Article:

Stovin, V.R. orcid.org/0000-0001-9444-5251 and Peng, Z. (2017) Independent Validation of the SWMM Green Roof Module. Journal of Hydrologic Engineering, 22 (9). ISSN 1084-0699

https://doi.org/10.1061/(ASCE)HE.1943-5584.0001558

Independent Validation of the SWMM Green Roof Module

Zhangjie Peng [1] and Virginia Stovin, Ph.D. [2]

[1] Graduate Student E-mail: pengzhangjie2016@163.com.

[2] Reader in Urban Drainage, Dept. of Civil and Structural Engineering, Univ. of Sheffield, Sir Frederick Mappin Building, Sheffield S1 3JD, U.K. E-mail: v.stovin@sheffield.ac.uk.

Abstract

Green roofs are a popular Sustainable Drainage Systems (SuDS) technology. They provide multiple benefits, amongst which the retention of rainfall and detention of runoff are of particular interest to stormwater engineers. The hydrological performance of green roofs has been represented in various models, including the Storm Water Management Model (SWMM). The latest version of SWMM includes a new LID green roof module, which makes it possible to model the hydrological performance of a green roof by directly defining the physical parameters of a green roof's three layers. However, to date, no study has validated the capability of this module for representing the hydrological performance of an extensive green roof in response to actual rainfall events. In this study, data from a previously-monitored extensive green roof test bed has been utilised to validate the SWMM green roof module for both long-term (173 events over a year) and short-term (per-event) simulations. With only 0.357% difference between measured and modelled annual retention, the uncalibrated model provided good estimates of total annual retention, but the modelled runoff depths deviated significantly from the measured data at certain times (particularly during summer) in the year. Retention results improved (with the difference between modelled and measured annual retention decreasing to 0.169% and the Nash-Sutcliffe Model Efficiency (NSME) coefficient for per-event rainfall depth reaching 0.948) when reductions in actual evapotranspiration due to reduced substrate moisture availability during prolonged dry conditions were used to provide revised estimates of monthly ET. However, this aspect of the model's performance is ultimately limited by the failure to account for the influence of substrate moisture on actual ET rates. With significant differences existing between measured and simulated runoff and NSME coefficients of below 0.5, the uncalibrated model failed to provide reasonable predictions of the green roof's detention performance, although this was significantly improved through calibration. To precisely model the hydrological behaviour of an extensive green roof with a plastic board drainage layer, some of the modelling structures in SWMM green roof module require further refinement.

Keywords: Green Roof, SWMM, Hydrological Performance, Validation, Retention, Detention

Introduction

Urbanisation leads to an increase in impermeable area and a decrease in vegetated area, which prevents stormwater infiltration or evapotranspiration and increases the volume of surface runoff. Sustainable Drainage Systems (SuDS), which share the same principles as BMPs (Best Management Practices), LID (Low Impact Development), WSUD (Water Sensitive Urban Design) or GI (Green Infrastructure), aim to reduce the on-site surface runoff to a greenfield state. Besides the benefits in runoff quantity control, SuDS can also manage water quality, prevent pollution, and provide amenity and biodiversity benefits (Woods Ballard 2015). Green roofs as a form of SuDS, manage stormwater directly at source, providing both rainfall retention and runoff detention (Stovin et al. 2015a). Retention refers to the rainfall losses due to the storage capacity of green roof's substrate. Detention refers to the delay in runoff (Time to Start of Runoff, Peak Delay, Centroid Delay or t_{50} Delay) and the reduction in peak runoff (usually defined as peak attenuation) (Stovin et al. 2015b).

Monitoring studies have been conducted to understand green roof hydrological performance. Many studies have focused on retention performance, with reported cumulative retention for extensive green roofs ranging from 15% to 80.8% (Getter et al. 2007; Fioretti et al. 2010; Stovin et al. 2012; Nawaz et al. 2015). For single rainfall events, retention can be up to 100% and as low as zero (Stovin et al. 2012). Detention in response to single rainfall events has also been studied by many authors. A green roof in Sheffield, UK was found to provide an average peak flow reduction of 60% based on 5-minute data (Stovin et al. 2012) and in the context of New Zealand's climate, green roofs were found to have 73% to 89% peak flow reduction (Fassman-Beck et al. 2013).

As monitoring studies only reflect the hydrological performance of a specific type of green roof, and cannot be used for predictions, more generic approaches (e.g. conceptual models and physically-based models) have been explored that permit the modelling of green roof hydrological performance.

Based on the understanding that rainfall retention depends upon substrate moisture being removed by evapotranspiration (ET) during dry weather periods, several authors have proposed and validated conceptual models for rainfall retention that use estimates of ET to determine the substrate moisture deficit at the onset of a storm event. The most recent of these have clearly established the need to account for substrate moisture content in determining actual ET rather than potential ET (PET) (Stovin et al. 2013; Locatelli et al. 2014). Several of these authors have combined their rainfall loss models with semi-empirical runoff detention models to provide temporal runoff profiles. However, one limitation of this approach to the detention modelling component is that models which are not based directly on physical processes can only be used to model the performance of the specific system that they were developed from. For example, the unit hydrograph-based detention model derived by Villarreal and Bengtsson (2005) is only valid to estimate the runoff from green roofs that have the same characteristics as the one used in their experiments. Similarly, the two-stage non-linear reservoir routing model proposed by Vesuviano et al. (2014) is only valid for systems with comparable substrate and drainage layer characteristics.

Hilten et al. (2008) used the physically-based detention model in Hydrus-1D to simulate the hydrological performance of a green roof and concluded that Hydrus-1D can predict runoff accurately in response to small rainfall events. She and Pang (2010) explored a more sophisticated physically-based green roof detention model that combined infiltration models with nonlinear storage routing and concluded that the model performs reasonably for long term simulations. Physically-based detention models have potentially much greater generic value, but they are reliant upon user-input parameters that may be uncertain.

Among the commercial models, SWMM is the most commonly used and it provides a quick assessment tool to predict the performance of a green roof (Li and Babcock 2014; Cipolla et al. 2016). SWMM is a rainfall-runoff simulation model, which can be used to model the quality and quantity of runoff from sub-catchments. Early versions of SWMM did not include a specific green roof module. Instead, two methods were widely adopted for representing green roofs: curve number (CN) (e.g. Carter and Jackson 2007) and storage node (e.g. Alfredo et al. 2010). However, the CN approach does not explicitly link rainfall losses to the actual losses due to evapotranspiration during the antecedent dry period; instead it assumes a representative percentage runoff. Similarly, without taking evapotranspiration into consideration at all, the storage node method can only simulate green roof detention processes, which makes it invalid for long-time simulations. To make SWMM valid for long-term simulations, Palla et al. (2011) modelled green roofs as a permeable area using a modified Green-Ampt infiltration model together with an evapotranspiration model.

From SWMM5 version 5.0.19, new LID Modules were added, which make it possible to model various SuDS devices (e.g. infiltration trench, bio-retention cells and vegetated swales) by directly defining properties of different layers (such as thickness, conductivity, porosity etc.) and, as evapotranspiration can be set separately, these modules can be used for both long-term or single event simulations (Burszta-Adamiak and Mrowiec 2013).

As a green roof is comparable in some ways to a bio-retention cell, Burszta-Adamiak and Mrowiec (2013) used the Bio-Retention module in SWMM (Version 5.0.022) to simulate the performance of three green roofs before the green roof specific module was introduced. As many external factors (i.e. temperature, wind and insulation) that influence the drying processes in the substrate and drainage layer are not taken into account in the SWMM model, the authors claimed that the bio-retention module in SWMM has limited capabilities for correctly representing the runoff from green roofs. A specific green roof module was introduced in 2014. Palla and Gnecco (2015) tested the performance of the SWMM green roof module based on laboratory measurements and concluded that the green roof module can be successfully used to represent the hydrological performance of a green roof using calibrated soil parameters. However, both Burszta-Adamiak and Mrowiec (2013) and Palla and Gnecco (2015), conducted simulations for single events and they did not take evapotranspiration into account. Many authors (Stovin et al. 2013; Yang et al. 2015; Poë et al. 2015; Cipolla et al. 2016) have highlighted that evapotranspiration controls the recovery of retention capacity and it is therefore critical to include ET in long-term simulations. Cipolla et al. (2016) modelled the long-term performance of a full-scale green roof using the bio-retention module in SWMM, demonstrating a good comparison between monitored runoff and the SWMM simulation results.

