

# Impact of rainfall properties on the performance of hydrological models for green roofs simulation

Mirka Mobilia and Antonia Longobardi

## ABSTRACT

Green roofs (GR) are effective tools for the mitigation of the negative hydrological impact linked to uncontrolled urbanization. Models for runoff response of vegetated covers support planning decisions about the use of this technology in ever-expanding areas, but there is still large uncertainty in this research area. The goal of the present study was to define the accuracy of three selected models for the simulation of the hydrological behavior of a GR, with a particular focus on the precipitation pattern characteristics. The Nash cascade model, Storm Water Management Model (SWMM), and HYDRUS-1D models were selected. Each model was calibrated over 24 rainfall-runoff events collected at the experimental site located in Southern Italy. Rainfall events were characterized using several criteria and were divided into convective, stratiform, and tropical precipitation types according to the shape of the rainfall profile identified by the rainfall binary shape code. The models returned overall satisfactory performances with average Nash–Sutcliffe Efficiency index of 0.65 for the SWMM and HYDRUS and 0.73 for the Nash model. In general, the models were better performing for stratiform and tropical events. SWMM and HYDRUS predicted with higher accuracy the convective events while the Nash model appeared more suitable for stratiform events.

**Key words** | green roof, HYDRUS, Mediterranean climate, Nash cascade, runoff, SWMM

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## INTRODUCTION

An alternative solution to the mitigation of the negative impact of uncontrolled and rapid overbuilding in urban areas on the water cycle is represented by using best management practices (BMP). The BMP, also known as sustainable urban drainage systems (SuDS) or low impact development (LID), are control measures with the primary objective of reducing and locally treating urban stormwater runoff (Moura *et al.* 2016). These technologies include a number of engineered facilities, such as infiltration trenches and basins, green roofs, permeable pavement systems, vegetated filter strips, and many others. The choice of the most suitable BMP depends on a number of factors; first of all is the space constraints, typical of densely urbanized areas. In this respect, green roofs (GR) overcome this limitation because they can replace impervious existing buildings' roofs without further land consumption (Cascone *et al.* 2018). Eco-covers have proven over time to be very effective in mitigating the hydrological risks associated with urbanization. Many studies have shown that a vegetated roof can increase up to 30 min the delay time at which runoff

occurs after a rainfall event and reduces peak flow rate by 22–93% (Yanling & Babcock 2014). Not less important is the effect on runoff volume, which can be reduced to 40–90% depending on the system configuration and the climate conditions (Kohler *et al.* 2001; Sartor *et al.* 2018). In order to optimize the application of GR techniques, it is important to quantify the GR stormwater mitigation ability so as to support urban planners and developers in this respect. A wide range of models have been used by many authors to assess the performance of green infrastructure (Mobilia *et al.* 2017; Mobilia & Longobardi 2020). They can be mainly classified into two categories: conceptual and physically based models. The conceptual models often include cascades of reservoirs. The underlying assumption is that the system is idealized as composed of two or more individual stores mutually interacting to transform rainfall input into stormwater runoff (Carbone *et al.* 2014; Locatelli *et al.* 2014). Physically based models describe the unsaturated flow in the porous media of the GR layers and include the Storm Water Management Model (SWMM), HYDRUS-1D,

Soil and Water Management Service-2D, and Soil Water Atmosphere and Plant (Cipolla *et al.* 2016). Both categories have a number of advantages and disadvantages. In general, the use of the physically based model needs relevant computational efforts and technical expertise. Liong *et al.* (1991) stressed how the algorithm of these approaches is not readily understood by users and algorithm changes are not easily managed. This class of model successfully simulates the green roof behavior (She & Pang 2009). The conceptual models are very intuitive for the users and they need minimal calibration requirement and poor input data. However, a clear relationship between the design parameter of the roof and its hydrological performance cannot be found (Li & Babcock 2013). Due to the considerable differences in GR response to rainfall input reported by the literature, choosing the most appropriate model to be used to simulate the response of a green roof system is not as simple as it may seem. This is why, over time, many researchers have carried out detailed studies comparing the prediction performances of different models (Palla *et al.* 2012). Nevertheless, it is still challenging to obtain a clear prospect of the issue and further research is encouraged. Hydrological models require event rainfall temporal sequence as an input and frequently suffer in the calibration and validation phases because of the high variability of rainfall intensity during the event (Kassim & Kottegoda 1991).

The purpose of the present work is based on the idea that event rainfall pattern characteristics could be a major source of a model's uncertainty and it compared the adequacy of three hydrological models in predicting GR stormwater. The selected models are Nash cascade model, SWMM, and HYDRUS-1D. SWMM and HYDRUS are two of the most commonly used models for green roofs within the class of the physically based approach. The Nash model belongs to the category of the conceptual models. It has usually been used to simulate the hydrological behavior of natural river basins but was recently implemented with reference to green infrastructures (Krasnogorskaya *et al.* 2019). A green roof experimental system, located in the Mediterranean region, has been analyzed. Twenty-four rainfall-runoff events during the period from June 2017 to November 2018 have been selected. The rainfall patterns have been described according to a number of criteria, including duration, cumulated rainfall, maximum intensity, return period, and n-index. The binary shape code (BSC), which is a probabilistic description of the variability of precipitation over time, allowed selected events to be grouped into three classes, namely convective, stratiform, and

tropical. The previously mentioned models are calibrated using the observed rainfall-runoff events. For the purpose of comparison only one parameter for each model is calibrated, while the remaining are set according to literature data. The calibration parameters are the storage coefficient, the suction head, and the saturated hydraulic conductivity for Nash cascade model, SWMM, and HYDRUS-1D, respectively. Finally, the prediction performances of the three models for each type of event are compared using three goodness-of-fit indices, which are root mean square error (RMSE), mean absolute error (MAE) and Nash-Sutcliffe Efficiency index (NSE). The findings of the current research provide recommendations to the users about the most effective model to be used to predict the hydrological behavior of a GR depending on the type of rainfall event.

