

Modeling Stormwater Runoff from extensive green roof using the Conceptual Model "SIGMA DRAIN"

Modélisation du ruissellement d'une toiture végétalisée extensive avec le modèle conceptuel "SIGMA DRAIN"

Principato Francesca^{1,2}, Carbone Marco², Piro Patrizia²

1: Dept. of Civil, Chemical and Environmental Engineering, University of Genoa, Via Montallegro 1, 16145 Genova, Italy

2: Department of Civil Engineering, University of Calabria, Ponte P. Bucci, Cubo 42 B, 87036 Rende (CS), Italy

Emails: francesca.principato@unical.it;
marco.carbone@unical.it;
patrizia.piro@unical.it

RÉSUMÉ

La toiture végétalisée (TV) est une technologie émergente internationalement comme une approche alternative à faible impact (LID) pour la gestion des eaux pluviales dans les centres urbains. Cette étude propose le modèle conceptuel SIGMA DRAIN (SD), développé pour simuler la réponse hydrologique d'une TV extensive installée à l'Université de Calabre (Unical), dans le sud de l'Italie, afin de quantifier l'efficacité du système. Deux réservoirs sont utilisés dans le modèle pour simuler la percolation à travers le substrat et le transport à travers la couche de drainage. Une équation de bilan de masse est appliquée à chaque réservoir et le débit est représenté par l'équation de Richard. Le logiciel HYDRUS-1D est utilisé comme référence pour la validation du modèle conceptuel. Les données de pluie collectées sur le site de sept. 2012 à avril 2013 au pas de temps d'une minute, ont été utilisées pour caler et valider le modèle proposé. Les flux sortant du toit, calculés par les deux modèles, ont été comparés. Les simulations effectuées en continu (multi-événement) ont montré une valeur moyenne de l'indicateur Nash-Sutcliffe de 0.76, en mettant en évidence l'influence déterminante des conditions inter-événementielles sur la réponse du modèle. Les résultats obtenus confirment la pertinence du modèle SD pour décrire correctement le comportement hydrologique de la toiture végétalisée de l'Unical.

ABSTRACT

Green roof (GR) technology is emerging internationally as a viable low impact design (LID) approach for stormwater management in urban areas. This study proposes the SIGMA DRAIN (SD) conceptual model, developed to simulate the hydrologic response of the extensive GR installed at the University of Calabria (Unical), south Italy, in order to quantify the effectiveness of the system. In the model, two reservoirs are used to simulate percolation in the substrate and the transport through the drainage layer. A mass balance equation is applied to each block and the flow is instead represented by the Richard's equation. HYDRUS-1D software is used as a benchmark for the conceptual model validation. Rainfall data, collected at the study site from Sept. 2012 to Apr. 2013, with 1 min. time step, were used for the calibration and validation of the proposed model. Roof outflows computed by the two models were compared. The simulations carried out continuously (multi event), showed an average Nash-Sutcliffe index value of 0.76, demonstrating that the inter-event conditions are considered to be relevant in the assessment of response model. The results obtained therefore confirmed the suitability of the Sigma Drain model for correctly describing the hydrologic behavior of the Unical green roof.

KEYWORDS

Conceptual model, Green roof, LID, Runoff, Stormwater

1 INTRODUCTION

In the last decades, the urbanization process increased the imperviousness of surfaces by modifying the physical properties of soils surfaces. This loss of natural soils and vegetation within urban catchments can significantly affect the natural hydrologic cycle by increasing runoff rates and volumes and shortening times of concentration. Given the huge amount of unused roof in urban areas (up to 40-50% of the total impermeable surfaces) (Dunnett & Kingsbury, 2004), green roofs may represent a valid solution for urban stormwater management, by retaining water, reducing peak flow, improving biodiversity and mitigating heat island. Although the benefits are evident, a limiting factor in spreading the use of such systems is the lack of proper modelling tools for design.

Therefore, the aim of this paper is to formulate, calibrate and test a green roof model (Sigma Drain) to investigate the hydrologic response of the GR installed at University of Calabria on a rainfall event basis. From a practical point of view, this model is intended to provide a tool for practitioners, regulators and policymakers, requiring quantitative performance data, and to improve decision-making and design of sustainable stormwater drainage systems in a Mediterranean climate conditions.

The expected result is to demonstrate the value of this conceptual model to understanding the influence of roof configuration on the hydrologic performance of green roof systems.