The objective of this study is to evaluate the accuracy of the SWMM (Version 5.1. 011) green roof module for modelling an extensive green roof. To achieve the objective, the observed runoff from an extensive green roof test bed was modelled using the SWMM green roof module in response to both an annual time-series and 8 single rainfalls. A comparison was made between the modelled runoff and measured data and the differences were subsequently minimised through calibration. Recommendations are made based on the modelled and calibrated results.

Materials and Methods

Green Roof Test Bed

The test bed was located on the top of the Mappin building, the University of Sheffield UK. The dimensions of the test bed were 3 (length) × 1 (width) m and it was a standard commercial extensive green roof system. The vegetation growing on the 80 mm mixed crushed brick and fines substrate was sedum. The drainage layer was a Floradrain FD 25 'egg box' drainage layer with a retention capacity of 3 l/m^2, equivalent to 3 mm rainfall. The drainage layer was separated from the overlying substrate by a fine particle filter membrane. The base of the rig was laid at a slope of 1.5°. Rainfall data were collected by an Environmental Measures ARG100 tipping bucket rain gauge with 0.2 mm resolution sited adjacent to the test bed. Runoff from the green roof bed was collected in a tank below the test bed, with a pressure transducer in the tank providing a continuous record of the cumulative runoff. Rainfall and runoff data were logged using a Campbell Scientific data logger (CR1000) at 1-min intervals, the data were collected from 01/01/2007 to 05/31/2009, and the data from the calendar year 2007 were used in this study. Detailed descriptions of the green roof test bed may be found in Stovin et al. (2012).

Overview of the SWMM Green Roof Module

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman 2015). The LID module in SWMM is specifically designed for modelling SuDS devices. The LID controls are represented by performing moisture balance that tracks water movement vertically between different layers.

To model the restoration of retention capacity associated with evapotranspiration (ET) in long-term simulations, SWMM provides five methods for computing potential ET: constant value; monthly average; time-series; computed from temperatures and directly from a climate file (Rossman 2015). In this study monthly average PET values that were calculated from the Thornthwaite equations (Stovin et al. 2013) were input. Note that SWMM does not explicitly model the reduced levels of actual ET that are known to arise when substrate moisture availability becomes restricted. Instead, the actual ET rate is modelled as a constant proportion of PET. This proportion can be used to represent a crop-specific factor and/or to account for reductions in actual ET when the substrate moisture content falls below field capacity. Initially it was assumed that the factor was 1.0.

For green roof detention modelling, five equations are used to describe the processes in the three layers (surface, substrate and drainage layer). A routing equation (Eq. 1) is used to quantify water flow through the surface. The Green-Ampt infiltration model (Eq. 2 and 3) is adopted to calculate how much water infiltrates into the substrate. Taking the form of the relative hydraulic conductivity equation derived by Mualem (1976) and assuming the matric potential (ψ) varies linearly (constant α) with water content (θ) and porosity (Φ) (ψ=α (θ-Φ)), Eq. 4 is used to model detention in the green roof's substrate. Finally, another routing equation (Eq. 5), with the discharge exponent fixed to 5/3, is used to calculate the amount of water drained out of the green roof system as runoff.

$$Q_s = (\frac{S_1}{nA})wD^{\frac{5}{3}} \tag{1}$$

$$f = k_{sat}(1 + \frac{(\phi-\theta)\psi}{F}) \tag{2}$$

$$k_{sat}t = F - (\phi - \theta)\psi ln(1 + \frac{F}{(\phi-\theta)\psi}) \tag{3}$$

$$f_p = k_{sat}\exp(-(\phi - \theta)S) \tag{4}$$

$$Q_d = (\frac{S_1 WFr}{NA})d^{\frac{5}{3}} \tag{5}$$

where Q_s = surface overflow rate; S_1 = surface slope; n = surface roughness; A = flow area; W = the width of the sub-catchment; D = the depth of water above the surface; f = infiltration rate; K_{sat} = saturated hydraulic conductivity; Φ = soil porosity; θ = moisture content, ψ = suction head; F = cumulative infiltration (from time 0 to time t), t= time, f_p = percolation rate; S = conductivity slope; Q_d = runoff from drainage layer; Fr = the void fraction of drainage layer; N = drainage layer roughness; d = water depth in the drainage layer.

Modelling a Green Roof in SWMM

The green roof test bed was modelled as a sub-catchment that is 100% occupied by green roof and, to make a closed network, a junction and an outlet were added. The dimension of the sub-catchment is 3 (length) × 1 (width) m which is exactly the size of the test bed. To test the accuracy of the ET component of the model for predicting long-term volumetric retention, the SWMM green roof module was first used to regenerate the runoff in response to the rainfall during the whole year of 2007. Temporal runoff responses corresponding to eight 'significant' rainfall events were then used to evaluate the detention modelling component. A 'significant' event was defined as a rainfall event with return period greater than 1 year (Stovin et al. 2012).

Input Data

The long-term simulations used the observed rainfall at 1-hour intervals from the experimental site in Sheffield during 2007. Further details of the monitored rainfall can be found in Stovin et al. 2012. The monthly PET rates were calculated based on the monthly average temperature and the hours between sunrise and sunset using the Thornthwaite Equations (Table 1). The % initially saturated was set to be zero.

Insert Table 1.

Significant rainfall events were used for short-term simulations and – with the emphasis on temporal detention effects – the reporting time step for short-term simulations was 5-min. The internal simulation time-step was 1 second. In Sheffield, during the year of 2007, there were 8 significant rainfall events. Characteristics of these events are summarised in Table 2. The % initially saturated before each significant event (Table 2) was calculated from the difference between each event's total rainfall and measured runoff.

Insert Table 2.

Parameter Estimation

The initial green roof parameter values were estimated from field measurements, literature or defaults; the values and sources for parameters required by SWMM Green Roof Module are presented in Table 3.

Insert Table 3.

Sensitivity Analysis

In order to identify which parameters would influence the model results most significantly (and therefore which parameters would be most effective in minimising the difference between observed and simulated results) sensitivity analysis was performed. The significant rainfall event on 06/13/2007 and the long-term simulation of 2007 were used in the sensitivity analysis. Following the approach suggested by Jewell et al. (1978) and Rosa et al. (2015), for single parameter analysis, each parameter was adjusted over a range of $\pm$50% of its original value while keeping all other parameters the same. Difference in annual retention, runoff volume, peak runoff, peak delay and the time to start of runoff were determined. Sensitivity was calculated using Eq. 6 (Rosa et al. 2015).

$$\text{Sensitivity}=\left(\frac{\partial R}{\partial P}\right)\left(\frac{P}{R}\right) \quad (6)$$

Where ∂R = the difference between the original and the new model output, ∂P = the difference between original and adjusted parameter value, R = the original model output, and P = the original value of the parameter (Rosa et al., 2015).

Validation and Calibration

The Nash-Sutcliffe Model Efficiency (NSME) coefficient (Eq. 7, Nash and Sutcliffe, 1970) was used to assess how well the runoff performance variables were predicted by the SWMM green roof module. With NSME = 1.0, the model can predict the performance of green roof perfectly, whilst an NSME greater than 0.5 indicates acceptable model performance (Zhao et al. 2009; Rosa et al. 2015).

$$\text{NSME} = 1 - \left[\frac{\sum_1^N (Q_m - Q_p)^2}{\sum_1^N (Q_m - Q_{Am})^2}\right] \quad (7)$$

Where N = the number of samples; Q_m = the runoff observed; Q_p = the modelled runoff; Q_{Am} = mean observed runoff.

The uncalibrated runoff predictions were initially compared with the observed data. This exercise provides an indication of the model accuracy when it is applied to an unmonitored system. The model predictions were subsequently refined by a calibration process which was informed by the previously-described sensitivity analysis.

Detention processes are more evident in single rainfall event simulations, so it is more appropriate to calibrate the detention parameters using short-term simulations. Of the 8 significant rainfall events, the rainfall events on 06/13/2007 and 06/24/2007 were used for calibration. For continuous simulations over long time periods, the retention parameters, percentage retention and total volume of runoff, are of interest. Continuous simulations were used for retention model validation and calibration. The retention performance is mainly influenced by the evapotranspiration model.

During the calibration, the parameters identified as being relevant during the sensitivity analysis were adjusted one at a time until the difference between measured and simulated values was minimized. The significant events on 01/18/2007, 01/20/2007, 05/13/2007, 06/15/2007 and 07/26/2007 were used to validate the calibrated parameters.

