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A Generic Hydrological Model for a Green Roof Drainage Layer

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ABSTRACT

A rainfall simulator of length five metres and width one metre was used to supply constant intensity and largely spatially uniform water inflow events to 100 different configurations of commercially available green roof drainage layer and protection mat. The runoff from each inflow event was collected and sampled at one-second intervals. Time-series runoff responses were subsequently produced for each of the tested configurations, using the average response of three repeat tests.

Runoff models, based on storage routing ($dS/dt = I - Q$) and a power-law relationship between storage and runoff ($Q = kS^n$), and incorporating a delay parameter, were created. The parameters k, n and *delay* were optimized to best fit each of the runoff responses individually. The range and pattern of optimized parameter values was analysed with respect to roof and event configuration. An analysis was performed to determine the sensitivity of the shape of the runoff profile to changes in parameter values. There appears to be potential to consolidate values of n by roof slope and drainage component material.

KEYWORDS

Urban drainage, SUDS, green roof, drainage layer, detention, modelling

1 INTRODUCTION

Urbanization has led to the replacement of natural land with impervious surfaces, into which water cannot infiltrate. The purpose of traditional stormwater drainage systems is to convey excess water from precipitation away from the impervious surfaces of urban areas into nearby natural watercourses as rapidly as possible. This has mainly been achieved through the building of pipe networks, which, in many areas of the world, and especially in older cities, are shared with wastewater. In the event that a large storm overwhelms the combined sewer network, a mixture of stormwater and untreated sewage may be discharged from an overflow pipe directly into a river, lake or the ocean. However, if the rate of discharge from these overflow pipes is not high enough, localized flooding will occur elsewhere in the network, which in the worst case will result in combined sewage emerging onto city streets.

Sustainable Drainage Systems (SUDS) are a more recent water management concept, which has among its aims the management of the volume and flow rate of surface runoff (CIRIA, 2009). Green roofs are one particular SUDS component that can retain, temporarily detain, filter and treat rainwater exactly where it lands. They can also provide other benefits, including carbon sequestration in the plants, the creation of specific habitats or thermal buffering to the building below. Advantageously, in comparison to many other SUDS devices, the land area required exclusively and specifically for the green roof itself is zero. Furthermore, as roofs may account for up to 50% of the impermeable surfaces in an urban area (Dunnett & Kingsbury, 2004), opportunities to place green roofs are ample.

From top to bottom, the components of a typical green roof are: vegetation layer; substrate layer (a growing medium for the vegetation); filter sheet (to prevent small particles washing out of the substrate); drainage layer (to quickly remove excess precipitation that has passed through the substrate); protection mat (to prevent damage to the root barrier); and root barrier (to protect the roof construction from damage that the vegetation may cause). The drainage layer comes in a variety of forms, including aggregate and various types of geocomposite: entangled polymeric filaments, shaped plastic modules, porous synthetic mats and foam boards (Wingfield, 2005). The modular and board drainage layers serve a secondary function of storing additional water that would otherwise become runoff, which is released through evaporation over a long time period. The protection mat may take the form of a rubber sheet or it may be fibrous. Fibrous protection mats are also capable of storing additional water from a rainfall event, which is subsequently released at a very slow rate. These mats may be referred to as moisture retention mats, retention mats or moisture mats. However, no protection mat is present in inverted roofs as the root barrier and waterproofing are protected from mechanical damage by the roof's insulation layer, which is brought above the waterproofing into the green roof construction (Getter et al., 2011).

