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# A Two-Stage Storage Routing Model for Green Roof Runoff Detention

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## ABSTRACT

Green roofs have been adopted in urban drainage systems to control the total quantity and volumetric flow rate of runoff. Modern green roof designs are multi-layered, their main components being vegetation, substrate and, in almost all cases, a separate drainage layer. Most current hydrological models of green roofs combine the modelling of the separate layers into a single process; these models have limited predictive capability for roofs not sharing the same design. An adaptable, generic, two-stage model for a system consisting of a granular substrate over a hard plastic "egg box"-style drainage layer and fibrous protection mat is presented. The substrate and drainage layer/protection mat are modelled separately by previously verified sub-models. Controlled storm events are applied to a green roof system in a rainfall simulator. The time-series modelled runoff is compared to the monitored runoff for each storm event. The modelled runoff profiles are accurate (mean $R_t^2 = 0.971$), but further characterization of the substrate component is required for the model to be generically applicable to other roof configurations with different substrate.

## KEYWORDS

Green roof, modelling, substrate, growing medium, drainage layer, storage routing, reservoir routing

## 1    INTRODUCTION

Green roofs are engineered, roof-level systems, consisting primarily of a vegetation layer, a layer of low-density substrate and a separate drainage layer. Between the substrate and drainage layer is a thin, highly permeable fibrous sheet, which prevents small particles in the substrate washing through to the drainage layer. Beneath the drainage layer is a protection mat, which may be rubbery or fibrous. Green roofs broadly divide into two categories: extensive, which are inaccessible and use low-growing, drought tolerant plants in 50-150 mm of substrate; and intensive, which are generally more accessible and support a wider variety of plants in a deeper layer of substrate.

Green roofs are able to influence urban runoff volumes through retention and detention processes. Retention of rainfall occurs primarily in the substrate, which is able to store water up to field capacity by capillarity in its smaller pores. Further retention may occur in the drainage layer and protection mat, if appropriately designed. Water retained in a green roof is returned to the atmosphere by evapotranspiration, so does not become runoff. The annual retention of rainfall by green roofs in different climates has been extensively studied; between them, Fioretti *et al.* (2010) and Gregoire and Clausen (2011) present comparisons of twenty-one long-term green roof retention studies. However, the maximum retention capacity is obviously finite for any particular roof. For an extensive green roof, this capacity ranges from approximately 15 to 40 mm. Therefore, the retention performance of a green roof can appear to decrease under large storms, simply because the volume available for storage is a smaller percentage of a larger storm (Carter & Rasmussen 2006; Voyde *et al.* 2010; Stovin *et al.* 2012).

Detention (temporary storage) occurs in the substrate, as rainfall percolates through larger pores, which cannot retain water, but do offer resistance to vertical flow-through. A fibrous protection mat may also significantly detain rainfall, due to lateral resistance to flow. As the purpose of the drainage layer is to quickly remove excess water that cannot be retained elsewhere in the green roof system, its detention effects are low. Detained water leaves the green roof via conventional drainage systems, but over a longer time period, at a reduced peak and average flow rate. In a time-series profile of roof runoff, detention is observable as a reduction in the peak runoff rate in comparison to the peak rainfall rate and/or as a time delay between the mid points of the rainfall and runoff profile. These effects are often significant even when retention effects are small. Moran *et al.* (2004), Carter and Rasmussen (2006), Stovin (2010), Voyde *et al.* (2010) and Carpenter and Kaluvakolanu (2011) all report consistently higher percentage values for peak flow reduction than for retention.

While data are available for the performance of green roofs in different climates, the huge variations in climate around the world, coupled with the small-scale variations in microclimate within cities, imply that performance metrics and/or empirical models generated from specific installations will have limited generic applicability. Similarly, the wide variation in green roof construction characteristics, such as depth, slope and substrate composition, greatly limits the use of roof-specific models, particularly if these models are also climate-specific e.g. empirical models based on field monitoring studies. Furthermore, as the internal conditions of a green roof are dependent on the effects of previous storms and weather, it is extremely unlikely that the response of a roof to two identical storms will be identical. Generic modelling of the roof's internal water processes enables the effects of climate and construction to be decoupled from runoff response, allowing the model to remain applicable independently of climate and construction.