As noted above, the modelling time-steps adopted for the long term (retention) and short term (detention) model evaluations were one hour and five-minutes respectively. The internal simulation time-step needs to be equal to or smaller than the input rainfall time intervals. In all cases the internal simulation time-step was set to one second. However, a larger step may lead to a faster simulation, so a small sensitivity analysis on simulation time-step was undertaken. For one storm event (event on 06/13/2007) a comparison was made between the results obtained from a 1 second versus a 5 minute internal simulation time step.

Results

Uncalibrated Long-term Simulations

Long-term simulations using the initial parameter values generally achieved good agreement between measured and simulated runoff from the green roof test bed. During the year, 497.875 mm runoff (equivalent to 43.139% annual retention) was predicted by SWMM and 494.751 mm of runoff (equivalent to 43.496% annual retention) was collected from the green roof. As Fig. 1 (a) shows, the simulated cumulative runoff was very close to the measured data, which indicates good model performance. However, runoff is predicted to be lower than observed during the summer and higher in winter. In the worst case, summer runoff is predicted to be 100% lower (i.e. 0.00 mm rather than 5.66 mm) than recorded during a nearly two-day period (from 06/29/2007 15:00 to 07/01/2007 07:00) and winter runoff over eight hours (from 12/08/2007 12:00 to 12/08/2007 21:00) is predicted to be 28889% higher (i.e. 12.841 mm rather than 0.044 mm) than recorded. Fig. 1 (b) compares observed and modelled runoff volumes for 173 rainfall events. In terms of single rainfall events, the retention simulation results are accurate, with the NSME = 0.951.

Insert Fig. 1.

The lower modelled runoff in summer may be interpreted as an over-prediction of evapotranspiration. This is consistent with what was anticipated for a model that does not account for the reduction in actual evapotranspiration (compared to potential evapotranspiration) that is known to occur when moisture is restricted.

Uncalibrated Single Event Simulations

The results of short-term simulations using the initial parameters are shown in Fig. 2. In general they show relatively poor agreement between measured and simulated runoff from the green roof test bed, with NSME falling below 0.5 in two events (05/13/2007 and 06/12/2007). Except for the event on 06/12/2007, all the predicted peak runoffs are lower than the measured. Unless it was continuous heavy rainfall the modelled runoff profiles appear to oscillate sharply. For most of the events, the time to the start of runoff was predicted to be later than observed. For all the events, the duration of runoff was predicted to be shorter than observed and the time of peak runoff did not match the observed time. All these phenomena indicate that the green roof detention processes are not well represented within the uncalibrated SWMM model.

Insert Fig. 2.

Sensitivity Analysis

Retention Parameters

The results of the retention sensitivity analysis are presented in Table 4 and Fig. 3a. Unsurprisingly, the annual retention and total volume of runoff were found to be influenced by the evapotranspiration coefficient, soil porosity, field capacity, wilting point and conductivity slope; surface slope, suction head, drainage layer void fraction and roughness were found to have minor impact on the model results. Total annual runoff is most sensitive to the evapotranspiration coefficient, followed by field capacity, soil porosity and soil conductivity (Fig. 3a). The evapotranspiration coefficient determines the retention recovery and field capacity determines the retention capacity, they are the two major parameters that influence green roof retention performance. The importance of evapotranspiration to the retention performance of green roof has been highlighted in many previous studies (Stovin et al. 2013; Burszta-Adamiak and Mrowiec 2013; Yang et al. 2015; Poë et al. 2015; Cipolla et al. 2016) and it has been demonstrated again in this study. Decreases in soil moisture content due to evapotranspiration are the only way for a green roof's storage capacity to be restored.

Insert Fig. 3 and Table 4.

Detention Parameters

The significant event on 06/13/2007 was used in the detention parameter sensitivity analysis. As evapotranspiration was set to zero during the short-term simulations, the influence of the evapotranspiration coefficient was excluded from the sensitivity analysis. The influence of parameters was evaluated with respect to four performance indicators: peak runoff; peak delay; time to start of runoff and runoff duration. Table 5 presents the relative sensitivity. Suction head was found to have no influence on any of these four aspects; the influences of surface slope, drainage layer void fraction and roughness are not significant and no parameter was found to influence the peak runoff delay. In terms of peak runoff, it is most sensitive to the conductivity slope, followed by field capacity and soil conductivity.

Other parameters have little impact on peak runoff (Fig. 3b). The time to start of runoff was found to be most sensitive to field capacity followed by % initially saturated and wilting point (Fig. 3c). Soil porosity and field capacity influence the duration of runoff most, but % initially saturated, soil conductivity and wilting point have little impact on the duration of runoff (Fig. 3d). Normally, there is no ponding on the surface of a green roof and rainfall infiltrates quickly to the substrate, detention in SWMM is mainly modelled in the substrate through the percolation equation and in the drainage layer through the weir discharge equation. However, the drainage layer parameters are small and the possible ranges of these values are narrow, so the influences of the drainage layer cannot be as significant as the substrate. The percolation equation (Eq. 4) is the only equation describing the detention in the substrate; the parameters related to that equation influence the detention most. Soil conductivity and conductivity slope determine the rate of flow through the substrate, so they may influence the peak runoff; the soil porosity determines the rate of change in water content and influences the duration of runoff. The time to start of runoff should also be influenced by the initial water content and the field capacity of the substrate, as they determine how much water can be retained in the soil before runoff is generated.

It should be noted that the sensitivity analysis in this study explored the influence of each parameter independently, but parameters will interact with each other to influence the final model results.

Insert Table 5.

Calibration

Detention Parameter Calibration

The results of the uncalibrated simulations showed that the predicted peak runoff was lower than the measured and the runoff profile exhibited unrealistic temporal oscillations. The aims of the calibration were therefore to lengthen the duration of the runoff, raise the peak flow rate and smoothen the runoff profile. Though the field capacity, porosity and wilting point influence the detention modelling, the values applied here were measured in previous studies, and so they were not calibrated. The soil conductivity, conductivity slope, drainage layer void fraction and roughness parameters, which were not measured, were calibrated to minimise the differences between measured and modelled runoff.

The significant rainfall events on 06/13/2007 and 06/24/2007 were used for calibration. Table 6 lists the parameters values after calibration; all the values of calibrated parameters are in reasonable ranges. The conductivity seems high, but in practice, to avoid ponding on the surface of green roof, the conductivity of the substrate is usually very high. Palla and Gnecco (2015) also obtained good model results using 1000 mm/hr for conductivity in SWMM. The calibrated value of conductivity slope is also within the typical values of conductivity slope recommended by SWMM (30 to 60). Fig. 4 shows the hydrographs following calibration. The calibrated profiles match the measured profiles well and the NSME values for both events are above 0.9, which indicates accurate model results.

Insert Fig. 4 and Table 6.

Retention Parameter Calibration

Retention parameter calibration is mainly focused on the calibration of evapotranspiration rates to obtain a good match between modelled and measured annual retention. As detention performance may also influence retention, the retention parameters were calibrated based on the calibrated detention parameters. As the water available for ET will decrease with time during the dry periods, directly using the ET rates calculated from the Thornthwaite Equations will overestimate the ET (Stovin et al. 2013; Poë et al. 2015). If it is assumed that ET rates during the wet periods would be equal to the potential evapotranspiration rates calculated from the Thornthwaite Equations, then on a monthly basis, only the dry periods determine how far actual ET rates fall below the potential evapotranspiration rates. To revise the ET rates, firstly, the dry periods in each month were identified from the daily rainfall data; then the average actual ET rates during the dry periods were calculated from the ET decay curve plotted by Poë et al. (2015) under experimental conditions. It should be noted that Poë et al. (2015), only tested the ET decay under spring and summer conditions. In this study, the summer profile was used for the months from June to August and the spring profile was used for the rest of the year. The revised monthly mean ET rates were calculated by combining the wet period potential ET rates with the dry period ‘actual’ ET rates (Eq. 8) and the calculated results for each month of 2007 are in Table 7.

$$ET_{mean} = PET \times \left(\frac{\beta + \frac{1}{2} \times \sum_{1}^{x} n(1+\alpha)}{D}\right) \quad (8)$$

Where ET_{mean} = monthly mean ET rate (mm/day); PET = potential ET rate (mm/day) (calculated from the Thornthwaite Equations); β = wet days in the month; x = number of continuous dry period in the month; n = duration of dry period (day); α = actual ET rate at the end of the dry period (proportion of PET); D = total days in the month (day).

Insert Table 7.