When comparing runoff with conventional roofs, the primary hydrological benefits of a green roof are a reduction in peak runoff rate, a time delay before the start of runoff and often a significant reduction in total runoff volume (Carter & Rasmussen, 2006). Though the hydrological benefits of green roofs are widely recognized and reported, many of the published findings are specific to the exact system build-up used by the authors of a particular piece of research, and these system build-ups have not always been comparable to common practical designs. Consequently, these findings are not necessarily of use to drainage engineers who wish to know the time-series runoff response of a building or catchment that includes green roofs. Though research has been published attempting to model green roof storm response as a time series, these models have generally been based on existing soil models requiring high levels of specific parameterization (Qin et al., 2003; Hilten et al., 2008; Palla et al., 2009). Villarreal & Bengtsson (2005) modelled runoff using a generic deconvolution method. However, the nature of the method requires a different unit hydrograph for every specific roof design. Kasmin *et al.* (2010) modelled an entire green roof test bed using a storage routing method, ignoring the differences between the soil-like substrate and open-channel like drainage layer. The green roof model presented by She & Pang (2010) contains an independent drainage layer submodule, based on nonlinear storage routing, but does not consider the potential differences that may arise from different forms of drainage layers.

In order for a green roof model to be applicable to combinations of different substrate and drainage layer, it is necessary to be able to model each individually. This research will attempt to link the physical characteristics of green roof drainage layer configurations with parameter values in a nonlinear storage routing model, focusing only on the detention effects of the drainage layer.

2 EXPERIMENTAL SETUP

A test programme was developed, with the goal of evaluating the suitability of storage routing models to accurately predict the time-series runoff response of drainage layer components to specified water input events. A large rainfall simulator was modified in order to generate controllable and repeatable events with which various drainage layer and moisture mat components could be wetted.

The rainfall simulator (Figure 1) has a length of five metres and a width of one metre. The slope of the simulator is infinitely adjustable, from flat to over ten degrees. A screen is used to adjust the effective length of the simulator i.e. the length over which rain is made to fall. Rainfall is supplied by three networks of pressure compensating drippers, aligned to square grids, each with a different nominal intensity (0.3, 1.2 and 4.8 mm/minute). Consequently, only three constant rainfall rates can be produced; other rainfall rates, if required, are approximated by cyclically switching a dripper network on and off over a short time period. Each network is gated by an electromagnetic valve, which responds to a Netafim Miracle Plus controller (Netafim, Tel Aviv, Israel) designed specifically for this purpose. The distance between the drippers and the rainfall simulator channel bed is approximately 1.1 metres. A 1 mm mesh with 3 mm spacing is positioned approximately 0.6 m below the drippers to randomize the drop size and position.

The spatial uniformity of rainfall within the simulator was tested individually for each dripper network, by placing a square grid of 14 × 14 circular cups of 70 mm diameter at the centre, and at each end, of the simulator. One network was operated constantly until 24 mm of rainfall had been released. The position of each cup and the mass of water contained within it was recorded. By performing this test for each network individually, Christiansen's coefficient of uniformity, CU (Christiansen, 1942), was found to be 0.913, 0.832 and 0.457 for the high- medium and low-intensity networks respectively. It is important to note that, while a CU as low as 0.457 would be of concern for a full-system test, drainage layer components do not provide a serious impediment to lateral flow, hence, spatially uneven inflow is able to re-distribute itself within the drainage layer with ease.

Runoff from a test leaves the simulator through a full-width opening at its downstream end. The runoff is then collected in a semicircular roof gutter with a vertical outlet into a collection barrel. The collection barrel is made from a vertically standing DN 315 drain pipe (British Standards Institution, 2009) with a capped bottom. The depth of water in this barrel is recorded at one-second intervals by a Druck PTX 1730 pressure transducer (GE Sensing, Groby, UK). The height of the barrel for which the cross-section is constant gives a collection volume of approximately 50 litres, for which recorded pressure can be converted to cumulative collected volume by multiplication with a constant. The time-series volumetric runoff record is then given as the differential increase in volume over each time step. The rate at which water is supplied to a dripper network is confirmed using a nutating disk volumetric flow meter (Badger Meter Europa GmbH, Neuffen, Germany) with a volume resolution of 0.1 litres and a time resolution of 15 seconds.

A drainage layer in a green roof should never be subjected directly to rainfall; the "rainfall" supplied in these tests can be considered as the arrival at the drainage layer of water that has percolated through the substrate.