Runoff modelling methods for green roofs have been presented since the mid-2000s. Villarreal and Bengtsson (2005) derived and then verified a unit hydrograph approach. Though the verification responses were of similar quality to the calibration responses, the derived unit hydrograph is configuration-specific and therefore the method is not generically applicable.

Hilten *et al.* (2008) used daily rainfall-runoff records to parameterize a test-scale system and then predict runoff volumes in response to 24-hour SCS design storms (United States Department of Agriculture, 1992) using Hydrus-1D. Almost no attenuation was simulated and these simulations were not verified experimentally. The use of Hydrus 1-D was extended by Palla *et al.* (2012) to a full-scale green roof with separate granular substrate and drainage layers. High Nash-Sutcliffe efficiencies were observed for calibration and validation events. However, model use is complex: twelve input parameters, including six empirical (i.e. media-specific) coefficients, were required to model roof runoff.

Kasmin *et al.* (2010) applied nonlinear storage routing methods to model detention in a green roof test bed in Sheffield, UK, requiring only two modelling parameters. The resulting modelled runoff profiles were very accurate and detailed, though the overall value of the model was lowered by its combining of the entire system into one process and – once again – by its reliance on roof-specific empirically-derived parameter values.

She and Pang (2010) present perhaps the most comprehensive green roof model of all, which considers the substrate and drainage layer components separately and uses physically-based infiltration and open channel equations to model them. The performance of this model is reasonable, though it noticeably overestimates peak runoff flows for individual storm events. Various calibration parameters are included in the model without indication to the reader of what appropriate values may be; it is possible that the authors did not set these optimally in their model verification.

The aim of this research paper is to produce and test a green roof detention model that: is based on hydrological processes so as to be applicable in all climates; models the processes in the substrate and drainage

layer separately so as not to be limited to a single configuration; is easy to use; and easy to accurately parameterize. Specifically, a two-stage storage routing model is tested, using routing parameters derived from previous experimental programmes which modelled the runoff response of individual component layers under constant intensity storm events.

## 2 METHODS

### 2.1 EXPERIMENTAL SETUP

All tests were conducted in a rainfall simulator (Figure 1), whose design evolved from that described in Vesuviano & Stovin (2013). Modifications have since been made to the collection barrel, monitoring systems and dripper network control system. The exact specifications for all parts of the rainfall simulator and its associated systems are contained in an unpublished technical manual written by ZinCo GmbH.

The rainfall simulator test bed is one metre wide, five metres long and was set at a slope of 2% for this experimental programme. The channel, into which test components can be placed, is 20 cm deep. Clear plastic walls extend for a further metre above this, allowing the inside of the simulator to be seen. Rainfall is supplied by three independent networks of Netafim PCJ-LCNL pressure-compensating drippers located 1.12 metres above the channel bed. Drippers with two different flow rates, 0.5 and 2.0 l/hour, are arranged in two different square grid patterns, 36/m$^2$ and 144/m$^2$, to give different nominal rainfall intensities for each of the three networks, specifically 0.3, 1.2 and 4.8 mm/minute. Different flow rates of dripper are not mixed within a network; this ensures that rainfall distribution is as regular as is possible over the entire area of the simulator. An electromagnetic valve gates each network separately, and each valve can be pulsed in a repeating pattern in order to simulate other rainfall intensities. To avoid erosion of any substrate placed in the channel bed, drop size and position is randomized by a mesh (1 mm wire, 3 mm spacing) placed 0.56 metres below the dripper networks. A full-width opening at the downstream end of the simulator test bed allows runoff to leave the chamber. Runoff is collected in a semicircular gutter, from which a downpipe extends to a collection barrel of capacity 34 mm equivalent rainfall depth. For collection of greater runoff volumes, a pump can operate during tests.

Each 0.02 mm of rainfall is registered by a Badger Meter RCDL M25 LCR nutating disc flow meter, sampled at 0.5-second intervals. Runoff is measured at 0.5-second intervals by a Druck PDCR 1830 pressure transducer. Both are connected to a Campbell Scientific CR1000 data logger. A Campbell Scientific SDM-CD16AC relay controller is connected to the data logger, the barrel pump and each of the electromagnetic valves gating the dripper networks, and can operate any of these. Software was developed to allow all dripper networks to be operated over independent timing cycles, enabling time-varying rainfall events to be imposed.

