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Green roofs effects on the urban water cycle components

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Abstract

Green roofs are emerging as an increasingly popular Sustainable Urban Drainage Systems (SUDS) technique for urban stormwater management. Indeed, they allow a significant reduction of peak flows and runoff volumes collected by drainage system, with consequent reduction of flooding events and pollution masses discharges by CSO. To estimate the imperviousness of a green roof and to evaluate its hydrological impact within an urban watershed, a bucket model was developed to simulate a rainfall-runoff relationship for a single green roof. The objective is modeling hydrological fluxes in relation to climate forcing, basic technology components and geometric characteristics of green roof systems.

1. Introduction

In the last decades the importance of storm water management in urban areas has increased considerably, due to both urbanization extension and to a greater concern for environment pollution. Urbanization leads to an increase in impervious surfaces – rooftops, driveways, roads, car parking, and footpaths – which are connected with hydraulically efficient pipes to receiving waters. The natural roughness and filtering action of vegetation, and the infiltration and storage capacity of the underlying soils, is replaced by compacted soils and hydraulically-smooth impervious surfaces at the expense of hydrologic functions such as interception by plants, depression storage, infiltration, soil water storage and flow retardation due to surface roughness. This creates a greater volume of excess water which runs off more quickly for a given rainfall event.

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Traditional storm water control practices, based on the "all to the sewer" attitude, rely on conveyance to route storm water runoff from urban impervious surfaces towards the nearby natural water bodies. On the contrary, green roofs are designed to capture, temporarily retain and infiltrate storm water, promote evapotranspiration and harvest water at the source, encouraging in general evaporation, evapotranspiration and the re-use of storm water. Such technique can provide an opportunity to reduce and attenuate storm runoff at source; in this way, many studies suggest that green roofs can reduce storm water runoff in comparison to conventional roofs with volume retention scores in the order of 40–80% of the total rainfall volume. From literature's data it is also evident that a decrease of 60–80% in runoff peak rates is to be expected from a green roof (Köhler et al., 2001; Hutchinson et al., 2003; Liu, 2003; Moran et al., 2004; Bengtsson et al., 2005; VanWoert et al., 2005; Berghage et al., 2009).

However, the dynamic stormwater response of a green roof to precipitation events is highly variable and related to a particular set of climate conditions and changes with green roof design.

In recent years, due to their particular efficiency in restoring a balance in hydrological cycle quite equal to quite pre-urbanization condition, the impact of green roof implementation in urban watersheds has become a hot research topic. The effect of green roofs has been studied by various methods and several studies, based usually on water-balance models that treat green roofs as simple reservoirs with restricted outlets, examined their hydrologic response. Cater and Jackson (2006), for example, used the Soil Conservation Service (SCS) Curve Number (CN) method as the infiltration and runoff model to test green roof impact at multiple spatial scales. Hilten et al. (2008) conducted a study on the effectiveness of green roofs to mitigate stormwater runoff by using HYDRUS-1D. Hollander (2007) used a modified Green-Ampt method and a physical model to research the effect of green roof implementations; Palla et al. (2009) used the SWMS_2D model, based on Richards' law and the Van Genuchten– Mualem functions to simulate the variably saturated flow within the green roof system; She and Pang (2010) constructed a physics-based model to simulate rain water movement with green roof medium; Sherrard et al. (2012) built a simple bucket model for a single green roof and extrapolated it to an urban scale to test its stormwater reduction effects