## MATERIALS AND METHODS

### Case study

The case study is an extensive green roof test bed located within the campus of the University of Salerno (40° 46' 14" N, 14° 47' 22" E, 282 m above sea level) in Fisciano. Fisciano enjoys a mild Mediterranean climate with average annual rainfall and temperature respectively of 821 mm and 14.8 °C. The experimental roof, with a pitch slope of 1%, was planted with *Mesembryanthemum*, succulent plants native to the specific climate. The roof was placed on a steel bench with area of 2.5 m<sup>2</sup> (1 × 2.5 m) and surrounded by channels for the collection of the runoff fluxes. The channels have a square section of 10 cm × 10 cm and allow the flow of the rainwater toward the outlet section and finally into a tank whose weight was monitored every 5 min by a calibrated digital scale. The green roof is made up of three layers for a total thickness of 15 cm: the vegetation layer housing the plants, 10 cm deep support substrate, and a water storage layer of approximately 5 cm. The support layer is a mix of peat and zeolite with anabolic natural proteic properties developed from the new Low Peat Humidity technology. A polyester geotextile filter fabric, interposed between the growing and the retention layers, acts as a filter cloth and is able to hold the soil in place to avoid small particles clogging the drainage composite below. The storage layer is made up of expanded clay with grain size between 8 and 20 mm. The experimental site is equipped with a meteorological station, which includes a raingauge, a thermohygrometer, and a pyranometer with recording time step of 5 min (Figure 1). Additional details are provided in Mobilia & Longobardi (2017).

## Datasets and properties of rainfall

Twenty-four rainfall-runoff events between June 2017 and November 2018 have been selected for the present study. These events were chosen where 5 min of data were recorded for the whole extent of the event and where no overflow from the tanks was detected. Despite this selection, a good coverage of the four seasons and therefore of different weather conditions was ensured (Table 2).

A detailed analysis was carried out to characterize the rainstorms in terms of magnitude, probability of occurrence, temporal structure, and pattern. The criteria used to describe the rainfall events were duration ' $d$ ', cumulative rainfall ' $C_R$ ', peak intensity ' $P$ ', return period ' $T$ ', 'n-index', and 'BSC' (Huff 1969; Mobilia *et al.* 2015).

The n-index represents the temporal concentration of precipitation (Monjo 2016). This parameter is the exponent of a power law describing the correlation that exists between the maximum average intensity  $I(t)$  and the event duration ' $t$ ' according to the following equation:

$$I(t) = I(t_0) \left( \frac{t_0}{t} \right)^n \quad (1)$$

and

$$I(t) = \frac{P_{max}}{t} \quad (2)$$

where  $t_0$  is the reference time step,  $I(t_0)$  is the intensity at  $t_0$  and  $P_{max}$  is the maximum cumulative precipitation at time  $t$ .

The n-index ranges between 0 and 1. The lower the value, the more regular the temporal distribution of the rainfall event.

The BSC is a four-digit binary code that identifies the shape of the profile of a rainfall event (Terranova *et al.* 2011). The BSC is based on the comparison between the Standardized Rainfall Profile (SRP) and the USRP (Uniform SRP) for 0.25, 0.5, 0.75 quantiles where the SRP represents a probabilistic description of the high variability of rainfall event in time. If within a dimensionless duration interval ' $\tau$ ' between a given quartile and the subsequent one, the area ' $A_\tau$ ' below the USRP is larger than the area ' $A_\tau^*$ ' below the SRP, the digit ' $S_\tau$ ' of the code corresponding to this dimensionless duration interval would be '0' and '1' in the reverse case. The BSC takes the following form:

$$BSC = S_1 S_2 S_3 S_4 \quad (3)$$

where  $S_\tau = 0$  if  $A_\tau > A_\tau^*$  and  $S_\tau = 1$  if  $A_\tau < A_\tau^*$  for  $\tau = 1, \dots, 4$ .

The BSC can identify three types of events. Convective precipitations are characterized by large amounts of precipitation in the initial part of the event, such as BSC 1111, 1110, 1100, or 1000. If most of the rain falls in the middle part of the event, the event is classified as tropical-like and typically corresponds to BSC 0010, 0110, 0001, and 0100. In the other cases, the precipitation



Figure 1 | The experimental green roof site.