The test green roof system (Figure 2a) consisted of a 10 cm layer of substrate (55% crushed brick, 30% pumice, 10% coir, 5% compost) over a ZinCo Floradrain FD 25 drainage layer. These two components were
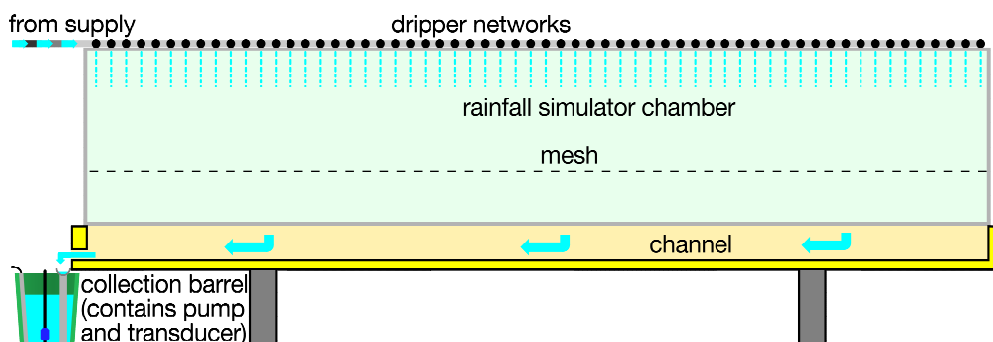


Figure 1. The rainfall simulator.

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separated by a ZinCo Systemfilter SF particle filter sheet, which was taped to the internal walls of the simulator channel to prevent it from moving during the experimental programme. A fibrous ZinCo SSM 45 protection mat was laid under the drainage layer. The substrate was not compacted, as no repeatable methodology for compaction was considered practical at this scale. As compaction simulates the effects of age and weathering, the tested experimental setup can be considered similar to a new green roof. The system was not planted.

## 2.2　TEST PROGRAMME

The test programme was designed to assess the validity of the two-stage model under different simulated storm profiles, and hence the model's independence from specific rainfall input. Five different storm profiles, each of 60-minute duration, were considered. Each profile was applied to the system three times, to assess the consistency of monitored runoff under identical rainfall inputs. Three rainfall profiles were of constant intensity (0.3, 0.6 and 1.2 mm/minute), while two represented the 1-in-10 and 1-in-100 year 75% summer storm profiles for central Sheffield, discretized into 15 four-minute steps. The time-varying events were included to provide useful information and observations to drainage engineers, and to test modelling parameter values that were derived under constant intensity rainfalls under more realistic time-dependent rainfall conditions. The order of tests was randomized to prevent any systematic, rainfall-related effects from carrying over between tests. All tests were performed continuously, spaced at 17-hour intervals, to allow the system to return to field capacity between tests while minimizing inter-event evaporation. Prior to the first test, a 72 mm storm was applied to the entire system, wetting it to above field capacity. The system was then left to drain for 16 hours before the first test began.

The 1-in-100 year, 0.6 and 1.2 mm/minute storm events exceeded the capacity of the collection barrel and so water was pumped out during these tests. The rate of runoff during pumping was back-calculated by linear interpolation between the known values of runoff rate immediately before and after the pumping event.

