A two-stage storage routing model for green roof runoff detention

Essai d'un modèle de stockage de toitures végétalisées

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RÉSUMÉ

Les toits végétalisés ont été adoptés dans le développement urbain pour tout un tas de raisons, souvent pour réduire la quantité totale et le débit volumétrique du ruissellement urbain. Les toits végétalisés modernes présentent une conception en multicouche, leurs composants principaux étant constitués d'une couche de végétation, d'un substrat et, dans pratiquement tous les cas, d'une couche de drainage séparée. La plupart des modèles hydrologiques actuels des toits végétalisés sont adaptés à une couche unique, en général le substrat granuleux, ou modélisent des couches séparées en un processus unique ; ces modèles sont applicables uniquement à une seule configuration de toit et n'ont pas de capacité prédictive pour d'autres configurations de toit. Les auteurs présentent ici un modèle générique à deux niveaux et adaptable pour un système composé d'un substrat granuleux au-dessus d'une couche de drainage en plastique dur de style « boîte à œufs » et un tapis de protection fibreux, dans lequel le substrat et la couche de drainage / tapis de protection sont modélisés séparément par des sous-modèles vérifiés au préalable. Des averses contrôlées d'intensité constante et de durée variable sont appliquées à un système de toit végétalisé dans un simulateur de pluie. La chronique de ruissellement modélisé est comparée au ruissellement observé pour chaque averse. Les profils des ruissellements modélisés et observés sont très proches (à savoir R_t^2 = 0,971), mais une caractérisation supplémentaire du composant substrat est nécessaire pour que le modèle soit applicable de façon généralisée à d'autres configurations de toit avec des substrats différents.

ABSTRACT

Green or vegetated roofs have been adopted into urban development for a variety of reasons, though frequently as a means of reducing the total quantity and volumetric flow rate of urban runoff. Modern green roof designs are multi-layered, their main components being a vegetation layer, a layer of growing medium and, in almost all cases, a separate drainage layer. Most current hydrological models of green roofs are either suitable for one layer only, usually the granular growing medium, or combine the modelling of the separate layers into a single process; these models are applicable to one roof configuration only and have no predictive capability for other roof configurations. The authors here present an adaptable, generic, two-stage model for a system consisting of a granular growing medium over a hard plastic "egg box"-style drainage layer and fibrous protection mat, in which the growing medium and drainage layer/protection mat are modelled separately by previously verified sub-models. Controlled constant-intensity and time-varying 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 and monitored runoff profiles are highly similar (mean R_t^2 = 0.971), but further characterization of the growing medium component is required for the model to be generically applicable to other roof configurations with different growing media.

KEYWORDS

Drainage layer, Green roof, Growing medium, Modelling, Storage routing

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1 INTRODUCTION

1.1 Green Roofs and Performance

The construction of impermeable surfaces, such as roads and the roofs of buildings, results in an equal reduction in the area of permeable ground, such as exposed soil and turf. Increasing the impermeability of an area increases the risk of local pluvial flooding, as any rainwater landing on that area is less likely or able to infiltrate into the ground. This is of particular concern in urban areas, as these are both the least permeable and most densely-populated parts of the world. The traditional response to stormwater management in urban areas has been to build underground pipe networks to rapidly transport rainfall away. However, due to continuous increases in most urban populations, and more intense and larger storms resulting from climate change, sewer systems may now be less able to successfully transport rainwater away in sufficient quantities to prevent urban flooding, and water entering the network at one point may be forced back onto the surface elsewhere. As the majority of existing sewers carry a combination of rainwater and sanitary sewage, there is a very real potential for public health issues to result from contaminants and diseases in waste, in addition to the damage to built structures that may be caused strictly by the volume of flood water and any large objects transported by it.

Sustainable drainage systems (SUDS) and equivalents in other countries (low impact development, water sensitive urban design, etc) are new methods of draining surface runoff, aimed at reducing the risks associated with conventional drainage systems by incorporating rainwater treatment and infiltration into the design of an area’s drainage network. Examples of components that may be used in a SUDS treatment train include ponds (which treat and allow settlement of contamination in storm runoff over a period of days), permeable paving (which is an alternative to a traditional road or footpath surface that allows water through for infiltration into the underlying ground) and green roofs.

