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Research article

Management strategies for maximizing the ecohydrological benefits of multilayer blue-green roofs in mediterranean urban areas

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ABSTRACT

Multilayer Blue-Green Roofs are powerful nature-based solutions that can contribute to the creation of smart and resilient cities. These tools combine the retention capacity of traditional green roofs with the water storage of a rainwater harvesting tank. The additional storage layer enables to accumulate the rainwater percolating from the soil layer, that, if properly treated, can be reused for domestic purposes. Here, we explore the behavior of a Multilayer Blue-Green Roof prototype installed in Cagliari (Italy) in 2019, that have been equipped with a remotely controlled gate to regulate the storage capacity of the system. The gate installation allows to manage the Multilayer Blue-Green Roof in order to increase the flood mitigation capacity, minimizing the water stress for vegetation and limiting the roof load with adequate management practices. In this work, 10 rules for the management of the Multilayer Blue-Green Roof gate have been investigated and their performances in achieving different management goals (i.e., mitigating urban flood, increasing water storage and limiting roof load on the building) have been evaluated, with the aim to identify the most efficient approach to maximize the benefits of this nature based solution. An ecohydrological model have been calibrated based on field measurements carried out for 6 months. The model has been used to simulate the system performance in achieving the proposed goals, using as input nowdays and future rainfall and temperature time series. The analysis reveled the importance of the correct management of the gate, highthing how choosing and applying a specific management rule helps increasing the performance in reaching the desired goal.

1. Introduction

In the last decades, different solutions have been developed to adapt to climate change and to mitigate the pluvial flood risk in urban areas, contributing to the creation of smart, sustainable, and resilient cities. Among the different nature-based solutions proposed in the literature, green roofs have been largely investigated as sustainable tools capable to reduce the runoff generation coming from the city rooftops. Several studies investigated the retention capacity of this tool in different regions around the world (Liu et al., 2020; Stojkov et al., 2018; Karteris et al., 2016; Johannessen et al., 2018; Stovin et al., 2012; Stovin, 2010), showing an overall good flood mitigation potential, which is, however, influenced by climatic conditions, soil type and thickness and vegetation coverage (Getter et al., 2007; Hellies et al., 2018; VanWoert et al., 2005; Viola et al., 2017).

Beside the high retention capacity, green roofs have shown multiple benefits (Cristiano et al., 2021a; Hashemi, Mahmud, and Ashraf 2015; Shafique et al., 2018): they increase biodiversity, attracting several animal species, they facilitate the thermal insulation of the buildings, with a consequently energy saving (Niachou et al., 2001; Castleton et al., 2010; Coma et al., 2016; Lazzarin et al., 2005); they contribute to the heat island reduction, lowering the temperature of the surrounding area (Solcerova et al., 2017; Solcerova et al., 2018; Takebayashi and Moriyama, 2007; Santamouris, 2014; Susca et al., 2011; Alexandri and Jones, 2008); they reduce air and water pollution, retaining CO_2 during the evapotranspiration processes and contaminants in the soil (Vijayaraghavan and Franklin, 2014; Gnecco et al., 2013); and last but not least, they add aesthetic values to urban environments (Berardi et al., 2014).

However, green roof retention capacity, especially at large urban scale is limited compared to other traditional pluvial flood mitigation, such as rainwater harvesting systems (Cristiano et al., 2021b, 2023; Charalambous et al., 2019). Rainwater harvesting systems were originally developed in Mediterranean areas to collect water in large tanks or cisterns during rainfall events and to store it and reuse it during the drought periods (Beckers et al., 2013). If properly stored and treated, the

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collected water can be, in fact, used for several domestic purposes, such as home garden irrigation, street cleaning and flushing the toilets. Recently, rainwater harvesting systems have been also used to mitigate extreme rainfall events, especially in urban areas (Adugna et al., 2018; Boers and Ben-Asher, 1982; Zhang and Hu, 2014; Campisano and Carlo Modica, 2015). The urban flood mitigation capacity of rainwater harvesting systems is influenced by several factors: buildings, tank capacity, rainfall characteristics, and land use (Zhang and Hu, 2014; Teston et al., 2018; Palla et al., 2017). Freni and Liuzzo (2019) showed how the installation of a 5 m^3 water tank for each building of a neighborhood (1.6 km^2) in Palermo (Sicily, Italy), can reduce the flooded area up to 35% during intense rainfall events (up to 50 mm rainfall depth). Similar results have been found by Akter et al. (2020), who developed a model for the Chittagong City in Bangladesh, coupling SWMM and HEC-RAS, with the aim to evaluate the impact of a large scale installation of rainwater harvesting system in reducing the flooded area.