**Table 1** | Input parameters for Nash, SWMM and HYDRUS hydrological models

Model	Parameter	Initial values	Data sources
Nash	n (-)	2	Analysis of hydrograph patterns
	$\varphi$ (%)	4–100	Mobilia <i>et al.</i> (2020)
	k (hours)	Calibrated	–
SWMM	Subcatchment		
	A (m <sup>2</sup> )	2.5	System geometrical characteristics
	W (m)	1	Literature data
	$\theta$ (%)	0–35	Field measurements
	Surface layer		
	N (m <sup>-1/3</sup> s)	0.24	Literature data
	S <sub>1</sub> (%)	0	System geometrical characteristics
	Soil (Loam)		
	$\phi$ (-)	0.95	Physical characteristics
	S (-)	35	Literature data
	$\Psi$ (mm)	To be calibrated	–
Storage layer (Expanded clay)			
Fr (-)	0.75	Literature data	
HYDRUS	Soil (Loam)		
	Q <sub>r</sub> (-)	0.078	Literature data
	Q <sub>s</sub> (-)	0.43	
	$\alpha$ (1/cm)	0.0036	
	n (-)	1.56	
	I (-)	0.5	
	K <sub>sat</sub> (cm/day)	10.4	
	Storage layer (Expanded clay)		
	Q <sub>r</sub> (-)	0.045	Literature data
	Q <sub>s</sub> (-)	0.43	
	$\alpha$ (1/cm)	0.0145	
n (-)	2.68		
I (-)	0.5		
K <sub>sat</sub> (cm/day)	To be calibrated		

can be classified as a stratiform event. For the purpose of interpretation of the results corresponding to the rainfall events classification, it is important to stress here that the BSC can indicate the approximate location of the peak but does not provide information about the presence of secondary peaks or the span of time where the largest fraction of rain occurs.

### Models' descriptions

Three hydrological models have been selected and compared in the present study. The models are the Nash cascade model, SWMM, and HYDRUS-1D. The Nash model belongs to the category of the conceptual model while SWMM and HYDRUS are physically based approaches.

### The Nash model

The Nash model introduced by Nash (1957) uses a cascade of 'n' (-) linear reservoirs with identical storage coefficient 'k' (hours). Each reservoir empties into the next one until the runoff is generated. The instantaneous unit hydrograph (IUH) 'h' (mm) is obtained by routing the instantaneous unit inflow through the series of storage tanks considering the outflow from the previous reservoir as the inflow into the next one. The mathematical equation, which expresses the concept formulated by Nash (1957), is:

$$h(t) = \frac{t^{n-1}}{(n-1)!k^n} e^{-\frac{t}{k}} \text{ if } n = 2 \rightarrow h(t) = \frac{t}{k^2} e^{-\frac{t}{k}} \quad (4)$$

where  $t$  (-) is the routing time.

The effective rainfall  $p(t)$  (mm) is converted to direct runoff hydrograph  $q(t)$  (mm) by means of IUH according to:

$$q(t) = \int_0^t p(\tau) \cdot h(t - \tau) d\tau \quad (5)$$

where  $\tau$  (-) is the time variable of integration and the effective rainfall is estimated as a fraction  $\varphi$  (loss coefficient) of the total rainfall  $r$ :

$$p(t) = \varphi r(t) \quad (6)$$

The input requirements for the Nash cascade model include the number of stores  $n$  and the loss coefficient  $\varphi$  as well as the storage coefficient  $k$ . In the following section details about the model set up and calibration have been provided.

### The SWMM model

The SWMM implemented by the US Environmental Protection Agency is a dynamic hydrology-hydraulic simulation model. It is equipped with LID control modules that mimic the behavior of different SuDS devices, including GR, in response to rainfall events. The LID units are represented as a structure of overlapping layers with only vertical movement of water within and between the layers described by the Green-Ampt infiltration law (Dahdouh &

**Table 2** | The rainfall characteristics of the selected events

Date	C <sub>r</sub> <sup>a</sup> (mm)	d <sup>b</sup> (min)	I <sup>c</sup> (mm/h)	n-index (-)	T <sup>d</sup> (years)	BSC <sup>e</sup> (-)	Precipitation type
25/07/2017	2.8	420	2.0	0.2	–	1000	Convective
07/09/2017	4.6	540	2.3	0.8	–	1100	
07/11/2017	15.2	360	9.4	0.7	2	1110	
10/01/2018	30.2	540	10.2	0.0	3	1100	
11/01/2018	20.1	960	9.4	0.7	5	1000	
12/01/2018	5.3	300	2.0	0.0	–	1110	
17/01/2018	1.3	180	1.0	0.3	–	1000	
17/01/2018	3.6	60	3.6	–	–	–	
01/02/2018	3.3	300	1.5	0.6	–	1100	
13/02/2018	0.8	60	0.8	–	–	–	
02/03/2018	3.3	240	1.8	0.1	–	1110	
09/04/2018	6.1	180	3.6	0.0	–	1111	
17/04/2018	5.8	360	5.3	0.6	2	1100	
04/05/2018	1.3	300	0.5	0.4	–	1100	
23/05/2018	13.0	300	4.8	0.0	2	1100	
07/11/2018	16.0	360	6.4	0.3	2	1100	Stratiform
03/02/2018	12.4	1,200	3.8	0.2	2	0000	
07/02/2018	11.2	840	4.8	0.0	2	0000	
18/02/2018	11.2	1,800	1.3	0.2	–	0000	
20/02/2018	11.4	1,080	2.3	0.6	2	0000	
03/03/2018	11.4	720	2.3	0.9	–	0000	Tropical
03/05/2018	7.1	180	4.8	0.9	–	0011	
14/02/2018	4.8	240	2.5	0.7	–	0110	
05/10/2018	2.8	240	1.3	0.8	–	0110	

Only the return periods larger than or equal to 2 years have been indicated.

<sup>a</sup>Cumulated rainfall.

<sup>b</sup>Duration.

<sup>c</sup>Peak intensity.

<sup>d</sup>Return period.

<sup>e</sup>Binary shape code.