2.1 Test Programme

The total test programme consisted of 100 configurations of drainage layer and inflow (rainfall) intensity. In total, four ZinCo drainage layer components were tested (ZinCo, Nurtingen, Germany): These were: two HDPE sheet modules, namely Floradrain FD 25 and Floradrain FD 40, the expanded polystyrene module Floraset FS 50, and Floradrain FD 25 in combination with a fibrous protection mat, w/ SSM 45. Additionally, the runoff response of the bare channel of the rainfall simulator (a rubbery grey sheet waterproofing material)

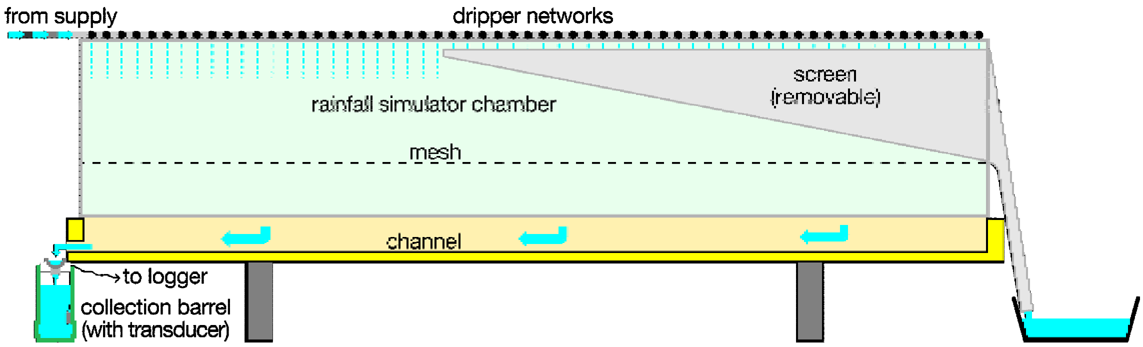

Figure 1. Rainfall Simulator

was also tested. Five inflow rates were used: 0.1, 0.3, 0.6, 1.2 and 2.0 mm/minute. Two of these (0.3 and 1.2) were constant inflows, while the rest were approximated by short looping cycles of 10 seconds of rainfall, followed by a pause of appropriate length. Two roof slopes were used: 1.15° and 10°, following general recommendations for the minimum and maximum slope of an extensive roof. Two roof lengths were tested: 2 metres and 5 metres. No combination of component, inflow rate, roof slope and roof length was skipped. Each configuration was tested a minimum of three times to assess the consistency of results obtained from repeat tests.

The durations of inflow for individual tests were selected to allow equilibrium to be reached between runoff and inflow rates. The maximum duration of any test was limited by the 50-litre volume of the collecting barrel. In general, the duration of a test was ten minutes for the three lower rates of inflow and five minutes for the two higher rates of inflow. For inflow rates approximated by looping on/off cycles, the test duration was extended by 8-16 seconds beyond the nominal five/ten minutes to allow an integer number of cycles to complete. As the same cyclic pattern was always used for the same approximated inflow rate, the exact extension depended solely on the rate of inflow that was approximated, and not on any physical properties of the experimental setup. Longer test durations were used for the FD 25/SSM 45 combination at a drainage length of 5 metres, due to the slow equilibration of runoff and inflow observed when testing these components. These were: 7.5 minutes (1.2 mm/minute) 15 minutes (0.6 mm/minute), either 15 or 20 minutes (0.3 mm/minute), and 20 minutes (0.1 mm/minute). For some test configurations, a shorter duration of 5 minutes was used for inflow rates of 0.3 or 0.6 mm/minute, as this was initially considered sufficiently long for equilibration. The runoff records for these tests were checked later, and any that did not show equilibration after five minutes were discarded and replaced by equivalent tests of ten-minute inflow duration.