A recent and innovative solution relies in the installation on city rooftops of multilayer blue-green roofs (MBGR), that combines the storage capacity typical of rainwater harvesting systems with the multiple advantages of traditional green roof retention capacity, in terms of energetic and ecological benefits (Andenæs et al., 2018; Muhammad and Kim, 2017; Shafique et al., 2016a; ;Shafique et al., 2016b Skjeldrum et al., 2017; Cristiano et al., 2021a; Busker et al., 2022). Compared to traditional green roofs, the multilayer ones indeed present an additional layer, that enables to store the water percolating from the soil layer, and to reuse it, if properly treated, for different domestic purposes or released it when the drainage system is not under pressure. The water volume that is stored in the MBGR can be eventually regulated with a gate, that can generally be manually or remotely controlled.

The regulation of gate opening/closing is the key point of the MBGR management and determinates the performance of this tool. Finding an optimal solution, which guarantees the availability of water for different purposes, without overloading the rooftop and, at the same time, ensuring the pluvial flood mitigation during extreme rainfall events, is an interesting challenge for engineers, water managers and policy makers. This challenging problem is in some way similar to the optimization of a reservoir, which has been largely addressed in the literature (Fayaed et al., 2013; Jothiprakash and Arunkumar 2013; Napolitano and Sechi, 2020; Ahmad et al., 2014; Hossain and El-shafie 2013). While for artificial reservoir the problem is to find a balance between flood mitigation and water availability for irrigation and hydropower plants (Hossain and El-shafie 2013), here the issue is to minimize urban floods while storing water for potential reuses.

Embedding weather forecast in operational rules for gate opening/closing is another key factor for the optimal management of the rainwater harvesting tanks: a recent work, proposed by Xu et al. (2020), highlighted the importance of including a 7-day weather forecasts to improve the management of a real time control water tank, balancing the water storage, flood mitigation and environmental protection.

A very recent study by Busker et al. (2022) evaluated the performance of a blue-green roof located in Amsterdam in reducing the runoff generation during extreme rainfall events, integrating weather forecast in the management of the gate. Results showed that the retention capacity of the blue-green roofs during extreme events, can increase from about 59% when the gate is closed up to 70%–97% if the gate is correctly regulated based on the rainfall forecast. Their findings underline the importance of an optimized gate management to increase retention performance.

MBGRs, however, could be used for other purposes than mitigating pluvial floods, and the gate management should be regulated accordingly. In this work we aimed to investigate ten options to manage the gate opening, in order to maximize the efficiency of the MBGR in reaching three specific purposes, i.e., mitigating urban flood, increasing water storage and reducing the roof load on the building. The proposed ten management rules explore the following options: (i) keeping the gate always open, (ii) keeping the gate always closed or (iii) varying the gate opening depending on seasonality, on the water accumulated in the storage layer or on actual and predicted rainfall occurrences. Five significant indices have been introduced to measure the MBGR performance in correspondence of each management rule in achieving three main goals. These analyses have been developed with the help of a conceptual ecohydrological model calibrated to represent a MBGR prototype.

The paper is structured as follows. The conceptual ecohydrological model used to simulate the behavior of a MBGR, is described in Section 2, together with the illustration of the case study used for the calibration and validation. Section 3 delineates the methodology followed to identify the rules that can be applied to manage the gate opening and the goals that can be achieved in terms of runoff reduction and water availability for different purposes. Results are presented in Section 4, where the performance related to the proposed rules are evaluated for each expected goal. Section 5 discuss the results obtained highlighting the possible interconnections and exploring the potential impacts. Finally, in Section 6 the main conclusions of this analysis, and the possible impacts and future works are summarized.

