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Analysis of potential benefits on flood mitigation of a CAM green roof in Mediterranean urban areas

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A B S T R A C T

In the last decades, green roofs have been proposed among several nature-based solutions, as promising and sustainable tools to mitigate urban flood risk and adapt to climate changes. Several vegetation types have been suggested as green roof top layers, depending on the region and the purpose of the roof. In a Mediterranean climate, the Crassulacean Acid Metabolism (CAM) vegetation represents a particularly advantageous choice for green roofs since it does not require artificial irrigation and maintenance. However, the flood mitigation performance of CAM green roofs has not been investigated as adequately as other vegetation types. In this framework, we aim to define the potential retention capacity of a no maintenance-cost spontaneous CAM green roof, located at the entrance of the University of Cagliari (Italy) and to compare it to C3 vegetation type. The structure has been equipped with gauges to measure the water fluxes in and out of the roof. Local observations are used to calibrate a conceptual ecohydrological model. A 51-year rainfall time series and corresponding potential evapotranspiration are then used to simulate and compare the relative performance of green roofs vegetated with spontaneous CAM and more common C3 plants. Results show the good performances of the CAM green roof in mitigating rainfall extremes, with an average retention capacity of 0.52 over the whole investigated period, while C3 presents an index of retention equal to 0.71, but it requires frequent irrigation. Moreover, this work highlights some potential economic and environmental benefits of CAM green roof implementation in Mediterranean areas.

1. Introduction

In Mediterranean areas, climate change is leading to an increase in intense precipitation extremes in winter [1–4]. In the last decades, several solutions have been proposed to mitigate urban flood risk and to adapt to climate changes [5–8]. Green roofs have been introduced, among nature-based solutions, as a sustainable tool to mitigate the rainfall extreme effects and improve the water management [9–11]. Indeed, green roofs contribute to mitigating the flood generation, storing rainfall in the soil substrate and delaying the runoff peak generation [12–15].

Installation of green roofs in urban and densely populated areas offers several benefits besides the runoff generation mitigation [16–18]. They can help to increase biodiversity, attracting insects and small animals. In addition, the activation of a latent heat flux component contributes to the energy saving of the building, limiting the cooling requirements [19,20], while reducing the warming of the surrounding environment [18,21]. Green roofs can help prevent and reduce pollution [22], retain zinc and other contaminants from rainfall, and they have shown to be a sustainable solution compared to other roof solutions, such as self-protected roofs, gravel finishing roofs and floating flooring roofs [23]. Finally, green roof solutions enhance the aesthetic values of the urban area and contribute to improving the life quality of citizens [24].

The green roof installation, however, might be constrained by structural limitations, especially in old buildings, where the roof stability and mechanical resistance need to be carefully evaluated (Santos, Tenedório, and Gonçalves 2016). Moreover, most green roofs need constant maintenance and irrigation, with consequently high management costs.

Green roof structures can generally be classified as intensive or extensive. A thick substrate layer, that varies between 20 cm and 200 cm characterizes intensive green roofs, while extensive green roofs present a thin soil layer (smaller than 20 cm). Installation of extensive green roofs is easier, cheaper and more flexible than intensive green roofs and maintenance is less expensive [17]. The substrate depth has showed to

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have a strong influence on the retention capacity of green roofs, with a general increase in performance from extensive to intensive settings [14,25].

Different vegetation types are used as green roof top layers [26]. Native vegetation is usually preferred for several reasons [17]: (a) it is already adapted to the local climate conditions [27]; (b) it can help restore native ecosystems, attracting native species of various animals; (c) it increases the biodiversity of the ecological system. The most common plants chosen as green roof top layers are characterized by a C3 metabolism, in which the CO_2 is fixed into a compound containing three carbon atoms before entering the Calvin cycle of photosynthesis. C3 plants, e. g. lawn grasses and herbs, show high evapotranspiration rates and show good retention capacities and flood mitigation performances [15]. In arid and semi-arid areas, C3 plants require frequent artificial irrigation, thus Crassulacean Acid Metabolism (CAM) vegetation can be alternatively considered as a green roof top layer, since it presents a low evapotranspiration rate, due to the diurnal stomata closure, and it does not require irrigation to survive even in very arid environments. A drawback is that the metabolism of this vegetation type gives a smaller contribution to the air quality improvement and to the heat island reduction with respect to C3, since the evapotranspiration mechanisms are mainly active during the night. Among CAM vegetation, sedum species are the most common plants for extensive green roofs, thanks to their shallow roots and high capability to store water [17]. This contributes to low maintenance costs, with consequently high potential affordability and sustainability in Mediterranean urban areas. However, flood mitigation performances of CAM green roofs need further and more in-depth investigations, and in particular, the comparison to other vegetation types needs to be evaluated better. Several modelling approaches have been proposed to simulate green roof performances, based on the development of conceptual models [25,28–31] or on commercial software [32,33]. Indeed, hydrological models can offer a valid support to understand the behaviour of green roofs in different conditions.