2 METHODOLOGY

2.1 Study Area

The study was conducted on the green roof, developed and installed at the Cube 46/C of University of Calabria (Unical), Italy. The experimental site, situated on a fifth-floor terrace of a campus's building, is located in a Mediterranean climate region. The GR consists of four compartments, each one with an equal area of around 50 m² and a slope of 1%, which vary in their stratigraphy, composition elements and the presence, or not, of vegetation species. The sector considered consists of the following stratigraphy: i) a surface layer, covered with native Mediterranean vegetation species; ii) a mineral terrain substrate of 8 cm, built to comply with Italian regulation (UNI 11235); iii) a drainage and storage layer in polystyrene (with a storage capacity of 11 L/m²). A fine fibrous membrane was also placed between the substrate and the underlying drainage layer.

The model is calibrated and tested using a rainfall data collected from a rain gauge with a resolution of 0.2 mm, located at the experimental site. From the whole dataset only events with rainfall depth greater than 2 mm, and with a Minimum Inter-Event Time of 2 hours, were selected.

2.2 The *SIGMA DRAIN* Conceptual Model

The *SIGMA DRAIN* conceptual model, is a new tool developed to simulate the hydrologic response of the extensive green roof installed at the University of Calabria, realized using the calculation engine of EPA-SWMM (Storm Water Management Model) software (Rossman, 2010), while being completely independent of the user interface.

The *SIGMA DRAIN* model idealizes the GR as a system consisting of three individual components in series, each of them corresponding to the main technological modules of the green roof. The surface layer, exposed to the atmosphere and covered by vegetation, is conceptualized as sub-catchment; it is defined by the real size of the green roof surface (area and % slope), and is characterized by a specific permeability of the soil dependent on fraction of vegetation coverage. The following soil and drainage layers are schematized through two reservoir elements, which describe respectively the percolation in the substrate and the transport through the drainage layer. A mass balance equation is applied to each block, taking into account the specific physical phenomena that occur in each module and the flow is instead represented by the Richard's equation. Schematic structure of the model is showed in the Figure below.

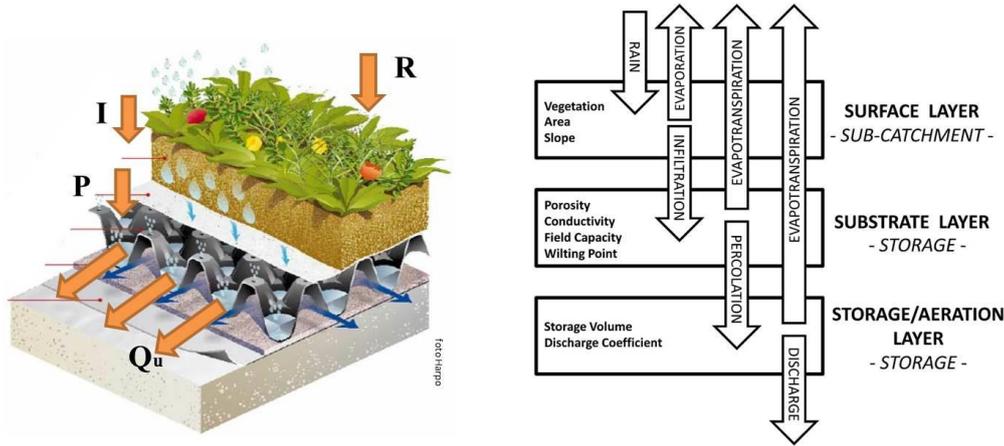


Figure 1 - Schematic structure of the SIGMA DRAIN Model.

In this study, evaporation (EV) and evapotranspiration (ETR) contributions are not considered, because the model calibration and validation are made at event scale, therefore when it rains EV and ETR are considered void. An overview of governing equations for the conceptual model, are listed below.

