A long-term hydrological modelling of an extensive green roof by means of SWMM

Sara Simona CIPOLLA[a], Marco MAGLIONICO[a], Irena STOJKOV[b]

[a]*Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy.*

[b]*Kleinfelder Northeast, Inc., 215 First Street, Suite 320, Cambridge, MA 02142, USA.*

**Corresponding author: Tel.: +39 051 2093354. E-mail address: sara.cipolla@unibo.it (S.S. Cipolla)*

ABSTRACT

Green roofs provide multiple environmental and social benefits, among which the opportunity to control storm water runoff as they limit the rate of runoff after urbanization to the rate that would have occurred before urban development. The hydrological behavior of a green roof is site specific, thus the local environmental parameters, the characteristics of the vegetation and the physical properties of its layers have to be considered in the evaluation of its performance. Furthermore, the hydrological performance of a green roof is influenced by the size of the plot (full-scale vs small scale), by the definition of "event", and by the number of events included in the research. From this broader context this paper first provides a review of the scientific literature, with a focus on the hydrological behaviour of experimental full-scale installations and on hydrological modelling of green roof performance. Second, the study presents the results of a monitoring activity of a full-scale extensive green roof in Bologna (Italy). Continuous weather data and runoff were collected between January and December 2014, resulting in 69 storm events suitable for the study. Experimental data show that single event rainfall attenuation ranged from 6.4% to 100% with an annual average value of 51.9% which is consistent with other author's findings. Last, the study uses the field data to calibrate and validate a numerical model realized with the commercial software SWMM 5.1. The model was used to simulate the long-term hydrologic response, over one year, of the same full-scale extensive green roof and to compare it to an adjacent impervious roof of the same size. Modelling results confirm the role of green roofs in restoring the natural water regime by reducing the annual runoff volume. The comparison of the results between the experimental green roof monitoring and the SWMM simulation proved that the suggested model has good capabilities in simulating the hydrograph of stormwater runoff from green roofs along the year, as demonstrated by the quite high values of NSE and the low value of RSR in both the calibration and validation phase. Furthermore, the low difference (< 9%) in total retention between the 69 measured and simulated events confirms the suitability of the model for long term simulations. The proposed modelling approach demonstrates that SWMM can be used for assessing the performance of LID systems (Low Impact Development), and consequently for supporting local authorities or designers in the evaluation of the hydrological efficiency of green roofs.

KEYWORDS

Green roof; LID, modelling; retention; stormwater management; SWMM*

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* **Abbreviations**: BRC-LID: "Bio-Retention Cell" LID Type; ET_0: potential evapotranspiration, ET_r: real evapotranspiration; GR: Green Roof; LID: Low Impact Development; GR-LID: "Green Roof" LID Type; NSE: Nash–Sutcliffe Efficiency index;

INTRODUCTION

A green roof (GR) is an extension of an existing or newly constructed roof which incorporates a multi-layer structure (water proofing membrane and root barrier, a filter, a drainage system and lightweight growing medium) and plants. The growing popularity of GRs in sustainable buildings is mainly due to their multiple environmental and social benefits (Bianchini and Hewage, 2012; Vijayaraghavan, 2016), among which the hydrological ones. It is repeatedly documented that GRs are a valid tool to restore the hydrological urban water balance by reducing and delaying stormwater runoff (Czemiel Berndtsson, 2010; Palla et al., 2010; Stovin et al., 2015, 2012). Furthermore, a GR acts as a Source Control technology (SC) providing a stormwater management opportunity in otherwise unused spaces: the rooftops. (Fassman-Beck et al., 2013; Fletcher et al., 2014; Versini et al., 2015). As a result, quantifying and improving the hydrological performance of a GR system is becoming increasingly important for stormwater engineers, architects and urban planners (Berardi et al., 2014; Czemiel Berndtsson, 2010; Fassman-Beck et al., 2013; Gambi et al., 2011; Lucas and Sample, 2015; Mentens et al., 2006; Stovin et al., 2012; Voyde et al., 2010b).

Stovin et al. (2012) clearly identified the key hydrological mechanisms operating within a GR; they could be summarized in: rainfall interception by leaves, infiltration and retention in the substrate, storage in the drainage layer, and runoff from the detention storage. Any excess of water, above retention capacity, is directed from the drainage layer

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RMSE: Root Mean Square Error; RR: Reference roof; RSR: RMSE-Observation Standard deviation Ratio; SC: Source Control technology; SR: Sedum Roof.

towards the downspouts, while retained water may subsequently leave the roof as evapotranspiration (Stovin et al., 2015). For improving the retention capacity, which to date is the most cited hydrological performance metric of a GR, a complete knowledge of these mechanisms is needed. Moreover, those processes must be carefully modelled to provide a valid prediction tool for stormwater engineers and municipalities in the design and verification phase, respectively.

Furthermore, in the past few years, due to a growing number of research studies (e.g. Blank et al., 2013; Li and Babcock, 2014; for an overview) which demonstrate the effectiveness of GRs from an ecological, social, and economical point of view, the local regulations of many countries have begun to suggest GRs for many purposes, such as urban stormwater management and urban heat island mitigation technologies. She and Pang (2010) underlined how many European countries and local governments in the United States are providing stimulus programs to promote GRs installation by private buildings owners. This is mainly due to the fact that GRs should be considered as a technology for providing an "all round" contribution as part of sustainable development and resilience strategies. This concept has been deemed essential by the European Commission through the HORIZON 2020 research program. At the moment the European Commission promotes research activities "focused on providing evidence that re-naturing of cities through the deployment of innovative, locally adapted, systemic solutions - that are inspired and supported by nature - can be a cost-effective and economically viable way to make cities more sustainable, resilient, greener, and healthier (European Commission, 2015).

Currently, several Italian regional and local regulations (as in the Autonomous Province of Bolzano, the Province of Rimini and in the city of Bologna through the Urban

Municipal Regulation, RUE) promote the use of GRs and other green technologies, because of their hydrological and environmental benefits, providing incentives such as extra building volumes or extra tax deductions (Bertocchi et al., 2011; Cipolla et al., 2016). It has therefore become essential to identify a method for forecasting the hydrological performance of GRs especially in order to fairly distribute such incentives.

1.1 Overview of the retention performance of full-scale green roofs

Several studies evaluated the hydrological performance of GRs through field monitoring activities, and their results have been compared by other authors through detailed overviews (Czemiel Berndtsson, 2010; Palla et al., 2010; Stovin et al., 2012). However, these authors frequently reported and compared the performance of GRs in terms of average annual retention without taking into account the possible differences between studies conducted on a pilot scale or on a full roof scale. Pilot scale studies are based on elevated test beds or similar modules, with a watershed area that can range between 0.37 and 12 m^2 (Carson et al., 2013), while full-scale GRs typically occupy bigger watershed areas and include non-vegetated regions, which are generally required for maintenance, rooftop equipment, egress or load restrictions. Furthermore, the pilot test beds are frequently elevated above the base level (Beecham and Razzaghmanesh, 2015; Stovin et al., 2015, 2012) while full-scale installations lay on the rooftop. This means that in the last case, the GR’s contact with the atmosphere is restricted to the vegetation-air interface while in the first case the bottom surface is usually not protected from weathering. These differences, at the moment not fully investigated, may be the cause of inaccuracies when comparing the overall retention of pilot test beds with full-scale installations. Moreover, considering that not only the physical configuration but also other parameters could influence the average retention (e.g. number of events, definition of events, climatic condition at the study site, green roof type etc.), to reduce the inaccuracy from the comparison between full-scale vs pilot green roof, from this point forward only studies based on retention data provided by experimental studies on full-scale installations will be taken into consideration.