In this work, we investigate the retention performance of a CAM green roof at building scale in an urban context and compare it with C3 vegetation, characterized by a higher evapotranspiration rate and higher maintenance costs. Analysis will be developed with the help of the conceptual lumped Ecohydrological Streamflow Model (EHSM), proposed by Refs. [31]. This model will be calibrated using field data gathered on a CAM green roof located at the University of Cagliari (Italy) and then used to simulate the green roof retention performance with different vegetation types. A 51-year historical rainfall time series (from January 1, 1947 to December 31, 1997) and a related evapotranspiration rate will be used as input to the aforementioned conceptual model. A performance analysis will show the potential of CAM green roofs, highlighting the lower maintenance costs in comparison to C3 vegetation.

The paper is structured as follows. Section 2 presents the conceptual ecohydrological model chosen for this study, highlighting the parameters involved. The CAM green roof located at the University of Cagliari (Italy) and rainfall and outflow measurements are described in Section 3. Section 4 explains the calibration of the EHSM model based on field data recorded on the CAM green roof in Cagliari and describes the index used to evaluate the roof retention performances. Calibration results are presented and discussed in Section 5, where the comparison between CAM and C3 green roofs is investigated in detail. Here, the behaviour of both green roofs is simulated over a long time series and their performances are evaluated.

2. Methodology

2.1. Model description

To investigate the retention and rainfall peak mitigation performances of green roofs at daily scale, the Ecohydrological Streamflow Model (EHSM) proposed by Ref. [31] is used in this work. EHSM is a parsimonious conceptual lumped model, based on water balance, developed to simulate the daily streamflow in semi-arid areas. Although the model was built for natural river basins, parameters can be calibrated in order to represent the hydrological behaviour of green roofs, following the approach presented by Ref. [14,25].

The EHSM is made of a soil bucket and two parallel linear reservoirs. The two reservoirs present different input sources: the first one is fed directly by the rain, while the second receives water from instantaneous leakage pulses coming from the soil bucket. Rainfall and the potential evapotranspiration rate constitute the numerical input of the model, representing the external climatic forcing. Rainfall and the potential evapotranspiration rate are given as time series at daily scale. The EHSM has seven lumped parameters to describe soil characteristics, the top layer and the two linear reservoirs. To describe the soil characteristics, the model uses the active soil depth (nZ_r), which is the product of soil depth and porosity, the soil moisture values triggering the leakage (S_{fc}), and the hygroscopic point (S_u). The fraction of impervious area (C) and the vegetational coefficient (K_c) describe the top layer, while the linear reservoirs are fully defined by the 2 constants K_{sup} and K_{sub}, which are the inverse of the mean residence time of water particles within each conceptual system. These model parameters were calibrated based on the measurements from the CAM green roof located at the University of Cagliari (Italy).

The model simulates soil moisture dynamics, which in turn influence evapotranspiration rates. When soil moisture is not limiting, evapotranspiration coincides with the potential evapotranspiration ETp, while, when soil dries up, evapotranspiration is linearly reduced to zero. ETp is defined as the combination of potential evapotranspiration from a standardized vegetated surface $ET0$ and the vegetation coefficient K_c that characterizes the vegetation type.

$$ETp = ET0 * K_c$$

2.2. Index of retention ***IOR***

The retention performances of the green roof are evaluated with the Index of Retention (IOR) defined as:

$$IOR = 1 - \frac{h_{out}}{R}$$

where R is the rainfall depth and h_{out} is the water depth that flows out of the green roof. IOR represents the portion of rainfall that is retained from the vegetated roof and it can vary between 1 (in the case of complete retention) and 0 (when there are no mitigation effects). This index can be estimated at daily scale, event scale or considering a multiyear time series.

The factor IOR_{xx} was defined as the retention percentage computed on N rainfall events with rainfall intensity exceeding the xx%-quantile of the cumulative probability distribution of non-zero rainfall daily time series.

$$IOR_{xx} = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{hxx_i}{Rxx_i}\right)$$

This factor was derived at daily scale for the 75% and 95% cumulative probability. The IOR_{95} was estimated, following the definition given by Refs. [25]; in order to investigate only the extreme rainfall events, focusing on the ability of the green roof in mitigating the rainfall peaks. On the other hand, the IOR_{75} was here introduced in order to explore a wider range of rainfall events, including the medium-intensity rainfall events. IOR_{95} corresponds to an average measure of the water storm attenuation, due to infiltration losses, during extreme rainfall events, while IOR_{75} quantifies the storm attenuation for common rainfall events.

3. Study case

The behaviour of an intensive green roof, located at the entrance of the Engineering Faculty at the University of Cagliari (39.228614°N, 9.110513°E, Fig. 1(a)) has been investigated, with the aim to identify its flood mitigation capability. The city of Cagliari is characterized by a Mediterranean climate, identified as *Csa* (temperate climate, with hot and dry summers) by the Köppen–Geiger climate classification system [35]. Average annual rainfall is around 500 mm, mainly concentrated in winter.

