then experience further delay as it passes horizontally through the drainage layer and/or moisture mat. The effects of this component on detention are considered by Vesuviano and Stovin (2012). In practice, unless the substrate is at field capacity at the start of the rainfall event, some retention might also be expected. Nonetheless, the beneficial detention effects associated with a deeper substrate and/or a substrate that includes a significant organic fraction are clearly demonstrated.

4 CONCLUSIONS

- New laboratory data has shown that the detention in green roof substrates increases as a function of depth and organic matter content. The latter is associated with a reduction in permeability.

- The most suitable model structure to represent the substrate layer appears to comprise an initial delay plus a one-parameter reservoir routing model. The reservoir routing parameters are largely independent of rainfall intensity, and it appears feasible to predict them from known physical characteristics of the substrate, specifically its depth and permeability.

5 ACKNOWLEDGEMENTS

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