Green roofs are engineered, roof-level systems, consisting primarily of a vegetation layer, a layer of low-density growing medium and a separate drainage layer (Figure 1). Between the growing medium and drainage layer is a thin, highly permeable fibrous sheet, which prevents small particles in the growing medium washing through to the drainage layer. Beneath the drainage layer is a protection mat, which may be rubbery or fibrous. Unlike many other SUDS components, green roofs do not require any land, except for the tops of buildings, and so do not impact upon the available land for development in a plot. Green roofs broadly divide into two categories: extensive, which are inaccessible and use low-growing and drought tolerant plants in 50-150 mm of growing medium; and intensive, which are generally more accessible and can support a wider variety of plants, up to and including trees, in a deeper layer of growing medium. The maintenance requirements of extensive green roofs are generally low, as they are not publicly accessible, and the plants are drought tolerant and small.

Green roofs are able to influence urban runoff volumes through retention and detention processes. Retention of rainfall occurs primarily in the growing medium, which is able to store water up to field capacity by capillarity in its smaller pores. Further retention may occur in the drainage layer, as many synthetic drainage components incorporate cups into their design. If the protection mat is fibrous, additional retention may also occur in the protection mat. Water retained in a green roof does not become runoff; it is returned to the atmosphere by evapotranspiration. The annual retention of rainfall

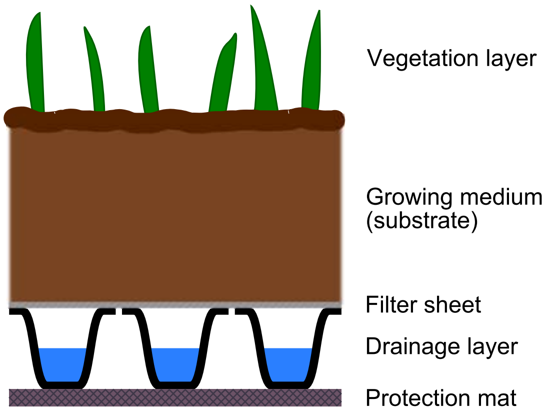


Figure 1. Cross-section of a typical green roof system.

by green roofs in different climates has been extensively studied; Fioretti *et al.* (2010) and Gregoire and Clausen (2011) graphically present comparisons of over twenty long-term green roof retention studies between them. However, the maximum volume of water that can be retained at one time is finite for any particular roof; it is limited by the volume of pores of the right size in the growing medium and the geometry of the drainage layer. For an extensive green roof, this finite capacity varies from approximately 15 to 40 mm. After this capacity is reached, no further retention can occur. Therefore, the retention performance of a green roof can appear to decrease under large storms, simply because a volume available for storage is a smaller percentage of a larger storm (Stovin *et al.*, 2012). Studies conducted by Carter and Rasmussen (2006) and Voyde *et al.* (2010) group storms by depth and consider green roof performance separately for each group, showing percentage retention to decrease as storm depth increases. During the dry period after a storm, evapotranspiration removes retained water from the green roof system, generating capacity for retention in the next storm.

Detention (temporary storage) of rainfall occurs in the growing medium, as rainfall percolates through larger pores, which are unable to store water, but still offer some resistance to vertical flow-through. If present, a fibrous protection mat may also provide significant rainfall detention due to lateral resistance to flow. As the purpose of the drainage layer is to quickly remove excess water that cannot be retained anywhere in the green roof system, the detention effects of the drainage layer are low. Detained water leaves the green roof via conventional drainage systems e.g. downpipes, 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 flow rate of runoff compared 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 geographical variations in microclimate within cities, preclude a meaningful individual study and modelling of green roof performance in each one, due to the excessive level of time and resources required. Similarly, the wide variation in green roof construction characteristics, such as depth, growing medium composition and roof slope, 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 behaviour of a roof in response to two identical storms will be identical. Generic modelling of the internal water processes within a green roof enables the effects of climate and construction to be decoupled from a green roof's runoff response, allowing the model to be applicable, and hence green roof performance estimated, when climatic factors are unknown and construction is dissimilar to others nearby.

1.2 Existing Approaches to Modelling

Runoff modelling methods for green roofs have been presented since the mid-2000s. Villarreal and Bengtsson (2005) analyzed data from several controlled uniform wetting events on a small green roof test bed by means of linear programming to estimate a single average unit hydrograph (corresponding to an input of 1 mm in one minute) for all events. The unit hydrograph was convolved with real storm records to predict runoff responses. Though the modelled runoff profiles were similar in shape to the monitored runoff profiles, the unit hydrograph derived in this experimental programme can only be guaranteed applicable for green roofs identical to the one tested, which was both small (1.54 m^2) and shallow (40 mm) in comparison to many other green roofs.