The green roof was built in 1980 for architectural and aesthetical purposes and only in 2016 was equipped with sensors in order to investigate the hydrological behaviour. The green roof is made of 2 hydraulic-independent twin modules of 48 m^2 (16 m × 3 m, as shown in Fig. 1(b)), for a total surface of 96 m^2. The green roof twin modules are covered with several American Agave plants, characterized by CAM metabolism, which have spontaneously grown, without artificial irrigation or maintenance. The soil layer presents a thickness of 30 cm and from a granulometric analysis (Fig. 1(c)) it was classified as sand, according to the Unified Soil Classification System (USCS).

The green roof was equipped with gauges for rainfall and outflow measurements. Kalyx-RG rain gauges (UM-780-700), produced by Environmental Measurements Limited (EML), with 0.2 mm resolution and 99% accuracy up to 120 mm/h, have been located over the roof top of the Engineering Faculty of the University of Cagliari. Water that is not retained by the green roof and that flows out from each module is collected and delivered through a gutter channel to a Kalyx-RG rain gauges (UM-780-700), situated on the ground (Fig. 2 for details). The outflow is recorded with a 5-min time step.

Rainfall and outflow observation, aggregated at daily scale, are plotted in Fig. 3. The twin modules present similar behaviour and the small differences between outputs are due to temporary failure of one module. Rainfall and outflow time series recorded from October 2018 to September 2019 are used to investigate the retention capacity of the green roof and provide the input to calibrate the hydrological conceptual model.

Six major events have been selected from the available time series for the period October 2018–September 2019. We assume that the beginning of each event coincides with the beginning of the rainfall event, while the end corresponds with the end of the outflow. The main characteristics of the selected rainfall events, ordered in terms of total rainfall depth, are presented in Table 1.

Monthly average potential evapotraspiration $ET0_i$ data were provided by the *Agenzia Regionale* per *la Protezione dell'Ambiente della Sardegna* (ARPAS, Regional Agency for the Environment Protection in Sardinia) for the city of Cagliari during the calibration period, for each month *i* from October 2018 to September 2019. In order to evaluate $ET0_i$ for simulation purposes (1947–1997), the Thornthwaite equation was applied [36], using monthly average temperature T_i, obtained from the same Agency, with the following equation:

$$ET0_i = 16.2 b_i \left(\frac{10 T_i}{I} \right)^a$$

where b_i is a parameter depending on the hours of astronomic bright sunshine in month *i*. The coefficients *I* and *a* are estimated with the following expressions:

$$I = \sum_{m=1}^{12} \left(\frac{T_m}{5} \right)^{1.15}$$

$$a = 0.5 + 0.01\ I$$

where T_m is the historical monthly average temperature for the city of Cagliari.

