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Drainage flux simulation of green roofs under wet conditions

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Abstract

The role of green roofs in reducing drainage fluxes is known, but despite extensive analysis in the literature, methods to predict the hydrologic performance for a given green roof composition are scarce. These methods are useful for the hydraulic design and for planning regulations that impose specific hydrological responses. This research investigates on the prediction of the drainage fluxes produced below a green roof with initial water content equal to its water retention capacity (worst-case scenario). Laboratory tests were performed to analyse the rainfall-drainage relationship for green-roof and single components (growing media and drainage storage layers) under specific rainfall intensities. Two types of largely used drainage/storage layers and growth media were analysed, both singularly and in combination. The experiments consider two rainfall events lasting 10 min with constant intensity. The results indicate that the Curve Number (CN) method (U.S. Soil Conservation Service) with a simple adaptation can be used to reproduce the green-roof hydrologic behaviour under antecedent moisture conditions comparable with those of the experiments. In fact, the water retention capacity, controlling the water-output initiation below the green roof, can be used as threshold variable of a step function, above which the CN method is applicable and below which drainage fluxes are practically null. Through this position, the CN assignment for a composite green-roof can be consistently estimated using the proprieties of the single components (drainage/storage layer and growing medium) and it provides values that are very close to those of waterproof media and quite higher than those suggested in companion researches. Drainage amounts are predicted with a standard error equal to 1.50 mm, which corresponds to 5.7% of the mean value observed. After rain initiation, the steady state condition of the drainage flux has proved to be markedly affected by the growing medium and drainage layer composing the system, which result effective in discriminating the green roof performance.

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Introduction

Observed global warming has been linked to changes in the hydrological cycle. The frequency and intensity of heavy rainfall events is likely going to increase in North America and Europe (IPCC, 2014). In Italy, the intensity of rainfall shows overall positive trends, especially for the northern area of the peninsula. Land conversion to urban uses (Northern Italy) associated with the increasing rate of the intense rainfalls, is generating great impact on the safety of the urban environment (Sofia *et al*., 2017). Effectively, high-intensity rain causes problems such as flooding because of limitations in the existing urban drainage systems. In this context, green roofs might play a major role in mitigation of flooding, being recently considered a valuable tool for flood risk mitigation (Masseroni and Cislaghi, 2016). Therefore, practical methods to predict the expected performance of a green-roof system are required. Understanding the hydrological performance characteristics of green-roof components is a key factor to their successful development and implementation (Stovin *et al*., 2013). This can be especially useful at the design phase for planning and regulatory issues, and for predicting green-roof effects in flooding risk mitigation thanks to water storage increment, increase of concentration times, and consequent reduction of the peak discharges. In the literature different models have been used to reproduce the green roof hydrological performance, such as conceptual models (Alfredo *et al*., 2010; Palla *et al*., 2012; Stovin *et al*., 2013; Vesuviano *et al*., 2014; Versini *et al*., 2015), and physically based models (She and Pang, 2010; Palla *et al*., 2012). The majority of the hydrological models of green roofs simulate the hydrological behaviour of the various layers as a single combined process, and only few consider the substrate and drainage layer components separately. Models of the latter type are those described by She and Pang (2010), Vesuviano *et al*. (2014), and Versini *et al*.

(2015). She and Pang (2010) used a physically based approach (Green-Ampt equations for infiltration) to simulate the substrate, and open channel equations to simulate the drainage layer. Vesuviano *et al*. (2014) proposed and validated a two-stage reservoir routing model. Similarly, Versini *et al*. (2015) represented each layer of green roof infrastructure (vegetation, substrate and drainage) by means of three different reservoirs.

The aim of this study is to analyse the hydrological behaviour of green-roofs test beds and their single components in the case where a rainfall event occurs when the water holding capacity of the green-roof system is exhausted. Such a *worst case* scenario is quite probable in Thornthwait's climatic zones Perhumid and Humid (*e.g*., range of mean annual rainfall greater than 800 mm and range of mean annual temperature of 5-25°C) where a rainstorm combination occurring within 1-3 days is very probable. In the case of extensive low-thickness green roofs (having a water retention capacity of about 35-60 mm) specific experiments are scarce despite the fact that a sequence of two/three close events (*e.g*. within 24-72 h) affects the hydrologic response heavily due to the limited evapotranspiration occurrence (autumn/winter season) during the intermediate no-rain period. In this sense, the green-roof initial condition referring to an exhausted water retention capacity could be a reliable hypothesis for design purposes by adding to it a following high-intensity/low-medium return period rain storm.

Hydrological characterisation was pursued through the U.S. Soil Conservation Service Curve Number (SCS CN) approach (NRCS, 1986), which is still an empirical rainfall-runoff model frequently proposed to characterise vegetated roofs and whose application is carried out in the literature by considering the drainage fluxes (the water outflowing from a green roof system to the drainage network) as a runoff in the SCS CN method (Carter and Rasmussen, 2006; Getter *et al*., 2007; Alfredo *et al*., 2010; Damodaram *et al*., 2010; Fassman-Beck *et al*., 2016).

The CN procedure contains some shortcomings such as the difficulties outlined by Hjelmfelt (1991) in continuous modelling, use in estimating infiltration rate, clear definition of *intermediate* antecedent moisture conditions (AMC), lack of a standard physical significance of the maximum potential retention (S) as well as the assumption of the initial abstraction (I_a) being a constant fraction of S (Muzik, 1994). Although the accuracy of the CN procedure has been questioned (Dietz, 2007) particularly for small rainfall events (Hjelmfelt, 1991) this method is still investigated, under improvements, and widely applied due to ease of use, robustness, and integration in models (Mishra *et al*., 2014). However, in the application of the CN method to green roof, the assumptions partially diverge from those of the original version. For example, the subsurface flow outflowing below the green roof (that is the drainage water) is considered the runoff affecting the urban drainage network. Nonetheless, the CN model is currently used for the continuous modelling of green roofs and other sustainable drainage systems, also for the purposes of defining the hydraulic hazard in urban areas. As a consequence, our research aims to provide some indications for a more correct application of the model, avoiding the overestimation of the effect of the green roofs in terms of runoff reduction.