2.2 Modelling Methods

For each configuration, an average runoff profile was generated by taking the mean value of runoff across repeat tests, at each time step, giving the averaged time-series runoff profile. As the runoff enters the collection barrel from above, the average runoff profile was smoothed over a centred 19-sample moving average, to minimize the effects of oscillations caused by surface disturbance. A storage routing model of the form $Q_t = kS_{t-1}^{\ n}$ was used with continuity of volume, $S_t = S_{t-1} + (I_t - Q_t)\Delta t$, to predict the rate of runoff for sequential time steps. For rate of outflow, Q, and rate of inflow, I, both in litres/second, depth of water in storage, S, in litres and dimensionless n, k takes the dimension of litres$^{1\text{-}n}$/second. A curve-fitting algorithm, *lsqcurvefit*, from Matlab's optimization toolbox (MathWorks, 2012), was used to find the values of the constants k and n for which the modelled runoff profile most closely matched that observed. The two governing equations were not combined, despite Q_t appearing in both, as an explicit solution of Q was required for the use of *lsqcurvefit*. A *delay* parameter, which time-shifts the entire predicted runoff profile, was included to account for any time delays between a quantity of runoff leaving the simulator chamber and being recorded by the pressure transducer, due to travel time along the gutter. For each configuration, the best-fitting values for k and n were identified for all integer *delay* values from 0 to 100 seconds. The final optimized values of k, n and *delay* for each configuration were chosen as the single combination of all three that gave the highest R_t^2 value. To prevent the curve-fitting algorithm from unduly prioritizing long strings of near-zero, noisy samples during the optimization routine, each of the average runoff profiles was trimmed – after the average runoff rate over 60 consecutive samples had fallen below 1% of the rate of inflow, all subsequent samples were deleted.

Due to the relative granularity of the nutating disk meter in comparison to the pressure transducer, the inflow record was reconstructed individually for each test, by dividing a test's total runoff volume equally among all time samples for which inflow occurred.

2.3 Statistical Methods

The ultimate aim of this research is to build a parameterized model for a green roof drainage layer, for which parameter estimates can be obtained as a function of the measurable physical characteristics of the drainage layer. As the shape of the runoff profile given by the proposed model is dependent on the values assigned to the variables *k*, *n* and *delay*, it is anticipated that each of these values can be estimated from some combination of the roof slope, drainage length and component characteristics of the drainage layer.

To ascertain the importance of each of the individual test variables upon the variation of the model parameters, the optimized values of the parameters *k*, *n* and *delay* were grouped according to the divisions within one test variable e.g. for drainage length, the 100 values of *k* (or *n* or *delay*) were divided into two groups of fifty, where one group contained only optimized *k* values derived from tests with drainage length 2 metres and the other group contained only optimized *k* values derived from tests with drainage length 5 metres. For variables dividing into two groups (i.e. drainage length and roof slope), Welch's unpaired two-sample *t*-test, a modification of Student's *t*-test for populations with unequal variances (Welch, 1947) was used to assess whether the means of the two groups are different from each other, at a significance level of 0.05. For variables dividing into five groups (i.e. inflow rate and drainage component), one-way ANOVA was used to compare the means of all groups simultaneously.

3 RESULTS AND DISCUSSION

At every configuration, tests were found to be highly repeatable. When plotted together, the three runoff records, and hence the averaged runoff record, from any particular configuration show almost no deviation from each other, and even follow the same miniature oscillations during tests with non-constant inflow intensities, on a second-by-second basis.

The time delay between the mid-point of cumulative inflow to the system and the mid-point of cumulative runoff from the system (t_{50}, see also Figure 2 caption), averaged across all configurations, was found to be 111 seconds – varying from an average of 55 seconds for the 20 tests with a bare channel in all configurations to 188 seconds for the 20 tests with FD 25 and SSM 45 in combination, or from 44 seconds for all tests at an inflow rate of 2.0 mm/minute to 216 seconds at an inflow rate of 0.1 mm/minute. The configurations