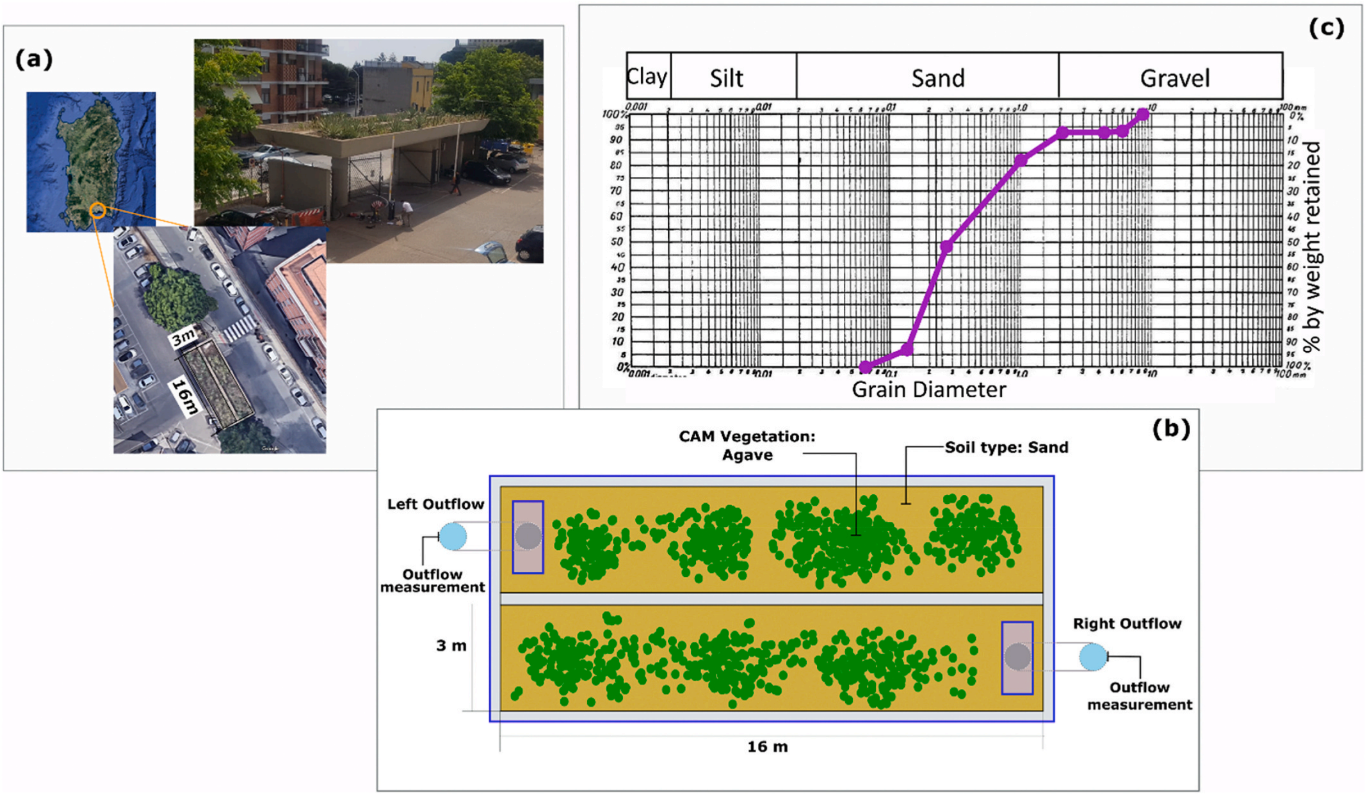

Fig. 1. (a) Location of the CAM green roof at the Engineering Faculty of the University of Cagliari. (b) Schematization of the twin module CAM green roof. (c) Granulometric curve derived from a sample of the green roof soil, based on [34] scheme. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 2. (a) Top view of the green roof and (b) detail of the water outflow measurement system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

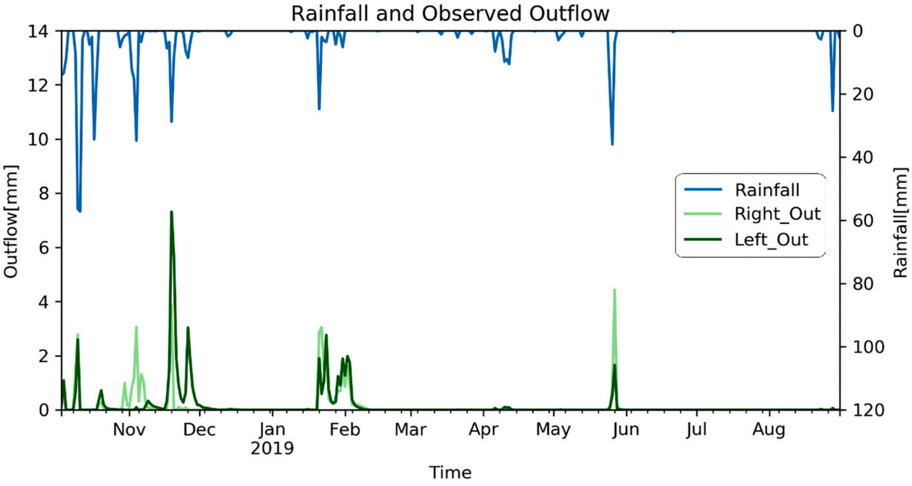

Fig. 3. Observed rainfall and outflow from both twin modules of the green roof at daily scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Characteristics of the selected rainfall events.

ID	Start	End	Duration [days]	Total depth [mm]	Max daily intensity [mm/day]	Antecedent dry period [days]
EV1	May 25, 2019	June 05, 2019	12	58.8	36.0	11
EV2	January 21, 2019	February 11, 2019	22	45.0	24.8	2
EV3	April 06, 2019	April 14, 2019	9	42.4	10.6	3
EV4	August 28, 2019	August 28, 2019	1	25.4	25.4	4
EV5	May 03, 2019	May 05, 2019	3	5.8	3.0	9
EV6	January 16, 2019	January 19, 2019	3	2.8	2.4	6

4. EHSM calibration and performance assessment

The EHSM model was calibrated to represent the CAM green roof in Cagliari. Few model parameters (e.g. n, K_c) were obtained from a priori knowledge, directly from measurements or derived from literature, while the other parameters (e.g. Z_r, S_{fc}, S_u) were estimated maximizing the Nash Sutcliff efficiency *NSE* (Nash and Sutcliffe 1970), defined as:

$$NSE = 1 - \frac{\sum_i^N \left(Q_i^m - Q_i^o\right)^2}{\sum_i^N \left(Q_i^o - \overline{Q^o}\right)^2}$$

where Q_i^m and Q_i^o are the modelled and observed outflow at the i-th time step respectively, $\overline{Q^o}$ is the averaged observed outflow and N is the total number of time steps considering all 6 events in Table 1. *NSE* varies between $-inf$ and 1, where 1 indicates the perfect model representation of the observations.