Different methods are proposed in the literature to identify an appropriate CN in cases for which no data are available to represent the hydrological characteristics. Studies have also analysed this topic for low impact development (LID). Damodaram *et al*. (2010) applied the approaches defined as the *S-storage CN method* to permeable pavements and the *Ia-storage CN approach* to rainwater harvesting systems. Following these approaches, the CN method parameters were calculated starting from the characteristics of the LID, which are depth and porosity for permeable pavements and volume of storage and area of the rooftop for rainwater harvesting systems. For green roofs, Damodaram *et al*. (2010) generalised the modelling results of Carter and Rasmussen (2006) to assess the CN of green roofs and set the CN equal to 86 a priori. This value was identified by Carter and Rasmussen (2006) for a living roof in Georgia. Authors identified the CN value via a regression method that estimates the maximum retention potential S using an iteration procedure. In this procedure, the initial abstractions are assumed to be I_a=0.2 S as initially proposed by the conventional CN approach. Similarly, Getter *et al*. (2007) derived CN values to be 84, 87, 89, and 90 for green roof test beds with 2, 7, 15, and 25% slopes, respectively, considering varying antecedent moisture conditions and varying storm volumes. Alfredo *et al*. (2010) calibrated $92<CN<95$ for green roofs, with antecedent moisture content between 67 and 93%, modelling laboratory-derived hydrographs in storm water management model (SWMM). Finally, Fassman-Beck *et al*. (2016), through the analysis of a literature-based dataset combined with previously-unpublished data, suggest a step function in using the CN method: i) runoff volume =0 for design rainfall events lower than the maximum water storage in the growing media; ii) runoff determined with CN =84 for larger rainfall events.

Dissimilarly to previous research, our study aims to identify both CN and I_a values of single green roof layers (growing media and drainage/storage layer), and to determine a methodology to combine these separate features into one unique hydrological computation. To this purpose, laboratory tests on green roof test beds and single layers were performed and analysed. Experiments considered test beds with initial high water content (worst-case scenario), because drainage occurs only when initial moisture approaches the water retention capacity (Fassman and Simcock, 2012; Fassman-Beck *et al*., 2016). For design purposes, laboratory experiments became essential because in many cases the observational records of field monitoring studies are relatively short (less than two years), as observed by Stovin *et al*. (2013), and do not account for extreme rainfall events. Vegetation was not considered due to its lower influence for high intensity rainfall events in reducing the drainage outflow (Dunnett *et al*., 2008).

Materials and methods

Laboratory tests focused on the hydrological behaviour of a drainage layer and growth media layer singularly and combined. Two types of each layer and their respective combinations were analysed by means of selected rainfall simulations (Figure 1). Hereafter, the term *drainage* is used to indicate the drainage fluxes through the green-roof layers, which in turn corresponds to the runoff discharge outflowing below the green-roof and captured by the gutter in the reality (tank in Figure 1 in our experiments).

Study site and rainfall statistics

Following the Köppen-Geiger climate classification, the Venetian Plain (northeast of Italy) is characterised by a warm, humid, temperate climate with a hot summer. The mean annual temperature of the region ranges from 13°C to 14°C, and the annual precipitation is between 700 and 1000 mm (Barbi *et al*., 2013). Winter is typically the driest season, and precipitation mostly falls in spring and autumn. In the summer, storms are quite frequent, albeit irregularly distributed in time. Convective storms (10-15 min in duration), at times associated with hail, are not infrequent during late summer or early autumn and are the most critical events for urban drainage systems because they cause temporary flooding. For this reason, the reference rain duration, which occurs after a preparatory event, was set to 10 min. For the study purposes, the rainfall analysis was conducted based on the extreme rainfall data series from 1992 to 2013 from the rain gauge station of the Regional Agency for Environmental Prevention and Protection of Veneto (ARPAV), located in close proximity (~300 m) to the location of our experiments (rain gauge coordinates: 45°20'50.48"N, 11°57'7.67"E).

The description of the extreme values of precipitation for 10 minutes duration was pursued by fining the Gumbel distributions EV1 (extreme value type 1) to the observations, which provided precipitation of 16.8 and 30.2 mm for return periods of 2 and 30 years, respectively (corresponding rainfall intensities of 100.8 and 181.2 mm/h).

The data set of the rain depths shows that the return period of precipitations with a duration of 1, 2, and 3 days, and cumulated rainfall of 50 mm is less than one year. The value of 50 mm is significant to indicate approximately the expected water retention capacity of an extensive green roof (lightweight green roofs with a shallow layer of growing substrate - generally lower than 200 mm deep). According to the EV1 distribution adaptation, the same value has frequencies of 1.9, 5.9 and 12.1 times/year, considering the rain durations of 1, 2 and 3 days, respectively. This support the choice that a rain simulation far exceeding the water holding capacity is significant for design purposes and for the verification of the hydrological effectiveness of the green roof components.

Green-roof samples and layers

Green-roof samples were constructed in plastic boxes with external dimensions equal to 0.80 m in length, 0.60 m in width and 0.22 m in height (internal dimensions: 0.77×0.57×0.22 m).

The materials used to set up the green-roof samples were selected from those suitable for green roofs in the climate conditions of interest, the Venetian Plain.

Two different types of both drainage/storage layers and growth media were used to build the green-roof samples. The growth media tested were: i) a volcanic medium (VM) (Vulcaflor Extensive by Europomice S.r.l., thickness of 12.0 cm) composed of pumice stones, volcanic lapillus (maximum particle dimensions equal to 10 mm); and ii) blonde peat and a recycled medium (RM) (Zinco System Substrate *Rockery Type Plants* by Zinco GmbH., thickness of 12.0 cm) consisting of recycled crushed bricks (Zincolit Plus) enriched with compost and fibrous matter (Zincohum). The two drainage/storage layers tested were: i) a preformed layer (PL) made from recycled high-density polyethylene combined with a protection and filtration layer of polyester (Bauder DSE 40 and Buader FSM 600 by BauderGmbH, total thickness of 4.4 cm) and ii) a mineral layer (ML) composed of expanded perlite, which is an amorphous volcanic glass frequently used as a soil amendment or medium (Igroperlite Type 3 and Ecodren SD5 by Perlite Italiana S.r.l., total thickness of 5.4 cm). PL and ML include a bottom protection layer commonly installed between the waterproofing membrane and the drainage storage layers. Table 1 reports the main characteristics of the different materials as provided by the manufacturers.

The water retention capacity listed in Table 1 (see the explanation in the note) is obtainable from the material features provided by the manufacturers and is the only usable variable both for the substrate and the drainage layer (*e.g.*, PL does not have neither porosity nor permeability). Accordingly, the application of the concept of field capacity to a growing media could result questionable and not extendible to the whole green roof.

The four layers were tested singularly, and in combination in order to mimic the structure of a complete green roof. Therefore, the assembled green-roof structures (without vegetation) under test are VM with PL, VM with ML, RM with PL, and RM with ML. A filter fleece (polypropylene textile, thickness of 1 mm and weight of 0.105 kg/m^2) was used to separate the growth medium from the drainage/storage layer to prevent medium fines from washing into the drainage layer.