Querdachi 2018):

$$f = k_{sat} \left[ 1 + \frac{(\phi - \theta)\psi}{F} \right] \quad (7)$$

The detention in the substrate can be modeled using:

$$f_p = k_{sat} \exp[-(\phi - \theta)S] \quad (8)$$

where  $k_{sat}$  (mm/h) represents the saturated hydraulic conductivity calculated as follows:

$$k_{sat} = F - (\phi - \theta)\psi \ln \left[ 1 + \frac{F}{(\phi - \theta)\psi} \right] \quad (9)$$

In Equations (7) and (8),  $f$  (mm/h) and  $f_p$  (mm/h) are the infiltration and percolation rate, respectively,  $\phi$  (-) is the soil porosity,  $\theta$  (%) indicates the water content,  $\psi$  (mm) corresponds to the suction head,  $F$  (mm) is the cumulative amount of infiltrated water and  $S$  (-) is the conductivity slope.

Finally, the equation that expresses the runoff drained from the LID system is:

$$Q_d = \left( \frac{S_1 \cdot W \cdot F_r}{NA} \right) d^{\frac{5}{3}} \quad (10)$$

where  $Q_d$  (m/s) is runoff from drainage layer,  $A$  (m<sup>2</sup>) is flow area,  $S_1$  (‰) represents the surface slope,  $d$  (m) corresponds to the depth of water above the surface,  $W$  (m) stands for the

width of the sub-catchment,  $F_r$  (-) indicates the void fraction of drainage, and  $N$  ( $m^{-1/3}$  s) is the surface roughness.

In this study, Bio-Retention Cell LID Type within the SWMM LID controls has been selected for GR modeling. It is preferred to the green roof LID unit because its configuration is closest to the actual setup of the experimental system. Indeed, the GR control consists of surface and soil layers and drainage mat while the bio-retention LID module also includes a storage layer.

### The HYDRUS model

HYDRUS is a finite element model used to simulate the one-dimensional movement of water in variably saturated porous soil. It numerically solves Richards' equation for one-dimensional saturated-unsaturated water flow:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[ k(\theta) \left( \frac{\partial \psi}{\partial z} + 1 \right) \right]}{\partial z} \quad (11)$$

where  $\theta$  (-) is the volumetric water content,  $k$  (cm/day) is the hydraulic conductivity,  $z$  (cm) is the vertical coordinate, and  $\psi$  (cm) is the hydraulic head.

In order to solve Equation (11) the knowledge of two hydraulic functions related to the soil water retention and hydraulic conductivity media are required. The hydraulic functions proposed by Van Genuchten (1980) have been adopted in the present model:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{1 + (\alpha \psi)^n} \quad (12)$$

$$k = k_{sat} \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^\eta \quad (13)$$

with:

$$\eta = \frac{2}{mn} + 2 + I \quad (14)$$

and

$$m = 1 - \frac{2}{n} \quad (15)$$

where  $\theta_r$  (-) and  $\theta_s$  (-) are soil residual and saturated water contents,  $\alpha$  (1/cm) and  $n$  (-) are empirical parameters, and  $I$  (-) is the tortuosity parameter.

### Models' calibration and evaluation

The calibration of the models has been performed at the event scale for each model. For each event the calibration parameters have been iteratively adjusted until a satisfactory solution that optimizes an objective function is obtained. The idea behind the optimization is to minimize the difference between the predicted and observed runoff time series at each time step. The agreement between modeled and measured runoff has been assessed using the NSE index given by the following equation (Dahdouh & Querdachi 2018):

$$NSE (-) = 1 - \frac{\sum_{i=1}^n (R_{obs,i} - R_{mod,i})^2}{\sum_{i=1}^n (R_{obs,i} - \bar{R}_{obs,i})^2} \quad (16)$$

where  $n$  represents the length of the sample,  $R_{mod,i}$  and  $R_{obs,i}$  represent the modeled and the observed runoff, respectively.

In the Nash model, the number of stores has been set at 2 as a result of a previous analysis of hydrograph patterns, whereas the loss coefficient  $\phi$  has been fixed on the base of an empirical study which relates the retention coefficient to the rainfall event properties (Krasnogorskaya *et al.* 2019; Longobardi *et al.* 2019; Mobilia *et al.* 2020). The calibration parameter in the Nash model is the storage coefficient  $k$ , which cannot be physically measured.

SWMM requires a number of input parameters to be run. They were estimated in different ways. The flow area  $A$  and the surface slope  $S_1$  are provided by the experimental site dimension and geometry, the soil porosity  $\phi$  is provided by the experimental site physical characteristics, the width of the sub-catchment  $W$ , the surface roughness  $N$ , the conductivity slope  $S$ , and the void fraction of drainage  $F_r$  have been established according to literature data, and the volumetric water content  $\theta$  derived from experimental site field measurements.

With regard to the HYDRUS model, all the used input parameters have been derived from the user manual. The calibration parameters for SWMM and HYDRUS are the suction head  $\Psi$  and the saturated hydraulic conductivity  $K_{sat}$  respectively. They have been selected according to sensitivity analysis performed over time by several authors to identify the parameters that significantly affect the simulation outputs and that minimize the differences between observed and predicted runoff during the calibration process (Palla *et al.* 2008; Wang & Altunkaynak 2011).

A list of initial information and their sources essential to run the models is reported in Table 1.

Additional indices have been evaluated to test the accuracy of the models in predicting the stormwater on the event basis. The selected goodness-of-fit indices are the RMSE and the MAE calculated as (Dahdouh & Ouerdachi 2018):

$$\text{RMSE (mm)} = \left[ \frac{1}{n} \sum_{i=1}^n (R_{\text{mod},i} - R_{\text{obs},i})^2 \right]^{\frac{1}{2}} \quad (17)$$

$$\text{MAE (mm)} = \frac{1}{n} \sum_{i=1}^n |R_{\text{mod},i} - R_{\text{obs},i}| \quad (18)$$

These indices suggest that the larger the errors, the lower the model simulation performances.