The average reduction in stormwater runoff would appear to provide an indication of the impervious contribution of a green roof; when green roofs are implemented into an urban system, they represent a third type of surface area which behaves as pervious before saturation and impervious after saturation. To estimate the imperviousness of a green roof and, as consequence, to evaluate its hydrological impact within a urban watershed, a simple bucket model was developed to simulate the water fluxes in soil layers and to generate a rainfall-runoff relationship for a single green roof. The model is based on the physical processes that affect the green roof stormwater response: during a storm event the key hydrological mechanisms operating within the green roof are the interception of rainfall by the plant layer, evapotranspiration, infiltration and storage in the substrate, and reservoir storage in the drainage layer. This model could only provide a tool for understanding how the implementation of green roofs can affect urban catchment under different conditions; indeed, the objective is modeling hydrological fluxes (interception, evapotranspiration, soil water fluxes in the surface and hypodermic components) in relation to climate forcing, basic technology components and geometric characteristics of green roof systems (thickness of the soil layers and materials, vegetation typology and density). To simplify model parameterization in this study we adopted a simplified bucket model that is conceptually similar to the TOPMODEL soil water accounting scheme (Beven and Kirkby, 1979).

2. Model description

2.1. Green roof design influence on soil-water fluxes

The hydrologic processes in a green roof consist of evapotranspiration, infiltration, and runoff generation. It is critical to quantify each part of the hydrologic budget to determine the efficiency of a green roof at reducing peak runoff rates and volumes. A hydrologic budget balances the inputs and outputs of water in the system with the change in volume of stored water. The hydrologic balance provides the governing equation for determining how much rainfall might be captured by a green roof at any given time.

Green roofs differ from a natural environment as they are on top of a building and are not connected to the natural ground; therefore it is critical that soils can drain and retain water simultaneously and that they work even in very shallow systems. Using the proper growing media is in fact crucial for the success of any green roof system. When the growing media is of poor or inferior quality, the plants cannot thrive and the green roof system will fail. The plants used on green roofs must be supported in soil, but natural soil is too heavy to use on rooftops. The soil or growing medium used for green roofs is specifically engineered to support the plants while meeting other rooftop requirements. It must be lightweight, able to retain some water while allowing excess water to drain, able to provide nutrients for plant growth and minimize the amount of nutrients leaching into water runoff. To achieve these characteristics, growing medium consists of soil mixed with aggregates (non-organic, absorbent fillers) and organic matter. Thus, vegetated roofs are engineered systems designed to drain completely so there is no standing water on the waterproofing membrane; to meet this requirement, typical systems are a combination of a synthetic drainage layer with a high performance media layer.

In this work, we focused the attention on hydraulic infiltration and, as consequence, on runoff generation processes: our aim is to describe and model these processes though a detailed but clear subsurface hydrology module, based on green roof vertical soil water movement reproduction. To do that, we decide to outline a single green roof with a one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme; this scheme consists of two reservoirs, one for the growing media and the other for the drainage layer (Fig. 2) so that each reservoir stores water and exchanges fluxes at its limits.

Our aim was to employ a model structure for handling soil water fluxes in each element (as opposed to the Darcy-Richards approach normally used in soil infiltration processes representation), with a bare minimum of "tuning variables" (six in this case) but to retain some physical basis and spatially explicit representation in the way we modeled storm flow generation. The work here is to develop a conceptual model based on empirical descriptions of the processes, that can be calibrated with observed data. To do this, a mathematical model for a single green roof was built in Matlab under the assumption of soil homogeneity for each layer and, at first instance in this analysis, neglecting evapotranspiration flows. This model was used to generate a rainfall-discharge relationship for a single green roof.

2.2. Subsurface module for a green roof: the Simplified Bucket Model

The subsurface fluxes in a green roof were studied using the Simplified Bucket Model (Vertessy and Elsenbeer, 1999). This model is typically used to represent the processes of infiltration in natural soils in unurbanized basins (Rulli and Rosso, 2007): our purpose is to adapt the model to soil characterized by a specific engineered stratigraphy, designed for extensive green roof systems in multilayer construction.

The Simplified Bucket Model is a mechanistic model and represents a good compromise between the difficulty of parameterization and accuracy in the description of the process of infiltration into the soil. In fact, it has a solid physical basis in the interpretation of soil saturation and it does not require a large number of input parameters (Vertessey et al., 1997).