Rainfall simulator and laboratory test design

A rainfall simulator similar to that used by Dunnett *et al*. (2008) was assembled and used to equally distribute an exact amount of rainfall over the samples. This rain simulator is composed of a plastic tank with a height of 44 cm and the same base dimensions as the green-roof samples (80×60 cm). The simulator was positioned using a metal framework located 0.7 m above the green-roof sample. The tank base was drilled with a grid of holes (4 cm spaced), and a needle was installed in each hole via press fitting. When the tank is filled, the head is kept constant using a set of distributed overflow points (holes) placed on the tank walls and feeding the tank with a constant water discharge controlled by a counter. The needles produce regular drops similar to those of real rainfall. The tank, grid of holes and needles (21 Gauge, diameter of 0.8 mm) were designed to reproduce the range of rainfall intensity listed in section *Study site and rainfall statistics*. The spatial uniformity of rainfall within the simulator was tested by placing under the simulator a square grid (6×4) of beakers of 11 cm diameter. A simulation of rainfall for each intensity has been carried out. The position of each beaker and the mass of water contained within it was recorded. Christiansen's coefficient of uniformity (Christiansen, 1942) was found to be 0.90 and 0.71 for the 30 years and 2 years return period precipitation, respectively.

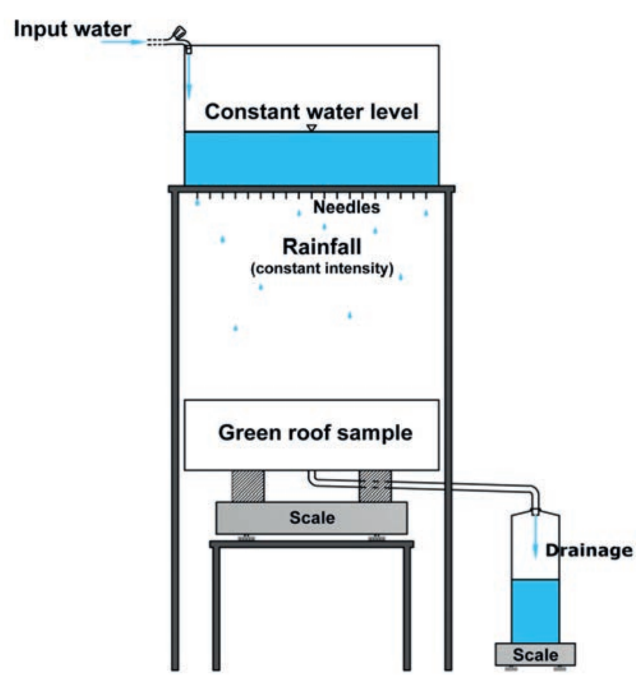

Figure 1. Schematic of the laboratory device.

A drain hole was installed in the centre of the bottom of the plastic box containing the green-roof sample. The drain hole was connected to a tank by a plastic tube to accumulate the drainage water. Two scales (precision of 0.001 kg) were positioned below the sample and the tank, respectively, to weigh the exact quantities of water accumulated in the green-roof sample and drained outward. A schematic of the laboratory setup is shown in Figure 1.

Based on the rainfall statistics, each rainfall simulation was composed by three steps: i) a first irrigation saturating the sample until the initiation of a drainage was observed (this irrigation has been realised manually without the use of the rainfall simulator); ii) the irrigation was stopped and a dripping period was left until the observed drainage rate was null; according to what suggested by the procedure to estimate the water retention capacity (*WRC*) of growing media (FLL, 2008), the maximum necessary dripping period resulted always in a duration shorter than 2 h. The water depth retained at the end of this stage (WRC_{ob1}) by single/double layer samples was measured by weighting the samples and it was also considered equivalent to an initial storage (s_i) caused by the anticipatory rain storm; iii) the irrigation was initiated again for the reference duration of 10 min, which simulated the design second storm after that associated to the initial storage; this second rain was a storm with constant intensity and return period of 2 or 30 years, which corresponded as illustrated above to 1.68 and 3.02 mm/min, respectively. The 10-min duration is also meaningful because it was sufficient to bring the green-roof layers under test at a steady-state drainage and a longer rain would not add any information. In fact, after reaching the steady drainage, the depletion phase after the rain end is not dependent on the second-event duration. For the 2-years return-period rain the water tank was filled to 5.6 cm, while for the most severe storm (30-years return-period) the tank was filled to 12.7 cm.

The water levels in the tank that simulate the desired rainfall events were identified during the simulator calibration. This procedure identified a relationship between the head in the tank and the rainfall intensity through successive measurements of the weight of the rainwater falling within a certain time during which the water level in the tank remains constant. This practice allows simulation of constant intensity rainfalls with a mean squared error of 4.85 mm/h and 7.36 mm/h (0.08 and 0.12 mm/min) with respect to the selected mean intensities of 100.8 and 181.2 mm/h (1.68 and 3.02 mm/min). It is important to notice that simulation of the second-event storm with intensities having a higher return period (*e.g.*, 100 year) were not interesting owing to the hypothesis of anticipatory rain is already severe for a designer. Moreover, the ponding conditions were excluded from the research aims because the hydraulic vertical conductivity was always higher than the rainfall intensity (Table 1).

The weights of sample and tank were recorded every 30 seconds. When time of the second storm expired, the simulator was moved to stop the rain over the green-roof sample and the recording of the weights of green roof and tank continued every 30 seconds until the weight stabilised. This check allowed for accurate measurement of the total rainfall P over the sample, and the volume of water draining out from the bottom of the samples (R) that reached the tank. The portion of rainfall stored in the i sample ($s=s_i$) results from the difference between P and R. Accounting for the scale precision, the measurement of P and R was affected by a maximum error lower than 0.1 mm over the rainfall simulation.

Rain simulations were carried out for each material and respective combinations that are listed in Table 1. Therefore, 16 tests were performed: four samples (two drainage/storage layers, PL and ML; two growth media, VM and RM) and their four combinations (VM/PL, VM/ML, RM/PL and RM/ML) were tested for two different precipitation intensities.

Data obtained from the laboratory tests were used to calculate the *WRC* of the samples and the parameters of the CN method that better replicated the measured drainage R. Two different values of *WRC* were obtained by the laboratory tests: the water storage measured at the end of the anticipatory rainstorm WRC_{ob1} (equal to s_i), and the maximum water storage measured while the second rain event fell over the sample WRC_{ob2} (maximum observed retention while the simulated rainfall was in progress). WRC_{ob2} is a dynamic variable and it depends on the rainfall intensity, because when the

Table 1. Main characteristics (provided by the manufacturers) of the tested materials used to assemble the green-roof samples for the laboratory tests.