Carson et al. (2013) proposed a detailed review of the hydrologic studies on full-scale GR systems, in both entire and partitioned sections of occupiable building rooftops. This review, updated with the results from the latest studies, is summarized in Table 1 and shows that the retention volume can range from 11.0 % to 76.4 %, which is generally lower than what reported for pilot test (Stovin et al., 2012). This is probably due, as underlined by Carson et al., (2013) and work undertaken at Pennsylvania State University (Berghage et al., 2007), to the presence of a gravel edge or non-vegetated sections and irrigation requirements for many full-scale systems. Moreover, the presence of air and of direct solar radiation to which many pilot test boxes are subject to on their bottom face, may influence the evapotranspiration process and consequently the overall hydrological performance (higher diurnal soil moisture loss).

Year	Authors	Study Location	Period [mm/yy-mm/yy]	Area [m^2]	Events	Substrate depth [cm]	Ret. [%]
2003	Hutchinson et al. (2003)	Portland, OR	1/02-4/03	240	NA	100-125	69.0
2005	Liu and Minor (2005)	Toronto, CA	3/03-11/04	200	NA	75	57.0
		Toronto, CA	4/03-11/04	200	NA	100	57.0
2005	Moran et al. (2005)	Goldsboro, NC	4/03-9/04	35	67	75	63.0
		Raleigh, NC	7/04-9/04	65	13	100	55.0
2005	Connelly et al. (2005)	Vancouver, CA	1/05-12/05	33	NA	75	29.0
		Vancouver, CA	1/05-12/05	33	NA	150	26.0
2007	Teemusk and Mander (2007)	Tartu, EE	8/04-9/04	120	3	100	19.6
2008	Berkompas et al. (2008)	Seattle, WA	2/07-12/07	743	NA	150	30.5

		Seattle, WA	4/07-6/07	1860	NA	100-125	33.0
		Seattle, WA	10/07-12/07	80	9	150	17.1
2008	Collins et al. (2008)	Goldsboro, NC	4/03-6/04	35	NA	75	64.0
2008	Kurtz Tim (2008)	Portland, OR	5/02-6/08	246	NA	125	56.0
		Portland, OR	3/07-6/08	465	NA	75	64.0
2008	Spolek (2008)	Portland, OR	10/04-4/07	290	NA	100-150	12.0
		Portland, OR	10/04-4/07	280	NA	100-150	17.0
		Portland, OR	1/05-10/07	500	NA	150	25.0
2009	Berghage et al. (2009)	Chicago, IL	8/07-7/09	7000	106	76	74.0
	Bliss et al. (2009)	Pittsburg, PA	8/06-1/07	330	13	140	21.8
2010	Palla et al. (2010)	Genova, IT	5/07-12/08	170	19	200	51.5
2010	Voyde et al. (2010a)	Auckland, NZ	10/08-10/09	41	91	50	66.0
		Auckland, NZ	10/08-10/09	13	91	50	66.0
		Auckland, NZ	10/08-10/09	46	91	70	66.0
		Auckland, NZ	10/08-10/09	45	91	70	66.0
		Auckland, NZ	10/08-10/09	12	91	70	66.0
		Auckland, NZ	10/08-10/09	38	91	50	66.0
2011	Gregoire and Clausen (2011)	Storrs, CT	12/09-2/10	307	NA	102	51.4
2013	Carson et al. (2013)	New York, NY	06/11-06/12	310	74	32	36.0
		New York, NY	06/11-06/13	390	108	100-200	47.0
		New York, NY	06/11-04/14	940	61	100	61.0
2013	Speak et al. (2013)	Manchester, UK	09/11-10/12	408	254	170	65.7
2014	Hakimdavar et al. (2014)	New York, NY	08/11-1/12	310	113	32	50.6
		New York, NY	8/11-06/12	99	110	32	61.3
2014	Yang et al. (2015)	Beijing, CN	04/12-7/12	120	13	150	76.4
2015	Versini et al. (2015)	Paris, FR	06/11-8/12	35	100	30	17.0
		Paris, FR	06/11-8/12	35	100	150	11.0

Table 1. Summary of studies on the hydrological performance of full-scale GRs. Columns from left to right identify: year of publication, authors reference, geographic location of the site, time period of data collection, size of the monitored drainage area, number of individual events observed, depth of the growing substrate, and average retention during the monitoring period for each study. The symbol NA is

used for fields where information was unavailable.

It should be noted that not only the size of GRs (full-size vs pilot) but also other factors such as the definition of the term “event", the number of considered events, the climatic conditions, the substrate depth and composition, and last but not least the vegetation planted, have a notable influence on the average retention of a GR. The definition of the term "event" strongly influences the retention and consequently the performance of a green roof as source control technology. In some previous studies the individual events were defined as being separated by continuous dry periods of at least six hours (Stovin, 2010; Stovin et al., 2013, 2012). For others, events were independent if separated by at least one hour of dry weather time (Locatelli et al., 2014) and a few studies did not define the minimum dry weather time before each event (Teemusk and Mander, 2010; Yang et al., 2014). When the antecedent dry weather time increases, small events (with retention equal to 100%) are embedded in the previous events, and this may cause the reduction of the overall retention of the roof. To contrast this ambiguity in the event definition, some manuscripts provide a detailed description of the procedure used for the data analysis (climate, number of events, rainfall depth) and on top of that, they provide a definition of events that take into account both precipitation and runoff (Carson et al., 2013; Hakimdavar et al., 2014). In particular, for those authors a storm event begins when rainfall is first recorded and ends when no precipitation or runoff has been recorded for at least 6 hours.

That being said, it is clear how the absence of common standards, for collecting and analysing data, determines a significant difficulty in the comparison of experimental results coming from different research activities. To overcome this, in this study the methodology used for event definition and data analysis, followed the procedures used by Carson et al. (2013) and by Hakimdavar et al. (2014) to analyze the hydrological behaviour of some full-scale GRs in New York City (USA). The aim is to develop and follow common standards for data recording and analysis, allowing at the same time an easier and better comparison of the results.

1.2 Overview of the hydrological models

In the last few years, researchers have proposed empirical relations between rainfall and runoff based on field experiments (Carson et al., 2013; Fassman-Beck et al., 2013), event-based hydrological models (Bengtsson et al., 2005; Carbone et al., 2014; Jarrett et al., 2006; Kasmin et al., 2010; Lamera et al., 2014; Palla et al., 2012; She and Pang, 2010), conceptual models for long term simulation (Locatelli et al., 2014; Stovin et al., 2013) , and numerical models by using commercial software such as HYDRUS (Hakimdavar et al., 2014; Hilten et al., 2008; Palla et al., 2012), EPA's SWMM (Bonoli et al., 2013; Burszta-Adamiak and Mrowiec, 2013; Krebs et al., 2014; Palla and Gnecco, 2015; Versini et al., 2015), MIKE URBAN (Locatelli et al., 2014), SWMS-2D and SWAP (see Li and Babcock, (2014) and Elliott and Trowsdale (2007) for an overview). Among several models used in GR studies, the gaps in model capabilities, in particular in long-term simulation, are continuously narrowed.