The Simplified Bucket Model considers the soil as a tank characterized by a certain depth z and divided into a surface unsaturated zone I and a saturated deeper zone S. The size of each of the two tanks varies with time and the water content of the two zones is expressed in units of length, in order to return to a height of water. The saturated zone is always considered to be such and the water content inside can vary in time only because of contractions or expansions, to the detriment of the unsaturated zone. The surface above the saturated zone can be roughly considered as the free surface of groundwater. The SBM was not designed to simulate groundwater dynamics and it makes the simplifying assumptions that the water table is almost parallel to the surface such that the effective hydraulic gradient is equal to the local surface slope.

The Simplified Bucket Model requires input data on precipitation, soil depth (z), saturated hydraulic conductivity at the soil surface (K_0), the decay rate of K_0 with depth (m), the empirical parameter (n), water content at saturation (θ_s) and residual (θ_{dry}). Were analyzed for each time step of the calculation, the infiltration and vertical percolation of water both through the unsaturated zone and from the saturated zone to the drainage layer,

passing through the geotextile filter fabric. The basic hypothesis is that the conductivity of the saturated soil K_s for the layer l (the original formulation refers only to one layer) decreases exponentially with depth z:

$$K_{s,l} = K_{0,l} e^{-f_l z_{i,l}} \tag{1}$$

where f is a scale parameter equal to:

$$f_l = \frac{\theta_{s,l} - \theta_{dry,l}}{m_l} \tag{2}$$

The area corresponding to the depth z_i, above the saturated zone, can be considered approximately the free surface of groundwater. The amount of water contained within the saturated zone at each time instant is equal to:

$$S_l = (z_{t,l} - z_{i,l}) \cdot (\theta_{s,l} - \theta_{dry,l}) \tag{3}$$

The water deficit I_d so that the volume of the tank of the unsaturated zone is complete and reaches the saturation is expressed by the following equation:

$$I_{d,l} = z_{i,l} \cdot (\theta_{s,l} - \theta_{dry,l}) - I_{s,l} \tag{4}$$

$$I_{s,l} = I_l - I_{d,l} \tag{5}$$

The tank S for all the time is considered full as said before, therefore the increase or the loss flows from it, is expressed simply by means of expansions and contractions of its size. In the model is also defined S_d, the deficit compared to the saturation of the soil calculated for the entire soil profile as follows:

$$S_{d,l} = z_{t,l} \cdot (\theta_{s,l} - \theta_{dry,l}) - S_{,l} \tag{6}$$

The amount of water which infiltrates into the ground (*in*) is regulated by the hydraulic conductivity of the soil and by the deficit of the unsaturated zone compared to the saturation I_d. The vertical movement from the unsaturated soil towards the saturated zone *st* is adjusted by the hydraulic conductivity K_s (Eq.1) to the depth z_i and from the relationship between I_s and S_d:

$$st_l = K_{s,l} \left(\frac{I_{s,l}}{S_{d,l}} \right)^n \tag{7}$$

This report does not consider the soil water contained in the unsaturated zone I, as it is evaluated as the height of water required to achieve the complete saturation of the soil. The stream from the saturated to the saturated is adjusted by an equation similar to the equation of Darcy where, however, the saturated hydraulic conductivity K_s decreases with depth in accordance with a negative exponential (Eq.1).

In the original Simplified Bucket Model formulation, the amount of water present within the saturated zone tends to flow from each element in the form of sub-surface runoff (*sf*). For each time interval, the value of *sf*, calculated per unit of area of the element, is obtained through the following relation:

$$sf_l = \tan(\beta_l) \cdot K_{s,l} \cdot e^{\frac{-S_{d,l}}{m_l}} \tag{8}$$

where β is the angle of inclination of the surface. This relationship is nothing more than the formulation of Darcy equation which indicates the flow in the saturated zone and relates it to the load via a constant that is the hydraulic conductivity K_s (Eq.1). The outflow sub-surface (Eq.8) is considered that it can only happen if in the soil profile develops a saturated zone, while in the unsaturated zone of the soil it has only the phenomenon of infiltration in the vertical direction (Eq.7).