Hilten *et al.* (2008) used Hydrus 1-D software, which numerically solves the Richards' equation for variably-saturated media, to predict runoff volumes from Green Roof Blocks, a modular system with 100 mm growing medium and no drainage layer. Their study identified a need to accurately characterize the growing medium, as it was specified as 100% sand solely to provide consistent model closure. One possible consequence of this is that the time-series runoff profiles simulated in response to 24-hour SCS design storms (United States Department of Agriculture, 1992) are unusually shaped, consisting of a long period of no runoff, followed by a very steep rising limb, followed by a close match to the remaining part of the rainfall profile. The modelled time-series runoff profiles in response to design storms were not verified experimentally; the modelling parameters input to Hydrus-1D for the design storms were those which gave the best fit between monitored and modelled runoff depth (irrespective of runoff profile shape) for each day (not each event) in June 2005. The use of Hydrus 1-D was extended by Palla *et al.* (2012) to a full-scale green roof consisting of two separate granular layers (growing medium and drainage layer). Input parameters for both layers were either referred from existing literature for appropriate soil grades or calibrated from five monitored events. Comparisons between time-series modelled and monitored runoff profiles were presented for five calibration and five validation storm events in this study. Nash-Sutcliffe Efficiency ranged from a minimum of 0.635 to a maximum of 0.970, with a mean of 0.868. However, Nash-Sutcliffe Efficiency was consistently lower for the validation events. The Hydrus-1D model is based on physical processes and so is applicable to all green roof growing media and, in general, all soils. However, in order to use the model, a total of twelve media-specific input parameters are required to be known accurately.

Kasmin *et al.* (2010) applied nonlinear storage routing methods to represent detention processes in a green roof test bed in Sheffield, UK, requiring only two modelling parameters. Though the modelled runoff profiles produced were highly accurate and detailed, the overall value of the model is somewhat lowered by its combining of the entire system into a single process.

Stovin *et al.* (2012) demonstrated the need for process-based modelling in a study which used storm event and climatic properties as inputs to predict eight hydrologic performance metrics, such as total runoff and peak-to-peak delay, for the same Sheffield test bed. The modelling equations were found to have poor predictive capability, even for the storms used to generate them, as they did not consider the hydrologic state of the test bed itself during and between storm events.

She and Pang (2010) present perhaps the most comprehensive green roof model of all, which considers the growing medium and drainage layer components separately, using Green-Ampt equations and Darcy's Law for the growing medium and Manning's Equation for the drainage layer. The performance of this model is reasonable, though it appears to noticeably overestimate runoff flow peaks in 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. Additionally, in order for it to behave as expected, the drainage layer is modelled as an open channel with a roughness coefficient far in excess of what is reasonable for smooth, hard plastic.

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, that models the processes in the growing medium and drainage layer separately so as not to be limited to a single configuration, and is easy to use and easy to accurately parameterize. Specifically, a two-stage storage routing model will be tested, using routing parameters derived from previous experimental programmes in which the runoff response of green roof component layers under constant intensity storm events was modelled.

2 METHODS

2.1 Experimental Setup

All tests were conducted in a rainfall simulator (Figure 2), whose design evolved from that described in detail in Vesuviano & Stovin (2012). 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, as of September 2012, 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 channel and inside of the chamber to be seen. Rainfall is supplied by three independent networks of Netafim PCJ-LCNL

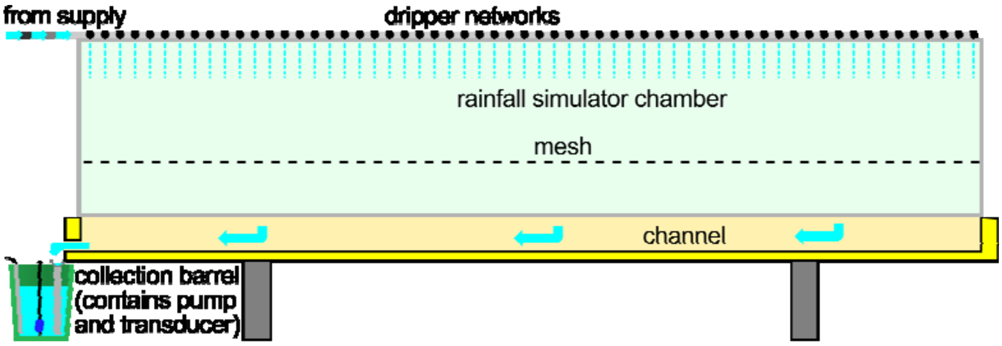


Figure 2. The rainfall simulator.

pressure-compensating drippers located 1.12 metres above the channel bed, near the top of the chamber. 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 it can be 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 growing media 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.