Green-roof layer	Layer type	ID code*	Composition	Manufacturer: product name	Thickness (cm)	Dry weight (kg/m^2)	Weight at max water capacity (kg/m^2)	Permeability (mm/min)	Water retention capacity (mm)
Growing media	Volcanic substrate	VM	Pumice-stones, volcanic lapillus and blonde peat	Europomice S.r.l.: Vulcaflor Extensive	12.0	120±6[a]	156	0.6-6.0[c]	36[b]
	Recycled substrate	RM	Recycled crushed bricks plus compost and fibrous matter	Zinco GmbH: Zinco System Substrate Rockery Type Plants	12.0	120±12[a]	168±12	0.6-70[c]	48±12[b]
Drainage/ storage layers	Preformed drainage layer	PL	Recycled high density polyethylene	Bauder GmbH: Bauder DSE 40 + Bauader FSM 600	4.4 (4.0+0.4)	2.4	18.3 (to 30 if infilled with mineral drain)	-	16.5 (13.5+3)
	Mineral drainage layer	ML	Expanded perlite bags of calendered geotextile	Perlite Italiana S.r.l.: Igroperlite Type 3 + Ecodren SD5	5.4 (5.0+0.4)	5.4±1.1[a]	24.3	400	18.0

VM, volcanic medium; RM, recycled medium; PL, preformed layer; ML, mineral layer. *The PL permeability is not provided because, unlike the ML, it is not a substrate. [a]Values of dry weight and weight at maximum water capacity with reference to the related layer thickness; [b]values of water retention capacity calculated as the product of water weight at maximum water capacity in kg/m^3 (obtained by subtracting the dry weight from the substrate weight at the maximum water capacity) and substrate thickness; [c]the minimum value corresponds to a compressed condition of the substrate.

maximum vertical hydraulic conductivity is reached, the water accumulates in the remaining empty pores of the media. Both values were obtained from analysis of the data collected by the scale placed below the sample (Figure 1), and the values were calculated as the mean value during each test.

Curve Number identification and double-layer models

The SCS CN approach (NRCS, 1986) uses the following equations to simulate cumulative runoff (R, expressed in mm) based on cumulative precipitation (P, expressed in mm):

$$R = \frac{(P-I_a)^2}{P+S-I_a} \tag{1}$$

$$I_a = \alpha S \tag{2}$$

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where CN is the Curve Number, which represents the rainfall-runoff characteristics of the area under simulation, S (in mm) is the maximum potential retention of the soil/material composing the contributing area, I_a (in mm) is the initial abstraction, α is a constant that usually ranges between 0.0 and 0.20. Hawkins and Woodward (2010) highlighted that a value of α=0.05 (range of 0.02-0.07) has resulted more accurate for runoff calculations.

In the green roof literature, the term runoff is generally adopted to indicate the total water outlet from the roof, which is composed by the outflow from the bottom of the drainage layers and the potential surface runoff in case of sloped roofs. In our case (horizontal test bed), the runoff amount is equal to the outflow from the bottom of the drainage layers and R has been defined as drainage or drainage flux hereafter; P excludes the anticipatory rain depth (first storm).

The parameters of the CN method were estimated using non-linear regression analysis (Levenberg-Marquardt algorithm) on the laboratory data. The Levenberg-Marquardt algorithm is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of nonlinear real-valued functions (Marquardt, 1963). This method has become a standard technique for nonlinear least-squares problems and is widely adopted in a broad spectrum of disciplines. The software Statgraphics Centurion XVI was used in the nonlinear regression analysis. Eq. (1) was used in the regression analysis to estimate the values of I_a and S for the substrates under analysis, and Eq. (3) was used to identify the corresponding CN value of each substrate.

Based on the regression results of the growth media and drainage/storage layers, two models were identified to derive the S values of the four green-roof combinations. A schematic of these models is shown in Figure 2. The first model (Model 1), referred to as the *layers sequence model*, applies the CN method by assuming that the various layers work in series and hence separately. In the Model 1, the precipitation P is the input of the first step, where the CN method is applied using the values of initial abstraction and maximum potential retention of the growth medium (I_{a1} and S_1). The resulting drainage is subsequently used as the input precipitation in a second application of the CN approach, where the initial abstraction and maximum potential retention are those of the lower drainage layer (I_{a2} and S_2). The resulting drainage should be that of the whole green-roof structure. The second model (Model 2), named as the *layers integration model*, carries out a unique application of the CN approach using a value of initial abstraction equal to the sum of I_{a1} and I_{a2} and a value of maximum potential retention equal to a fraction of the sum of S_1 and S_2. In fact, due to the high drainage capacity of the substrates, the overall (integrated) S value results a fraction (k) of the available maximum potential retention and it was set as k ($S_1 + S_2$). The I_{a1}, S_1, I_{a2} and S_2 and k values are those estimated from the nonlinear regression analysis of the laboratory data obtained from testing the growth media and drainage/storage layers singularly. The effectiveness of both models was tested by comparing their results with the drainage measured in the laboratory for each green-roof set. In addition, the results of the two models were compared with the drainage predicted by the CN approach directly calibrated on the complete green roof samples (drainage layer plus growing media, Table 2).

The Nash-Sutcliffe efficiency index (NSE) (Nash and Sutcliffe, 1970) was used to assess the model accuracy in reproducing the drainage. NSE is given by the following formula:

$$NSE = 1 - \frac{\sum_{t=1}^{n}(r_t - \overline{r}_t)^2}{\sum_{t=1}^{n}(\mu - \overline{r}_t)^2} \tag{4}$$

where r_t and $\overline{r}_t$ are the predicted and the observed values of the drainage, μ represents the mean value of the observed drainage data, t is the time instant, and n is the total number of steps for the rainfall event. NSE ranges from $-\infty$ to 1: NSE equal to 1 indicates a perfect match between the simulated and observed drainage, while an efficiency index lower than zero indicates that the model provides a less accurate estimation than the mean value of the observed data.

Results

Drainage/storage layers

Starting with an initial storage of water equal to s_i, drainage from PL began when the total rainfall (equal to the precipitation P plus the initial storage of water s_i) ranges from 14.2 to 14.4 mm, whereas ML drainage was observed starting from total rainfall between 17.3 and 18.0 mm. The amounts of water retained by PL and ML at the end of the tests (when the drainage stopped) were 13.2 and 18.1 mm, respectively, on average. Figure 3 reports the

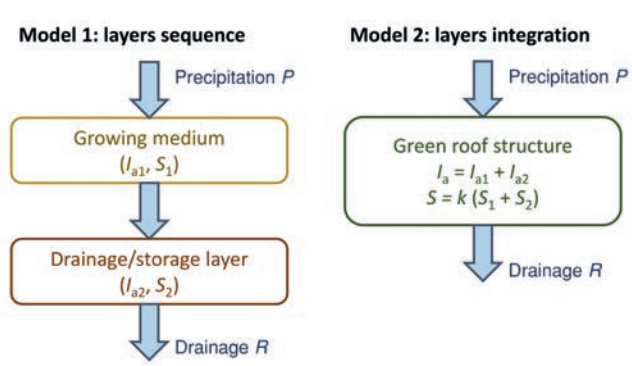

Figure 2. Graphical sketch displaying the structure of the two models used to apply the Curve Number method to green-roof structure starting from the hydrological proprieties of the single layers.