2. Methodology

2.1. Study case

As part of the Polder Roof field lab, a project in the framework of Climate-KIC, four MBGR prototypes, developed by the Dutch company Metropolder, have been installed in four Italian cities: Cagliari, Palermo, Perugia and Viterbo (Cristiano et al., 2022). The prototype installed at the University of Cagliari (Italy, 39.229086° N, 9.109277° E; mean elevation equal to 74 m a.s.l.) in June 2019 has been used as case study to calibrate the ecohydrological model presented in this work and used to simulate the processes and dynamics that characterize the MBGRs. The prototype is placed close to the Department of Hydraulics and Hydrology of the Civil Engineering Faculty on top of a wooden structure, 50 cm above the ground (Fig. 1a). The MBGR has a surface of 16 m^2 (4 m × 4 m) and it is characterized by several layers, including, from bottom to top: a waterproofing membrane, an anti-root barrier, a protection layer, a water storage layer of 8 cm, a filter layer, an 8 cm soil substrate, and vegetation. The prototype is characterized by the presence of common cactus plants (Cactaceae), which represent the local native vegetation (Fig. 1d). These plants show a Crassulacean Acid Metabolism (CAM), that enables them to close the stoma during the day, avoiding water dispersion. The evapotranspiration efficiency of CAM vegetation is lower with respect to other plants, but it ensures the survival of the species even during very hot and dry periods (Cristiano et al., 2020). Moreover, CAM vegetation requires very low maintenance, with consequently low costs. For these reasons, this type of vegetation is particularly suitable for regions characterized by long hot and dry summers, such as the Mediterranean areas. The soil has been classified as *loamy sand* and a porosity of 0.42 has been assumed accordingly (Laio et al., 2001).

The MBGR is equipped with multiple sensors to monitor rainfall intensity, water level in the storage layer, runoff generation and air and water temperature. All sensors are connected to an online platform, which enable to easily read the different measurements and to regulate the water level in the storage layer, varying the opening degree of the gate (Fig. 1c). The green roof outflow is directed into a 350-L rain barrel equipped with a sensor to measure piezometric water level (Fig. 1b).

Water level and outflow data have been recorded with a 10-min time resolution for six months, from November 1st, 2020, to April 10th, 2021. Rainfall data and temperature data, used to estimate the potential evapotranspiration, have been recorded at 1 min temporal resolution from the weather station network of the Regional Agency for the Protection of the Environment of Sardinia (ARPAS) for the same period. These data have been used to calibrate the hydrological model that simulates the hydrological processes acting within the green roofs.

Fig. 1. MBGR located in Cagliari. (a) Top view of the global structure after the installation in June 2019; (b)Details of monitoring station, gate and rain barrel to measure the outflow; (c) Detail of the gate; (d) Example of the CAM vegetation installed in the prototype after few months from the installation.