## 2.3　MODELLING METHODS

Within the green roof test bed, all water that is detained will eventually become runoff. In order for this to happen, it must first percolate vertically through the substrate. Drops of water will form on the filter sheet, which is connected to the underside of the substrate. These will fall under gravity into the drainage layer below, then flow horizontally through the drainage layer and protection mat to the roof outlet. As all detained
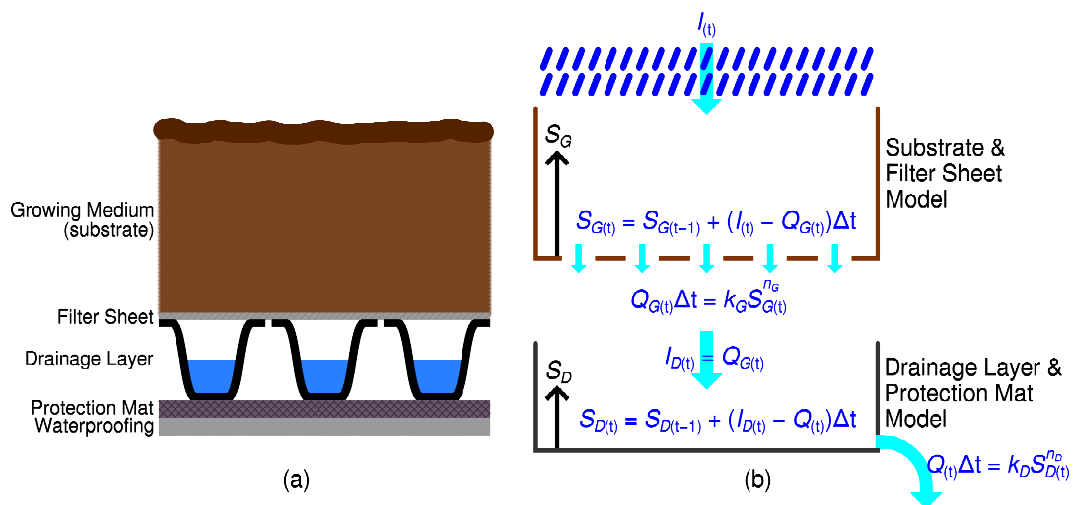


Figure 2. Cross-section of tested green roof system (a) and corresponding two-stage nonlinear storage routing model (b).

water passes first through the substrate/filter and then through the drainage/protection layer, with no reverse transfers taking place, the two component sets may be modelled as two nonlinear reservoirs in series, the inflow profile to the drainage layer being equivalent to the outflow profile from the substrate (Figure 2b). For each reservoir, the volume of water in storage is equal to the cumulative difference between inflow to and outflow from the reservoir, and the rate of outflow is predicted by a nonlinear storage-discharge relationship. The two equations governing each reservoir are therefore:

$$S_{t+1} = S_t + (Q_{t+1} - I_{t+1})\Delta t \tag{1}$$

$$Q_{t+1} = kS_t^n \tag{2}$$

Where $S$ is the reservoir storage depth, $Q$ is outflow rate, $I$ is inflow rate and $\Delta t$ is time step. $n$ is a dimensionless exponent parameter and $k$ is a scale parameter, in units of $mm^{1-n}/\Delta t$. Values of both $k$ and $n$ are constant and separate for each reservoir. Nonlinear storage routing was chosen due to previous success by the authors in using this method to model the runoff response of drainage layers (Vesuviano & Stovin 2013) and substrate samples (Yio *et al.* 2013) separately. In this experimental programme, a modelling time step of one minute was used. The exact $k$ and $n$ parameters used for each storage-discharge relationship were taken from previous studies and were $n_G = 2.97$, $k_G = 0.00365$ $mm^{1-n}/minute$, $n_D = 1.49$ and $k_D = 0.200$ $mm^{1-n}/minute$, where subscripts $G$ and $D$ refer to substrate (growing medium) and drainage layer/protection mat respectively. This experimental programme is therefore intended to provide an independent verification of previous modelling work. Delay parameters featured in the models developed by Vesuviano & Stovin (2013) and Yio *et al.* (2013), to account for time delays introduced by the monitoring equipment. Equivalent parameters are not included here, as the values predicted in earlier studies were generally far below the one-minute resolution of the runoff record.

## 3    RESULTS AND DISCUSSION

Tests were performed over eleven days (15-26th September 2012). Overall, the experimental system exhibited excellent mass balance and reproducibility. The total recorded rainfall volume over the test period was 2827.1 litres, while the total recorded runoff volume was 2819.7 litres. Within individual tests, the lowest recovery of runoff was 98.0% and the highest was 101.0%. The quantity of rainfall supplied in repeat tests varied by no more than 0.4% within each constant-intensity storm profile and by no more than 0.8% within each design storm profile.

Using the parameter values derived from previous studies, the model was able to generate accurate runoff predictions for all rainfall-runoff pairs, five of which are shown in Figure 3. This is despite potential inconsistency between batches of substrate and samples from these batches. Although green roof substrates are mixed according to specific recipes, some variation between and within specific batches should be expected. Nonetheless, the results provide confidence that parameters derived from one sample are applicable to other samples of the same nominal substrate mix. Inconsistencies in drainage layer and protection mat should be minimal, as one is a moulded HDPE sheet and the other a woven mat of fibres. Correspondingly, $k_D$ and $n_D$ should not vary greatly between different "batches" of these components.