2.3. The multi-layer Simplified Bucket Model

The multi-layer SBM is an extension of the original model where each layer l works as a bucket and communicates with each other; each layer appears again to be divided at the top by a vadose zone and in the deep part from a saturated zone (Fig. 1).

The potential of the multi-layer SBM, compared to physically based models, is related to the difficulty that the latter present at the interface between the layers. The laboriousness that involves having to define for each layer the related parameters, creates problems in correspondence of the discontinuities: in particular, the marked difference between the hydraulic properties of the different layers results in an equally strong discontinuity in the content of water at the interface, which leads to problems of non-convergence of the solution. The multi-layer SBM presents no problems of this type, since, due to its simplicity, has no problems of numerical instability and convergence.

The SBM analyzes the process of infiltration with an approach to the "equivalent continuous", i.e. flows are described as if they take place in a single domain, represented by the porous matrix.

The infiltration (*lin*) from one layer l to the underlying one $l+1$, occurs only if it develops a saturated zone; it is governed by the relative conductivity at the interface between the two layers K_i multiplied by the ratio between the quantity of water contained in the saturated zone S of the current layer, and the saturation deficit I_d of the unsaturated zone of the layer below:

$$lin_l = K_{i,l} \cdot \frac{S_l}{I_{d,l+1}} \tag{9}$$

If the height of water table of the upper layer in the unit of time express by Eq. 9 is less than the conductivity at soil interface and less than the amount I_d, assessed per unit of time, then it empties all in the ground, except to the residual content integral with the solid skeleton.

The aquifer suspended in the first bucket, and all the water present in it, continues to infiltrate in the vertical direction if the layer infiltration (Eq.9), governed by the conductivity at the interface between the two soils, turns out to be exceeding the quantity of water contained within the saturated zone of the upper layer; on the contrary, a perched water table is formed.

It is noted that the hydraulic conductivity at the interface between the two layers is linked both to the subsequent transition to a soil with different properties and to the partial saturation of the underlying zone; therefore, to model the two phenomena a value of permeability at the interface K_i is required, that is able to estimate the conductivity even when the high area of the layer below is unsaturated. Usually a green roof system is structured in such a way that between the surface layer (i.e., the growing medium) and the drainage layer is interposed a geotextile, which acts as a filter and has a specific hydraulic conductivity, dependent on the structure of the filter fabric itself. The infiltration process is therefore governed by the value of such conductivity, which regulates not only the flow of water that feeds the layer of drainage, and therefore any subsurface discharge, but also the moisture content of the root layer and the eventual saturation of the latter.

The sub-surface flow in the multi-layer SBM is calculated only for the last layer of the roof system (i.e. the drainage layer). Because of the size of the thickness z_D of this layer is usually very small, it was considered necessary to modify the equation that describes this flow, in order to take into account the influence of the bottom of the layer, overlooked in the original formulation, as in natural soils, the thickness going deeper tend to increase in thickness and the influence of bedrock is usually negligible:

$$sf_l = \tan(\beta_l) \cdot \frac{K_{0,l}}{f_l} \cdot \left(e^{-f_l z_{i,l}} - e^{-f_l z_{D,l}} \right) \qquad (10)$$