drainage data collected during the second storm (10 min duration) against the total inflow volume. This last was represented as the sum of the precipitation P that fell during the test and the initial storage s_i that is WRC_{ob1}. For graphical clearness the data of 2 years-return period storm are plotted in Figure 3A, while those of 30 years-return period storm are reported in Figure 3B. After the end of the second precipitation, drainage data were collected until the discharge was approximately equal to zero. During this time, the drainage discharge showed a rapid decrease, close to zero (<0.1 mm/min) on average after 3.7 min for ML and after 2.2 min for PL. An example of the drainage discharge measured during a test is shown in Figure 4 for the 30-years return period rainfall intensity (the drainage-discharge trend exhibits a similar pattern for the other layer type). The drainage reaches values comparable to the rainfall intensity (difference between drainage and rainfall intensity ≤0.1 mm/min) in average (mean value of all the tests) after 4.25 min from the beginning of the precipitation in the 2 years return period tests, and after 5.63 min in the 30 years return period tests.

Data for precipitation P and drainage R were used in the regression analysis to identify the parameters of the CN method. After a first round of the regression analysis, I_a was assumed equal to zero. In fact, considering I_a as a parameter under calibration, an average value equal to 0.09 mm (maximum value of 0.5 mm) would have been obtained, which is on the same order or lower as the precision in measurement of R and P. Therefore, assuming I_a equal to zero does not lead to significant errors.

Table 2 summarises the results of the regression analysis for all layers and layer combinations tested.

Growth media

Tests performed using the rainfall simulator show that RM and VM generated drainage when $P + s_i$ reached values from 39.7 to 40.4 mm for RM and from 31.9 to 34.7 mm for VM (Figure 3). The water into RM and VM at the end of the tests when the drainage was finished were 39.9 and 34.4 mm, respectively, on average. Data collected after interruption of the second rain input show that the growth media (VM and RM) drained water for a longer time than the drainage/storage layers, and the rising limb of the hydrograph increases less rapidly than the single drainage storage layers (*e.g.*, Figure 4). The drainage was less than 0.1 mm/min on average after 6.8 min for RM and after 14.5 min for VM (the values was obtained as the average of the 2 tested rainfall events - return time of 2 and 30 years).

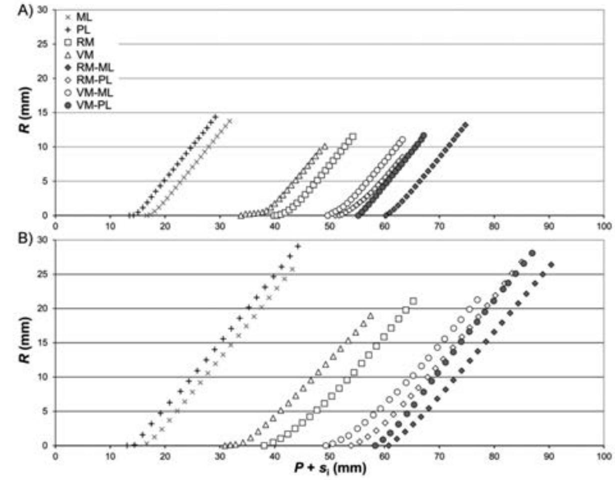

Figure 3. Drainage flux *R versus* the sum of the precipitation P and the initial water storage s_i (equal to $WRCob_1$) for the all tested samples. A) 2-years return period second storm; and B) 30-years return period second storm. ML, mineral layer; PL, preformed layer; RM, recycled medium; VM, volcanic medium.

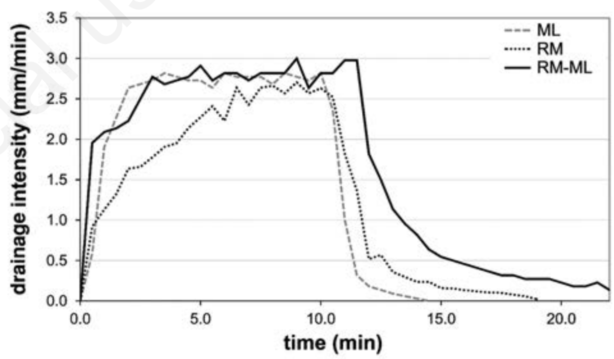

Figure 4. Drainage intensity collected during the tests on the mineral drainage/storage layer (ML), the growth media recycled medium (RM) and the green-roof samples RM-ML.

Table 2. Estimation of the parameters by the Curve Number method using regression analysis on the rainfall-drainage data of the drainage/storage layers, growth media, and green-roof samples.

Green roof layer	ID code	Initial abstraction* I_a (mm)	Maximum retention S, S_1, S_2 (mm)	Curve Number CN	Coefficient of determination R^2	Standard error of the regression of estimation SE
Drainage/storage layers	ML	0.0 [0.0]	2.0 (S2)	99.2	99.8	0.33
	PL	0.0 [0.0]	1.9 (S2)	99.3	99.9	0.26
Growing media	RM	0.0 [0.0]	6.7 (S1)	97.4	97.7	0.88
	VM	0.0 [0.5]	9.9 (S1)	96.3	99.4	0.41
Green roof samples	RM-ML	0.0 [0.0]	2.3 (S)	99.1	99.3	0.59
	RM-PL	0.0 [0.2]	5.4 (S)	97.9	100.0	0.16
	VM-ML	0.0 [0.0]	6.7 (S)	97.4	97.0	1.07
	VM-PL	0.0 [0.0]	0.6 (S)	99.8	99.9	0.24

VM, volcanic medium; RM, recycled medium; PL, preformed layer; ML, mineral layer; SE, standard error. *Enclosed in square brackets, the negligible I_a values obtained after the regression analysis.

The drainage discharge reaches values comparable to the rainfall intensity (difference between drainage and rainfall intensity ≤0.1 mm/min) in average after 7.25 min depending on growth-media type and rainfall intensity (minimum value equal to 5.00 min for the RM sample, maximum value equal to 10 min for the VM sample). The results of regression analysis are reported in Table 2. The listed values represent the parameters of the CN method for I_a equal to zero that better reproduce the hydrological behaviour of the growth media analysed. Similarly to the drainage layers, the I_a values resulting from the first round of regression are not significant (Table 2).

Green-roof samples

Drainage from the RM-ML green-roof began when the total rainfall reached values of 61.0-62.3 mm, from RM-PL when the total rainfall reached values of 51.7-53.9 mm, from VM-ML when the total rainfall reached values of 50.5 mm in both tests, and from VM-PL when the total rainfall reached values of 55.9-59.7 mm (Figure 3). Data collected after the rainfall show that the green-roof samples drained water for longer times in general than those of the single layers analysed in the previous subsections. The drainage values were lower than 0.1 mm/min on average (mean value between the two tested rainfall events - return time of 2 and 30 years) after 14.3 min for RM-ML, after 13.0 min for RM-PL, after 16.0 min for VM-ML, and after 11.50 min for VM-PL.