Li and Babcock (2014) underline that SWMM is a quick and valid assessment tool for quantifying the hydrological performance of a GR, which is also confirmed by the study of Palla and Gnecco (2015), who found that the LID (Low Impact Development) modules of SWMM, if correctly calibrated and validated (on an event basis, using events generated under controlled conditions in the laboratory), can be successfully implemented to study the hydrological response of a small urban catchment. On the contrary, Burszta-Adamiak and Mrowiec (2013) observed that SWMM has limited capabilities in correctly simulating the hydrograph of storm water runoff from a GR. However, simulations in both studies were conducted for each analyzed event separately (single event simulations), without taking into account the evapotranspiration (ET) process and the restoration of retention capacity associated with it. On the contrary, as highlighted by many authors (Berretta et al., 2014; Locatelli et al., 2014; Marasco et al., 2014; Poë et al., 2015; Stovin et al., 2012; Yang et al., 2014) ET is a keystone in long-term simulations, because it is the hydrological process responsible for the movement of water to the air from sources such as the substrate, the vegetation, and the drainage layer. Therefore, ET restores the GR's water holding capacity increasing its retention capacity. In this framework the present manuscript will provide a long-term simulation model that takes into account the evaporation process as well.

1.3 Objectives

The first objective of this study is to present the hydrological monitoring results of a full-scale extensive commercial GR located in Bologna (Italy), with the intent of filling a gap in knowledge of the stormwater retention performance of a full-scale commercial green roof in a temperate sub-continental climate region.

The second goal of the study is to simulate the hydrological performance of GRs by means of SWMM using the LID control modules (version 5.1.010) using long-term rainfall and temperature data. For this purpose, a commercial extensive GR has been modelled using the “bio-retention cell” LID module and the model has been calibrated and validated based on the measurement results obtained from rainfall and runoff monitoring presented in the first part of the study.

2 METHODOLOGY

2.1 Site description

A full-scale GR and an adjacent impervious roof area, both located above the LAGIRN laboratory (44.513058ºN, 11.318787ºE) at the Engineering Campus of the University of Bologna (UNIBO) have been used as case study.

The city of Bologna is located in northern Italy and has a humid temperate subcontinental climate with hot and muggy summers, cold winters, no dry season (Toreti et al., 2010) and an average precipitation of 700-800mm/year (Brunetti et al., 2006).

The experimental site (Bonoli et al., 2013; Maglionico et al., 2014) occupies about 120 m^2 of an existing flat roof, which was divided in two areas: one devoted to a newly added extensive commercial GR (Sedum Roof, SR), while the other area was retrofitted with a new membrane and was left bare as control plot (Reference Roof, RR) (Fig. 1). The SR (5.15 m x 11.30 m), with a slope of 0.5 %, is a built-in-place system realized using a commercial "green roof package" provided by Harpo Spa, Trieste, Italy, fully described in other studies (Palla and Gnecco, 2015; Raimondo et al., 2015; Savi et al., 2013) (Fig. 1). Six layers were laid in sequence above the flat concrete roof, from bottom to top: a) 4 mm of waterproofing PVC root barrier membrane; b) 3 mm of protection fabric; c) 25 mm of drainage; d) 0.5 mm of filter fabric; e) 100 mm of substrate to support plant growth; and f) a mix of Sedum vegetation (Fig. 1).

The GR plot is surrounded by a gravel strip (10 cm deep and 30 cm wide), placed above the layers (a-d), previously described, in place of the substrate (Fig. 1). The RR (5.15 m x 11.30 m), consists of a concrete flat roof insulated using a waterproofing PVC membrane (Fig. 1).

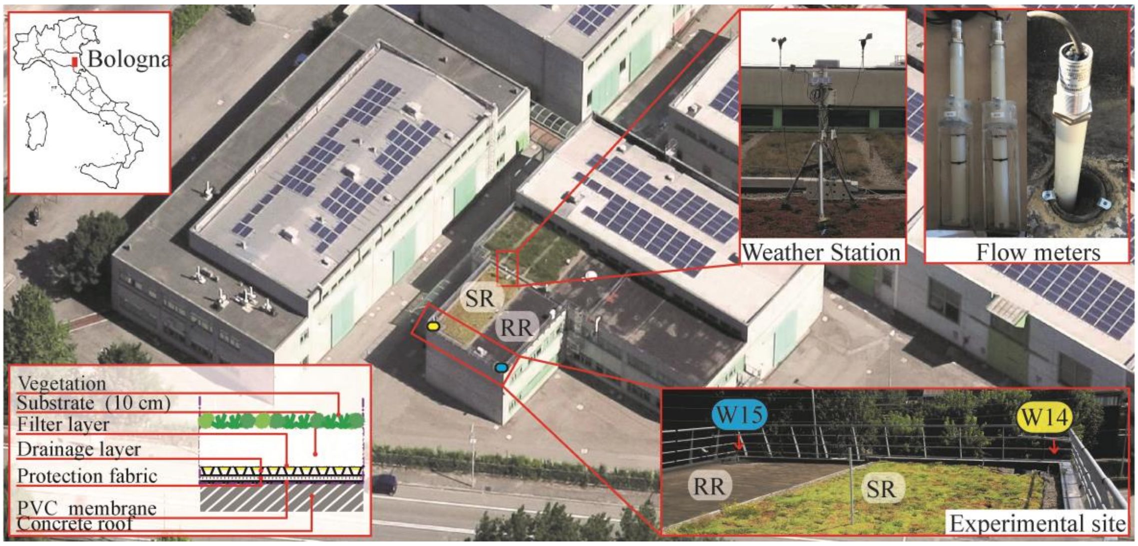


Fig. 1. Aerial view of the experimental site showing: the extensive green roof (SR) and the reference roof (RR), the position of the in-pipe flow meters (W15 and W14 respectively for RR and SR), the position of the weather station and the stratigraphy of the green roof.

2.2 Experimental setup and instrumentation

Each plot (SR and RR) has its own single, internal downspout (Fig. 1) and water cannot migrate from one plot to the other. Runoff from both plots was measured using two in-pipe flow meters, W14 and W15 for the SR and RR respectively (Fig. 1), designed at Columbia University (NYC) as those used in other studies (Carson et al., 2013; Hakimdavar et al., 2014) and directly connected to a HOBO Onset weather station. The aforementioned flow meters consist of a runoff chamber with an outlet weir and a Senix TSPC-30S1 ultrasonic sensor. The ultrasonic sensor detects the rise in water height and adjusts its output voltage accordingly. The voltage reading can then be related to a water flow rate by a calibration equation, to determine the runoff depth. The flow meters, the operating procedure and data transmission to the HOBO logger system is fully described in the study written by Carson et al. (2013). The Onset HOBO U30 weather station installed on site, above the GR plot, as showed in Fig. 1, records: rainfall, wind speed, gust speed, wind direction, relative humidity, atmospheric temperature, dew point, solar radiation and photosynthetically active radiation (PAR) at 5-minute intervals. Since May 2014, a Decagon's ECH2O sensor directly connected to the weather station, has monitored the volumetric water content of the soil by measuring the dielectric constant of the soil, which is a strong function of water content. Together with the sensor's data, this information is sent to a Wi-Fi data logger and an online platform, from which they can be easily accessed.

Single runoff events were defined following the procedure illustrated by other studies (Carson et al., 2013; Hakimdavar et al., 2014; Nawaz et al., 2015; Vanwoert et al., 2005): a storm event begins when rainfall is first recorded, with a minimum rain gauge sensitivity of 0.2 mm, and ends when no precipitation or runoff has been recorded for 6 hours. Afterwards, storm events were considered unsuitable for analysis and were discarded if they followed any of these unacceptability conditions: 1) the recorded peak runoff rate caused the depth of water behind the weir device face to exceed 90% of the notch height (in fact when flow rates exceed this amount, the turbulence within the runoff chamber could cause unreliable readings); 2) precipitation was in the form of snow; 3) the cumulative runoff exceeded total rainfall, and 4) the ultrasonic sensor lost power over the course of the storm event (see Carson et al. (2013) for more details).