2.2.1 Water balance in the substrate reservoir

The incoming flux to the substrate reservoir (q_1) equals the total precipitation collected from the surface layer. The flow from the substrate layer (*Storage 1*) to the drainage layer (*Storage 2*) is controlled by a Percolation equation (q_2), which was formulated from Darcy's Law for unsaturated flow:

$$q = K(\theta) \frac{\partial h}{\partial z} \quad \text{Eq. 1}$$

Where: q is the specific discharge rate or flux [LT^{-1}]; $K(\theta)$ is the unsaturated hydraulic conductivity [LT^{-1}]; θ the Volumetric water content or moisture content [L^3L^{-3}], and h is the total hydraulic head for unsaturated soil [L]. Since the hydraulic head for unsaturated soil h [L] is the sum of the negative water pressure head ψ [L] and the elevation head z [L], by using the chain rule Eq. 1 becomes:

$$q = K(\theta) \left(1 - \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial z} \right) \quad \text{Eq.2}$$

The two derivatives are values related to soil type and for this reasons they can be assumed constants. In particular:

$$\begin{cases} \frac{\partial \psi}{\partial \theta} = C_1 \\ \frac{\partial \theta}{\partial z} = \frac{(\theta_{cc} - \theta_r)}{\left(\frac{s}{2}\right)} = C_2 \end{cases} \quad \text{Eq. 3}$$

Where θ_{cc} is the Field Capacity and θ_w the Wilting Point (in the *Storage 1*), and s is the substrate depth. By substituting Eq. 3 in Eq. 2:

$$q = K(\theta)(1 - C_1 \cdot C_2) \quad \text{Eq. 4}$$

and by grouping the two constants in a single one can be simplified as:

$$q = K(\theta) \cdot C_3 \quad \text{Eq. 5}$$

Following Eq. 5, flow in substrate layer is related to the unsaturated hydraulic conductivity, which is a function of the soil water content. When direct measurements of the unsaturated hydraulic conductivity $K(\theta)$ are not obtainable, it is possible to estimate using more easily measured properties such as particle size distributions. For this study, the Mualem-van Genuchten relation (Mualem, 1976; Van Genuchten 1980), is used:

$$K_r(S_e) = S_e^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad \text{Eq. 6}$$

Where: $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ is the effective degree of saturation [-], with θ_r and θ_s respectively the residual and saturated water contents [L^3L^{-3}]; l is an empirical parameter that represents the effects of tortuosity

and pore connectivity, and is usually assumed to be equal to 0.5 (Mualem, 1976); m is the dimensionless parameters of the retention curve of soil water.

The Mualem-van Genuchten equation (Eq. 6) can be interpolated with an exponential function of the type:

$$K_r(\theta) \cong a S_e^b \quad \text{Eq. 7}$$

Therefore, by substituting the Eq. 7 in the Eq. 5, the following relation is obtained:

$$q = K_s \cdot C_3 \cdot (a S_e^b) \quad \text{Eq. 8}$$

Since the water level in the substrate reservoir (*Storage 1*) over the weir $h'(t)$ can be related to the value of the effective degree of saturation (S_e) by using the following equation:

$$h'(t) = S_e(t) \cdot n \cdot s \quad \xrightarrow{\text{yields}} \quad S_e(t) = \frac{h'(t)}{n \cdot s} \quad \text{Eq. 9}$$

where n is the porosity [$L^3 L^{-3}$] and s is the substrate depth [L]. Combining Eq. 9 with Eq. 8 leads to:

$$\text{Percolation} = q_2 = K_s \cdot C_3 \cdot a \cdot \left(\frac{1}{n \cdot s}\right)^b \cdot h'^b \quad \text{Eq. 10}$$

By grouping all known terms into a single parameter (α), the expression can be simplified in the form:

$$q_2(t) = \alpha \cdot h'^\beta \quad \text{Eq. 11}$$

This equation control the outflow rate of the substrate reservoir element and depends on the properties of the layer considered.

The percolation rate (q_2) is the input for the third module relating to the drainage layer (*Storage 2*), which is represented by a storage tank with geometrical characteristics dependent on the particular technology used. The relationships used to describe the hydraulic behavior of this module are the mass balance equation and the discharging equation.

2.3 Model Calibration and Validation

In order to estimate the reliability of the model, it was first calibrated and then validated with the software HYDRUS-1D, which has been used, in this study, as a benchmark to compare the outflow rates from the SIGMA DRAIN model. In order to perform the comparison between the two models, boundary conditions used to implement the HYDRUS-1D code and the input parameters required by software, must be defined. In this study, two Neumann boundary conditions have been applied: the *soil-atmosphere interface condition* and a *free-drainage condition*, were used for the upper and lower boundary respectively. The hydraulic properties of soil (θ_r , θ_s , α , n , and K_s), required in the dual porosity model, were evaluated during a laboratory experiment by using the UMS HYPROP[®] system (UMS, 2015). In the table below, in addition to the soil hydraulic parameters, are also listed the physical characteristics of the experimental site green roof.