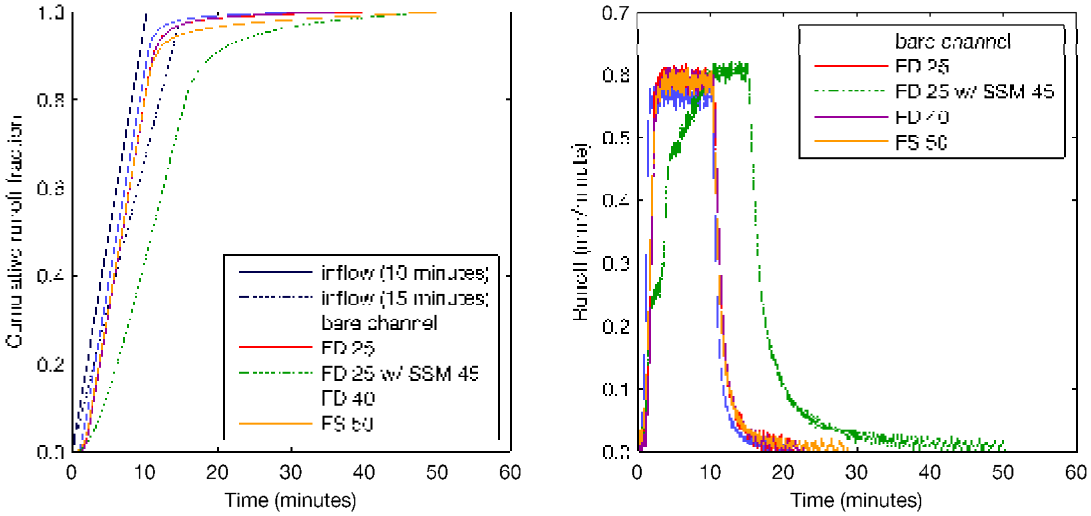

Figure 2. Cumulative and time-series comparison of all five drainage component configurations at a roof slope of 1.15°, drainage length of 5 metres and inflow rate of 0.6 mm/minute. The t_{50} for FD 25 w/ SSM 45 is shown on the cumulative plot as a horizontal grey line of length 217 seconds.

introducing the largest delay across all inflow rates were the FD 25/SSM 45 combinations at 5 metres, whose runoff profiles are not similarly shaped to any other configuration. It is believed that this unique behaviour, apparent only at a drainage length of 5 metres, is due to the 2 metre length of one FD 25 module. When the tested area is concurrent with the area of a single FD 25 panel, the opportunities for water, falling onto the panel from above, to find a pathway to the SSM 45 on the underside, are limited. However, when FD 25 and SSM 45 are used together at a 5 metre length, there are opportunities for water to enter the moisture mat at the joins between the panels, where horizontal water flow is comparatively severely restricted. The panel joins are located two and four metres from the drainage outlet, corresponding to 40% and 80% of the roof area from the outlet. This is believed to result in two distinct steps in the time-series runoff profile, at approximately 40% and 80% of the steady state runoff rate (see Figure 2).

Figure 2 also shows that the runoff profiles from those drainage layer configurations without SSM 45 were not very different to the runoff profile of the bare channel of the simulator itself. As the primary purpose of any drainage layer is to remove excess water as quickly as possible, low t_{50} values confirm that all tested drainage layers function as expected and suggest that the substrate depth and composition are likely to have a greater effect on the detention performance of a green roof.