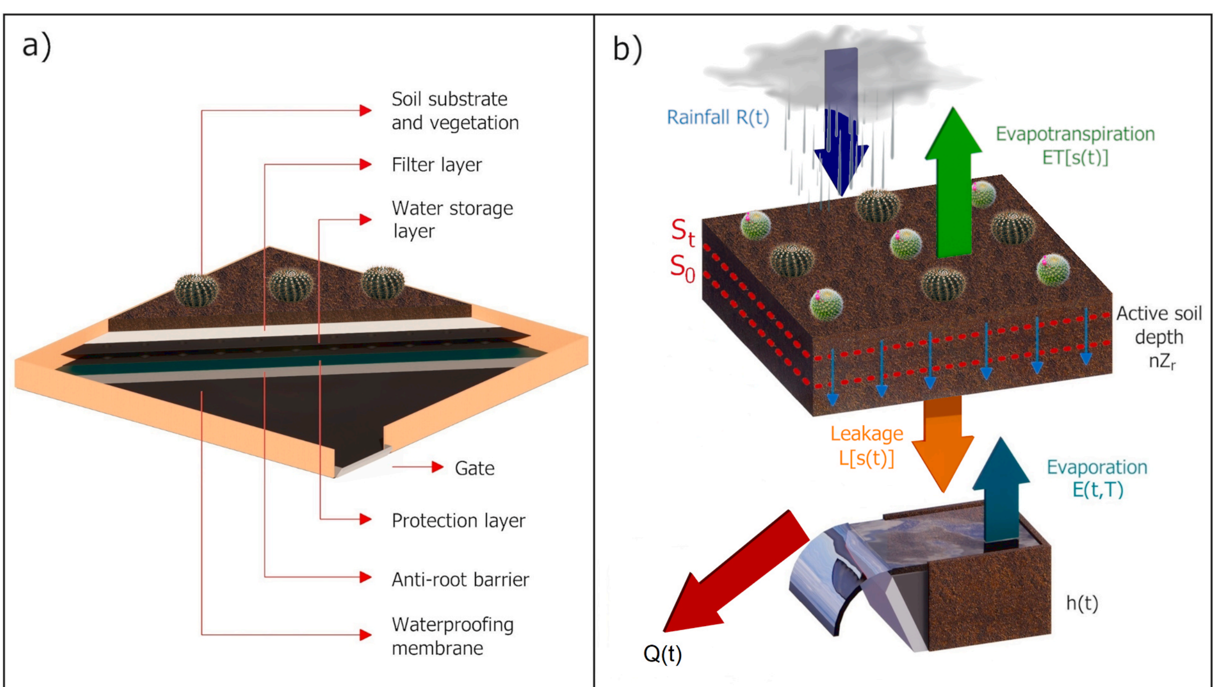

Fig. 2. MBGR. (a) Schematic representation of the different layers of a MBGR and (b) conceptualization of the model used to represent the ecohydrological behavior of this tool.

2.2. Model description

In this study, a conceptual ecohydrological model, based on the ecohydrological streamflow model EHSM, proposed by Viola et al. (2013), has been reshaped to simulate the hydraulic behavior of the MBGR. A schematic representation of the MBGR and the conceptual model used in this work is illustrated in Fig. 2. Precipitation, average temperature, potential evapotranspiration and gate opening level at 10-min temporal resolution are used as input for the model, which enable to simulate evapotranspiration and soil moisture dynamics in the soil layer and evaporation and water level in the storage layer. MBGR are supposed to be installed on building roofs with limited slope to ensure the highest performance (Getter et al., 2007). Although the building roofs are generally not completely flat, it can be assumed that the limited slope has negligible influence on the soil moisture dynamics, on the water retention dynamics in the soil and on the detention capacity of the blue layer of the multilayer blue-green roof.

The model interconnects two conceptual elements: a soil bucket and a reservoir. The rainfall volume infiltrates in the soil and, when the soil moisture reaches the field capacity, and it percolates towards the storage layer. Due to the flat soil layer, it is assumed that in the rare cases when the soil is saturated no surface runoff is generated, because all the excess is leaked toward the lower layer. The reservoir simulates the behavior of the storage layer of the MBGR, which is regulated through the gate, in accordance with specific management rules.

The soil behavior is represented by the active soil depth, expressed as the product of porosity n and the soil depth Z_r. Water content dynamics in the soil bucket is simulated by the following water balance equation:

$$\Delta s = \frac{1}{nZ_r}\,(R - ET - L) \tag{1}$$

where Δs is the variation of the water content in the soil bucket, R is the rainfall depth, ET is the actual evapotranspiration, L represents the loss of water by deep percolation. Evapotranspiration and percolation depend on the soil water content s, which can vary between 0 and 1, and they can be estimated with the following equations:

$$\mathrm{ET} = \begin{cases} 0 & 0 < s \le s_0 \\ \mathrm{ET}_{max}\left(\dfrac{s - s_0}{s_t - s_0}\right) & s_0 < s \le s_t \\ \mathrm{ET}_{max} & s_t < s \le 1 \end{cases} \tag{2}$$

$$\mathrm{L} = \begin{cases} 0 & 0 < s \le s_t \\ \mathrm{ET}_{max} + (s - s_t)\, n\, Z_r & s_t < s \end{cases} \tag{3}$$

where s_0 is the wilting point, s_t the field capacity and ET_{max} is the product of the vegetation coefficient K_v and the potential evapotranspiration ET_0(Thornthwaite, 1948): $ET_{max} = K_v\, ET_0$.