Using the revised ET rates, the NSME value of hourly runoff and per-event total runoff increased and the modelled annual retention was very close to the measured. The NSME of hourly runoff increased from 0.550 to 0.590, the difference between measured and modelled annual retention decreased to 0.169% (Fig. 5a) and – perhaps of greater significance – the NSME of per-event runoff also reached 0.948 (Fig. 5b). As Fig. 5a shows, even when using the mean actual ET rate for each month, the cumulative runoff during the summer still appears to be less than measured, which suggests that the revised method is still limited by the use of constant monthly values of ET that do not fully reflect the variations due to daily climatic fluctuations and changes in the substrate moisture content.

Insert Fig. 5.

Validation

The significant events on 01/18/2007, 01/20/2007, 05/13/2007, 06/15/2007 and 07/26/2007 were used to validate the calibrated detention parameters. Fig. 6 presents the results of validation using the parameters calibrated using the 06/13/2007 and 06/27/2007 significant rainfall events. Compared to the uncalibrated results, the differences between modelled and measured runoff are not as significant. The values of NSME are all raised through calibration and they are all above 0.5, which indicates that the model can simulate the temporal variations in runoff from the green roof well. However, there are still some differences; for example, the peak runoff typically does not match the measured peak runoff very well, the model tends to underestimate the peak runoff in most of the events, and the difference is significant for short heavy rainfall.

Insert Fig. 6.

Discussion

Assessment of SWMM Green Roof Module

Generally speaking, the SWMM green roof module can simulate the runoff from extensive green roof correctly on an annual and per-event basis after calibration. However, some limitations have been highlighted, which are partly attributable to the model structure.

There are two limitations of the evapotranspiration model in SMMM. The first, as highlighted within this paper, is that the model relies on potential evapotranspiration rates and fails to account for the fact that actual evapotranspiration rates decay with time during dry periods (Kasmin et al. 2010; Fassman-Beck and Simcock 2011) as the moisture available for evapotranspiration reduces (Stovin et al. 2013; Poë et al. 2015). A second potential limitation is that it assumes a fixed daily evapotranspiration rate, rather than a more realistic diurnal cycle (Feng and Burian 2016).

After calibration, the SWMM detention model was judged to be satisfactorily accurate for heavy, long-duration, rainfalls with high % initially saturated, but less accurate for short duration rainfall or rainfall with long antecedent dry periods. The inaccuracies may be attributed to the two detention models adopted by SWMM. The detention in the substrate is modelled by Eq. 4, assuming 1) the matric potential varies linearly with water content and porosity; 2) the wetting front advances at the same rate with depth. However, as experimental tests have shown, the soil moisture curve of green roof substrate is not a straight line (Berretta et al. 2014; Cipolla et al. 2016). In SWMM, detention in the drainage layer is modelled by a discharge equation (Eq. 5) with the discharge exponent fixed at 5/3, (or 1.67). However, previous experiments focusing on the specific drainage board installed in the test bed monitored here (Floradrain FD-25) suggest that the discharge exponent should be around 2.0 (Vesuviano and Stovin 2013).

As the components of the green roof test bed are different from the green roof SWMM intended to model, some of the processes in the drainage layer cannot be fully modelled. The drainage layer used for the green roof test bed in this study is an engineering material that can store water in the egg-shaped element and the water will drain out effectively as long as the water level in the drainage tray is replenished. The % initially saturated for this type of green roof refers to the water content in the substrate only. However, the green roof SWMM intended to model is the green roof with a gravel drainage layer, which has no retention capacity and the % initially saturated refers to the water content in the substrate and drainage layer. So there will be runoff from the green roof modelled by SWMM even when the % initially saturated does not exceed the field capacity.

Internal simulation time step also makes a difference to the detention simulations. Given the small area of the sub-catchment, the response to the rainfall is very quick. Using a large internal simulation time-step the model results are inaccurate and unstable. Using the rainfall event on 06/13/2007 and calibrated detention parameters, Fig. 7 compares the model results obtained from a 1 second and a 5 minute internal simulation time step. The runoff profile with 5 minute internal simulation time step is a serrated shape even though the other parameters were the same. Therefore, choosing a suitably small time-step for simulations is also vital to ensure good quality model results.

Insert Fig. 7.

Furthermore, the calibrated parameters in this study are only valid for a green roof that has the same components as the green roof test bed used in the study. Many parameters are required by SWMM and although the SWMM manual provides reference values for each parameter, it is clear that more accurate simulations will be obtained if system-specific values can be input.

Suggestions for Model Improvement

To model the hydrological performance of the green roof with a plastic board drainage layer accurately, four aspects of the SWMM green roof module require improvement. Firstly, the evapotranspiration model in SWMM should take water stress into account and calculate the evapotranspiration rates by keeping track of the water content in the substrate. Secondly, a more robust physically-based model should be used to model the detention in the substrate. The discharge exponent of drainage should not be fixed, allowing users to account for different types of drainage layers. Finally, the % initially saturated in the substrate and drainage layers should be separated to accommodate green roof systems with synthetic drainage board layers.

Conclusion

The comparison of the results obtained from the green roof test bed and the SWMM green roof module prove that the model can represent the hydrology of runoff from the green roof after calibration. Whilst the overall green roof retention was modelled reasonably well by SWMM even before calibration, the fact that the model does not continuously account for reduced evapotranspiration rates due to restricted moisture availability in summer leads to reduced confidence in its application. High quality detention model results were achieved with a limited amount of calibration.

Sensitivity analysis confirmed that the modelled retention performance is most sensitive to evapotranspiration. Many factors may influence the detention modelling of green roof, but the drainage layer parameters were shown to influence the peak runoff most and conductivity slope influences the smoothness of the runoff profile.

The calibration results are reasonable but the calibrated parameters are only valid for a green roof that has the same components as the one used in this study. As many parameters are required, the model is not generic and many uncertainties exist in estimating the values of the parameters.

Some processes in the green roof test bed are not represented using the SWMM green roof module. More robust retention and detention models are required to model the green roof. The retention capacity and the recovery of the capacity in the drainage layer cannot be modelled in the SWMM green roof module. The assumption that the % initially saturated in the substrate and in the drainage layer is the same requires improvement in the future.

References

Alfredo, K., Montalto, F., and Goldstein, A. (2010). "Observed and modelled performances of prototype green roof test plots subjected to simulated low-and high-intensity precipitations in a laboratory experiment." *J. Hydrol. Eng.*, 10.1061/(ASCE)HE. 1943-5584.0000135, 444-457.

Berretta, C., Poë, S., Stovin, V. (2014). "Moisture content behavior in extensive green roofd during dry periods: The influence of vegetation and substrate characteritics." *J. Hrdrol.,* 511, 374-386.

Burszta-Adamiak, E. A., and Mrowiec, M. (2013). "Modelling of green roofs' hydrologic performance using EPA's SWMM." *Water Sci. Technol*., 68(1), 36-42.

Carter, T., and Jackson, C. R. (2007). "Vegetated roofs for stormwater management at mutiple spatial sacles. " *Landscape Urban Plan.,* 80 (1-2), 84-94.

Cipolla, S. S., Maglionico, M., and Stojkov, I. (2016). "A long-term hydrological modelling of an extensive green roof by means of SWMM." *Ecol. Eng.,* 95, 876-887.

Fassman-Beck, E. A., and Simcock, R. (2011). "Moisture measurements as performance criteria for extensive living roof substrates." *J. Environ. Eng.,* 138 (8), 841-851.

Fassman-Beck, E. A., Simcock, R., Voyde, E., and Hong, Y. S. (2013). "4 Living roofs in 3 locations: Does configuration affect runoff mitigation?." *J. Hydrol.,* 490(2013), 11-20.

Feng, Y., and Burian, S. (2016). “Improving evapotranspiration mechanisms in the U.S. environmental protection agency’s storm water management model.” *J. Hydrol. Eng.,* 10.1061/(ASCE)HE.1943-5584.0001419, 06016007.

Fioretti, R., Palla, A., Lanza, L., and Principi, P. (2010). “Green roof energy and water related performance in the Mediterranean climate.” *Build. Environ.,* 45(8), 1890-1904.

Getter, K. L., Rowe, D. E., and Andresen, J. A. (2007). “Quantifying the effect of slope on extensive green roof stormwater retention.” *Ecol. Eng.,* 31(4), 225-231.

Hilten, R. N., Lawrence, T. M., and Tollner, E. W. (2008). “Modeling stormwater runoff from green roofs with HYDRUS-1D.” *J. Hydrol.,* 358 (3-4), 288-293.

Jewell, T. K., Adrian, D. D., and Nunno ,T. J. (1978). “Methodology for calibrating stormwater models.” *J. Environ. Eng. Div.,* 104 (3), 485-501.