Laboratory tests were performed to measure the physical properties and the water retention characteristics of the substrate. Tests included: particle size distribution, bulk density, particle density, porosity, water retention and hydraulic conductivity. Moisture release curves were determined using a WP4-T dew point meter (Decagon Devices, Pullman, WA) following the procedure illustrated by Bittelli and Flury (2009). To determine soil water fluxes in unsaturated soils, a common approach is to numerically solve the Richards equation, which generally requires the parametrization of the soil water retention curve (Bittelli and Flury, 2009; Campbell, 1985). The physical characteristics of the substrate and the parameters, obtained from the fitting with the modified van Genuchten-Mualenm model (Ippisch et al., 2006) of the water retention curve, are listed in Table 2, and the corresponding curves are shown in Fig. 2.

Fig. 2a shows the soil water retention curve, used to determine the Field Capacity (FC) at 0.01 bar suction and the permanent Wilting Point (WP) at 15 bar suction (as provided by the Italian standard (UNI EN 13041, 2012); while Fig. 2b shows the hydraulic conductivity curve used to obtain the saturated hydraulic conductivity (Ks).

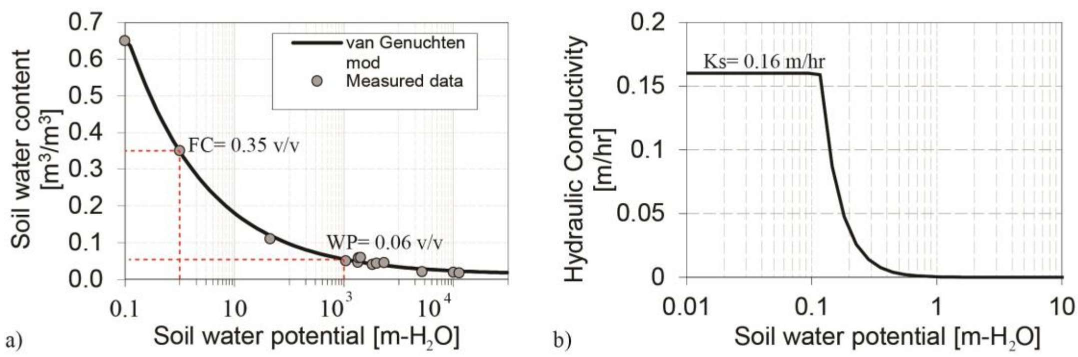


Fig. 2. Soil water retention curve (a) and hydraulic conductivity (b) for the 10 cm deep substrate (FC, field capacity at 0.01 bar suction; WP, wilting point at 15 bar suction; and Ks, saturated hydraulic conductivity).

Parameter	**System Unit**	**Substrate**
D_{50}	*mm*	6
Particle density, ρ_p	g/cm^3	2.70
Dry density, ρ_{dry}	g/cm^3	0.90
Porosity, n	*%*	62 %
Field capacity	m^3/m^3	0.35
Wilting point	m^3/m^3	0.06
Organic content	*%*	<4

Table 2. Substrate characteristics.

2.3 Climate analysis

The average rainfall in the city of Bologna fluctuates from around 400 mm to 1,000 mm a year. Most of the rainfall events usually occur in spring and fall. Although snow events are not uncommon, there was no snow during this case study monitoring period.

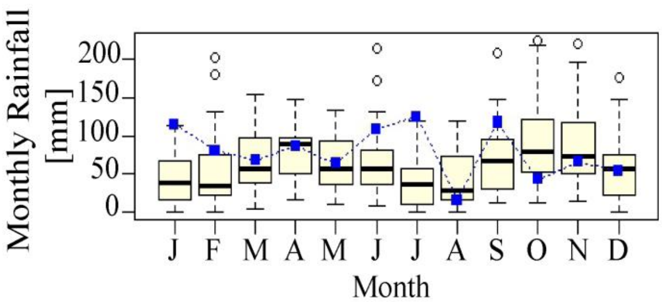


Fig. 3. Boxplot of the historical rainfall recorded over 26 years (1990-2015) for the city of Bologna. The bottom and the top of the box are the first and third quartiles, and the band inside the box is the second quartile (the median). The ends of the whiskers represent the lowest and the highest datum. Any data not included between the whiskers have been plotted as outliers. The blue trend line (square indicators) indicates the case study monthly rainfall depths for the monitoring period (from Jan/2014 to Dec/2014).

The climatic conditions gathered from the case study HOBO weather station over 12 months (January 2014 – December 2014) where compared to the historical data provided by the Regional Agency for Prevention, Environment and Energy in the Emilia-Romagna region, Italy (ARPAE, 2016). The variation of monthly rainfall, over 26 years (1990-2015), is shown in Fig.3 through the use of a box-plot for each month of the year, while the blue trend line (square indicators) shows the total monthly rainfall during the monitoring period. Overall, the rainfall data during the study period are consistent with the historical rainfall data. The cumulated monthly rainfall is above its average historical value for eight months out of 12, in particular summer 2014 was very rainy. During the months of June, July and September the rainfall was far above the median, while in August it was slightly below the median of the historical data.

3 EPA SWMM MODEL

3.1 Presentation of EPA SWMM

The EPA Storm Water Management Model (SWMM, version 5.1.010) was selected as the modelling platform for studying the hydrologic response of both the green roof and the conventional plot. SWMM is a dynamic hydrology-hydraulic and water quality simulation model that was primarily developed for urban areas allowing short and long-term simulations (Rossman, 2015, 2010).

LID control modules that provide detention storage, enhanced infiltration and evapotranspiration of runoff from localized surrounding areas (e.g. rain garden, bio-retention cell, permeable pavement, infiltration trench, etc.) have been implemented in SWMM to simulate the hydrological behaviour of such source control technologies since 2005 (Palla and Gnecco, 2015; Rossman, 2015; Versini et al., 2015). LID controls are represented by a combination of vertical layers whose properties (such as: thickness of the different layers, physical properties of the materials, and underdrain characteristics) are defined on a per-unit-area basis (Qin et al., 2013). This allows LIDs which differ in areal coverage only, and not in design, to be easily placed within different subcatchments in a study area (Palla and Gnecco, 2015).

To take into account the impact of climate data on the LID retention performance and compute the potential daily evapotranspiration, SWMM offers a climatology editor function with a single set of time-dependent temperatures applied throughout the study area (Rossman, 2015). Maximum and minimum daily temperatures and the study area's latitude are used by the software to compute the potential evapotranspiration applying the Hargraves method (Hargreaves and Samani, 1985), fully illustrated by Rossman (2016, 2015).

3.2 Modelling the green roof plot using the SWMM LID modules

Starting from version 5.1 (2014), the SWMM software is equipped with an additional LID module for GR modelling, "Green Roof" LID Type (GR-LID), which is a variation of a "Bio-Retention Cell" LID Type (BRC-LID). Generally, LID Controls are defined and assigned to subcatchments through a series of three different editor forms: i) The LID Control Editor, ii) the LID Group Editor and, iii) LID Usage Editor.