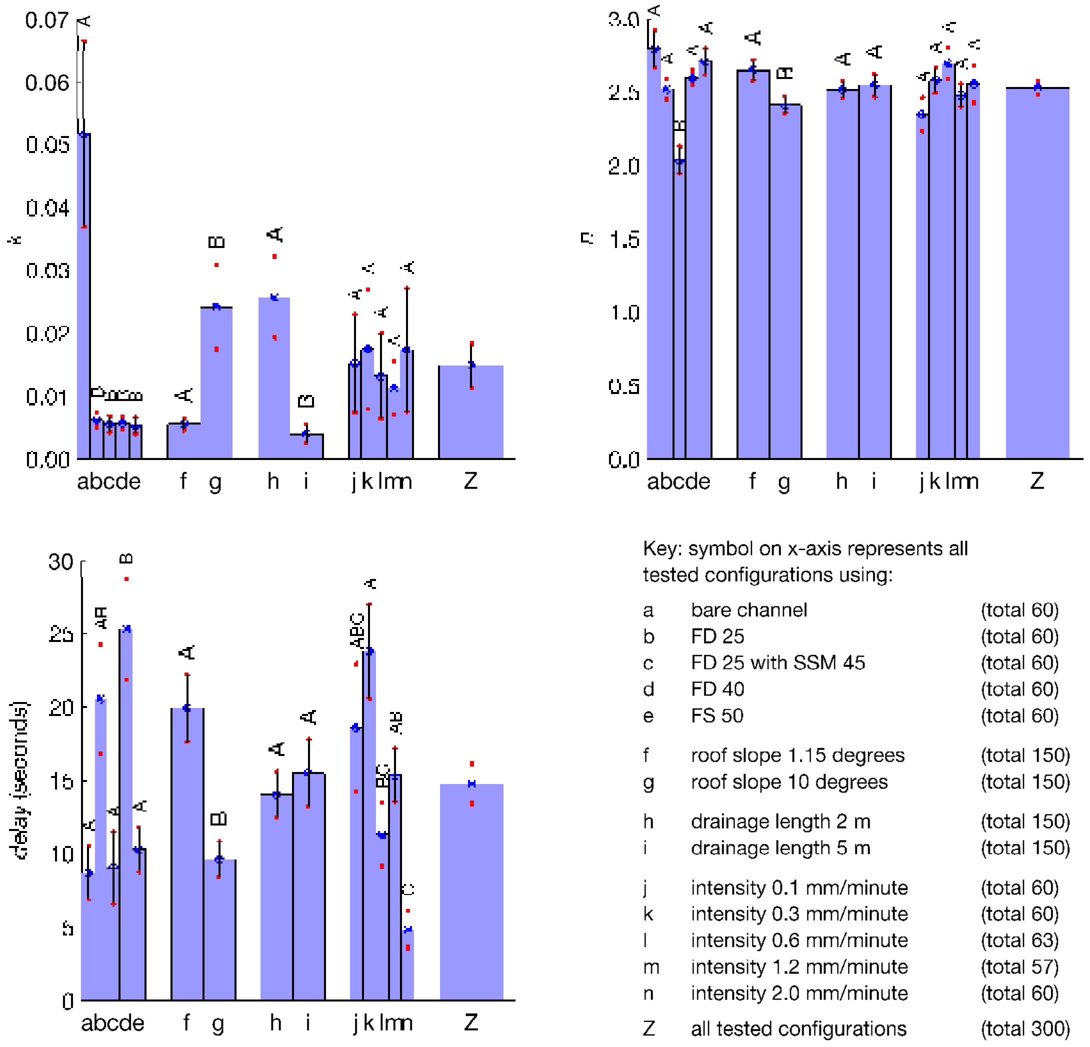

Figure 3. Variation of *k*, *n* and *delay* values by component and configuration. Light blue bars mark mean value, red dots standard error