Kasmin, H., Stovin, V., and Hathway, E. (2010). “Towards a generic rainfall-runoff model for green roofs.” *Water Sci. Technol.,* 62(4), 898-905.

Li, Y., and Babcock, R. (2014). “Green roof hydrologic performance and modeling: a review.” *Water Sci. Technol.,* 69(4), 727-738.

Locatelli, L., Mark, O., Mikkelsen, P. S., Arnberg-Nielsen, K., Jensen, M. B., and Binning, P. J. (2014). “Modelling of green roof hydrological performance for urban drainage applications.” *J. Hydrol.,* 519, 3237-3248.

Mualem, Y. (1976). “A new model for predicting the hydraulic conductivity of unsaturated porous media.” *Water Resour. Res.,* 12(3), 513–522.

Nash, J. E., and Sutcliffe, J. V. (1970). “River Flow Forecasting Through Conceptual Models Part I — A Discussion Of Principles.” *J. Hydrol.,* 10 (3), 282-290.

Nawaz, R., McDonald, A., and Postoyko, S. (2015). “Hydrological performance of a full-scale extensive green roof located in a temperate climate.” *Ecol. Eng.,* 82, 66-80.

Palla, A., Sansalone, J.J., Gnecco, I., and Lanza, L. G. (2011). “Storm water infiltration in a monitored green roof for hydrologic restoration.” *Water Sci. Technol.,* 62(3), 766-773.

Palla, A., and Gnecco., I. (2015). “Hydrologic modeling of low impact development systems at the urban catchment scale.” *J.Hydrol.,* 528, 361-368.

Poë, S., Stovin, V., and Berretta, C. (2015). “Parameters influencing the regeneration of a green roof’s retention capacity via evapotranspiration.” *J. Hydrol.,* 523, 356-367.

Rosa, D. J., Clausen, J. C., and Dietz, M. E. (2015). “Calibration and verification of SWMM for low impact development.” *J. American Water Resources Association (JAWRA),* 51 (3), 746-757.

Rossman, L. A. (2015). Storm water management model; Version 5.0, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati.

She, N., and Pang, J. (2010). “Physically Based Green Roof Model.” *J. Hydrol. Eng.,* 10.1061/(ASCE)HE. 1943-5584.0000138, 458-464.

Stovin, V., Vesuviano, G., and Kasmin, H. (2012). “The hydrological performance of a green roof test bed under UK climatic conditions.” *J. Hydrol.,* 414-415, 148-161.

Stovin, V., Poë, S., and Berretta, C. (2013). “A modelling study of long term green roof retention performance.” *J. Environ. Manage.,* 131, 206-215.

Stovin, V., Poë, S., De-Ville, S., and Berretta, C. (2015a). “The influence of substrate and vegetation configuration on green roof hydrological performance.” *Ecol. Eng.,* 85, 159-172.

Stovin, V., Vesuviano, G., and De-Ville, S. (2015b). “Defining green roof detention performance.” *Urban Water Journal,* 1-15.

Vesuviano, G., and Stovin, V. (2013). “A generic hydrological model for a green roof drainage layer.” *Water Sci. Technol.,* 68(4), 769-775.

Vesuviano, G., Sonnenwald, F., and Stovin, V. (2014). “A two-stage storage routing model for green roof runoff detention.” *Water Sci. Technol.,* 69(6), 1191-1197.

Villarreal E. L., and Bengtsson L. (2005). “Response of a sedum green-roof to individual rain events.” *Ecol. Eng.,* 25(1), 1-7.

Woods Ballard, B. (2015). The Suds Manual. London: CIRIA.

Yang, W., Li, D., Sun, T., and Ni., G. (2015). “Saturation-excess and infiltration-excess runoff on green roofs.” *Ecol. Eng.,* 74, 327-336.

Zhao, D., Chen, J., Wang, H., Tong, Q., Cao, S., and Sheng, Z. (2009). "GIS-based urban rainfall-runoff modeling using an automatic catchment-discretization approach: a case study in Macau." *Environ. Earth Sci.,* 59 (2), 465-472.

Table 1. Climatological Characteristics of Sheffield during the Study Period

Month	Average Temperature (°C)	Average Sunshine Duration (hours)	Potential Evapotranspiration Rate (Calculated from the Thornthwaite equations) (mm/day)
January	6.8	8.13	0.47
February	7.1	9.87	0.60
March	9.8	11.85	1.13
April	12.5	14	1.87
May	16.1	15.88	3.00
June	18.8	16.9	3.95
July	21.1	16.4	4.49
August	20.6	14.75	3.91
September	17.7	12.68	2.73
October	13.5	10.58	1.57
November	9.5	8.65	0.79
December	6.9	7.58	0.45

Table 2. Characteristics of the Significant Rainfall Events (Return Period > 1 year)

No. Event	Time of Event Starts	Rainfall Duration (hh:mm)	Antecedent Dry Weather Period (hh:mm)	Rainfall Depth (mm)	% Initially Saturated (%)
1	01/18/2007 01:15	24:17	10:26	27	57.281
2	01/20/2007 19:50	24:18	9:02	38.6	56.728
3	05/13/2007 12:35	21:30	16:04	29.8	0.563
4	06/12/2007 05:40	2:03	199:14	12.8	22.531
5	06/13/2007 15:40	42:29	31:58	99.6	21.441
6	06/15/2007 17:55	9:19	7:46	16.2	62.481
7	06/24/2007 22:15	22:41	6:00	58	62.391
8	07/26/2007 07:00	13:29	13:25	12.6	54.553

Table 3. SWMM Parameters and Initial Values for Uncalibrated Simulations

Parameter	Initial Value	Data Source
Sub-Catchment		
Evapotranspiration Coefficient	1	Default
Area	3 m^2	Stovin et al. 2012
Width	1 m	Stovin et al. 2012
Surface Layer		
Berm Height	0	Default
Vegetation Volume Fraction	0	Default
Surface Roughness	0.15	Default
Surface Slope	2.60%	Stovin et al. 2012
Soil (Substrate)		
Thickness	80 mm	Stovin et al. 2012
Porosity	0.45	Rosa et al. 2015
Field Capacity	0.3	Poë et al. 2015
Wilting Point	0.05	Rosa et al. 2015
Conductivity	25 mm/hr	Rosa et al. 2015
Conductivity Slope	15	Palla and Gnecco, 2015
Suction Head	110	Rosa et al. 2015
Drainage Layer		
Thickness	25 mm	Manufacturer Specifications
Void Fraction	0.4	Rossman 2015
Roughness	0.02	Palla and Gnecco 2015

Table 4. Sensitivity of Annual Retention and Annual Runoff Volume (173 events in 2007) to SWMM Green Roof Parameters Adjusted ±10% and ±50%

Parameter	-50%		-10%		+10%		+50%	
	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume	Annual Retention	Runoff Volume
ET Coefficient	-0.596	0.452	-0.600	0.455	0.596	-0.453	0.403	-0.306
Surface Slope	0.003	-0.002	0.001	-0.001	-0.001	0.001	-0.001	0.001
Soil Porosity	---	---	-0.243	0.184	0.345	-0.262	0.152	-0.116
Soil Field Capacity	-0.298	0.226	-0.054	0.041	0.296	-0.224	---	---
Soil Wilting Point	0.060	-0.046	0.105	-0.079	0.094	0.071	-0.058	0.044
Soil Conductivity	0.068	-0.052	0.035	-0.026	-0.014	0.011	-0.013	0.010
Conductivity Slope	-0.060	0.046	-0.005	0.004	0.111	-0.085	0.085	-0.064
Suction Head	0	0	0	0	0	0	0	0
Drainage Void Fraction	-0.002	0.001	-0.002	0.001	0.002	-0.002	0.002	-0.002
Drainage Roughness	0.068	-0.052	0.002	-0.002	-0.004	0.003	-0.003	0.003

Note: Negative relative sensitivity values indicate a decrease in the corresponding annual retention or total runoff volumes after adjustment and positive values indicate an increase. Soil porosity should not be smaller than field capacity and field capacity should smaller than soil porosity, --- indicates invalid values.