The LID Control editor is used to define a low impact development control that can be deployed throughout a study area to store, infiltrate, and evaporate subcatchment runoff (such as: bio-retention cell, rain garden, green roof, infiltration trench, permeable pavement, rain barrel, or vegetative swale). The LID Group Editor is used to add any type of LID controls to a specific subcatchment. Finally, the LID Usage Editor is used to describe how each LID control added to a LID group is deployed within the group's subcatchment. It is nested under the LID Group Editor to be able to specify the areal extent of the control, the portion of the subcatchment's runoff that it treats, and for some LID the "% Initially saturated" which define the degree to which the unit's soil is initially filled with water.

A GR-LID is composed of three layers: surface (vegetation), soil (substrate), and drainage material, while the BRC-LID differs because of the presence of two layers (storage and drain) instead of the drainage material only. The main difference between these LID types is that in the GR-LID the drain system is design-based, while in the BRC-LID it is performance-based (Rossman, 2016).

Palla and Gnecco (2015) demonstrate that a GR-LID can be successfully used for modelling the hydrological behavior of a GR, by using the property of the soil as calibration parameters and by fixing, as initial condition, the soil moisture content of the LID before each simulated event ("% Initially saturated" parameter). However, when the geometry of the drainage material is not standard, when all the physical properties of the layers are measured in laboratory, and last but not least when the degree of saturation of the LID before each storm event is automatically calculated by the model, as in a long-term simulation, the only way to regulate the outflow is the calibration of two parameters of the drain layer of a BRC-LID called "Drain coefficient" and "Drain exponent". Through these two parameters the software determines the flow rate through the drain itself (Rossman and Huber, 2016).

Based on the above considerations, in the present study the full-scale GR has been modelled by coupling two LID modules: i) a bio-retention cell for the GR system, and ii) a porous pavement for the gravel strip, both LID modules fully occupy the respective subcatchment.

As recommended by several authors (Alfredo et al., 2010; Burszta-Adamiak and Mrowiec, 2013; Mrowiec et al., 2014; Zhang and Guo, 2014), the SWMM LID model (SR surface) and the SWMM model (RR surface) have been calibrated and validated based on the experimental monitoring data.

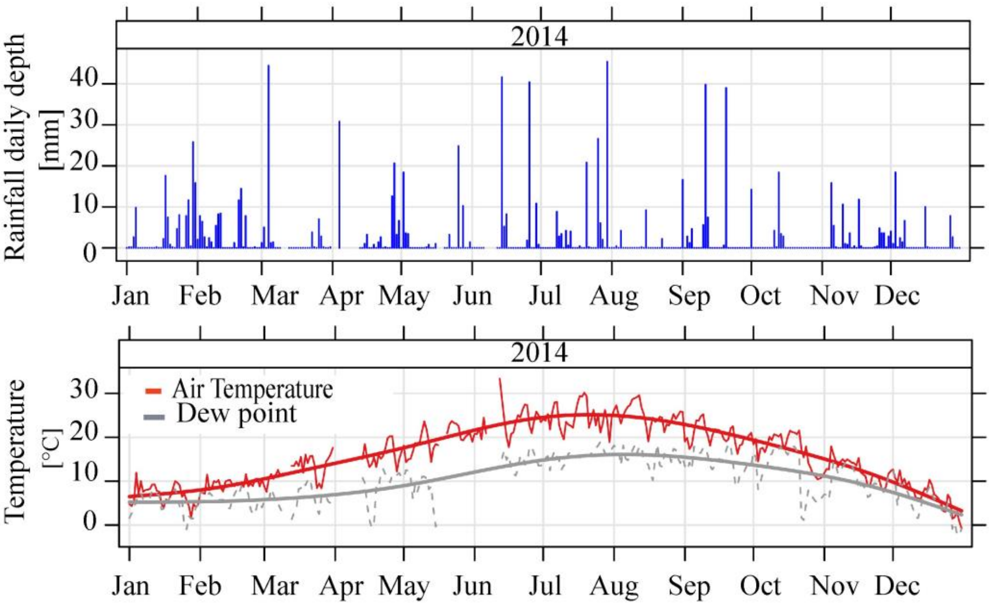


Fig. 4. Data acquisition during year 2014: cumulative daily rainfall (mm) (top), average hourly air temperature (°C) and dew point (°C) (bottom).

3.3 Input data

The rainfall and air temperature recorded by the on-site HOBO weather station in 2014, were used as input data to calibrate and validate the model. Fig. 4 shows the daily distribution of rainfall and the hourly average air temperature over year 2014.

In order to simulate the evapotranspiration process in a GR which is responsible for decreasing the substrate moisture content and thus for restoring the retention capacity of a GR (Berretta et al., 2014), the climatology editor of SWMM was set up. The software automatically applies an empirical formula (Hargreaves and Samani, 1985) for estimating potential daily evapotranspiration (ET_0) that depends on daily air temperature and solar radiation at the study site. However, potential evapotranspiration (ET_0) differs from real evapotranspiration (ET_r) because the first is related to a reference crop, which can be either grass or alfalfa (Hargreaves et al., 1985), and is affected only by climatic parameters, while the second is influenced by the type of plants, crop characteristics and cultivation practices (Allen et al., 1998). In the case of GRs, the real evapotranspiration may deviate from ET_0 due to the use of a non-standard plant (sedum) and of non-optimal conditions, such as low soil fertility, water shortage or waterlogging. To take into account this, in the present study the Hargreaves equation was adapted to the SR case specifying a monthly soil recovery pattern (Table 3), whose factors, multiplied by ET_0, transform ET_0 in ET_r and then adjust the rate at which infiltration capacity is recovered during periods with no precipitation.

Month	Value
January	0.05
February	0.05
March	0.15
April	0.60
May	1.00
June	1.15
July	1.15
August	1.15
September	0.30
October	0.20
November	0.15
December	0.05

Table 3: Monthly soil recovery pattern.

These coefficients were found through a procedure which takes into consideration, in similitude with the study done by Berretta et al. (2014), the experimental measurements of the substrate moisture content during dry periods and the comparison with simulated moisture content using a hydrologic model based on water balance and on the Hargreaves ET_o model. Altogether, these coefficients incorporate mainly crop characteristics and averaged effects of evaporation from the soil over the length of the growing season (Cipolla, 2015).

3.4 Calibration and validation procedures

Model calibration and validation is based on the comparison of the observed and modeled runoff flow rates. In order to assess the model performance on an event basis, the RMSE-Observation Standard Deviation Ratio (RSR) was calculated. The RSR is the ratio of the root mean square error (RMSE) to the standard deviation of measured data, and varies from the optimal value of 0, to a large positive value (Moriasi et al., 2007). Lower values of RSR correspond to lower RMSE values and to a better model simulation performance. Furthermore, the Nash–Sutcliffe Efficiency index (NSE) was evaluated to quantitatively assess the model accuracy in reproducing the runoff flow rate on an event basis (Nash and Sutcliffe, 1970).

4 RESULTS AND DISCUSSION

4.1 Hydrological Experimental Observations

Rainfall and runoff were continuously collected from 01/01/2014 to 31/12/2014 for the SR plot, whereas only from 01/01/2014 to 31/05/2014 for the RR.

The monitoring campaign resulted in 69 and 23 valid runoff measurements, from the original 122 storm events recorded, respectively for the SR and RR. Unfortunately, after 3 months of data collection, the W15 flow meter had a malfunction which temporary interrupted the recording of runoff data, thus a statistical analysis of those data will not be presented.