Table 1- Hydraulic Parameters of the green roof substrate

Parameter	Unit	Value	Definition
<i>Soil Hydraulic Parameters</i>			
θ_r	[-]	0.096	Soil Residual Water Content
θ_s	[-]	0.574	Soil Saturated Water Content
α	[1/cm]	0.8	Parameter related to the inverse of the air-entry pressure
n	[-]	1.499	Parameter related to the pore-size distribution
K_s	[cm/min]	4.916	Saturated hydraulic conductivity
θ	[-]	0.2	Initial Moisture Condition
<i>Green roof Physical Parameters</i>			
s	[cm]	8	Substrate depth
A	[m ²]	50	Reference Green Roof Area

The model is calibrated with two rainfall events observed from the monitoring campaign carried out in the Unical experimental site, while six events were chosen for the validation process. More in detail, the validation procedure was carried out prior at event scale and then, by combining consecutive events, at multi-event scale.

The calibration and validation strategy involved comparing the results, in terms of runoff, modeled with HYDRUS-1D and SIGMA DRAIN conceptual model. The goodness of fit between the two models was determined by the Nash-Sutcliffe efficiency coefficient (NS), which is one of the most widely used indices for characterizing the overall fit of hydrographs (Servat et al., 1990; Nash & Sutcliffe, 1970) and is computed as follows:

$$NS = 1 - \left[\frac{\sum_{i=1}^n (Q_i^{hyd} - Q_i^{SD})^2}{\sum_{i=1}^n (Q_i^{hyd} - Q_{mean}^{hyd})^2} \right] \quad \text{Eq. 12}$$

Where, Q_i^{hyd} is the i th value of HYDRUS model, Q_i^{SD} is the i th value of SIGMA DRAIN model, and Q_{mean}^{hyd} is the mean value of HYDRUS model, for n total number of observations. NS coefficient values range between $-\infty$ and 1.0, with NS=1 being the perfect agreement.

3 RESULTS AND DISCUSSIONS

An example of the hyetograph and the corresponding hydrographs measured with HYDRUS-1D (grey area) and simulated with SIGMA DRAIN (solid line) models, is illustrated in the Figures below, while the results for the whole validation dataset are show in table below.

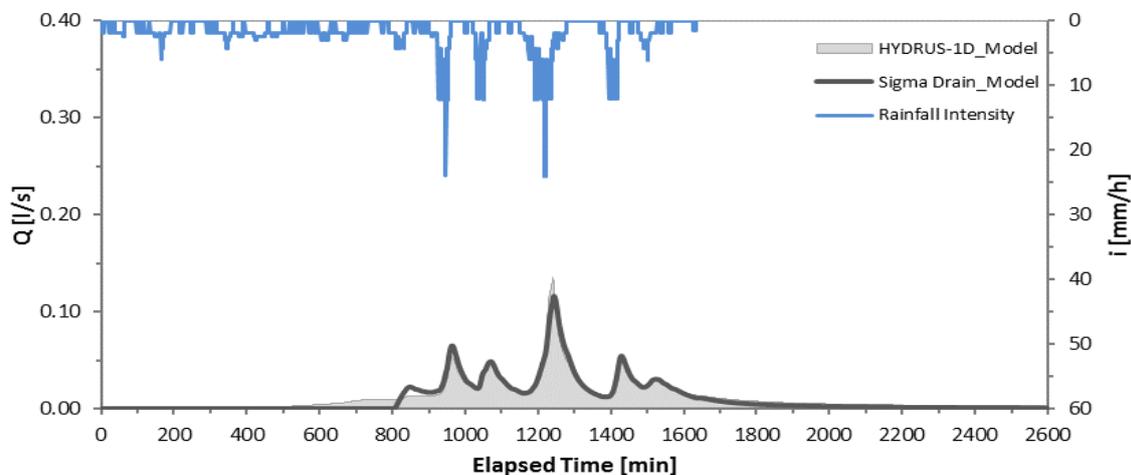


Fig. 2 - Hyetographs and corresponding SIGMA DRAIN and HYDRUS-1D hydrographs for rainfall event n. 24

Table 2 - Performance indicators of comparison between the SIGMA DRAIN model and HYDRUS-1D.