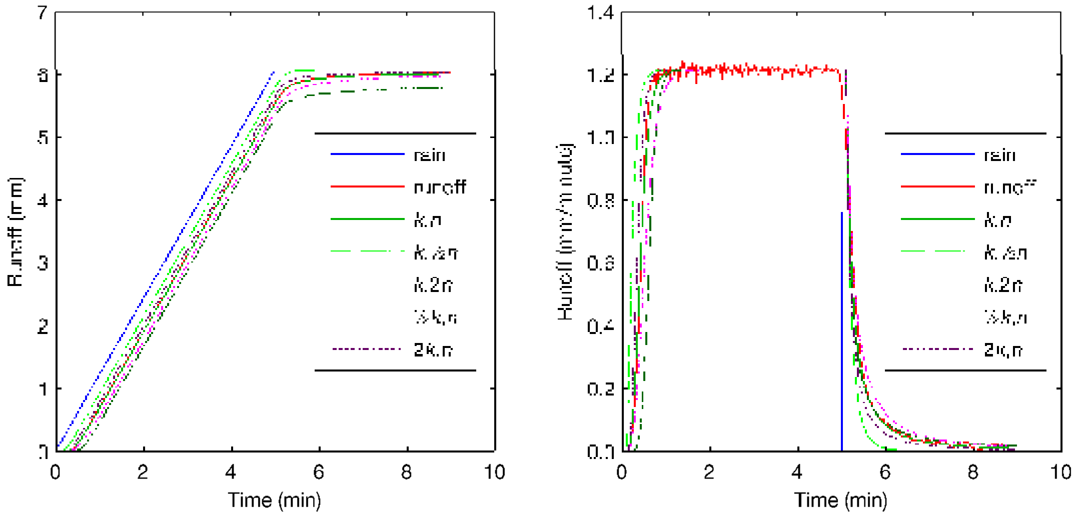

Figure 4. Cumulative and time-series runoff predictions for bare channel at 10°, 5 m, 1.2 mm/minute

For each configuration, *lsqcurvefit* was able to identify an optimal solution for *k*, *n* and *delay* in approximately 4 seconds on an Intel Core i3 laptop at 2.4 GHz with 8 GB of RAM (Dell, Dublin, Ireland). The mean R_t^2 of all 100 drainage configurations was 0.9889, ranging from 0.8865 to 0.9991, with 73 configurations having R_t^2 $\geq$ 0.99. The optimal solution was not dependent on the starting estimates for *k* and *n*. The optimized values of *k*, *n* and *delay* are presented in Figure 3.

Welch's unpaired two-sample *t*-test, or one-way ANOVA, both with a critical p-value of 0.05, was used to assess the dependence of the three parameters on drainage component, roof slope, drainage length and inflow rate. The results are plotted in Figure 3. Statistical groupings are separate for each of the four constituent variables making up a configuration e.g. statistical group "A" within the set of drainage layer components does not correspond to statistical group "A" within the set of inflow intensities.

The optimized estimates of *n* and *delay* are shown to be independent of drainage length, while roof slope is shown to always be significant. Inflow rate and *delay* are found to be linked, while *k*- and *n*-values are found to be independent of inflow rate; this lack of parameter dependency is observed within each of the individual physical test configurations. Optimized *k*-values are unrelated to drainage component at the chosen significance level. Drainage components do not consistently divide into the same statistical groupings for *k*, *n* and *delay*, but optimized values for FD 25 and FD 40 are closely matched for all three parameters. As these are the only two components made from the same material, this suggests that parameter values, and hence runoff behaviour, may be more dependent upon the properties of the material composing the drainage component e.g. surface roughness, than on other properties intrinsic to the drainage component.

A parameter sensitivity analysis was performed on one roof configuration with very high R_t^2 (0.9989) and optimized *k* and *n* close to their overall means (bare channel, 10° slope, 5 m length, 1.2 mm/minute inflow). The storage routing model was run with *k* and *n* fixed optimally at 1.59×10^{-2} and 2.48 respectively. Modelling was repeated with either *k* or *n* separately doubled or halved while *delay* was held at the optimal value of 6 seconds for all five runs. The results of this analysis are shown in Figure 4, where it is demonstrated that increasing either *k* or *n* increases the gradient of the rising and falling limbs, though slightly more so in the case of *n*. As varying *k* is shown to have the same effect as varying *n*, it follows that *k* and *n* are compensated parameters. There may therefore be multiple optima in the optimization procedure, leading to many optimal pairs of *k* and *n* for each modelled runoff profile. Hence, it may be possible to find optima for which *k* and *n* are both simultaneously independent of inflow rate across all configurations, as is currently the case. If goodness-of-fit is not strongly affected, it may then potentially be feasible to fix the value of *n* for all inflow rates and drainage lengths at each specific combination of component and slope, effectively simplifying the model to two variable parameters, *k* and *delay*, with the appropriate *n*-value taken from a table. Further work will aim to identify means of predicting *k* and *delay* from configuration characteristics.