The mean value of $R_t^2$ (Young *et al.* 1980) for constant-intensity tests was 0.981. However, the rising and falling limbs of the modelled runoff profile are generally slightly shallower than those of the monitored runoff profile for each test. This means that the model over-predicts the attenuation effects of the green roof, initially under-predicting runoff rate as it rises from zero to steady-state then over-predicting runoff rate as it falls back to zero after the storm. This is not a fault of the modelling methodology; it is most likely the result
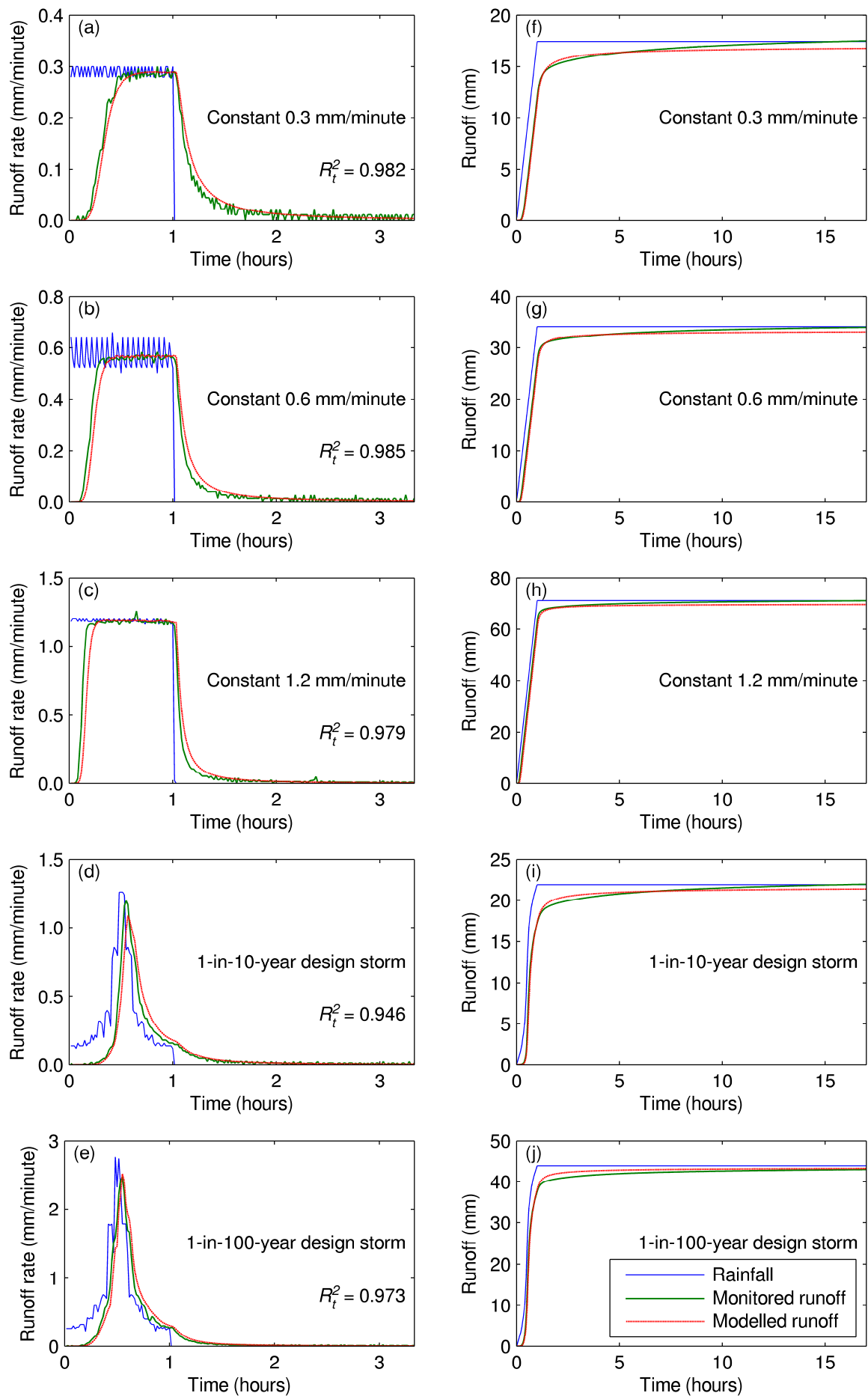
Figure 3. Time-series (a-e) and cumulative (f-j) rainfall, monitored runoff and modelled runoff profiles for storm events.