The variables I_s e z_i are updated at each time step through a balance of continuity of water flows.
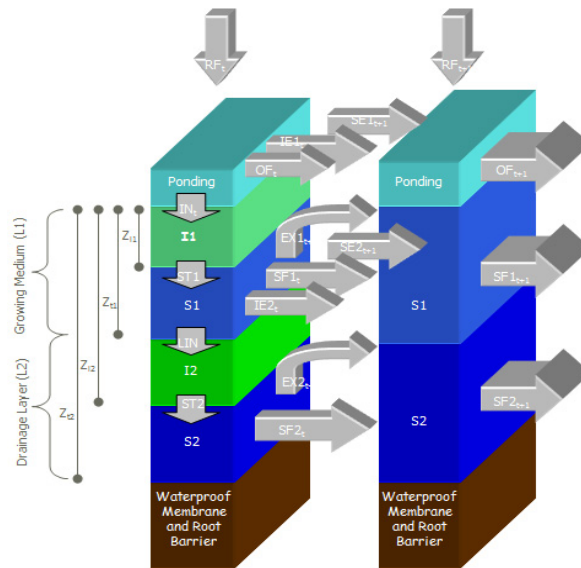

Fig. 1. Multi-Layer SBM scheme: RF=rainfall; I=unsatured store; S=satured store; SF=subsurface flow; EX=exfiltration; IE=infiltration excess; LIN=layer infiltration; IN=infiltration; SE= saturation excess; OF=overflow; ST=vertical drainage.

3. Results and discussion

3.1. Calibration and performance of the green roof model

The parameters needed in the hydrologic module cannot be simply taken from literature due to their high variability and since installation practices, such as the level of soil compaction, can have a significant impact on the value on these parameters. Focusing only on green roof runoff discharge simulations, calibration proves necessary and useful due to certain unknown parameters and to the limited available observations.

Three parameters need to be calibrated: the saturated hydraulic conductivity at the soil surface (K_0), the decay rate of K_0 with depth (m), the empirical parameter (n); the range of their possible values has been defined from physical consideration, as the values for the non-calibrated parameters – i.e. the water content at saturation (θ_s) and residual (θ_{dry}). The aim is to conduct a set of simulations using parameters randomly chosen from the range of their possible values. The calibration is done by comparing measured and simulated discharge using the well-known Nash-Sutcliffe criterion: the quality of these simulations has been estimated on runoff discharge selecting a subset of acceptable simulations that provides the best parameter set according to the selected criterion; the final values of the various parameters are chosen from among the subset of acceptable simulations (Fig.3). The hydraulic parameters required by the infiltration model for each green roof component are listed in Table 1 and 2 and were calibrated using selected rainfall events (see Table 3).
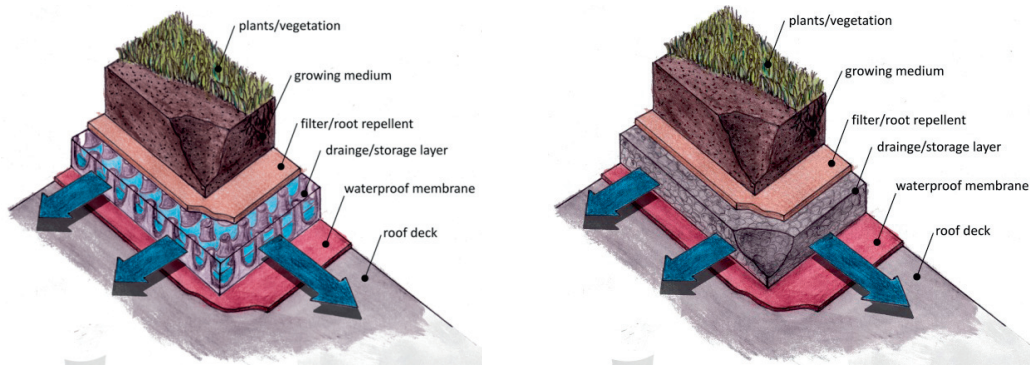
Fig. 2. (a) Green roof system with "egg box" drainage layer; (b) Green roof system with granular drainage layer.