The hydrographs for the highest rain intensity (*e.g.*, Figure 4 for RM-ML; 30-year return period) show a response with a certain irregular trend, and the drainage was equal to the rain intensity in average after 5.13 min (minimum value equal to 2.00 min for the VM-PL sample, maximum value equal to 9.50 min for the VM-ML sample). It is worth noting the rather long duration of the recession limb of the hydrograph (at least 10 min).

The results of regression analysis on the CN values are reported in Table 2. Again here, the final fitting was obtained taking I_a equal to zero, because I_a values of the first regression including this parameter were almost null (see Table 2).

Water retention capacity, Curve Number and model verification

Table 3 summarises the *WRC* values stemming from the experiments (WRC_{ob1} and WRC_{ob2}) and then compares them with those declared by the manufacturers.

Using the values of *S* from Table 2, the models sketched in Figure 2 (layers sequence and layers integration models) were applied to estimate the drainage for the green-roof structures as measured during the tests and shown in the previous section. Figure 5 reports the comparison between the drainage observed in the laboratory and that predicted by the two models (layers sequence model, Figure 5A; layers integration model, Figure 5B) and also the comparison between the drainage observed in the laboratory and that predicted by the CN approach using the global *S* values (I_a=0) of the green-roof samples listed in Table 2 (Figure 5C). The standard errors of the estimate and the NSE values are also listed in Table 4.

Discussion

The laboratory tests show that green-roof structures and the single components analysed (drainage storage layers and growth media) behave similarly when affected by high intensity rainfall. Structures accumulate the rainfall water and do not produce drainage until the moisture condition reaches values near the maximum *WRC*. Accordingly, Bengtsson (2005) and Bengtsson *et al*. (2005) observed that drainage occurs when the soil moisture exceeds the water holding capacity and large portions of the soil substrate are saturated. Fassman-Beck *et al*. (2016) also identified a threshold of storage potential for which no drainage occurs. This threshold is specific for any individual green roof and is equal to its total *WRC* (WRC_{ob1} in our analysis). This can be assumed as initial abstraction I_a in the CN model only in the case of rainfall occurring on a completely dry green-roof, while in the other cases

Table 3. Values of water retention capacity of the single layers analysed in the laboratory. The table shows the values provided by the manufacturers and those observed in the laboratory (water storage measured at the time of runoff discharge termination after the anticipatory rainfall and maximum water storage measured over the time in which the second simulated storm fell on the sample).

	Water retention capacity (mm)					
	Observed				Computed	
ID code	WRC_{man} Provided by manufacturers	$WRCob_1$ Observed: mean value of water storage at the end of the anticipatory rainfall	$WRCob_2$ Observed: maximum water storage measured during the second simulated storm	Final retained water: observed water storage measured at the end of the second simulated storm	Sum of the single layers water storage at the end of the anticipatory rainfall (WRC_{ob1} computed)	Sum of the single layers maximum water storage measured during the second simulated storm (WRC_{ob2} computed)
Single layers						
VM	36	32.4	38.8	34.4	-	-
RM	48±12	39.0	44.1	39.9	-	-
PL	16.5	13.3	16.1	13.6	-	-
ML	18	16.7	22.7	16.9	-	-
Complete green roofs						
RM-ML	-	60.5	63.9	55.4	53	66.8
RM-PL	-	52.5	60.6	48.2	48.1	60.2
VM-ML	-	49.5	55.7	45.5	51.2	61.5
VM-PL	-	56.8	59.5	51.1	46.3	54.9

WRC, water retention capacity; VM, volcanic medium; RM, recycled medium; PL, preformed layer; ML, mineral layer.

I_a should be assumed equal to the difference between *WRC* and the initial water content of the green roof. The time lag between the start of drainage and the reaching of drainage discharge values comparable with the rainfall intensity (Figure 4) was quite short (mean value equal to 5.13 min for the green-roof samples). When the two quantities are comparable, the pores of the structures are filled with water, the water transfer through the two layers is quite rapid (RM-ML, RM-PL, VM-ML, VM-PL), and total rainfall *versus* drainage data fall along a straight line (Figure 3). This evidence is the cause of the extremely high CN values (between 96.3 and 99.8; Table 2) resulting from our SCS CN method adaptation (step function) and following hydrologic calibration. Accordingly, Bengtsson *et al*. (2005) observed that after drainage is initiated, on a not very short time basis, the drainage equals the precipitation. Given such behaviour, our experiments highlight how is fundamental the precise overall *WRC* assignment being *WRC* the key control variable both for *R* initiation and in determining the drainage delay. The *WRC* of a green roof with respect to a precipitation event is related in general to the proprieties of the green-roof growth media, the initial water content, and meteorological conditions such as temperature, humidity, solar radiation, and wind speed (Li and Babcock, 2014). Our investigation focuses on the hydrological effect of green-roof structures without vegetation. Two different values of *WRC* were produced from the laboratory tests: the maximum water storage measured after the first sample saturation (WRC_{ob1}) and the maximum water storage measured during the second rain simulation (WRC_{ob2}). The second value is evidently higher than the first, and the measured difference is mainly due to gravitational water. Therefore, from the analysis of data on single layers of Table 3, the gravitational water ranges from 2.9 mm for PL to 9.2 mm for RM (mean value of the analysed layer equal to 5.6 mm). WRC_{ob1} can be described as the maximum water holding capacity of the green roof. The concept expressed by this term, generally used for a substrate to indicate the ability to hold water against gravity (Fassman and Simcock, 2012), can be extended to the entire green roof system. Differently, WRC_{ob2} can be considered a maximum dynamic water retention, *i.e.* the maximum water storage capacity available for a specific rainfall intensity and referring to a temporary state of gravitational water storage including the storage of capillary water.