The combined rate of flow into all three rainfall dripper networks is measured at 0.5-second intervals, to a resolution of 0.1 litres, using a Badger Meter RCDL M25 LCR nutating disc flow meter. Runoff is measured at 0.5-second intervals, with varying volumetric resolution, using a Druck PDCR 1830 pressure transducer. Both are connected to a Campbell Scientific CR1000 data logger. The Netafim MiraclePlus AC6 controller used by Vesuviano & Stovin (2012) has been replaced by a Campbell Scientific SDM-CD16AC relay controller, which is connected to the data logger, the barrel pump and each of the electromagnetic valves gating the dripper networks; the data logger can operate any of these. New software was developed to allow all dripper networks to be operated over independent timing cycles, enabling time-varying rainfall events to be imposed. The pulse timings for rainfall rates repeated from previous tests were taken directly from the old control system to allow direct comparability to be made.

The original cylindrical, 50-litre runoff collection barrel has been replaced by one with an effective 168-litre capacity, to allow for collection of larger storm events. Three cylindrical pipes are fitted inside the barrel. One is connected to a back-flow filter and permanently fixed pump, which is used to empty the barrel when it is full. Another houses the pressure transducer and acts as a baffle to reduce the effect of surface waves. The final pipe is a downpipe connected to the simulator gutter, which terminates below the barrel's minimum water level, and acts to help reduce the formation of surface waves caused by surface runoff splashing into the barrel from above. The shape of the new barrel is approximately a truncated cone; a calibration curve was established from 57 pressure readings taken at three-litre intervals over the available range of the barrel's usable capacity from 0 to 168 litres.

The test green roof system, laid on top of the channel bed, consisted of a 10 cm layer of growing medium (55% crushed brick, 30% pumice, 10% coir, 5% compost) over a ZinCo Floradrain FD 25 drainage layer. These two components were separated by a sheet of ZinCo Systemfilter SF particle filter, which was taped to the internal walls of the simulator channel to prevent it from moving during the experimental programme. A fibrous protection mat, SSM 45 was laid under the drainage layer. The amount of growing medium required for a 10 cm depth was calculated by sampling the density of the mixture used, to FLL guidelines, and multiplying by the required volume (5 m × 1 m × 0.1 m). This was added to the rainfall simulator channel by bucket, with the mass of growing medium in each bucket added to the channel being recorded and subtracted from the required total. The growing medium was not compacted as no repeatable methodology for compaction was considered practical at this scale. As compaction of the growing medium simulates the effects of age and weathering, the tested experimental setup can be considered similar to a new green roof. The test 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 data. Five different storm profiles, each of 60-minute duration, were used in total. Each storm profile was applied to the two-layered system three times (giving a total of fifteen tests) to assess the consistency of monitored runoff profiles for identical rainfall inputs. Three of the five storm profiles were of constant intensity (0.3, 0.6 and 1.2 mm/minute) and relate directly to three of the constant rainfall intensities used in previous experimental programmes to characterize the response of drainage layers and growing media in isolation. These three event profiles were used to verify the monitored runoff responses of the two-layered system, as the individual responses of each layer under identical storms are already known. The other two storm profiles represent the 60 minute, 1-in-10 and 1-in-100 year 75% summer storm profiles for central Sheffield, discretized into 15 steps of four minutes each, and were included to provide useful green roof runoff profile information and observations to drainage engineers. These two time-varying events also provide a more realistic test of a modelling approach and parameter sets that were derived under constant intensity rainfalls. The order of tests was randomized to prevent any systematic, rainfall-related effects that may have carried over from one test to the next. All tests were performed continuously, spaced at 17-hour intervals (60-minute test, 16 hour drainage time), to allow for the system to return to field capacity between tests while minimizing inter-event evaporation. Prior to the first test, a 60-minute, constant 1.2 mm/minute intensity 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. This ensured that only detention effects were observed from the first test onwards.