In the study case, the thickness of the green roof Z_r is equal to 30 cm. Sand porosity n usually varies between 0.3 and 0.5 and, consequently, the model parameter nZ_r can vary between 90 and 150 cm, which is the range used for the model calibration. The percentage of impervious area C is set equal to zero, since the green roof surface is completely permeable. Superficial and sub-superficial reservoir parameters, namely K_{sup} and K_{sub} are set equal to 1, assuming that the volume of water that it is not retained in the green roof, flows immediately out of the system, on the same day that it enters. The vegetation coefficient K_c, that characterizes a CAM vegetation, such as the American Agaves on the selected green roof, is derived from literature: it is usually lower than 1 and here set equal to 0.5 [37]. The canopy interception Δ was neglected, since the CAM vegetation interception does not give a significant contribution to the water balance of the green roof. The soil moisture value triggering the leakage S_{fc} ranges from 0.25 to 0.55 [37]. The hygroscopic point was derived as a random value smaller than S_{fc} and larger than 0.002. Both S_{fc}, S_u, together with nZ_r were calibrated maximizing the *NSE* coefficient, as anticipated before.

5. Results and discussion

5.1. Model calibration results

The model was independently calibrated for each twin module of the green roof, returning slightly different parameters. An average of the left and right green roof parameters was chosen as representative of the study case. Parameter ranges and values obtained from the model calibration are summarized in Table 2.

Fig. 4 compares the outflow simulated by EHSM with the measured outflow from each module of the green roof. Since the soil moisture at the beginning of the measurements was not known, a first period of warm up (October 2018–December 2018) was selected, in order to determine the initial conditions, while simulations and analysis focus on the following period, as can be seen from Fig. 4. The model gives a good estimation of the outflow from the CAM green roof, both in terms of intensity and timing, with a NSE equal to 0.3 and 0.25 for the right and left measurement respectively. Outflow peaks are well represented by the ecohydrological conceptual model.

For the 6 selected rainfall events presented in Table 1, the index of retention was determined. The values obtained for the outflow observed from the twin modules and simulated with the conceptual model are plotted in Fig. 5. *IOR* results highlight a good retention performance of both twin modules, with values generally close to 1, indicating that all the rainfall is retained by the green roof. For EV2, *IOR* is slightly lower (around 0.6), probably due to the long duration of the rainfall event which occurred after a short antecedent dry period, which suggests that the soil was not completely dry at the beginning of the event. As shown in Fig. 5(a), retention performance is affected by the antecedent moisture conditions and it is strongly dependent on the duration of the event. The retention capacity decreases with the increase of the rainfall duration, since the saturation degree of the soil is higher. Left and right green roofs show evident similarity and the model simulated well the retained volume.

5.2. Comparison between CAM and C3 vegetation

In this section, the flood mitigation capacity of a green roof at building scale is analysed for 2 different vegetation types: CAM and C3 plants. The behaviour of both green roof vegetation types is simulated for the 51-year time series (from January 1, 1947 to December 31, 1997) with the support of the calibrated conceptual model. The outcomes are here presented and discussed.

Table 2
Range of parameter variability used for the model calibration and selected values.

	Calibration Range	Right Module	Left Module	Selected Value
nZ_r- Unitary volume [mm]	90–150	149	141	144
S_{fc} - Soil moisture triggering leakage	0.250–0.550	0.530	0.540	0.535
S_u - Hygroscopic point	0.0020-S_{fc}	0.0035	0.0197	0.0116
K_c - Vegetation coefficient [−]	[−]	0.5	0.5	0.5

As already mentioned, CAM vegetation shows multiple benefits, such as low installation and maintenance costs, especially in Mediterranean areas, where the CAM plants are part of the native vegetation and do not need artificial irrigation. On the other hand, it could be argued that C3 plants guarantee a better performance in mitigating rainfall events, since they present a higher evapotranspiration rate. At the same time, C3 vegetation needs to be irrigated during dry periods to ensure tolerable water stress. For this reason, a volume of water was added to the rainfall to simulate the additional irrigation. This artificial water input, set equal to the potential evapotranspiration, was planned only for dry periods to ensure low water stress conditions for the plants.

To simulate the CAM green roof, model parameters were chosen equal to the ones derived for the Cagliari case study, again with a vegetation coefficient K_c set equal to 0.5 (see Table 2). For the C3 green roof the vegetation coefficient is generally higher than 1, and it was here chosen equal to 1.5 [37,38]. The simulated outflow for CAM and C3 green roof is presented in Fig. 6 for the 51-year rainfall time series. Outflow from the CAM green roof presents a similar pattern to the one from C3 green roof, but the total outflow volume of the CAM green roof is almost 2 times higher than the C3 outflow volume.