The laboratory values of *WRC* results generally similar to those provided by the manufacturer (Table 3). For the growth media, the *WRC* of VM provided by the manufacturer is in between those of WRC_{ob1} and WRC_{ob2}, whereas the value given for RM is greater than that observed in our laboratory tests. *WRC* values with better agreement with those provided by the manufacturer

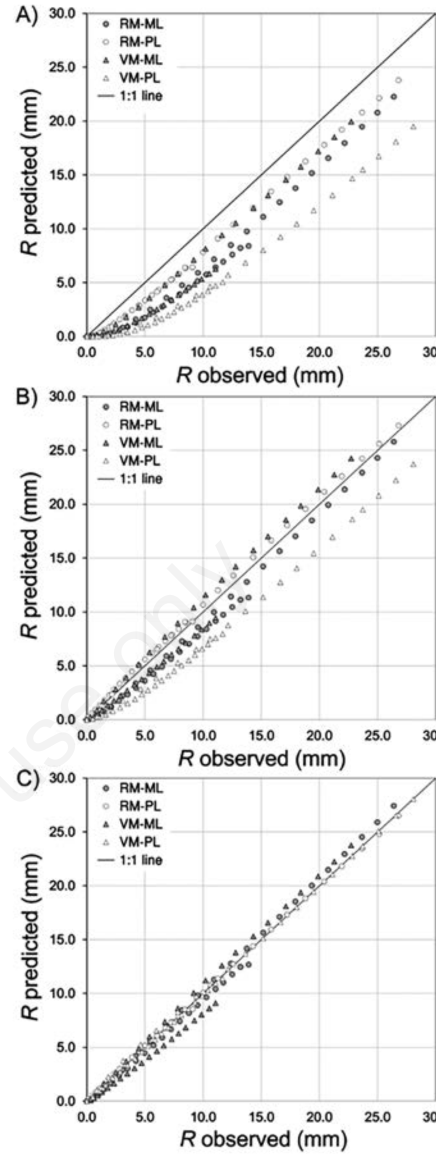

Figure 5. Comparison between the drainage observed in the laboratory and that predicted by A) the *layers sequence model*; B) the *layers integration model;* and C) the Curve Number method with the values of I_a and S directly calibrated on the whole green roofs (Table 2). RM, recycled medium; ML, mineral layer; PL, preformed layer; VM, volcanic medium.

Table 4. Standard errors of the estimate and Nash-Sutcliffe efficiency values for the models tested in the study and for the Curve Number method directly calibrated using laboratory data obtained from the tests on the green-roof structures.

ID code	Standard error of the estimate (mm)			Nash-Sutcliffe efficiency index		
	Model 1: layers sequence model	*Model 2 (k=0.5):* layers integration model	SCS CN approach: regression parameters of Table 2	*Model 1:* layers sequence model	*Model 2 (k=0.5)*: layers integration model	SCS CN approach: regression parameters of Table 2
RM-ML	3.66	1.27	0.58	0.70	0.96	0.99
RM-PL	2.21	0.55	0.16	0.91	0.99	1.00
VM-ML	3.16	1.11	1.07	0.78	0.96	0.97
VM-PL	5.66	3.05	0.24	0.32	0.80	1.00
Average	3.67	1.50	0.51	0.68	0.93	0.99

SCS CN, U.S. Soil Conservation Service Curve Number; VM, volcanic medium; RM, recycled medium; PL, preformed layer; ML, mineral layer.

were observed for the drainage/storage layers. The result is motivated by the higher homogeneity of the drainage material when compared to the growing-media layer.

The *WRC* values of single layers (Table 3) were used to predict the *WRC* of the complete green-roof structure by simply summing the resulting *WRC* values of the single layers that compose each constructive combination under analysis. The data do not show particular trends between observed and predicted values. In the case of WRC_{ob1} (water storage at the end of the first storm), computed values from the sum are on average (mean value of the four green roofs under test) 9.0% lower than those measured globally (maximum difference of –18.5% in the case of VM-PL). Differently, when considering WRC_{ob2} (maximum water storage measured during rain simulation) an average overestimation of 1.6% (maximum difference of +10.4% in the case of VM-ML) was observed between observed and predicted values. Differences between computed and observed values are probably due to the following reasons: i) the substrate behaves differently when tested singularly or in combination with a drainage/storage layer (complete green roof); ii) during the realised tests the single layers can present some little differences (*e.g.* relative position or thickness) when tested singularly or in the complete green roofs.

The *adapted* CN values obtained from regression analysis of the laboratory data range from 96.3 (growth media VM) to 99.8 (green-roof sample VM-PL). These CN values are generally greater than those observed in other studies, but are coherent with the *worst case scenario* conditions of our experiments and with the choice to consider *P* without the rain depth bringing the sample to the s_i (WRC_{ob1}) water content. Carter and Rasmussen (2006) found a Curve Number of 86 (S=40.5 mm) for a green roof with <2% slope and 7.62 cm of substrate thickness, whereas Getter *et al.* (2007) calculated Curve Numbers of 84, 87, 89, and 90 for roofs with slopes of 2%, 7%, 15%, and 25%, respectively. Alfredo *et al.* (2010) calibrated CN=92 to laboratory-derived hydrographs using SWMM. Fassman-Beck *et al.* (2016) suggest CN=84 for rainfall events larger than the maximum water storage in the growing media. These values were obtained through analysis of a wide range of rain events, *i.e.*, ranges of 2.8 to 84.2 mm in the analysis of Carter and Rasmussen (2006) and 2.0-40.0 mm in the study of Getter *et al.* (2007). The dataset considered by Fassman-Beck *et al.* (2016) include storms with rainfall depth from 2.0 to 213 mm. Therefore, these previously cited researches consider rainfall events with large variations in terms of precipitation depth and intensity as well as antecedent soil moisture conditions, and above all they fit the Equation 1 since the rain initiation. We acknowledge that the CN of a green roof is also strongly dependent on the characteristics of the roof itself (mainly layers thickness), but the high thickness of the layers of our experiments (Table 1), which is among the highest in the cited studies, lead us to consider the rainfall sequence (worst scenario) as the main factor affecting the CN values. In fact, our results are based on analysis of previously wetted green-roofs hit by a severe storm. We suggest that this condition, which can be associated to a kind of maximum AMC (in the SCS CN method), can be more safely used for robust planning/regulatory issues and design prescription against flooding hazard. Under this hypothesis we acknowledge that green roofs reach CN values comparable to those of traditional roofs, still providing the benefit to delay the runoff response by means of their *WRC* working as an initial storage. Similar values for CN (CN=96) were identified also by Fassman-Beck *et al.* (2016) for the green roofs of Brownstone (Michigan), Pittsburg (Pennsylvania), and Sheffield (U.K.). The comparison (Figure 5) between the drainage observed and predicted by the models described in Figure 2 shows that the *layers sequence model* (Model 1, Figure 5A) always underestimates the drainage (average difference equal to –3.4 mm), whereas the *layers integration model* (Model 2, Figure 5B) delivers more accurate results. In this case, the standard error of the estimate is equal to 1.50 mm, which corresponds to 5.7% of the mean drainage observed at the precipitation end. The CN or *S* values used in the models are those of single layers listed in Table 2.

Finally, as expected, the application of the CN approach using the parameters obtained directly from the calibrated data of the complete green-roof samples (Table 2, CN values of the complete green roofs) obviously offers the best results, with a mean value of the standard error of estimation equal to 0.51 mm, not too far from Model 2. These statements are confirmed by the NSE values (Table 4) that highlight an excellent performance for all green roof configurations. It can be concluded that the best solution for simulating the hydrological behaviour of a green roof in antecedent wet condition is to calibrate the CN-method parameters directly on the green roof's overall structure. The *layers integration model* (Model 2) can produce a fairly accurate calculation and can provide a reliable estimation of the effects of different layer combinations knowing the characteristics of each layer. Its scope includes small and large-scale applications, even though supplementary analyses are necessary to test and validate the model in real green roof structures and different drainage layer/growth media combinations.