Table 1. Variables and parameters used in the model for the green roof system with "egg box" drainage layer.

z_t	K_0	m	n	θ_s	θ_{dry}	β
(m)	(m/s)	(m)	(m)	(m^3/m^3)	(m^3/m^3)	(-)
0.08	0.002	0.3	2.5	0.4	0.165	0.026

Table 2. Variables and parameters used in the model for the green roof system with granular drainage layer.

z_t	K_0	m	n	θ_s	θ_{dry}	β
(m)	(m/s)	(m)	(m)	(m^3/m^3)	(m^3/m^3)	(-)
0.2	0.001	0.3	5.8	0.5	0.005	0.02
0.4	0.01	0.3	1.5	0.47	0.004	0.02

The numerical model is calibrated and validated using the events observed on the Mappin Roof, on top of the Sir Frederick Mappin Building in Sheffield, UK, since the end of 2006 (Stovin V. et al., 2007). The test bed ($3m^2$) uses a standard commercial extensive green roof system, comprising a sedum vegetation layer (80 mm depth of growing medium) with a slope of 1.5°. The substrate is composed of a mixture of crushed brick with a FloraDrain FD25 drainage layer with typical 'egg box' shape (retention capacity 3 l/m^2). The calibration and validation strategy is based on the comparison of the predicted and measured subsurface flow hydrographs. In particular, two variables are used to this aim: the discharge volume and the peak outflow rate.

In order to assess the model performance with respect to the above mentioned hydrograph variables, the relative percentage difference (RPD) was calculated as the ratio of the difference between the simulated and the observed values to the observed one for each rainfall event. Note that a Nash–Sutcliffe efficiency index equal to 1 indicates a perfect match between the predicted and observed outflow. Results confirm the suitability of the model to properly describe the hydrologic response of the green roof during the observed rainfall events (Fig.3). The RPD of the total effluent volume varies within a range of ± 30% while the RPD of the peak flow rate varies within ± 15% (Table 3).

Preliminary performance data from the rooftop of the Environmental Engineering laboratory building, at the University of Genova, Italy (flat roof with an extension of about 350 m^2, a drainage layer realized with Lapillus and a growing medium with mixed soil) for only two rainfall events confirm that the model correctly describes the variably saturated flow in the green roof stratigraphy (Palla A. et al., 2008 & 2011). By analyzing the results presented both in graphic form with the aid of performance indices is clear that the hydrological model well reproduces the response of the basin object of study and for the shape of the hydrograph and for the peak time and for its magnitude (Fig.4 and 5). It is also well re produced even the tail of the hydrograph.

Table 3. Nash–Sutcliffe efficiency coefficient and relative percentage deviation (RPD) of the total effluent volume and peak flow of observed rainfall events in Sheffield, UK (first five events) and in Genova, Italy (last two events);

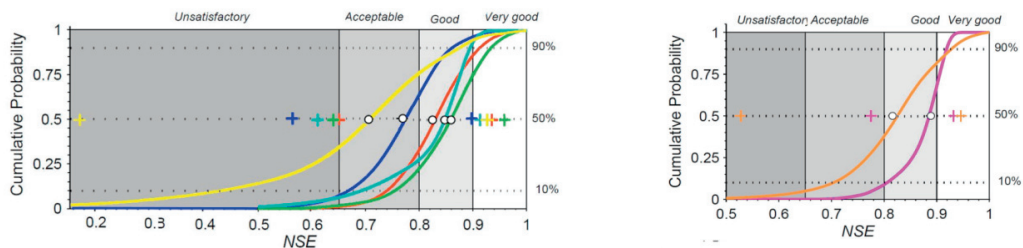| Rainfall event	Nash Sutcliff	RPD Volume	RPD Peak
	(-)	(%)	(%)
3 July 2009	0.768	31.63	-0.76
29 July 2009	0.824	12.56	9.08
30 July 2009	0.855	9.95	-16.11
25 August 2009	0.856	22.97	-1.24
26 August 2009	0.703	35.81	11.4
5 June 2007	0.889	8.6	11.96
28 October 2008	0.816	-40.37	14.76