In the storage layer, the water balance can be written as:

$$\Delta h = L - E - Q\Delta t \tag{4}$$

where Δh is the variation of water level in the storage layer, L is the leakage from the soil layer as defined in eq. (3), E is the evaporation in the storage layer, Q is the outflow from the MBGR and Δt is the considered time step. Evaporation E is estimated rescaling the reference evapotranspiration ET_0, defined with Thornthwaite equation:

$$E = K_E\, ET_0 \tag{5}$$

where E represents potential evaporation, K_E is a reduction coefficient, introduced to account for the limited flux exchange with the environment. The outflow Q from the water storage layer of the MBGR is calculated with the following relation:

$$Q(t) = \begin{cases} 0 & h(t) \le h_{lim}(t) \\ \mu\, B\, (h(t) - h_{lim}(t))\, \sqrt{2\, g\, (h(t) - h_{lim}(t))} & h(t) > h_{lim}(t) \end{cases} \tag{6}$$

where μ is the discharge coefficient, assumed equal to 0.38, B represents the width of the gate, h is the height of the water level in the storage layer and h_{lim} indicates the actual height of the gate: the latter could be regulated and, when the gate is fully open, it is equal to zero. Fig. 2b illustrates a schematic representation of the conceptual ecohydrological model, highlighting the different components and parameters involved.

2.3. Model calibration

The model described in the previous section is built on 5 parameters: three parameters characterize the soil type characterization (i.e., the active soil depth nZ_r, the soil moisture value exceeded which triggers losses by percolation s_t, and the hygroscopic point s_0), one describes the vegetation layer (the crop coefficient K_v), and the last one represents the evaporation reduction coefficient (K_E). The model has been calibrated to represent the MBGR prototype installed in Cagliari (described in Section 2.1), using the observations recorded during the 6-month period, from November 2020 to April 2021. In particular, rainfall and temperature time series recorded from the nearby station of the Regional Agency for the Protection of the Environment of Sardinia ARPAS has been used as model input. The model performance has been evaluated comparing observed and simulated water levels in the storage layer measurements.

Out of the five parameters, three parameters that characterized the soil type (i.e., the active soil depth nZ_r, the soil moisture value exceeded which triggers losses by percolation s_t, and the hygroscopic point s_0) have been derived from a granulometric analysis. As mentioned in Section 2.1, the soil has been classified as *loamy sand*, and consequently it was possible to assume nZ_r equal to 3.36 cm, s_t to 0.52 and s_0 to 0.08, based on the values available in the literature (Laio et al., 2001).

The remaining 2 parameters were calibrated using a Monte Carlo approach (De Fino et al., 2017). The proposed method consists in the generation of N random sets of parameters $\theta_n[K_v, K_E]$ from a range of plausible values, and evaluation of the model performance in correspondence of the selected parameter set. To provide a measure of the model's adaptation to observed data, has been used the efficiency criterion of Nash and Sutcliffe (Nash and Sutcliffe, 1970), based on the sum of squared errors. The Nash-Sutcliffe efficiency, *NSE*, is defined as:

$$NSE = 1 - \frac{\sum_i^N (h_{out\,i} - h_{obs\,i})^2}{\sum_i^N (h_{obs\,i} - \overline{h_{obs}})^2} \tag{7}$$

where $h_{out\,i}$ and $h_{obs\,i}$ are simulated and observed water height in the storage layer at *i-th* time step, while $\overline{h_{obs}}$ is the average of the observed water height in the storage layer and N is the total number of time steps. *NSE* can vary between –inf and 1, where 1 indicates the perfect correspondence between observed and simulated results.

In this analysis, 100,000 parameter sets with $NSE > 0$ has been identified with the Montecarlo approach, and the set θ_{best} which ensured the highest *NSE* has been selected to simulate the MBGR behavior. For each parameter a range of variability has been chosen from the literature and based on the MBGR characteristics (Laio et al., 2001). Although the vegetation coefficient K_v for a CAM vegetation is lower than 1, since the potential evapotranspiration of CAM plants is lower than the standard grass (Consoli et al., 2013; Divincula et al., 2019), K_v range was set between 0.01 and 2, while K_E has been allowed to vary between 0.1 and 1. The best parameter set, $\theta_{best}[K_v, K_E] = [0.2211, 0.7626]$, ensures a *NSE* equal to 0.911, meaning an excellent reproduction of the observed data by the model. It is worth noticing that the calibrated value of K_v is, as expected, lower than 1.