The average *IOR* over the whole 51-year rainfall time series was estimated for both CAM and C3 green roofs. For the CAM green roof, the index of retention is equal to 0.52, meaning that over the investigated period, more than half of the volume was retained. As expected, the C3 green roof shows a higher retention capacity, with *IOR* equal to 0.71. Although the C3 green roof retention capacity is higher, both green roofs can be considered as a valid tool to mitigate urban pluvial floods effects.

In order to evaluate the mitigation performances of green roofs with respect to rainfall peaks and extremes, IOR_{95} and IOR_{75} were estimated. The 95% quantile of the daily rainfall events for the investigated period (1947–1997) is equal to 18.6 mm. The 75% quantile is obviously lower than the 95% one and corresponds to 5.8 mm. Retention performances associated to rainfall events exceeding the 75% and 95% quantiles are presented in Fig. 7, for both CAM and C3 vegetation. Boxplots display the variability of *IOR* in correspondence to extreme rainfall events: these data are used to calculate IOR_{75} and IOR_{95}, which are represented by blue dots in the plot. The IOR_{95} and IOR_{75} for a CAM green roof are equal to 0.38 and 0.5 respectively. The C3 green roof presents higher retention capacity, showing an IOR_{95} equal to 0.55 and an IOR_{75} equal to 0.75. These values highlight a good capability of the CAM green roof to partially retain the rainfall extremes, reducing the flood risk in urban areas, without the need for external irrigation during dry periods. Results are comparable to the values estimated in Ref. [14] for the Mediterranean region.

The retention capacity of a green roof is strongly influenced by the soil moisture antecedent to the rainfall events. If the soil is completely dry, the green roof shows the best performance, with higher index of retention. Vice versa, if the antecedent dry period is short and the soil is already wet at the beginning of the rainfall event, the retention capacity of the green roof decreases. In order to investigate the relation between soil moisture conditions and retention performances during extreme rainfall events, *IOR* and soil moisture in the day before rainfall event (*Sw*) are plotted for both the CAM and C3 green roof (Fig. 8) with respect to rainfall events exceeding the 95% quantile. The probability density function for both *IOR* and antecedent soil moisture is also plotted for CAM and C3 green roofs aside the main plot. As expected, for high values of soil moisture the retention capacity drastically decreases for both green roofs, while for low values of soil moisture, corresponding to a dry soil, the retention capacity is generally equal to 1. It is possible to observe that CAM vegetation presents higher probability in correspondence to high antecedent soil moisture than C3 vegetation, due to the

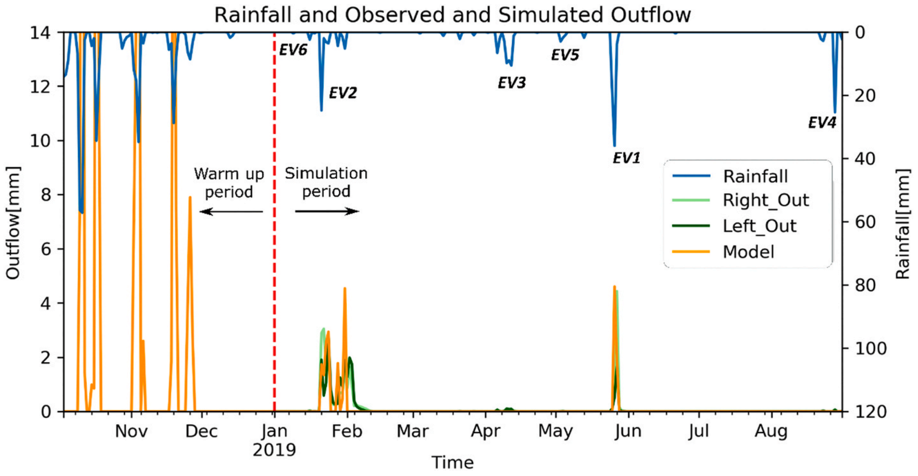

Fig. 4. Comparison between simulated and observed outflow. The dotted red line divides warm up period from simulation period. Selected events presented in Table 1 are highlighted in the plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