Table 5. Sensitivity of Detention Parameters (event on 06/13/2007) to SWMM Green Roof Module Parameters Adjusted ±10% and ±50%

Parameter	-50%				-10%				+10%				+50%			
	Peak Runoff	Peak Delay	Time to Start of Runoff	Runoff Duration	Peak Runoff	Peak Delay	Time to Start of Runoff	Runoff Duration	Peak Runoff	Peak Delay	Time to Start of Runoff	Runoff Duration	Peak Runoff	Peak Delay	Time to Start of Runoff	Runoff Duration
% Initially Saturated	0	0	1.309	-0.245	0	0	2.222	-0.416	0	0	-0.494	0.092	0	0	0.272	0.051
Surface Slope	-0.004	0	0.025	0.005	-0.002	0	0.123	0	0.002	0	0	0	0.002	0	0	0
Soil Porosity	---	---	---	---	0.706	0	2.222	-0.416	-0.222	0	-0.617	0.462	-0.046	0	-0.272	3.173
Soil Field Capacity	-0.046	0	-1.901	1.275	-0.217	0	-1.111	0.37	0.394	0	4.321	-0.808	---	---	---	---
Soil Wilting Point	0	0	0.815	-0.152	0	0	0.494	-0.092	0	0	-0.247	0.046	0	0	-0.198	0.037
Soil Conductivity	0.009	0	0	0.074	-0.112	0	0	0	0.096	0	0	0	0.071	0	0	0
Conductivity Slope	0.0411	0	0	0	-0.268	0	0	0	0.281	0	0	0.023	0.32	0	0	0.106
Suction Head	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drainage Void Fraction	0.004	0	0	0	0.003	0	0	0	-0.002	0	0	0.023	-0.002	0	0	0.005
Drainage Roughness	0.001	0	0	-0.005	0.005	0	0	0	-0.005	0	0	0.023	-0.004	0	0	0.005

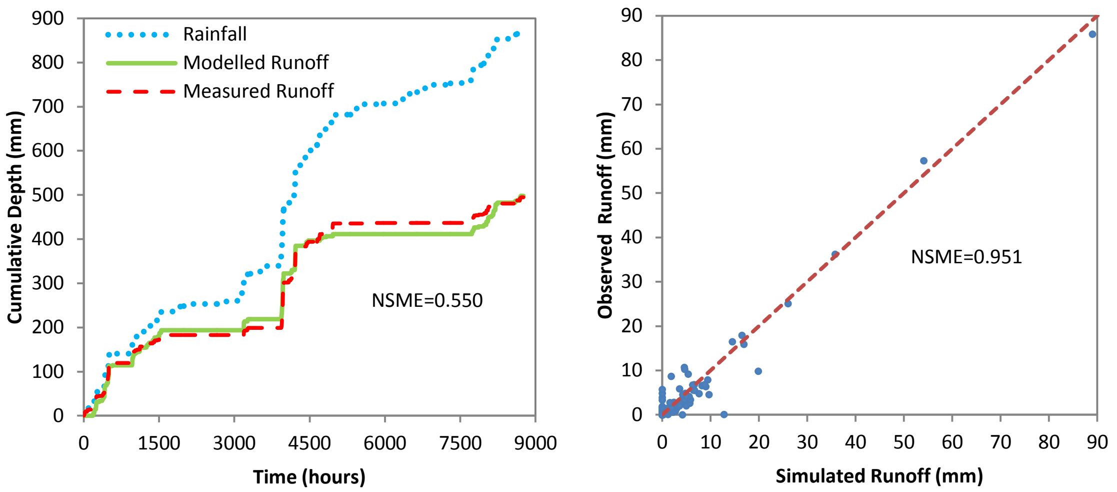
Note: Negative relative sensitivity values indicate a decrease in the corresponding detention parameters after adjustment and positive values indicate an increase. Soil porosity should not be smaller than field capacity and field capacity should not bigger than soil porosity, --- indicates the invalid values.

Table 6. Initial and Calibrated Parameter Values

Parameter	Initial Value	Calibrated Value
Conductivity	25 mm/hr	1000 mm/hr
Conductivity Slope	15	50
Void Fraction	0.4	0.6
Roughness	0.02	0.03

Table 7. Revised Evapotranspiration Rates

Month	Continuous Dry Periods (Days)	ET Rates at the End of the Dry Periods (Proportion of PET)	Dry Periods Average ET Rates (Proportion of PET)	Wet Periods (Days)	Monthly Mean ET Rates (Proportion of PET)	Monthly Mean ET Rates (mm/day)
January	2	0.70	0.85	24	0.96	0.45
	5	0.60	0.80			
February	8	0.65	0.83	18	0.94	0.56
	2	0.70	0.85			
March	6	0.65	0.83	20	0.93	1.05
	5	0.60	0.80			
April	23	0.15	0.58	5	0.66	1.23
	2	0.70	0.85			
May	7	0.64	0.82	20	0.99	2.97
	6	0.65	0.83			
June	2	0.79	0.90	20	0.93	3.67
	8	0.56	0.78			
July	2	0.79	0.90	29	0.99	4.45
August	12	0.35	0.68	8	0.77	3.01
	11	0.41	0.70			
September	2	0.70	0.85	13	0.86	2.35
	11	0.40	0.70			
	4	0.65	0.83			
October	3	0.76	0.88	10	0.82	1.32
	5	0.60	0.80			
	2	0.70	0.85			
	11	0.40	0.70			
November	7	0.65	0.83	16	0.91	0.74
	2	0.70	0.85			
	2	0.70	0.85			
	3	0.75	0.88			
December	11	0.40	0.70	20	0.89	0.40



(a) Cumulative Rainfall and Runoff Depths (b) Runoff Depths for 173 Events in 2007

Fig. 1. Uncalibrated long-term simulation (NSME in (a) was calculated from hourly runoff and NSME in (b) was calculated from total runoff depth in a single rainfall event).