In addition, the analysis of the laboratory tests can give indication also about the hydrological behaviour of a green roof with a given *initial moisture content* (*IMC*) affected by a rain event exceeding its *WRC* (WRC_{ob2} in our experiments) as a whole. In fact, we can conclude that, in this last case, a green roof behaves following the scheme of Figure 6 composed by three steps: i) Green roof stores water for a time period t_{stor} equal to the ratio between the difference WRC_{ob2} minus *IMC* and the mean rainfall intensity *J*; ii) Once the storage reaches the WRC_{ob2} of the green roof, drainage begins to flow with a discharge that quite rapidly (after the time t_{stor}) reaches values comparable to the rainfall intensity; the following *full drainage* duration t_r can be calculated as the difference between the precipitation duration t_p and t_{stor}; in our experiments the measured t_{stor} times deal with an hydrologic condition for which *WRC* has been largely already consumed (*IMC* equal to WRC_{ob1}) by a first preparatory storm; they vary taking the

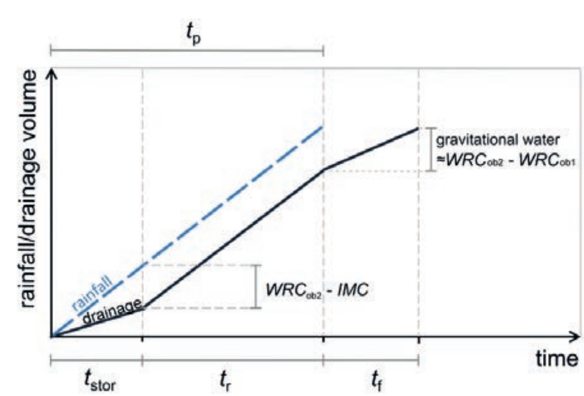

Figure 6. Schematic representation of the behaviour of a green roof with a given antecedent moisture content affected by high intensity rainfall; t_p is the precipitation duration, t_{stor} is the time required to reach WRC_{ob2} of the green roof, t_f is the delay between the conclusion of the storm and the time at which drainage stops flowing from the roof; IMC is the initial moisture content.

following values (averaged over the two storms under test with different return period): 3.75 min for RM-ML, 7.5 min for RM-PL, 7.25 min for VM-PL, 2.0 min for VM-PL; these values are minimum/unfavourable values and also highlight how the green-roof material selection and the growing medium-drainage layer combination can determine significant differences of the runoff delay; iii) At the conclusion of the storm, a *final drainage* occurs for a certain period of time t_f; this delay occurs because the final rain water entering the green roof must filter through substrate, drainage, and filter layers before it can outflow.

The time t_f, that is the drainage time after the precipitation ends, can be calculated as the ratio between the gravitational water depth and infiltration velocity v_f. Gravitational water can be identified through experimental analysis. For example, considering the difference between WRC_{ob2} and WRC_{ob1} observed in our tests, gravitational water ranges from 2.7 to 8.1 mm for the samples analysed in this study (computation from Table 3). In addition, in the t_f period, v_f was determined as ranging from 0.60 to 0.82 mm/min (mean value equal to 0.69 mm/min). The t_{stor} time and the green roof delay (t_f) are relevant in view of refining concentration time and runoff duration in urban catchments with green roofs (Fioretti *et al*., 2010). Moreover, simplified prediction of the drainage can be achieved, using the scheme above mentioned, also for green roofs under rainfalls of larger durations with respect to that experimented (10 min) accounting for the fact that t_r concerns a steady state condition. Being proved that the drainage discharge is fundamentally dependent on rainfall intensity and green-roof *WRC*, our results put in evidence that *WRC* can be used as threshold variable of a step function above which the Curve Number method is applicable and below which drainage fluxes are practically null. In short, drainage can be set to zero for rainfall less than *WRC;* it becomes almost equal to the rainfall intensity when rainfall exceed *WRC*; after the rainfall end, the drainage gets back to zero gradually through the drainage of the gravitational water.

A similar step function was proposed by Fassman-Beck *et al*. (2016), the only difference being the lower value of CN that leads to drainage fluxes lower than the rainfall intensity in the step 2. This difference is because, in the case studies reported in Fassman-Beck *et al*. (2016), green roofs did not present the high initial water content considered in our tests. As a consequence, the calculation of the CN values was strongly affected by the antecedent moisture conditions. Differently, our investigation is less uncertain for a designer or a planner because it focuses on a cautionary hypothesis (worst case scenario) and emphasises the key role of material selection of a green roof. This last determines the overall *WRC*, the kinematic of the hydrologic response of the green roof and, then, the assessment of an honest performance of the selected system.

Conclusions

Based on laboratory tests on green-roof samples and their single components, this work investigated on the drainage from green roofs in wet conditions (worst case scenario) under the extreme rainfall of the Venetian Plain (design storms), and the ability to identify the hydrological behaviour of a green roof based on the proprieties of each composing layer.

The results show that a simple adaptation of the SCS CN method may be calibrated to satisfactorily reproduce the drainage amount of the tested green roofs during the sequence of an anticipatory saturating precipitation followed by a severe storm. The standard error of the estimate between the measured and observed drainage was 1.50 mm, which corresponds to the 5.7% of the total observed at the end of precipitation. Under the severe storms simulated in the laboratory (100.8 and 181.2 mm/h, lasting 10 min), the calibrated CN parameter can reach values generally higher than those reported in previous studies and closer to those of black roofs. More specifically, the analysed structures accumulate the rainfall and do not produce significant drainage until the moisture condition reaches values correspondent to their maximum water retention capacity. After drainage is initiated, the drainage discharge equals the precipitation intensity over a quite short but variable period of time (range of 2.0-7.5 min), which depends on the green roof material of the composing layers. After the rain end, the drainage duration is controlled by the ratio between content of gravitational water and mean velocity of water infiltration (range of 0.6-0.8 mm/min).

Knowing the hydrological characteristics of the single layers that compose the green roof, the following assessment can be done: i) the sum of the water retention capacities of the single layers that compose a green-roof structure seems to offer an approximation of the global green-roof *WRC* that should be reduced by the 10% to be cautionary in terms of drainage estimation for the urban/hydrologic design; ii) the *layers integration model* proposed in this study appears to produce an accurate calculation of the green-roof drainage based on the characteristics of the single component layers; iii) further research is necessary to test the *layers integration model* in larger size green roof structures, and under different drainage layer/growth media combinations (typologies and thicknesses) without and with vegetation cover.

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