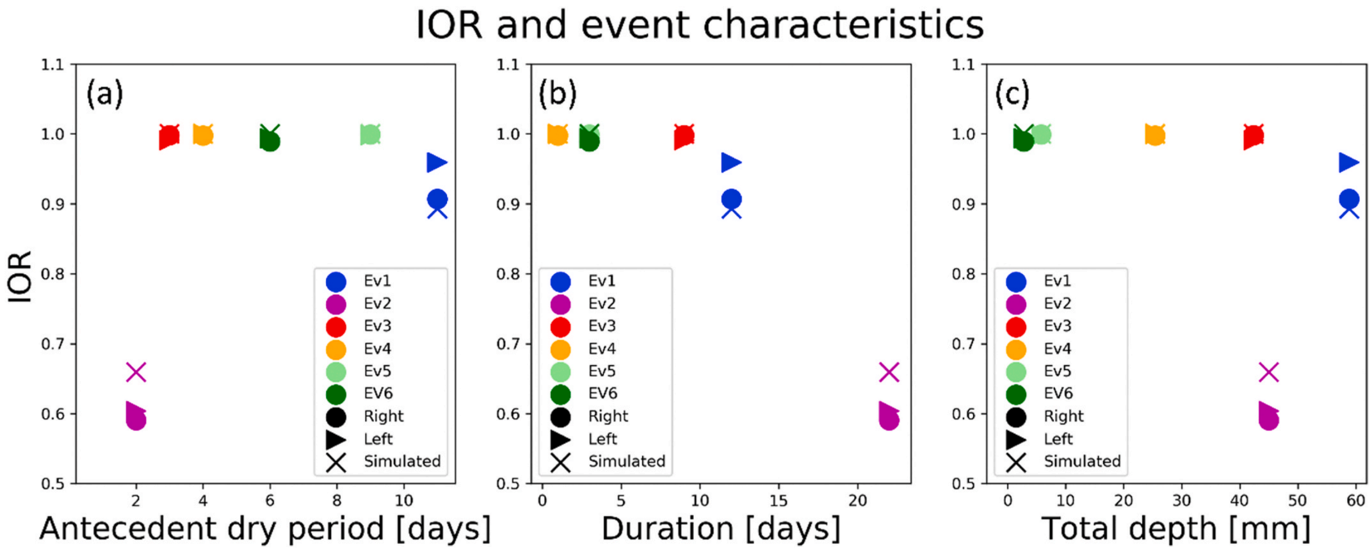

Fig. 5. Comparison between retention capacity and rainfall characteristics: (a) antecedent dry period, (b) rainfall event duration and (c) total rainfall depth.

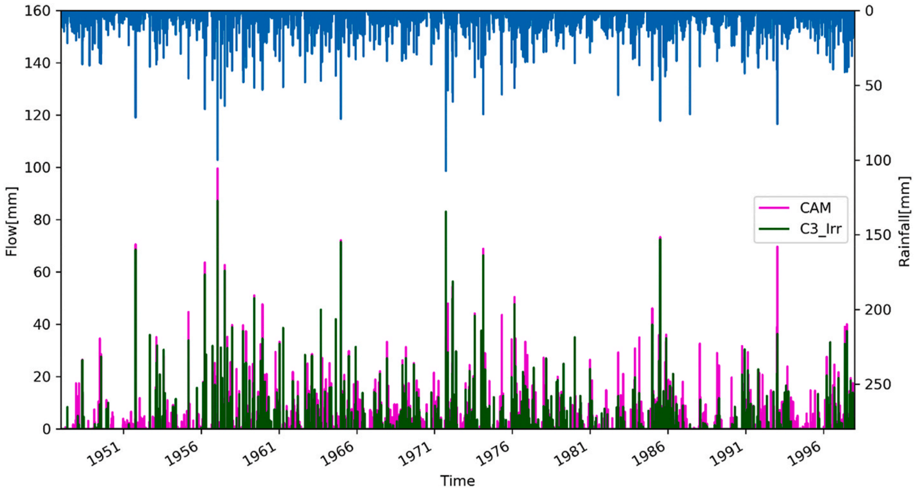

Fig. 6. Rainfall 51-year time series (blue) and simulated outflow for CAM (dry) and C3 (irrigated) green roofs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

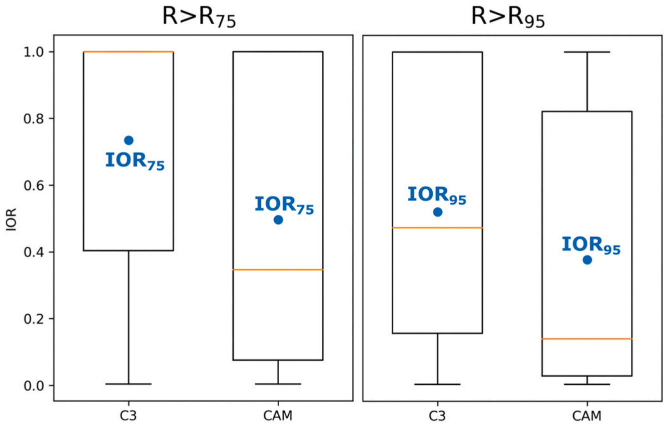

Fig. 7. Boxplot representing the IOR variability for rainfall events exceeding 75% and 95% quantiles, for both CAM and C3 green roofs. Orange lines represent the median of the data. Boxes extend from the lower to upper quartile values of the data, while whiskers vary from the minimum to the maximum. Blue dots represent the average, corresponding to IOR_{75} and IOR_{95}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

higher evapotranspiration rate of the C3 plants. Regarding the *IOR*, the probability is higher for lower values or retention capacity: this means that CAM vegetation shows lower performances more frequently. Extreme rainfall events are more likely to happen when the antecedent soil moisture is high (i.e. in winter season in Mediterranean areas), and in this case the retention capacity is quite low. The probability to have low *IOR* values is in fact higher for CAM green roofs.