The 1-in-100 year, 0.6 and 1.2 mm/minute storm events exceeded the 168-litre capacity of the collection barrel and so water was pumped out during these tests. The rate of runoff while the pump was active 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, rather than retained, will eventually become runoff. In order for rainfall landing on the surface of the green roof to become runoff, it must first percolate vertically through the growing medium. Drops of water will then form on the underside and fall under gravity into the drainage layer below, at which point the water, now detained in the drainage layer, will flow horizontally to the roof outlet, becoming green roof runoff as it leaves the drainage layer. As all detained water passes first through the growing medium and then through the drainage layer, with no reverse transfers taking place, the two components may be modelled in series, the outflow profile from the growing medium being used as the inflow profile to the drainage layer.

In this experimental programme, the response of the two-layered green roof system was modelled by a two-stage nonlinear storage routing method with one-minute time step (Figure 3). Both the growing medium and drainage layer are modelled as separate reservoirs in series. The rate of outflow from either reservoir at a future time step, Q_{t+1}, is predicted by a nonlinear storage-discharge relationship, $Q_{t+1} = kS_t^n$, where k and n are scale and exponent parameters, which are constant and separate for each reservoir. For each reservoir, the volume of water in storage is equal to the cumulative difference between inflow to and outflow from the reservoir, $S_{t+1} = S_t + Q_{t+1} - I_{t+1}$. Nonlinear storage routing was chosen to model each layer separately, due to its previous successful use by the authors of this paper in modelling the runoff response of drainage layers (Vesuviano & Stovin, 2012) and growing media samples (Yio *et al.*, 2012) tested in isolation. As the two reservoirs are arranged in series, outflow from the growing medium is equal to inflow to the drainage layer. In this experimental programme, the exact k and n parameters used for each reservoir were taken from previous studies conducted on nominally identical growing media samples and drainage layer components, using one-minute time steps. A delay parameter featured in the storage routing-based drainage layer model used by Vesuviano & Stovin (2012), to account for time delays introduced by the monitoring equipment. An identical parameter was included in the storage routing-based growing medium model of Yio *et al.* (2012). No delay parameter is included in either sub-model in this experimental programme, as the values of delay that would be required for either of the components used in this test system, under similar rainfall events, are generally below the one-minute resolution of the runoff record.

3 RESULTS AND DISCUSSION

3.1 Monitored Rainfall and Runoff

Tests were performed over eleven days, from 15-26th September 2012. Overall, the experimental system exhibited excellent mass balance and reproducibility. The total recorded volume of rainfall over the entire test period was 2827.1 litres, while the total recorded volume of runoff was 0.26% lower, at 2819.7 litres. Within individual tests, the lowest quantity of recovered runoff was 98.0% for the second test performed, a 1-in-100 year event, and the highest was 101.0% for the test immediately after, a 0.3 mm/minute constant intensity test. However, the actual excess runoff volume recorded in the third

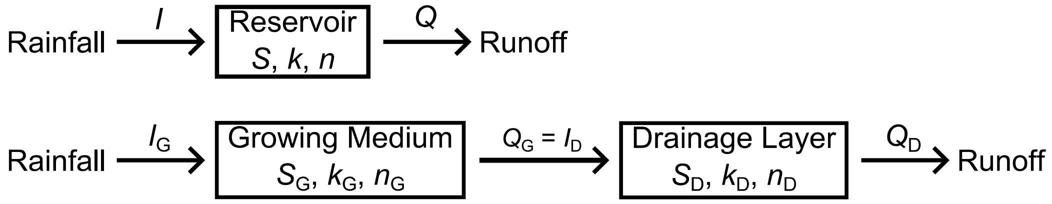


Figure 3. A standard nonlinear storage routing model (top) and the two-stage model used in this study (bottom).

test was less than one-quarter of the runoff deficit of the second test. The quantity of rainfall supplied in repeat tests varied by no more than 0.3 litres within each constant-intensity storm profile. For non-constant intensity storm profiles, a variation of up to one litre was found. In no case was the quantity of water delivered in any test more than 0.46% different from the mean quantity for the storm profile. Some variation in monitored rainfall and runoff volumes may have resulted from expansion and contraction of water as the result of ambient temperature fluctuations. A limited and variable amount of evaporation will have taken place between tests and may therefore have recharged a small but noticeable amount of water retention capacity in the test system.