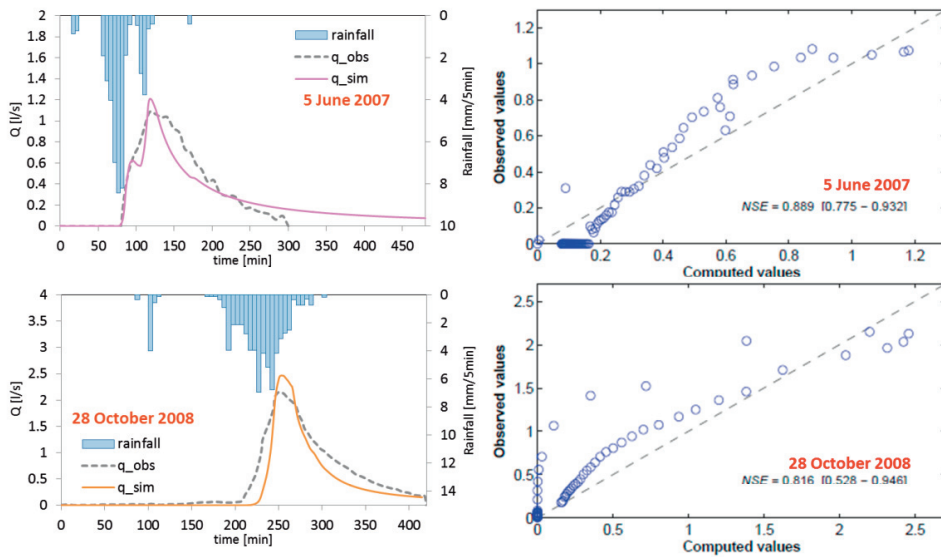Fig. 3. Nash–Sutcliffe efficiency coefficient values and related areas of acceptance for the selected events.