## RESULTS AND DISCUSSION

### Characteristics of the rainfall events

For each rainfall event considered in this study, the duration  $d$ , cumulative rainfall  $Cr$ , peak intensity  $I$ , return period  $T$ ,  $n$ -index, and BSC have been calculated. These rainfall characteristics have been reported in Table 2. In relation to the rainfall severity, only return periods equal or larger than 2 years have been highlighted in Table 2.

In general, the cumulative rainfall ranges between 0.8 and 30.2 mm, and the duration ranges from 60 min to 1,800 min, so all the events have a sub-daily duration, except for the event on 18/02/2018, which lasted about 30 h. The peak intensity assumes the minimum value of 0.5 mm/h and the maximum value of 10.2 mm/h. The return period is always less than 5 years while the  $n$ -index never exceeds 0.9. With reference to the BSC, it can be observed that the profiles 1111, 1110, 1100, and 1000 represent 67% of all the observed SRPs, while the profile 0110 is only 8% of the sample. The BSC groups the observed events into three categories depending on the shape of the rainfall profile: convective, stratiform, and tropical events. The class of tropical precipitation includes only two events and so the sample is not fairly representative. These two events have the same duration and return period and they present comparable values of  $C_R$  and  $n$ -index with a moderate intensity. The convective events have highly variable cumulative rainfall while the stratiform events exhibit a range of variability of  $C_R$  of 10%, excluding the only event of 03/05/2018 where the amount of precipitation is

significantly lower. Both the categories include regular and irregular events with rainfall intensity from light to heavy. The durations of the stratiform events are on average higher than that relating to convective events.

### Interpreting calibration results

The calibration parameters are the storage coefficient ( $h$ ) for Nash cascade model, the suction head (mm) for SWMM, and the saturated hydraulic conductivity  $K_{\text{sat}}$  for HYDRUS-1D. They were adjusted until the largest NSE coefficients were reached. The values of  $\Psi$ ,  $K$ , and  $K_{\text{sat}}$  resulting from the calibration procedure range from 1.22 mm to 300 mm, from 0.006 to 1.8 hours, and from 0.05 to 12.5 cm/day, respectively. The scatterplots in Figure 2 highlight the average values of 48 mm for  $\Psi$ , 0.46 hours for  $K$ , and 1.3 cm/day for  $K_{\text{sat}}$ . The empirical distribution of  $K$  values appears wider compared to the empirical distribution of the  $K_{\text{sat}}$  values. With the exception of the two outliers, low uncertainty can be set on the choice of the  $K_{\text{sat}}$  parameter for simulation purposes.

The calibration accuracy was verified using NSE, RMSE, and MAE. The Nash model has the largest RMSE and MAE errors of 0.36 mm and 0.24 mm, respectively. HYDRUS and SWMM have very similar errors, smaller than in the case of Nash. They amount to about 0.28 mm (RMSE) and 0.20 mm (MAE) (Figure 3(a) and 3(b)). The average NSE is larger than 0.5, and in particular, SWMM and HYDRUS return average NSE performance indices of 0.65 while for Nash the average NSE is 0.73 (Figure 3(c)).

For a qualitative assessment of the models' performances in predicting the observed runoff, in Figure 4 the estimates of Nash, SWMM, and HYDRUS models, resulting from the calibration process, are compared with observational data. For illustrative purposes, the behaviors of the selected models for three events belonging to the classes of convective, stratiform, and tropical precipitation have been shown. The SRP and the USRP associated with each event have been displayed together with the corresponding BSC (Equation (3)).

### Comparative assessment of the models' performances

For each class of events (convective, stratiform, and tropical), the prediction performances of the three selected hydrological models have been investigated and compared in terms of NSE, RMSE, and MAE using boxplots (Figure 5) with specific reference to the classes of precipitation type

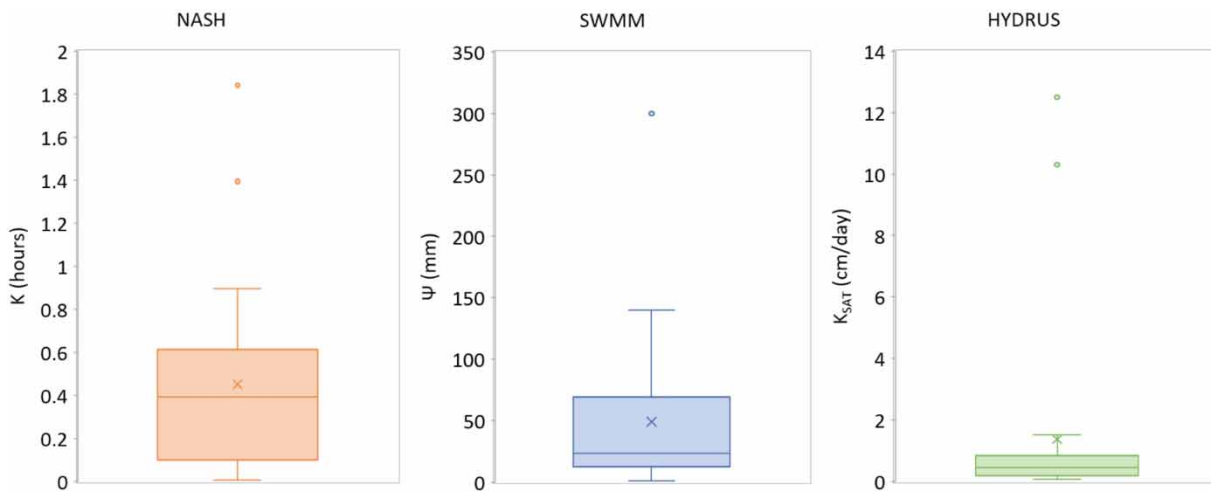


Figure 2 | Boxplots of calibrated  $K$  (Nash model),  $\psi$  (SWMM model), and  $K_{sat}$  (HYDRUS).

previously identified. The results can be summarized as in the following.