#	Rainfall Event [dd/mm/yyyy]	Rainfall Depth [mm]	Peak Intensity [mm/h]	Runoff Peak Flow [l/s]	NS
5	16/09/2013	42.2	144	0.6	0.5
17	22/11/2013	36.2	60	0.1	0.9
20	24/11/2013	18.4	24	0.02	0.2
24	30/11/2013	48.0	24	0.1	0.9
38	31/01/2014	31.0	24	0.06	0.8
61	27/03/2014	16.6	24	0.01	-0.6

Results obtained from the validation events, illustrated in Table 2 reveal the suitability of the SIGMA DRAIN model to well approximates the model HYDRUS-1D and therefore correctly describe the hydrologic behavior of the green roof, for precipitation above 20 mm, as also confirm by the NS coefficient major than 0.5.

At contrary, the performances of the model for event with a rainfall depth lower than 20 mm (i.e. #20 and #61) are not satisfactory. This behavior can be attributed to the fact that in the SIGMA DRAIN model, differently from HYDRUS-1D, the initial water content of the substrate is not taken into account. To prove that the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model, simulations by combining more consecutive events were conducted.

The multiple events were defined by combining two or more consecutive events, and include

individual events varying in the rainfall depth, with the aim to evaluate the green roof response also for low precipitations (with rainfall depth < 20 mm), which individually have not produced runoff.

For example, looking at the figures below, referring to the multi events (with a rainfall depth of 67.2 mm), which contains the rainfall event n. 20 characterized by a rainfall depth of 18.4 mm (<20mm and a NS=0.2; in Table 2 above), is possible to note how this event, that individually did not produce runoff, when grouped with others, gives results.

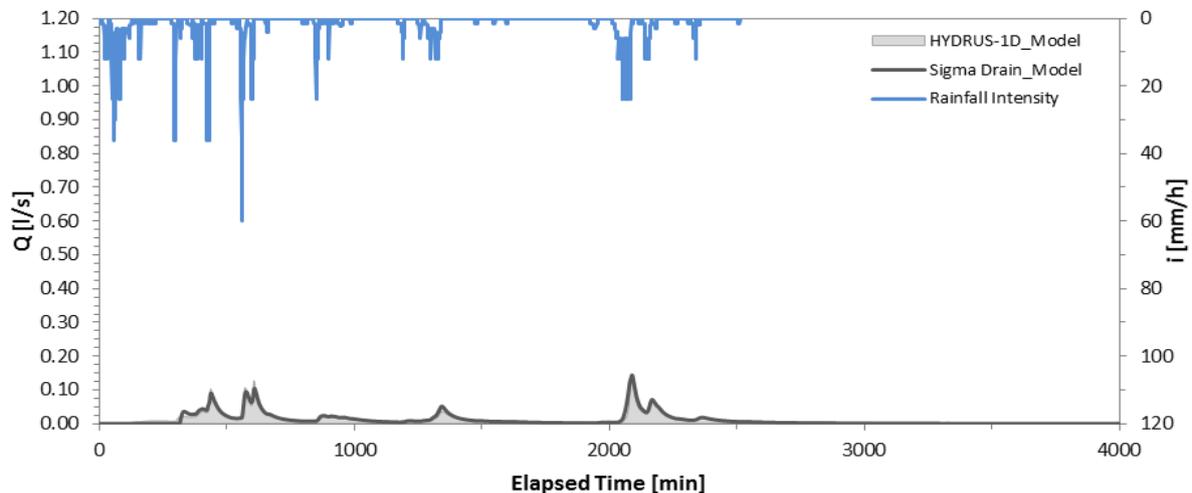


Fig. 3 - Hyetographs and corresponding SIGMA DRAIN and HYDRUS-1D hydrographs for multi-event

4 CONCLUSION

Results reveal the suitability of the SIGMA DRAIN model to well quantify the hydrologic response of HYDRUS-1D model, used as a benchmark. More in detail, at event scale, the SD model correctly describe the hydrologic behavior of the Unical green roof, for precipitation above 20 mm, as demonstrated by a Nash-Sutcliffe coefficient always >0.5. This can be explain to the fact that the initial water content of the substrate is not taken into account by the SIGMA DRAIN model, differently from HYDRUS-1D. As good evidence of this, the results of multi-event simulation, with a NS value of 0.9, have shown that the antecedent hydrologic-hydraulic conditions prior the event are relevant in assessing the response of the model. Indeed, from the simulation results, it is clear how small events that individually did not produce runoff, when grouped with others, produce a runoff. After this first phase of formulation, calibration and validation of SD model, through the software HYDRUS-1D (physically based), future research studies will evaluate the observed runoff versus modelled one.

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