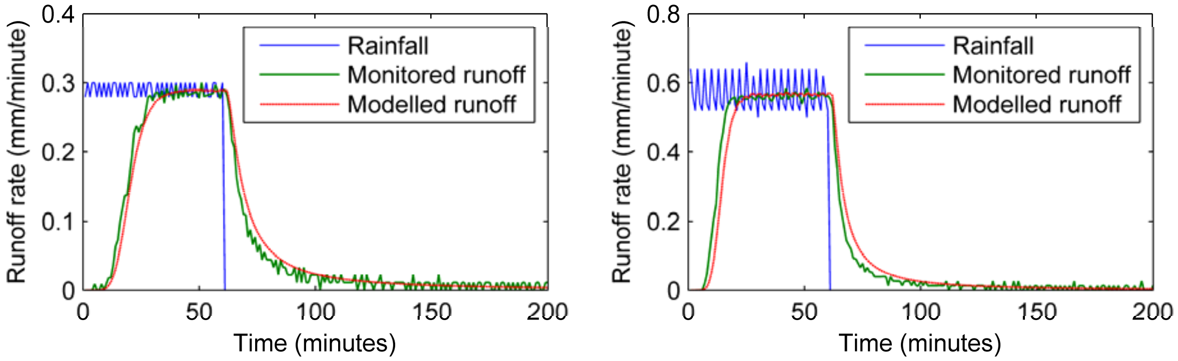
3.2 Modelled Runoff

Each of the fifteen recorded rainfall profiles was input to the two-stage storage routing model using routing parameters derived from two previous optimization studies, one on samples of growing media with an underlying filter sheet, the other on drainage layers with and without underlying protection mats. The specific parameters used in this model were those derived from individually-tested growing medium and drainage layer configurations which were most similar to those used in this experimental programme; numeric values were $n_G = 2.97$, $k_G = 0.00365$, $n_D = 1.49$, $k_D = 0.200$, where subscripts G and D refer to growing medium and drainage layer respectively. As the growing medium and drainage layer models are in series, the discharge profile output given by the growing medium sub-model in response to a rainfall event is used as the input profile to the drainage layer sub-model and the discharge profile output from the drainage layer sub-model is taken as the system's runoff profile in response to a particular rainfall event.

Using the specified parameters, the model was able to generate accurate runoff predictions for all rainfall-runoff pairs (one event of each profile is shown in Figure 4). This is despite inconsistency between batches of growing media and samples from these batches; it is highly unlikely that a small sample taken from a much larger batch of material will be of the same composition as the overall or nominal batch. Additionally, it is also highly unlikely that two samples from different batches of the same nominal mix, such as the sample used for these tests and the sample used for growing medium-only tests, will be entirely similar. Furthermore, when a mix with a wide particle size distribution is removed from its container and installed in a test bed, the settling of the particles, and hence the exact inter-particle spacing distribution, is unknown. However, as the parameters derived from one sample of growing medium with filter sheet, in isolation, appear to be directly applicable to a sample from a different batch made to the same nominal recipe, it is likely that the effects of variations in mixing, sampling and installation are low in relation to the green roof's runoff response. Any inconsistencies in drainage layer and protection mat should be very small, as one is a moulded HDPE sheet and the other a woven mat of fibres, and so k_D and n_D should not vary greatly between different "batches" of the same components.

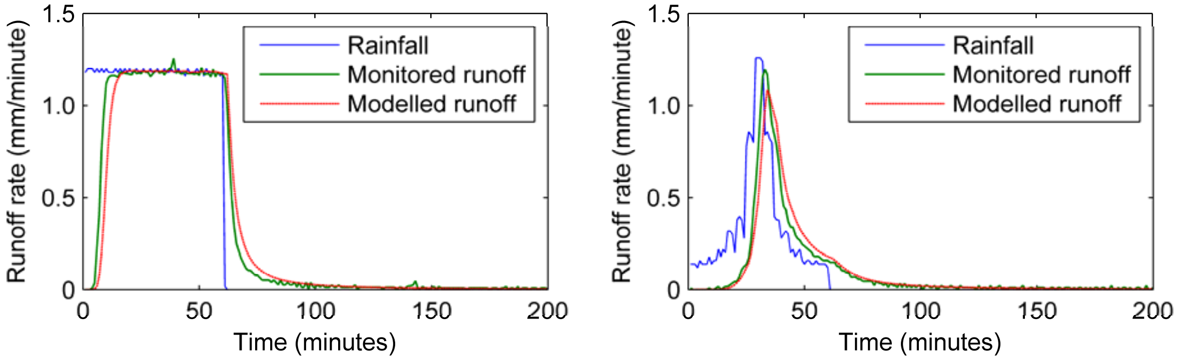
Considering the tests of constant-intensity first, the mean coefficient of determination (R_t^2) was 0.981. However, the rising and falling limbs of the modelled runoff profile are generally slightly shallower than those in the monitored runoff profile of each test. This means that the model over-predicts the attenuation effects of the green roof, initially under-predicting runoff rate as it increases from zero to steady-state, then over-predicting runoff rate as it falls back to zero after a storm. This is not a fault of the modelling methodology; it is most likely the result of imperfect values being specified for k_G and n_G, as potential sources for variation in growing media are large in comparison to potential sources for variation in synthetic drainage layers and protection mats. However, the 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 of the constant intensity tests.