Regardless of the specific model, in terms of RMSE and MAE (Figure 5(a) and 5(b)), the group of the convective events shows larger interquartile ranges than the stratiform events. No indication can be provided for the tropical type as this group only includes two events. Larger interquartile range indicates wider distribution in terms of model performances and thus large uncertainty in the models' predictions. The stratiform events group has a significant less variability in model performance indices, and thus a greater model accuracy from this point of view. With regard to NSE (Figure 5(c)), the same considerations remain valid for the Nash model but an inverse situation occurs for the SWMM and HYDRUS models.

The average RMSE and MAE are larger for the convective events (Figure 5(a) and 5(b)), smaller for stratiform events, and even smaller for the tropical events. The models seem to less successfully simulate the first class of events. This trend is confirmed by the values of NSE (Figure 5(c)), which show a better fit between the measures and the predictions by the Nash model for the stratiform and the tropical events than for the convective ones. In SWMM and HYDRUS, the performances for the three classes are rather comparable.

The average values of RMSE and MAE indicate that the Nash model better predicts the stratiform and tropical events than SWMM and HYDRUS, while the latter exhibit higher performances in reproducing the convective events.

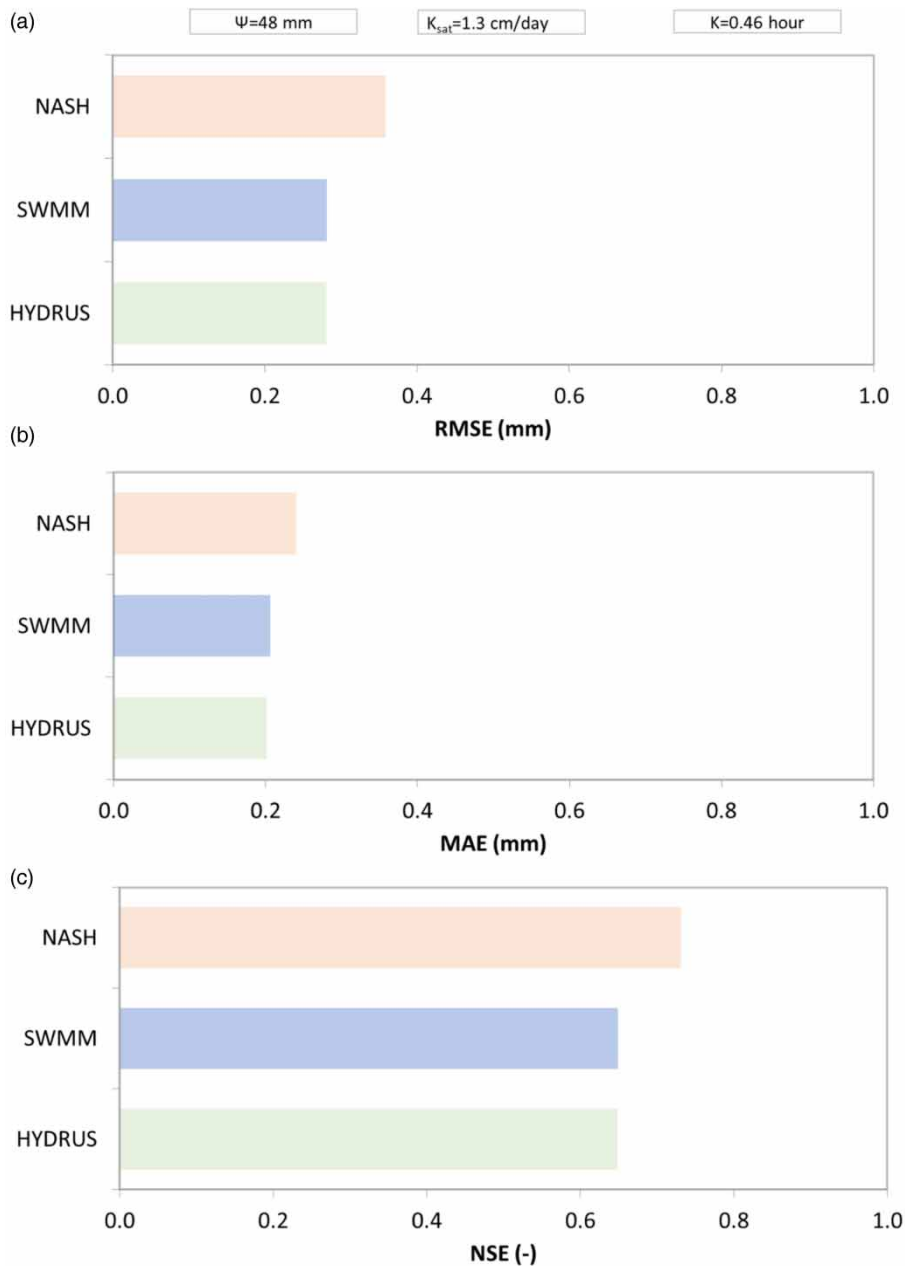
HYDRUS and SWMM have similar behavior with comparable ranges of variation and average errors.