4 CONCLUSIONS

Controllable, steady-state water input events were applied to 20 physical configurations of drainage layer at five inflow intensities in a 5 × 1 m rainfall simulator. Time-series runoff was monitored for every configuration at 1-second intervals. The average median-to-median runoff delay was 111 seconds and the longest 596 seconds. Three-parameter storage routing models were applied to each runoff curve and the parameters optimized. Goodness-of-fit was typically found to be high (mean $R_t^2 = 0.9889$). Statistical analyses found *n* and *delay* to be independent of drainage length. Values of *k* and *n* were found to be independent of inflow rate, across and within individual physical test configurations. All three parameters were found to be dependent on roof slope and drainage component, but the significance groupings suggested that, in the case of drainage component, material properties may be the controlling factor. A sensitivity analysis found the model slightly more sensitive to changes in *n* than in *k*, but concluded that both parameters influenced the shape of the runoff curve in a similar way. It is suggested that *n* may be able to take a constant value for each combination of component (or component material) and roof slope, hence simplifying the model to two variable parameters, *k* and *delay*, with future work aiming to predict these values from measurable configuration characteristics.

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LIST OF REFERENCES

British Standards Institution (2009). BS EN 1401-1:2009 Plastic piping systems for non-pressure underground drainage and sewerage. Unplasticized poly(vinyl chloride) (PVC-U). BSI, London.

Carter TL and Rasmussen TC (2006). Hydrologic behavior of vegetated roofs. *JAWRA Journal of the American Water Resources Association*, 42(5), 1261-1274.

Christiansen JE (1942) Irrigation by Sprinkling. *California Agricultural Experiment Station Bulletin*, 670.

CIRIA (2009). SUDS - Sustainable drainage systems. http://www.ciria.com/suds/suds_principles.htm (accessed 9th March 2012).

Dunnett N and Kingsbury N (2004).*Planting Green Roofs and Living Walls*.Timber Press, Portland.

Getter KL, Rowe DB, Andresen JA and Wichman IS (2011). Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. *Energy and Buildings*, 43(12), 3548-3557.

Hilten RN, Lawrence TM and Tollner EW (2008). Modeling stormwater runoff from green roofs with HYDRUS-1D. *Journal of Hydrology*, 358(3–4), 288-293.

Kasmin H, Stovin VR and Hathway EA (2010). Towards a generic rainfall-runoff model for green roofs. *Water Science and Technology*, 62(4), 898-905.

MathWorks (2012). Solve nonlinear curve-fitting (data-fitting) problems in least-squares sense – MATLAB. http://www.mathworks.co.uk/help/toolbox/optim/ug/lsqcurvefit.html (accessed 9th March 2012).

Palla A, Gnecco I and Lanza LG (2009). Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. *Journal of Hydrology*, 379(1-2), 193-204.

Qin XS, Huang GH, Zeng GM and Bass B (2003). *Distributed hydrologic models for municipal green roof systems*. In: *Proceedings of the EnerEnv'2003 Conference*, Changsha, China, 11-14 October 2003.

She N and Pang J (2010). Physically based green roof model. *Journal of Hydrologic Engineering*, 15(6), 458-464.

Villarreal EL and Bengtsson L (2005). Response of a Sedum green-roof to individual rain events. *Ecological Engineering*, 25(1), 1-7.

Welch BL (1947). The Generalization of 'Student's' Problem when Several Different Population Variances are Involved. *Biometrika*, 34(1/2), 28-35.

Wingfield A (2005). The Filter, Drain, and Water Holding Components of Green Roof Design. http://www.greenroofs.com/archives/gf_mar05.htm (accessed 3rd April 2012).