The model's response to storm events of varying rainfall profile generally fits closely to the monitored runoff response (Figures 4 (d) and (e)), with a mean R_t^2 of 0.957. As the model can be applied to design storms of varying intensity with only a low loss of accuracy, this demonstrates that the routing parameters, derived from constant-intensity storms, are also 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 mean 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, mean the peak flow reduction for the 1-in-100 year storm was 10.3%, which the model over-predicted by a mean of 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



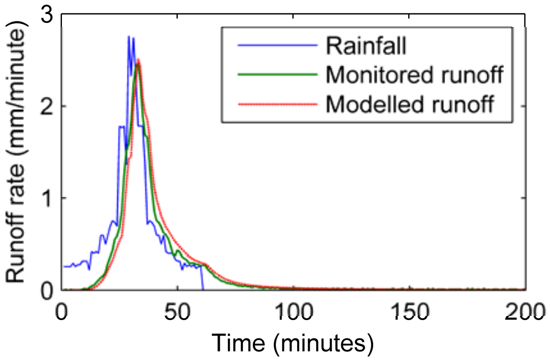
(a) 0.3 mm/minute constant

(b) 0.6 mm/minute constant



(c) 1.2 mm/minute constant

(d) 1-in-10 year storm event

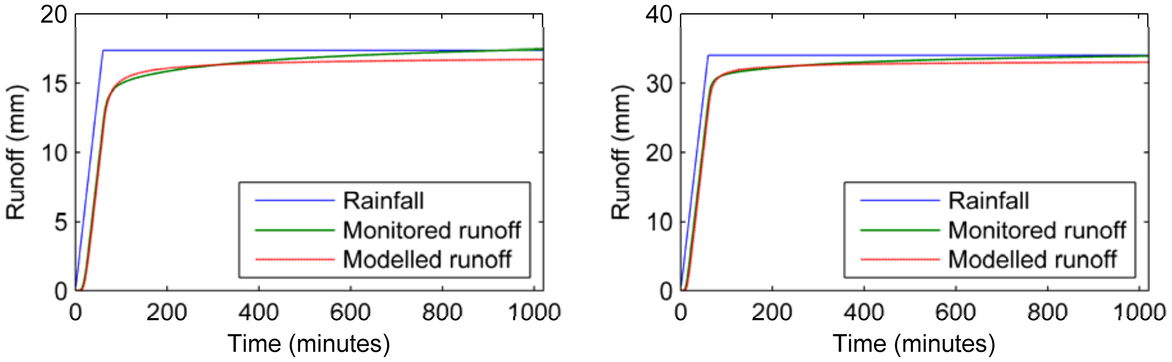


(e) 1-in-100 year storm event

Figure 4. Time-series rainfall, monitored runoff and modelled runoff profiles for storm events.

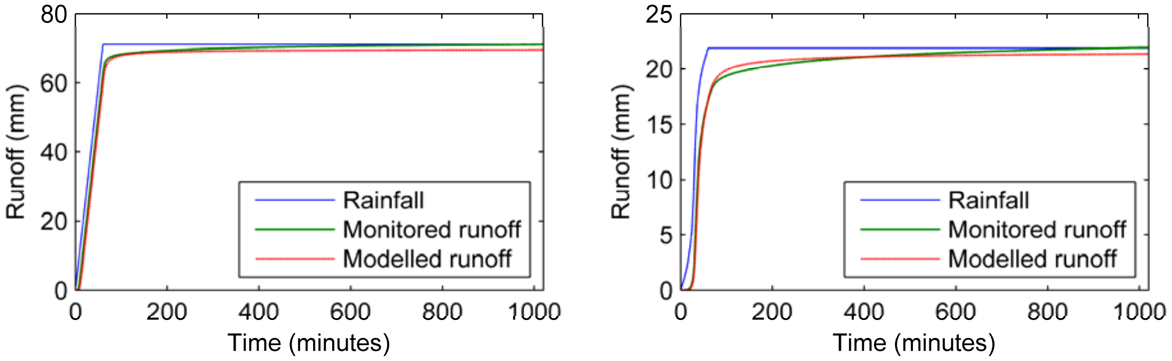
simulator. Figure 4 (e) shows that the four minutes comprising the rainfall peak consist of alternating spikes and troughs. Any rainfall intensity aside from a constant 0.3, 1.2 or 4.8 mm/minute must be approximated by activating and deactivating rainfall dripper networks. As a consequence, the peak period of 2.577 mm/minute consists of greatly varying rainfall rates that average out over four minutes.