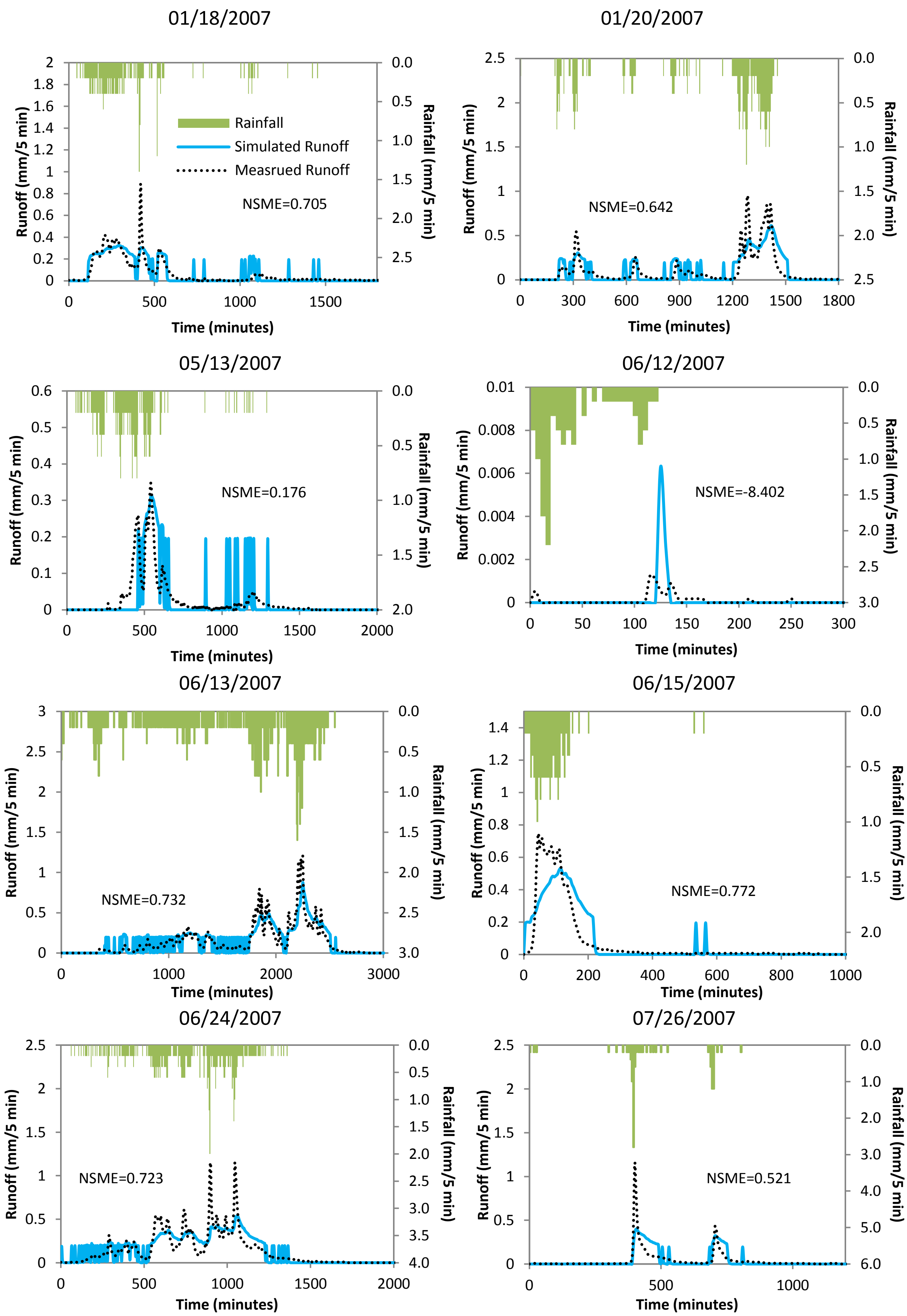
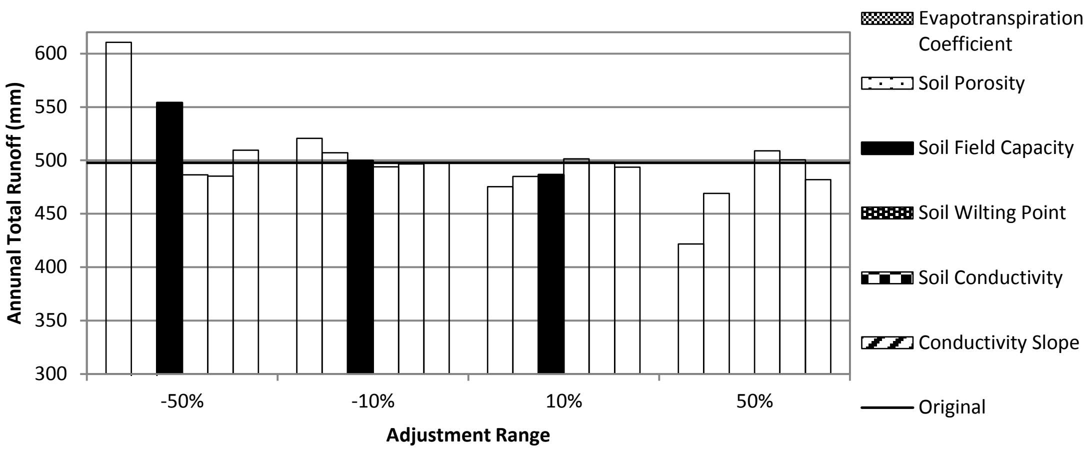
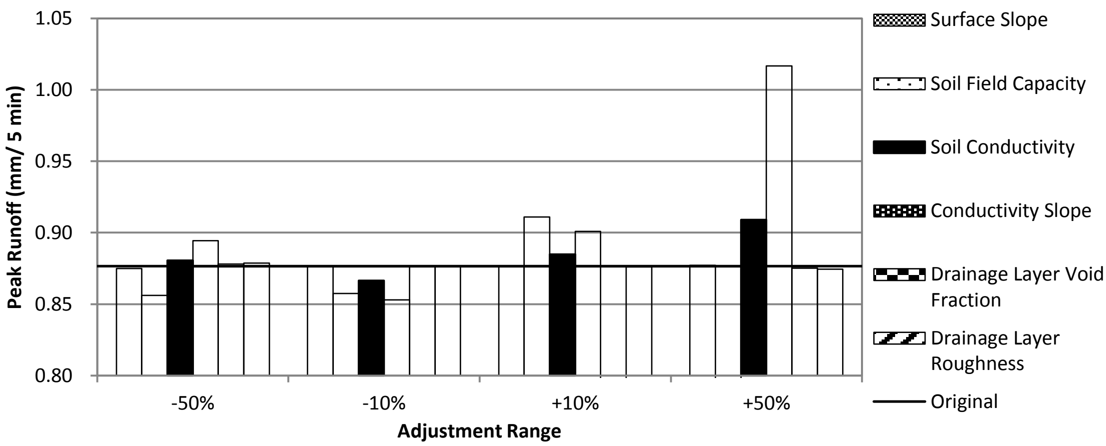


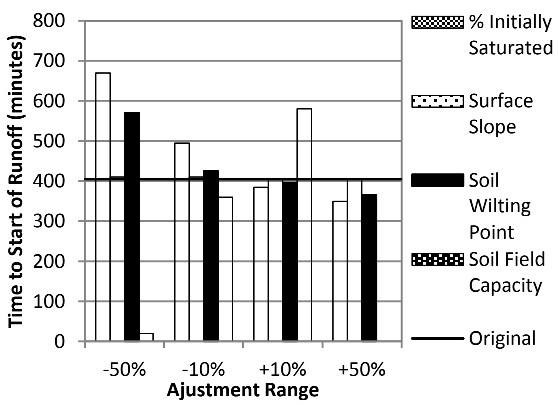
Fig. 2. Uncalibrated time-series rainfall, measured runoff and modelled runoff profiles for 8 significant events.

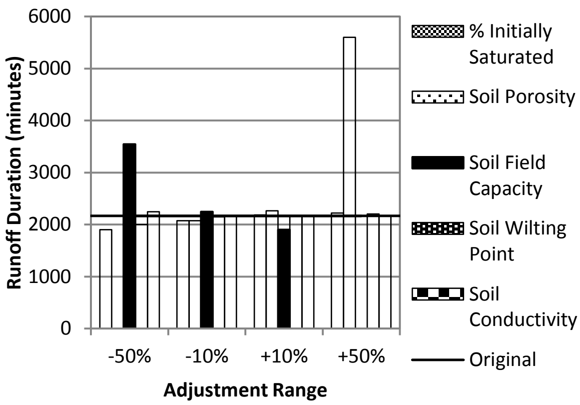


(a)



(b)





(c) (d)

Fig. 3. Sensitivity of model predictions to selected parameter values. Plot (a) is for the long-term simulation of 2007; Plots (b), (c) and (d) are for the 06/13/2007 event. Empty columns represent invalid input parameter combinations.

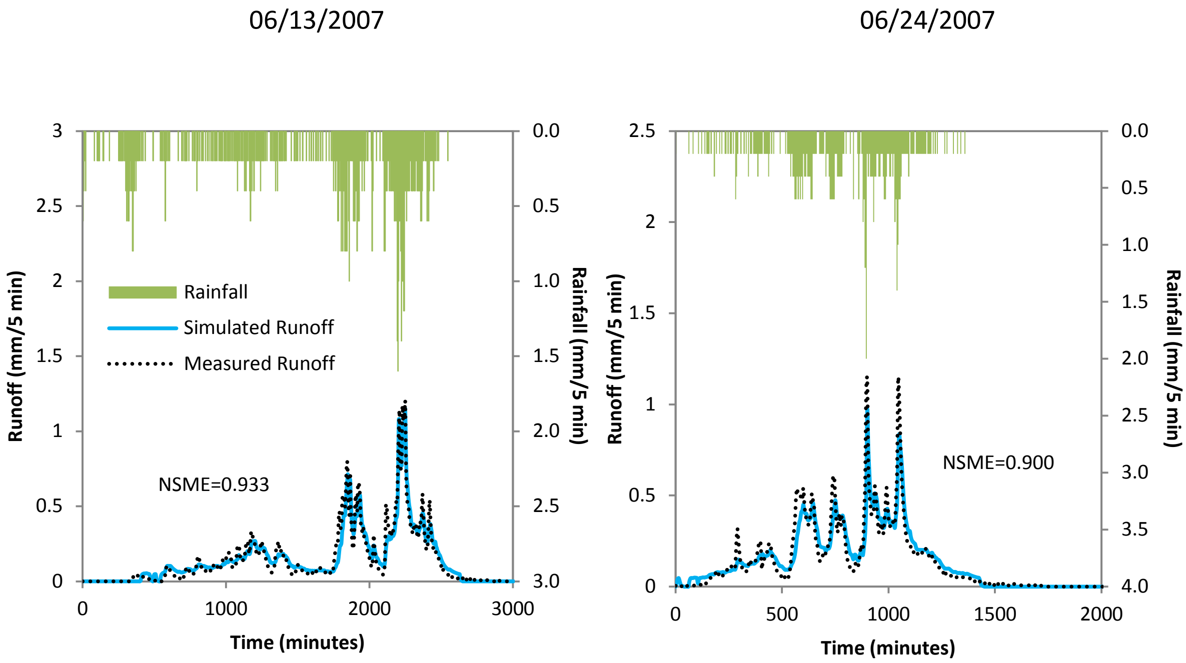
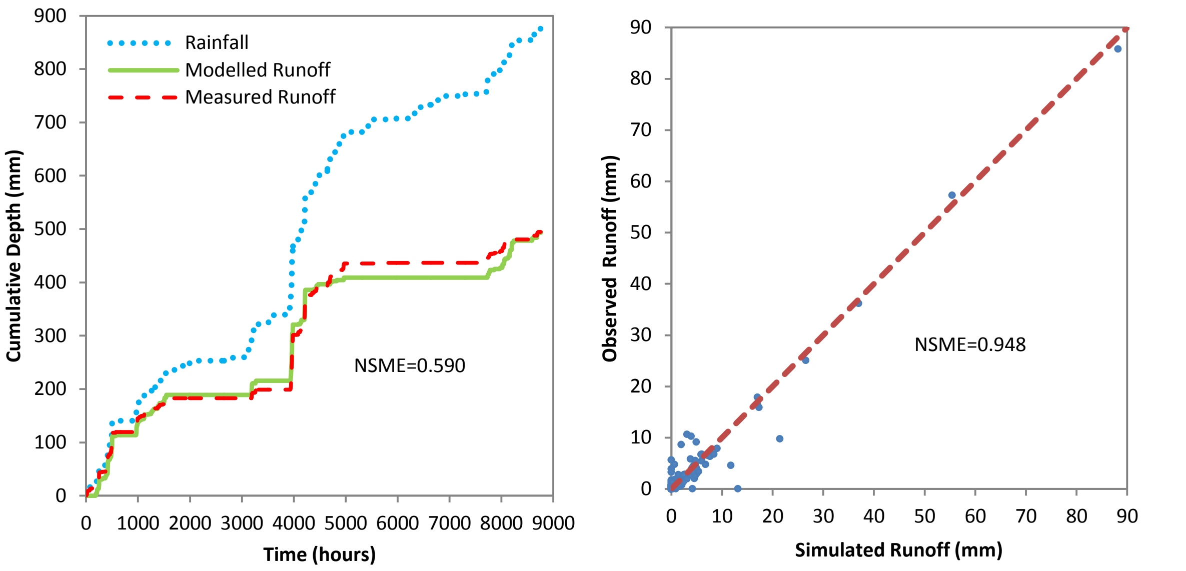