The measured rainfall depth of the 69 storm events, that generated a valid runoff measurement for SR, ranged from 0.2 to 41.6 mm, while the normalised runoff varied from 0 to 33.1 mm. Rainfall attenuation of individual events ranged widely from 6.4% to

100%. The total number of storm events that generated zero runoff was 34 out of which 19 had a rainfall depth higher than 0.2 mm; the largest event with 100% retention was 7.8 mm (26/03/2014). During the monitoring period the SR has demonstrated a retention capacity of 51.9% of the total rainfall volume from suitable events. This may be compared to the previously-published annual retention data for similar GRs (Table 1). From a range of studies, including only full-scale installation with 10 cm of substrate depth, the retention capacity ranged between 12% and 74% (Berkompas et al., 2008; Carson et al., 2013; Hutchinson et al., 2003; Liu and Minor, 2005; Moran et al., 2005; Spolek, 2008). The performance of the Bologna full-scale GR falls slightly above the average value (46.7%) of previously reported data (Table 1).

4.2 Calibration and validation results

The experimental site was simplified in 3 subcatchments: two for simulating the SR plot and one for the RR, 4 junctions, 2 outfalls, and 4 conduits.

The model was calibrated over 6 events (2 for the RR and 4 for the SR), reported in Table 4, and was verified by simulating a complete 1 year (2014) data period and then validated with 6 rain events (2 for the RR and 4 for the SR) spread out along the year.

The experimental rainfall time series were analyzed against Bologna historical records obtained from the Regional Agency for Prevention, Environment and Energy in the Emilia-Romagna region, Italy (ARPAE, 2016). Fig. 5 compares all the 69 monitored events (SR plot) in terms of total rainfall depth and duration (red hollow circles) to the relevant Intensity-Duration-Frequency (IDF) curves taking into account the event return periods found using the historical data. The majority of the events fall below the 2 year return period threshold, as happened in other similar studies (Stovin et al., 2012), with 4 events with a return period bigger than 2 years. The rainfall record contains a reasonable distribution of short and long-duration events. The black and grey indicators in Fig. 5, show the events used for calibration and validation for the SR and RR model respectively.

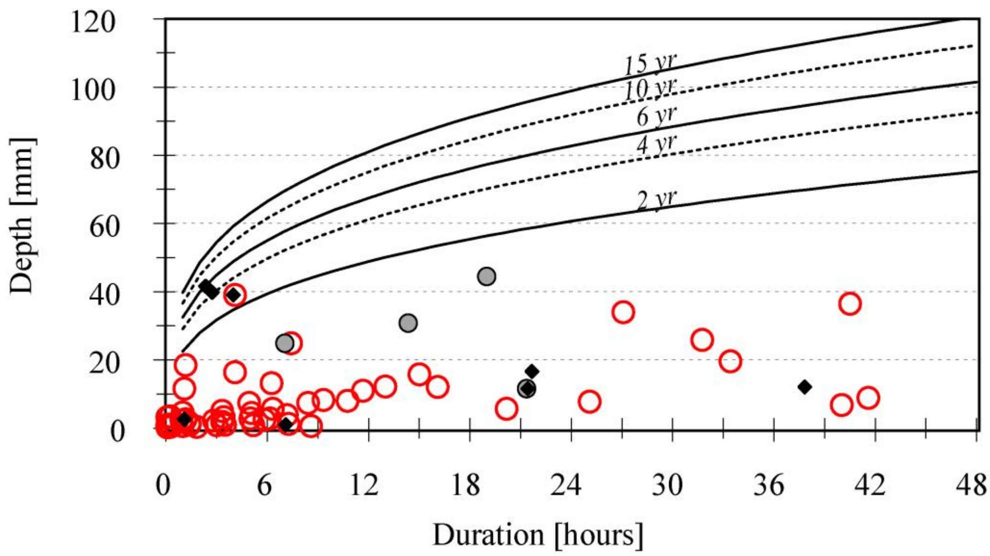


Fig. 5. Rainfall characteristics for the 12 month data series compared with the IDF return period curves estimated for Bologna. The black and grey full indicators show the events used for calibration and validation for the SR and RR model respectively.

For the events chosen for calibration and validation the rainfall characteristics are summarized in table 4 in terms of rain duration, rainfall depth, peak intensity and return period.

The 12 storms vary widely (Table 4), ranging in duration from 65 minutes to almost 37 hours and in depth from 2.6 to 44.4 mm. Pursuing the purpose of observing the behaviour of the model under different weather conditions, the calibration/validation events have been chosen in different seasons of the year and with a wide range of rainfall intensity and return period.

Plot	Events Date [dd/mm/yy]	Rain Duration [min]	Rainfall depth [mm]	Peak 5-min Intensity [mm/h]	Return period (year)					
					Event	0.5 h	1 h	3 h	6 h	12 h
RR	19/02/14[C]	1282	11.6	16.8	<2	<2	<2	<2	<2	<2
	04/03/14	1140	44.4	9.6	<2	<2	<2	<2	<2	<2
	04/04/14[C]	860	30.8	38.4	<2	<2	<2	<2	<2	<2
	26/05/14	440	24.8	88.8	<2	<2	<2	<2	<2	
SR	10-12/02/14[C]	1300	16.6	9.6	<2	<2	<2	<2	<2	<2
	22/04/14	65	2.6	12.0	<2	<2	<2	<2	<2	
	14/06/14[C]	140	41.6	168.0	6	48	14	5		
	11/09/14	165	39.8	48.0	4	<2	4	4.5		
	20/09/14[C]	240	39	69.6	4	3	3	4	2	
	10-11/11/14	1285	11.6	9.6	<2	<2	<2	<2	<2	<2
	17-18/11/14[C]	2270	12	4.8	<2	<2	<2	<2	<2	<2
	03/12/14	425	1	2.4	<2	<2	<2	<2	<2	

Table 4. Rainfall characteristics for the calibration/validation rainfall events. The superscript 'C' denotes the calibration events.

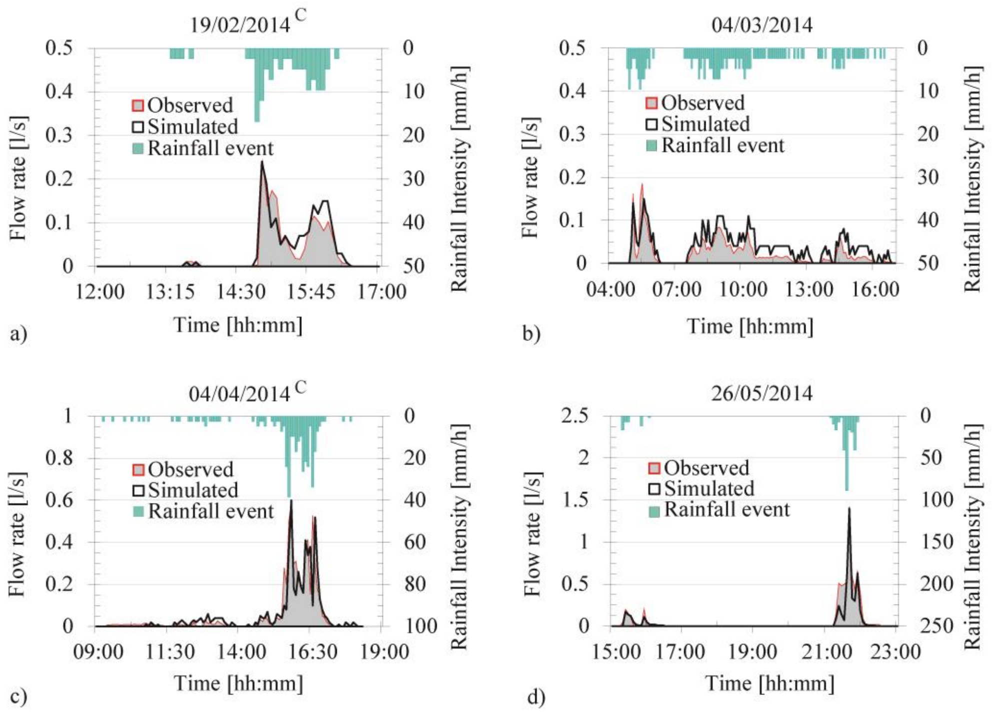


Fig. 6. Rainfall hyetographs and the corresponding measured runoff (grey area) compared to the simulated runoff (black line) for RR during 2 events used for calibration and 2 validation events. The

events correspond to: a) February 19th, 2014, b) March 4th, 2014 c) April 4th, 2014 d) May 26th, 2014. The superscript 'C' denotes the calibration events.