Figure 5 shows the cumulative profiles corresponding to the time-series profiles in Figure 4. These all show a close fit for the duration of the storm, followed by an under-estimation of cumulative runoff in the long-term. Figure 5 (e), shows the only test for which cumulative runoff was over-estimated at the end of the seventeen-hour test period; this is the test in which cumulative monitored runoff depth was 98% of rainfall depth. This indicates that the model is likely to under-predict total runoff depths from a storm event. The mean under-prediction for these fifteen events was 2.4%, while the greatest under-prediction was 4.9% for a constant 0.3 mm/minute storm event. However, as no storage routing method is able to permanently retain water, the under-prediction is simply a result of insufficient time being allowed for the runoff tail to fully decay to zero. A conservative estimate would be to ignore the modelled cumulative runoff depth at the final time point and instead assume that the actual runoff depth is equal to the rainfall depth.



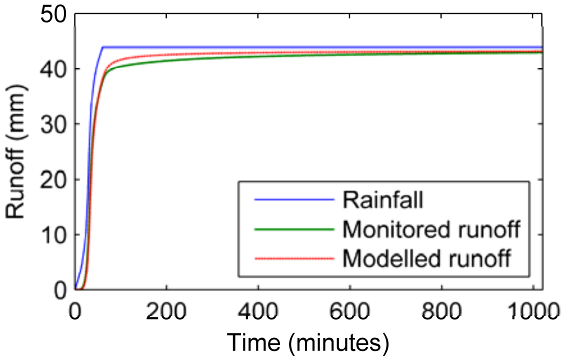
(a) 0.3 mm/minute constant

(b) 0.6 mm/minute constant



(c) 1.2 mm/minute constant

(d) 1-in-10 year storm event



(e) 1-in-100 year storm event

Figure 5. Cumulative rainfall, monitored runoff and modelled runoff profiles for storm events.

For all tests, the time delay between half of the cumulative rainfall depth falling on and leaving the growing medium sub-model was found, as was the time delay between this same depth entering and leaving the drainage layer and protection mat sub-model. The detention effects in the growing medium, measured as a time delay, were found to be 1.6-3.6 times greater than those in the drainage layer and protection mat. As peak rainfall intensity increased, detention decreased in both stages, though noticeably more so in the growing medium than in the drainage layer and protection mat.

4 CONCLUSIONS

It is shown that the two-stage storage routing model produces consistently high-quality results, for both constant- and variable-intensity rainfall events. Furthermore, it is shown that the many potential inconsistencies and variations between different batches and samples of nominally identical growing media do not greatly affect the parameterization of the model, though in this case, attenuation effects were slightly over-estimated. This over-attenuation may cause short runoff peaks, in response to a time-varying rainfall profile, to be under-predicted. However, this is a consequence of imperfect parameterization of the growing medium and not a fault of the model itself. Cumulative, per-event runoff was under-predicted by 2.4% on average. However, as the model is intended purely for detention, true cumulative runoff can be assumed equal to the rainfall depth for any storm event. An analysis of the cumulative rainfall profile, modelled runoff profile and intermediate drainage layer inflow profile found that the greatest detention effects were found in the growing medium, 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 growing media e.g. permeability (Yio *et al.*, 2012) in order for the two-stage storage routing model described here to be accurate and applicable to green roofs generally.

ACKNOWLEDGEMENTS

The use of the rainfall simulator was provided by ZinCo GmbH as part of the EU FP7 Marie-Curie Industry-Academia Partnerships and Pathways Green Roof Systems Project, a collaboration between the University of Sheffield (UK) and ZinCo GmbH (Germany).

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