Fig. 4. The hyetographs, the corresponding measured and simulated hydrographs and some goodness-of-fit evaluation of the selected events in Genova, Italy.
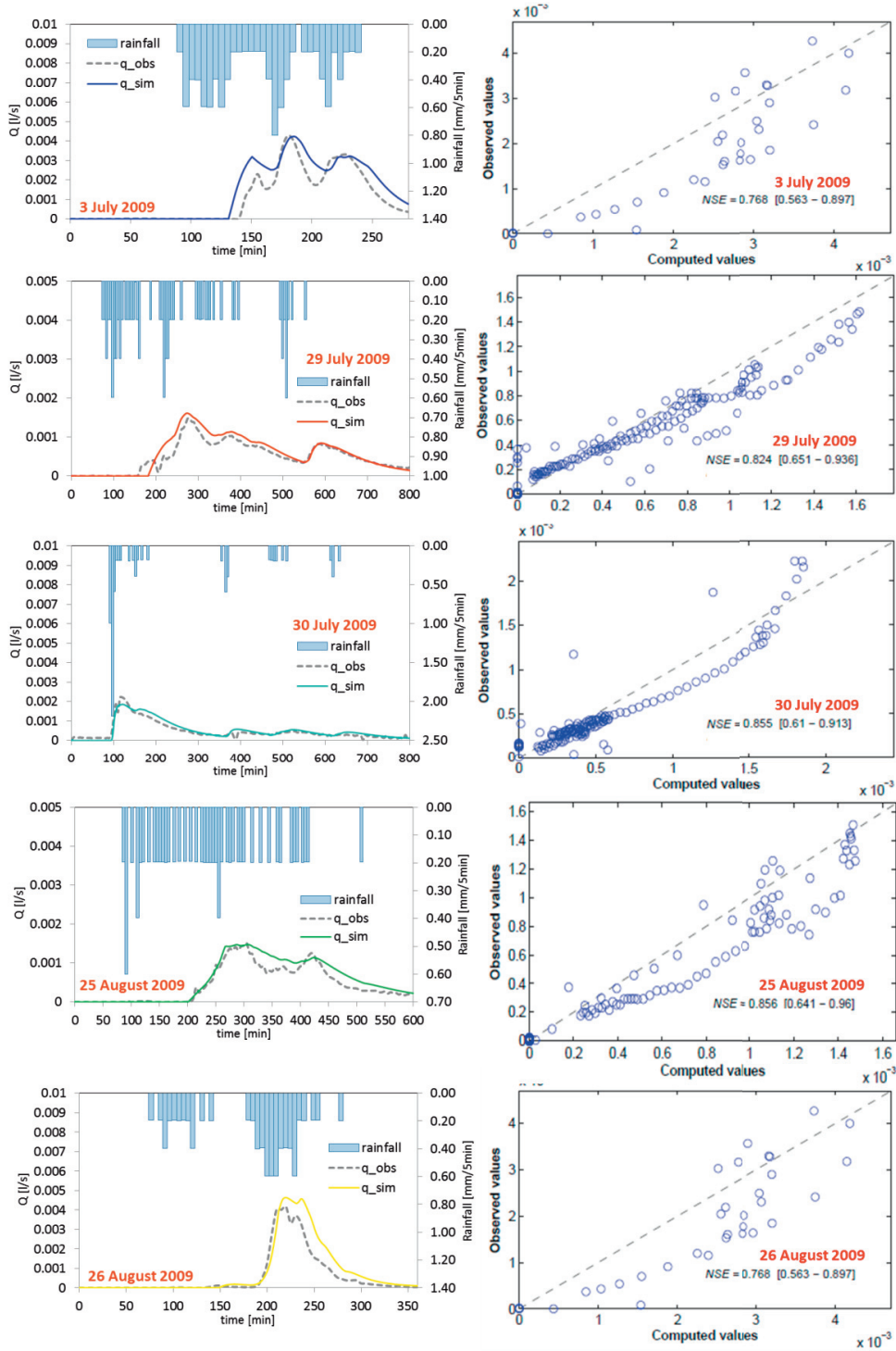
Fig. 5. The hyetographs, the corresponding measured and simulated hydrographs and some goodness-of-fit evaluation of some selected events in Sheffield, UK.

4. Conclusions

A detailed analysis of the hydrological dynamics, connected both with the characteristics of the climatic context and with the green roof technical design, is essential in order to obtain a full characterization of the hydrologic behavior of a green roof system and its effects on the urban water cycle components.

The present study concurs to characterize the hydrologic soil dynamics of a green roof system and it is a first step to develop a robust model of green roof hydrological behavior. In particular the work presented herein analyzes two construction technologies with different types of drainage layer (Fig. 2) and different climate area; drainage type (a) utilizes drainage plates, waffled plastic sheets that store water above and drain water below; drainage type (b) utilizes a lightweight, porous inorganic granular media.

A multi-layer Bucket Model has been applied to examine the hydrological response of the green roof system. Following a stage of validation and calibration, the model tested presents rather good performance in both cases: the discharge hydrograph profile, volume and timing predicted by the model matched experimental measurements as demonstrated by the limited relative percentage deviations obtained for the total discharged volume and the peak flow (Fig.4 and 5). The timing between the simulated and the observed hydrographs is satisfactory while the model generally overestimate the effluent volumes. The hydrographs characterized by a single peak flow as well as more complex shape-long lasting hydrographs are properly reproduced as confirmed by the Nash-Sutcliffe model efficiency index values close to 1.

In term of future developments and prospects, the actual limit of the research is certainly the limited database used to develop and calibrated the model. If the objective is to build a robust model allowing extrapolation to other green roof schemes and adjustable to different climate contexts, the work must take into account more important database in term of duration, climate, and also measured variables.

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