The Nash model typically fails in modeling those convective events featured by a cumulative precipitation larger than 13 mm, as represented by the outliers clearly visible in the assessment of RMSE and MAE patterns variability for this specific model (Figure 5(a) and 5(b)).

## CONCLUSIONS

Green roofs are effective tools for stormwater runoff mitigation in urban areas. Accurate hydrological models can be used for the prediction of GR performances to support urban planners or designers in the definition of realistic urban greening scenarios. Several models have been proposed over time in the scientific literature for assessing the stormwater generation from GR systems. In the present study three models were selected and compared based on the idea that event rainfall pattern characteristics could be a major source of models' uncertainty. The tested modeling approaches are the Nash cascade model, SWMM, and HYDRUS. Each approach was calibrated over 24 rainfall-runoff events collected at an experimental site located in the Mediterranean climate between June 2017 and November 2018. These events were characterized in terms of duration, cumulative rainfall, peak intensity, return period, and n-index, and the BSC distinguished between convective, stratiform, and tropical precipitation types. For the purpose of comparison, only one parameter for each model was calibrated, while the remaining were set according to literature data. The parameters subjected to the calibration procedure were the suction head for SWMM, the storage coefficient for





**Figure 3** | Average values of (a) RMSE, (b) MAE, and (c) NSE for calibrated SWMM, Nash, and HYDRUS (averaged over the 24 rainfall-runoff events).

the Nash model, and the saturated hydraulic conductivity for HYDRUS-1D. The model parameters were iteratively adjusted until the NSE index was optimized. The average values were found to be 48 mm for  $\Psi$ , 0.46 h for K, and 1.3 cm/day for  $K_{sat}$ . The calibration of the HYDRUS  $K_{sat}$  parameter was found to be least affected by uncertainty. The results of the calibration show that all the selected models reproduce the GR behavior with an acceptable efficiency, as confirmed by NSE indices which are larger than

0.6 and maximum for the Nash model. Overall, the analysis suggested that the models are better able to reproduce the behavior of the GR in response to stratiform and tropical rainfall events (the result for this last category is, however, affected by the small number of events it includes), while they are less accurate with convective events and specifically with those characterized by high cumulative precipitation (greater than 13 mm at the experimental site) and regular distribution. HYDRUS and SWMM exhibited similar