4.2.1 The RR surface model

The RR model is calibrated and validated based on 4 events, measured by the on-site W15 flow meter and collected between February and May 2014; the February 19th, 2014 and the April 4th, 2014 events were selected for the calibration phase. The rainfall intensity, the observed and the modeled flow rates for the selected calibration and validation events are shown in Fig. 6. While the calibrated SWMM parameters (Depression depth, N Manning and % Zero-Imperv) are reported in Table 5.

SWMM Parameter	SU	Values
Depression depth	mm	1
N Manning	-	0.011
% Zero-Imperv	%	5

Table 5. Parameters assigned in the SWMM RR model.

Fig. 6a and Fig. 6c show the rainfall hyetograph and the corresponding simulated and observed runoff for the two calibration events. The model reproduces with good matching capabilities the complex-shape (multi-peaks) outflow regime for both low (< 20 mm/h) and average (< 40 mm/h) rainfall intensities. The model is able to accurately reproduce the timing and the magnitude of the peak flow rate. NSE values (see Table 6) are greater than 0.7 confirming the suitability of the model to describe the hydrologic response of a traditional impervious roof, while the low value of RSR (0.36) indicates a good model performance. Fig. 6b and Fig 6d show the rainfall hyetograph and the corresponding simulated and observed runoff for the validation events. The model provides a good description of the runoff response (Fig.6b and Fig. 6d) both in terms of shape and peak of the outflow hydrograph. NSE and RSR values (see Table 6) are good for the 26/05/2014 event while the performance of the model decrease for the 04/03/2014.

Plot	Events Date (dd/mm/yy)	NSE (-)	RSR (-)
RR	19/02/14[C]	0.87	0.36
	04/03/14	0.41	0.77
	04/04/14[C]	0.72	0.36
	26/05/14	0.85	0.35
SR	10-12/02/14[C]	0.58	0.65
	22/04/14	0.60	0.63
	14/06/14 [C]	0.66	0.59
	11/09/14	0.85	0.39
	20/09/14[C]	0.93	0.27
	10-11/11/14	0.44	0.75
	17-18/11/14[C]	0.61	0.62
	03/12/14	0.76	0.49

Table 6: Nash–Sutcliffe Efficiency (NSE) index and Observation Standard Deviation ratio (RSR) of the total effluent volume for the observed rainfall events used for the calibration and validation. The superscript ‘C’ denotes the calibration events.

4.2.2 The SR green roof model

The SR numerical model is developed by coupling two LID modules, as explained in section 3.2. The model is calibrated based on experimental rainfall/runoff data collected in 2014 for the full-scale SR. Table 7 shows the parameters required by the bio-retention cell and the permeable pavement LID control modules. The SR model is calibrated and validated based on 8 events measured by the W14 flow meter and collected between February and December 2014 (Table 4 and Table 6).

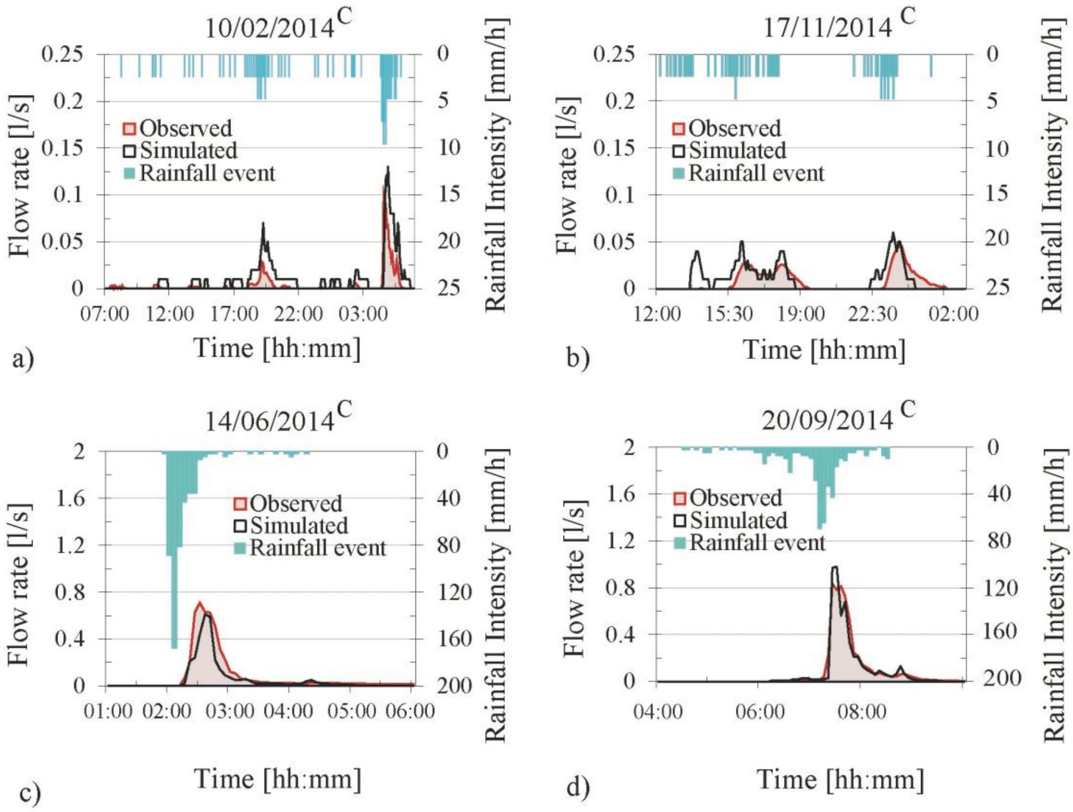
Burszta-Adamiak and Mrowiec (2013) affirm that the main parameter influencing the simulation results of a LID is called "% Initially saturated" (specified in LID Usage Editor). For each LID type this parameter expresses the degree to which the unit's substrate is initially filled with water (0% saturation corresponds to the wilting-point moisture content, 100% saturation has the moisture content equal to the porosity). Also Palla and Gnecco (2015) recognize the importance of this parameter by doing a sensitivity analysis to understand how the uncertainty in the outflow (such as volume, peak and shape) can be apportioned to different sources of uncertainty compared to the initial moisture content value. Pursuing the goal of reducing the dependence of the model on this parameter, its value was set equal to 100%, as initial condition. This means that it is the model itself that, as a function of the weather data and of the ET rate, estimates the degree of saturation of LIDs before a rainfall event. This assumption generates a runoff rate during the first day (01/01/2014) of the long-term simulation, which disappears from the second day forward. Furthermore, during the second day of simulation (02/01/2014) the substrate moisture content in the model has a value equal to the field capacity (0.35 v/v), which is coherent with the results of on field moisture content measurements made in January 2014 and 2015 by the authors.