of imperfect values being specified for $k_G$ and $n_G$, as potential variations in substrate are large in comparison to potential variations in synthetic drainage layers/protection mats. However, over-prediction of attenuation is slight, as the lag time of the modelled runoff profile is in the order of minutes or seconds for all constant-intensity tests.

The model's response to storm events of varying rainfall profile generally fits closely to the monitored runoff response (Figures 3 (d) and (e)), with a mean $R_t^2$ of 0.957. As the model can be applied to variable-intensity design storms with only a low loss of accuracy, this demonstrates that the routing parameters derived from constant-intensity storms are applicable to time-varying inputs. In common with the constant-intensity storms, the rising and falling limbs of the modelled runoff profile are shallower than the rising and falling limbs of the monitored runoff profile. For the 1-in-10 year storm events, the peak intensity of monitored runoff was 4.9% below the peak storm intensity. However, the model under-predicts the test bed's peak runoff rate by an average of 9.4%. This is again due to the attenuation effects of the green roof being over-estimated by the model; the peak of the storm is of a short duration, and so the rainfall rate starts to fall before the modelled runoff rate has risen to the peak runoff rate. Conversely, the monitored peak flow reduction for the 1-in-100 year storm was 10.3%, which the model typically over-predicted by 2%. The over-prediction is likely due to the sudden spike in rainfall intensity at the beginning of the peak period, which is a limitation of the rainfall simulator. Figure 3 (e) shows the four minutes comprising the rainfall peak to consist of alternating spikes and troughs. Any rainfall intensity aside from a constant 0.3, 1.2 or 4.8 mm/minute is approximated by activating and deactivating rainfall dripper networks. Consequently, the peak period of 2.577 mm/minute consists of greatly varying rainfall rates that average out over four minutes.

Figure 3 (f) to (j) show the cumulative profiles corresponding to Figure 3 (a) to (e). These all show a close fit for the duration of the storm, followed by an under-estimation of cumulative runoff in the long-term. However, as the storage routing method is unable to permanently retain water, the under-prediction is purely a result of insufficient time being allowed for the modelled runoff rate to decay to zero. Conservatively, the modelled cumulative runoff depth at the final time point should be assumed equal to the rainfall depth.

For all tests, cumulative median-to-median delay was quantified separately for the substrate and drainage layer. Detention effects in the substrate were found to be 1.6-3.6 times greater than those in the drainage layer/protection mat. As peak rainfall intensity increased, detention decreased in both stages, though noticeably more so in the substrate.

## 4    CONCLUSIONS

It is shown that the two-stage storage routing model produces consistently high-quality results. Furthermore, it is shown that the many potential inconsistencies and variations between different batches and samples of nominally identical substrate do not greatly affect the parameterization of the model, though in this case attenuation effects were slightly over-estimated. This may cause short runoff peaks, in response to short rainfall peaks, to be under-predicted. However, this is a consequence of imperfect parameterization and not a fault of the underlying conceptual model. An analysis of the cumulative rainfall profile, modelled runoff profile and intermediate drainage layer inflow profile found that the greatest detention effects occurred in the substrate, but that their relative magnitude decreased as peak storm intensity increased.

It is suggested in Vesuviano and Stovin (2012) that the $k_D$ and $n_D$ parameter values for a drainage layer may be dependent only on the roof slope, drainage length and surface roughness of the drainage component material. Therefore, values for $k_D$ and $n_D$ may be estimated for untested drainage layers of similar material to those already tested. Further work should attempt to link values of $k_G$ and $n_G$ to measurable or estimable characteristics of substrate (Yio *et al.* 2013) in order for the two-stage storage routing model described here to be applicable to green roofs generally.

## ACKNOWLEDGEMENTS

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