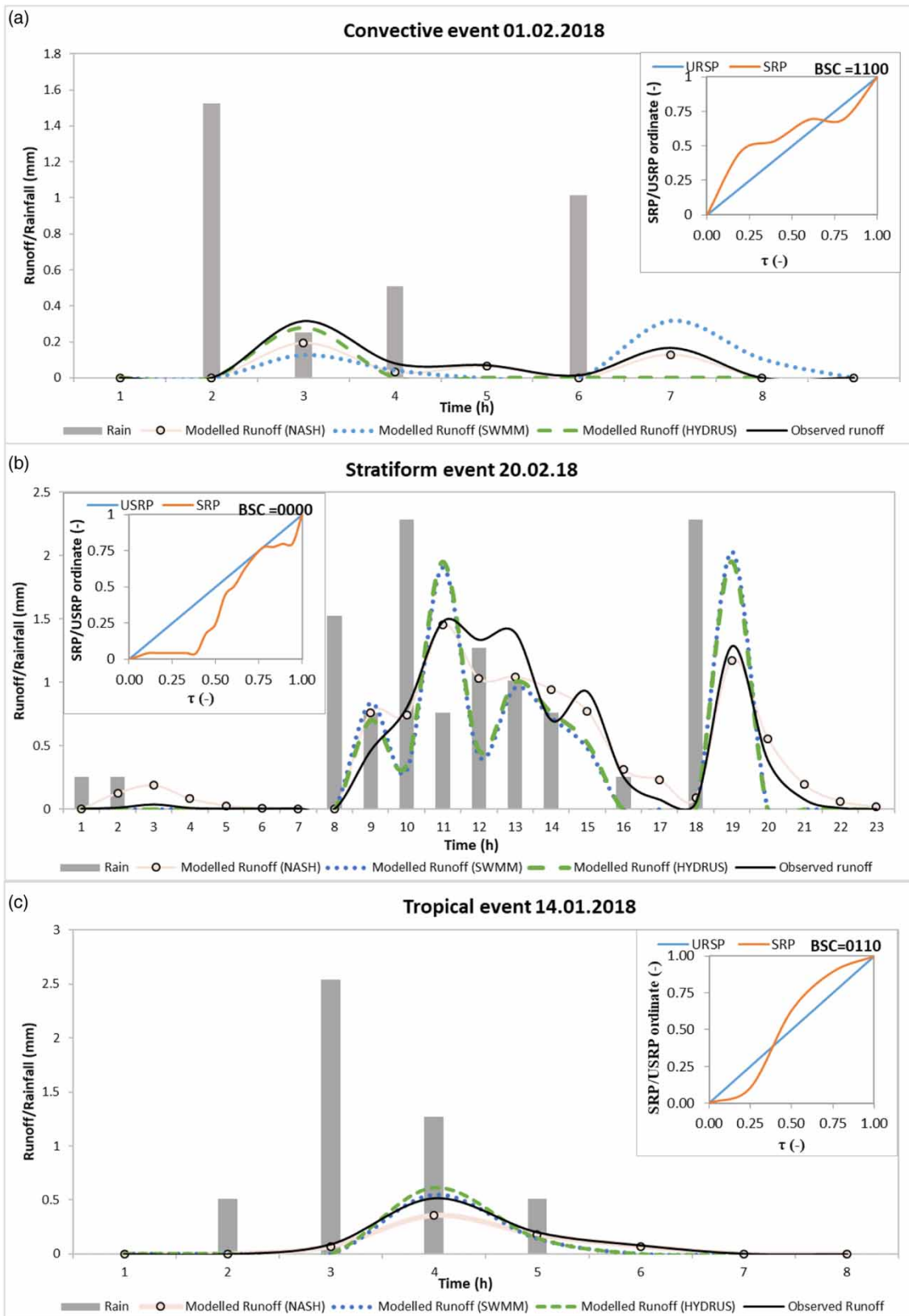
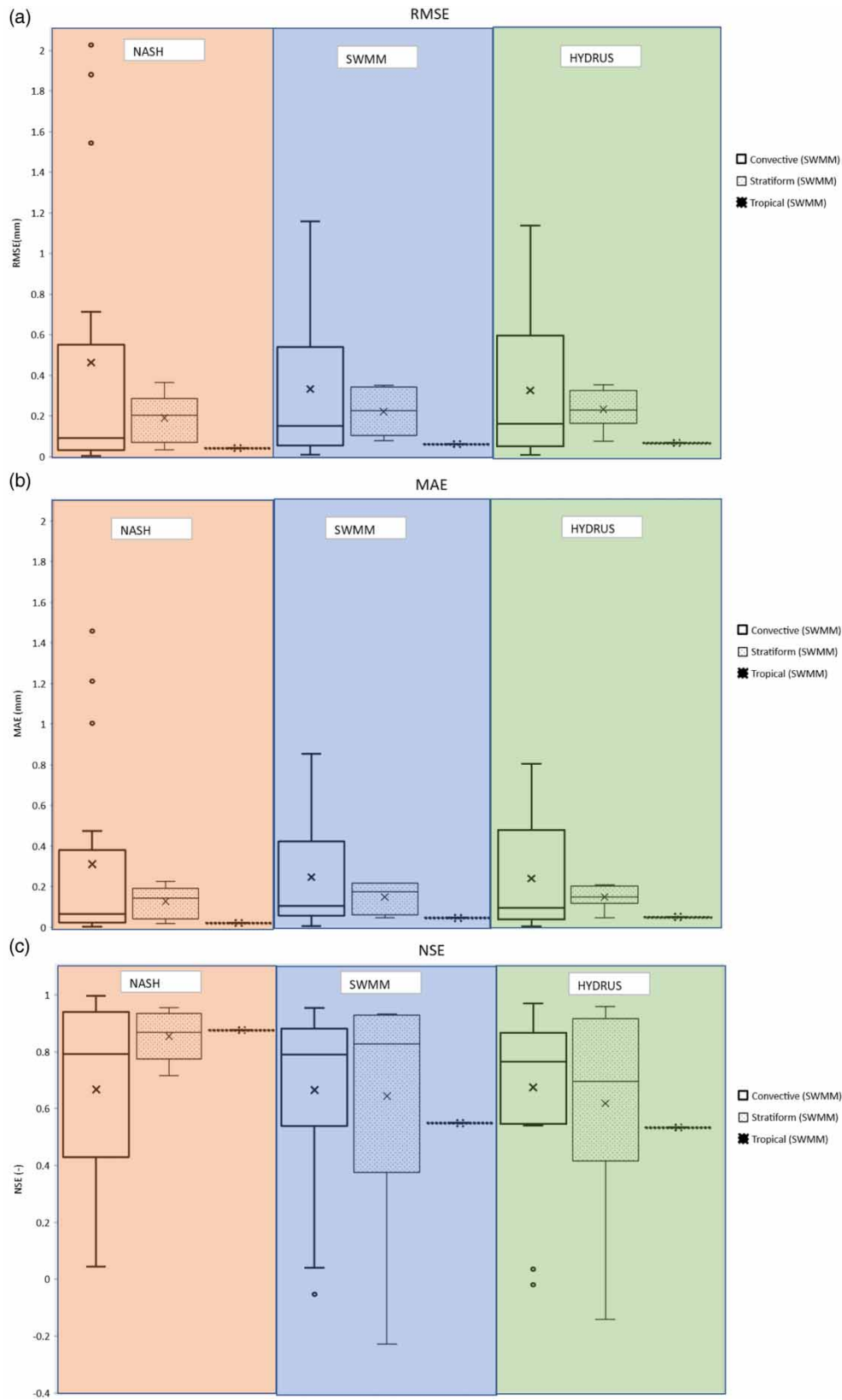


Figure 4 | Modeled vs observed runoff patterns for (a) a convective event, (b) a stratiform event, and (c) a tropical event. For each event, the SRP and USRP are displayed.



**Figure 5** | Boxplots of (a) RMSE, (b) MAE, and (c) NSE indices for the three different models and precipitation types.

hydrological performances. They better simulate the convective events, while Nash had a better predictive effectiveness with stratiform and tropical events. The hydrological response of a GR to a rainfall input is very sensitive to a number of factors and the current research set the base to understand if rainfall properties also play a role in this sense, providing recommendations about the most effective model to be used to predict the hydrological behavior of a GR depending on the type of rainfall event, for particular building practices, and climate settings similar to the one investigated in this research.

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