Layer	**Parameter**	**SU**	**Bio-retention Cells**	**Permeable Pavement**
Surface	Berm Height	mm	3	3
	Vegetation Volume Fraction		0.15	0
	Surface Roughness	$m^{1/3}/s$	0.2	0.02
	Surface Slope	%	0.5	0.5
Pavement	Thickness	mm	-	100
	Void Ratio		-	0.4
	Impervious Surface Fraction		-	0
	Permeability	mm/h	-	3000
	Clogging Factor		-	0
Soil	Thickness	mm	100	-
	Porosity	%	0.65	-
	Field Capacity	m^3/ m^3	0.35	-
	Wilting Point	m^3/ m^3	0.06	-
	Conductivity	mm/h	160	-
	Conductivity Slope		5	-
	Suction Head	mm	25	-
Storage	Thickness	mm	25	25
	Void Ratio		0.5	0.5
	Seepage Rate	mm/h	0	0
	Clogging Factor		0	0

Underdrain	Drain Coefficient		2	0.15
	Drain Exponent		2.1	1.6
	Offset Height	mm	3	3

510 **Table 7:** Parameters assigned in the SWMM model-LID control section for the GR (modelled as a bio-

511 retention cell) and for the gravel stripe (modelled as a permeable pavement).



512

513 **Fig. 7**: The rainfall hyetographs and the corresponding measured runoff (grey area) compared to the

514 simulated runoff (black line) for SR during 4 events used for calibration. The events correspond to: a)

515 February 10th, 2014; b) November 17th, 2014; c) June 14th, 2014 and d) September 20th, 2014.

516 The hyetographs, the corresponding measured and simulated hydrographs for the four

517 calibration events are illustrated in Fig. 7, while the NSE and the RSR index for both

518 calibration and validation events are reported in Table 6. During the calibration phase the

519 SR model showed a good ability in reproducing the complex-shape outflow, in particular

520 the magnitude and the timing of the peak flow rate were accurately predicted in all the

521 seasons (Fig. 7), as confirmed by NSE values >0.58 and RSR <0.65. Results of the

validation procedure confirm the suitability of the model in reproducing the outflow: not only the mean NSE value is 0.66 (standard deviation 0.032) for the four validation events, but also the average RSR is 0.56 (standard deviation 0.025); those values clearly reveal the model accuracy in predicting the outflow of the full-scale GR.

4.3 Long term simulation in SWMM

Once the RR and SR models were calibrated and validated on experimental measurements of rainfall and relative runoff, a one-year simulation was launched. Summarizing from above, the input data were: the rainfall data with a 5-minute time step, the maximum and minimum daily temperatures, the latitude of the site, and a set of monthly soil recovering coefficients (Table 3). In addition, the LID modules were considered fully saturated, as initial condition.

Predicted cumulative runoff at the SR plot is in good agreement with the experimental measurements. The cumulative outflow volume of the 69 measured events, was in fact only 9% lower than the discharge volume obtained through the SWMM modeling, which proves the ability of the model in predicting the overall hydrological process. Fig. 8 shows that in winter (Jan-Mar 2014), the difference between the runoff from RR and SR is minimal. This is certainly due to the fact that the substrate moisture content never drops below the field capacity. The cumulative annual water balance is displayed in Fig. 8 for the SR and RR plots respectively. The simulated cumulative runoff volumes were 48.1 m^3 and 27.7 m^3, respectively for RR and SR, and correspond to an annual retention of 11% and 48%. The cumulative retention results demonstrate that the SR, despite having only 10 cm of substrate depth, can make a significant contribution in reducing the total volume of stormwater that might otherwise impact watercourses, require treatment or flood the city.

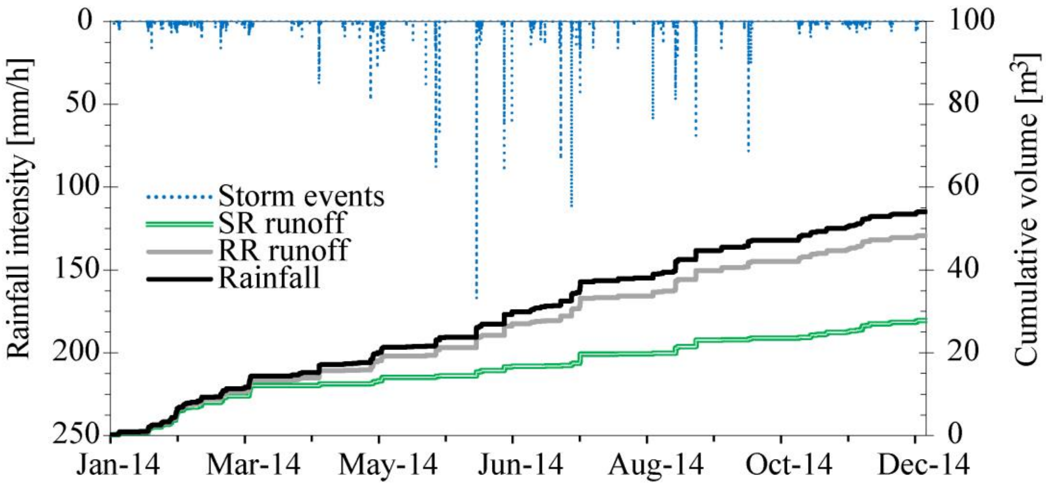


Fig. 8. Storm events (blue line), cumulative rainfall (black line) and cumulative simulated runoff from the conventional RR (gray line) and the green roof SR (green line).

5 CONCLUSION

GRs are becoming one of the key technologies for achieving a sustainable urban drainage system; however, their level of performance is very site specific because of the impact of the layer materials, vegetation, physical properties of the substrate, design specification and climate conditions. Furthermore, the hydrological performance of a GR is strongly influenced by the size of the studied plots (full-scale vs small scale), the definition of "event", and the number of events included in the study (Carson et al., 2013).

Experimental studies have the ability to narrow the gap between hydrological model simulations and reality, especially if performed on full-scale green roofs with the support of field data monitoring.

Given the above, this study first provided an accurate review of the scientific literature, with a focus on experimental studies on full-scale installation. Previous studies found that the annual retention volume can range from 11.0 % to 76.4 % with an average retention value of 46.7% (Table 1). In addition, the study provided a synthetic literature review about hydrological models in this field, which also underlined the difficulty of complete numerical models in long terms simulations.

The second part of the study was devoted to the description of the experimental site and instrumentation. The results of the monitoring campaign performed from January 2014 to December 2014 were later used to calculate the experimental green roof's (SR) annual average retention, found to be 51.9 %. This value falls in the average range of the values indicated by previous studies (Table 1).

Finally, the study described a numerical model realized by means of SWMM 5.1, which was calibrated and validated using field measurements and then used to simulate the long term hydrologic response of two adjacent experimental surfaces of the same size: an impervious and a green full-scale roof. Modelling results confirmed the role of GRs in restoring the natural regime reducing the annual runoff volume. The comparison of the results obtained for the experimental green roof SR to the SWMM simulation results proved that the suggested model has good capabilities in correctly simulating the hydrograph of storm water runoff from GRs along the year. This is confirmed by the quite high values of NSE and the low values of RSR obtained in both the calibration and validation phases. Furthermore, the low difference (< 9%) in total retention between the 69 measured and simulated events confirms the suitability of the model for long-term simulations.

The proposed modelling approach demonstrated that SWMM can be suitably used for assessing the continuous LID performance, and consequently for supporting local authorities or designers in the evaluation of the hydrological efficiency of green roofs.

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