Fig. 4. Calibrated time-series rainfall, measured runoff and modelled runoff profiles for 2 significant events.



(a) Cumulative Rainfall and Runoff Depths (b) Runoff Depths for 173 Events in 2007

Fig. 5. Calibrated long-term simulation (NSME in (a) was calculated from hourly runoff and NSME in (b) was calculated from total runoff depth in a single rainfall event).

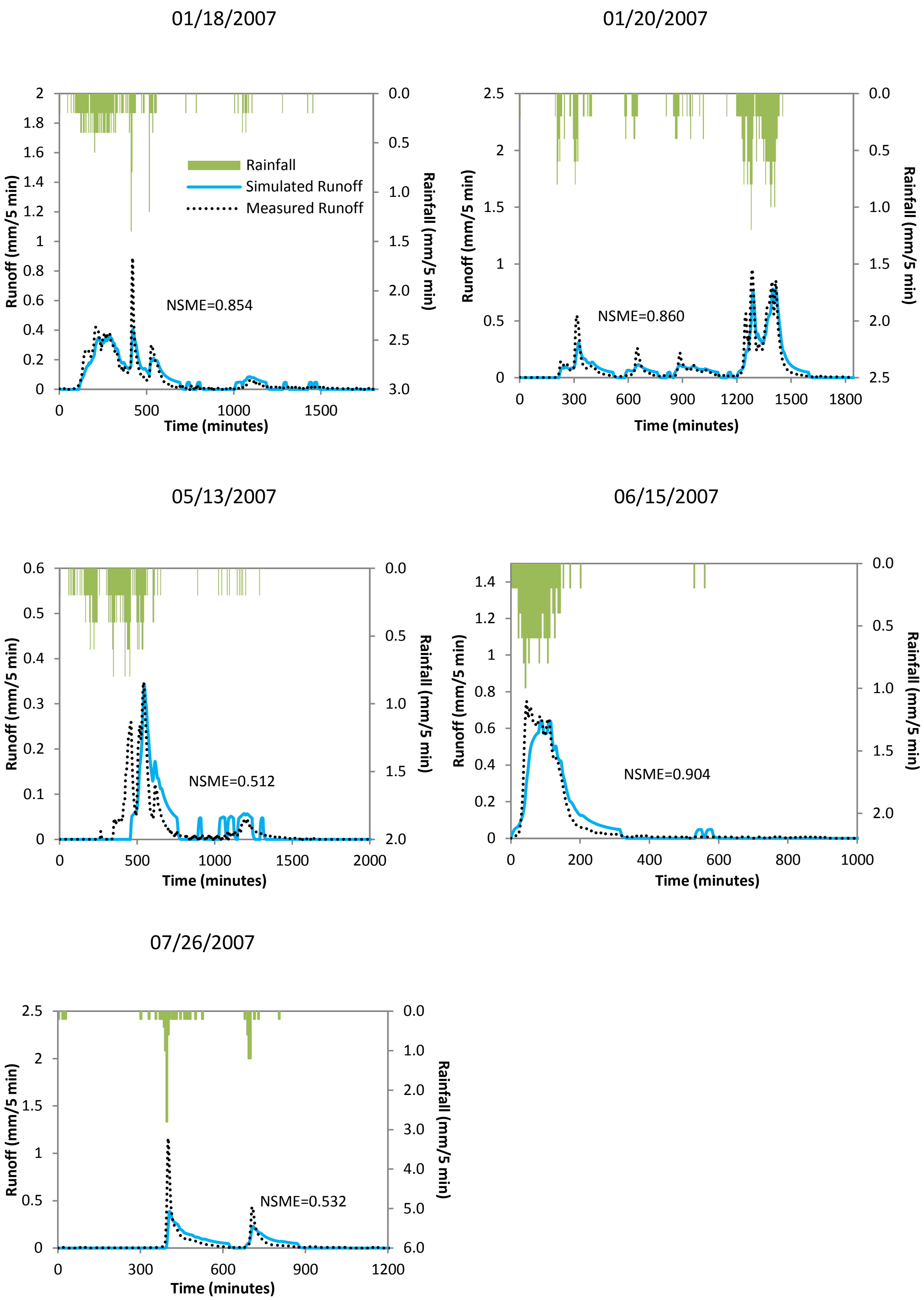


Fig. 6. Time-series rainfall, measured runoff and modelled runoff profiles for 5 significant events using calibrated parameters.

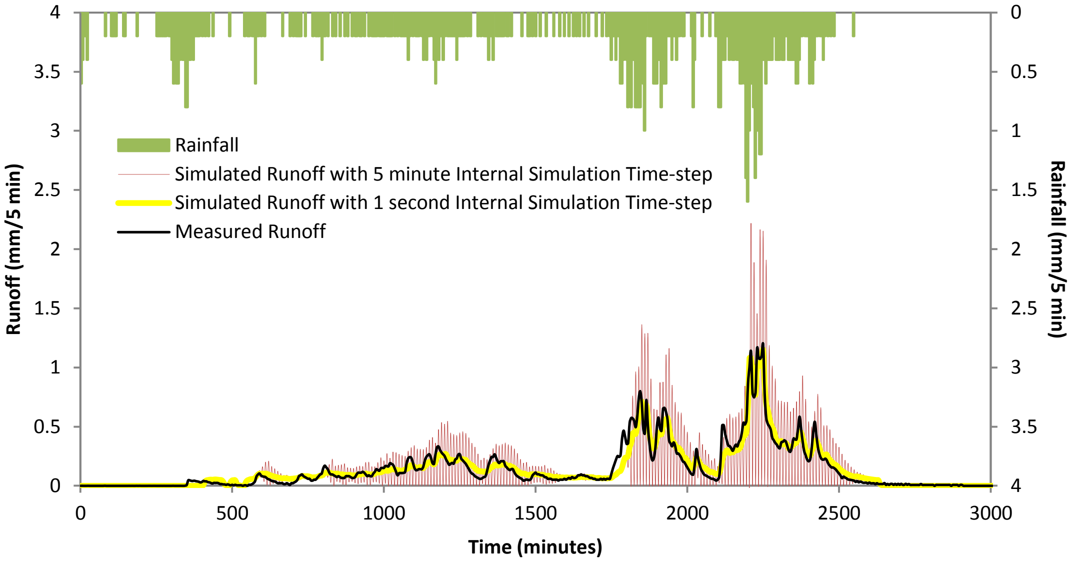


Fig. 7. A comparison of simulation results obtained from a 1 second versus a 5 minute internal simulation time-step for event 06/13/2007.