The total water depth needed for the irrigation of a C3 green roof was assumed to be equal to the potential evapotranspiration *ET*0, distributed during the growing months. This corresponds to an average of about 500 mm y^{-1} for a green roof located in Cagliari or in a similar climatological area. Considering the green roof located at the University, the total volume of water per year requested for the growth of C3 plants is 48 m^3 for the whole roof (96 m^2). Assuming a unitary cost of 1.5 euros per m^3 for tap water, having a 96 m^2 CAM green roof will guarantee a saving of 75 euros per year. Unless there is space available to install water tanks and there are the financial conditions to install a pumping and irrigation system, the water used for irrigation is generally potable water, withdrawn from the supply system in summer, which corresponds to the most critical period for the water management in Mediterranean areas. The choice of CAM vegetation instead of C3 plants contributes to a more sustainable water management in urban areas, while mitigating floods and reducing the pressure on the water supply system.

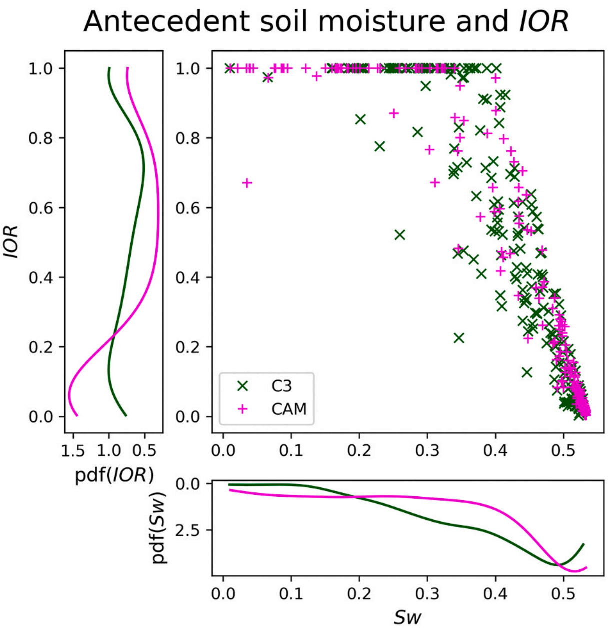

Fig. 8. Average soil moisture (*Sw*) estimated before extreme rainfall events versus the relative values of the Index of Retention (*IOR*). Probability density function of *IOR* and of antecedent soil moisture are plotted close to the vertical and horizontal axis respectively.

6. Conclusions and future work

In this work, the flood mitigation performance of a CAM green roof was compared to the one obtainable with C3 vegetation. Retention of both green roofs was simulated with the conceptual Ecohydrological Streamflow Model (EHSM) proposed by Ref. [31]. A 51-year rainfall time series was used as input for the model, which was previously calibrated taking advantage of field measurements carried out on a CAM green roof located at the Engineering Faculty of the University of Cagliari (Italy). Field measurements showed, as expected, that CAM green roof retention performances are directly related to rainfall depth, event duration and antecedent dry period length.

Model results state that both CAM and C3 green roofs offer good retention capacity, with an *IOR* over the 51-year time series of 0.52 and 0.71 respectively. Due to the higher evapotranspiration rate, C3 green roofs present higher retention capability than CAM green roofs. However, in Mediterranean regions the differences in terms of performances between the two vegetation types are not large enough to justify the additional irrigation costs of the C3 green roof. In urban areas characterized by a Mediterranean climate, the choice of CAM vegetation for green roofs is to be preferred, not only because CAM plants represent one of the spontaneous vegetation of the region, but also because they greatly contribute to rainfall peak reduction with low maintenance costs. In this work, the analysis is developed at building scale, investigating the potential runoff generation reduction corresponding to a single structure. This step is fundamental in understanding the hydrological processes and in investigating the potential flood mitigation on the entire city. A large-scale analysis, which will include the potential runoff reduction over the entire neighbourhood or city, needs to be carried out to define the total impact of green roof installation.

Further investigation of CAM green roof retention capacity will be carried out in the Polder Roof® field lab, a project in the framework of Climate-KIC. The Polder Roof® (Polderdark) is a prototype, developed by the Dutch company Metropolder, which enables the green roof outflow to be collected in water tanks, measured, controlled and reused during droughts. This instrument will be particularly interesting in Mediterranean areas, where both pluvial floods in winter and droughts in summer are still a problem. The installation of a CAM Polder Roof® in Cagliari will allow comparison with the already existing CAM green roof located in the area and will help to investigate the potential benefits of these structures on the water management system. Soil moisture sensors will be installed in the Polder Roof and this will help to understand better the hydrological dynamics. Soil moisture measurements would be, indeed, beneficial for the model and they could constrain model parameters better. Future studies will also investigate the combination of different vegetation types on the same green roof, in order to maximize all the potential benefits of the green roofs, including the improvement of the ecosystem due to an increase of vegetation diversity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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