Fig. 3 illustrates the observed and simulated water levels in the storage layer (blue and orange line, respectively) for the period November 2020–10 April 2021, plotted together with the rainfall time series used as input for the model. The gate height during the calibration period was set at 8 cm (maximum water level in the storage layer). This plot shows how the calibrated model well represents the behavior of the

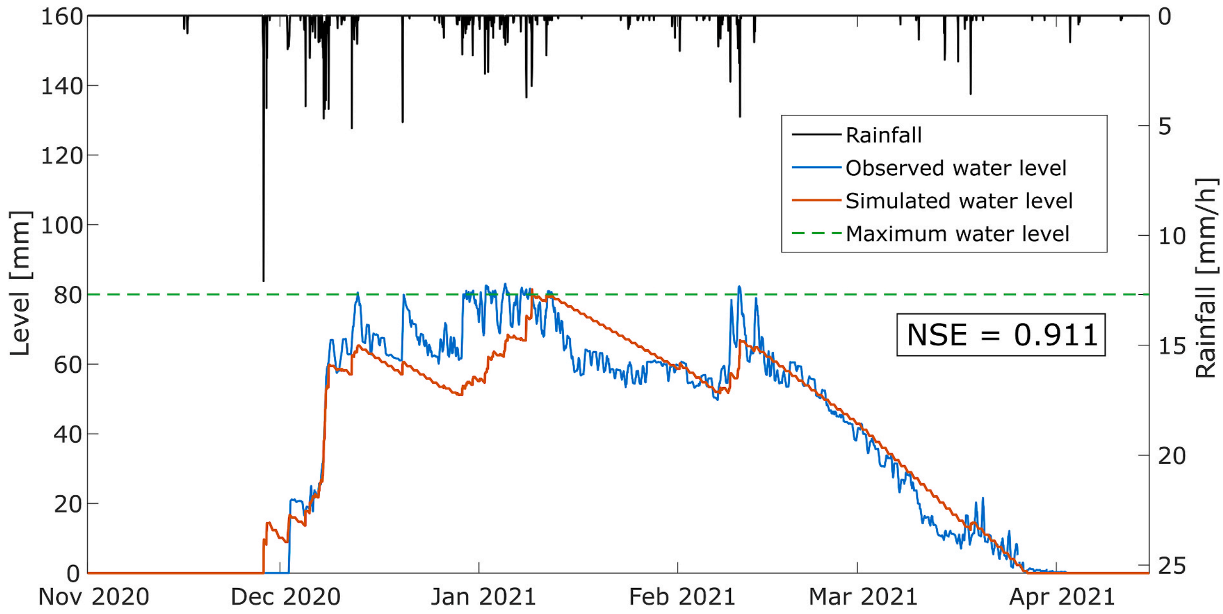

Fig. 3. Water level observed and simulated with the calibrated model for the period November 2020–April 2021.

MBGR, both in terms of water height and timing of the peaks.

2.4. Stochastic rainfall and temperature generation

Once the model was calibrated as described in Section 2.3, it was applied and used in a Monte Carlo framework to evaluate the performances with different management rules. With this aim, rainfall time series generated with a simple stochastic model has been used as input. The time series were obtained applying Neyman-Scott Rectangular Pulse (NSRP) model, which is based on a stochastic point modelling process of rainfall (Rodriguez-Iturbe et al., 1987a; Rodríguez-Iturbe et al., 1987b; Cowpertwait, 1991). The NSRP model was built using three exponential distributions to describe: the time between consecutive events, the duration and intensity of each event. The parameters (τ_m, d_m, i_m) of the exponential distributions have been estimated at monthly scale ($m = 1 \ldots 12$) to describe the seasonality of precipitation.

Three 1000-year rainfall time series have been generated, explicitly including the most likely effects of climate changes, which are projected to lead to an increase of interarrival time between two following rainfall events and at the same time to an increase of rainfall intensity, with a constant or decreased mean annual precipitation (MAP). The first synthetic rainfall time series, S1, is generated using the parameters estimated from a 16-years historical series (2006–2021) provided by ARPAS. S1 enables to investigate the behavior of the MBGR under current climatic conditions. With the aim to investigate the potential benefits of the MBGR installation, it is important to evaluate the long-term performance of this nature-based solution, which is directly influenced by climate changes. For this reason, two additional rainfall time series (S2 and S3) have been generated, modifying the NSRP model parameters derived from the historical time series, accordingly to future climatic projections, presented by the Intergovernmental Panel on Climate Change (IPCC et al., 2019).

The time series S2 has been generated by keeping the mean annual precipitation similar to S1: this condition has been achieved by increasing the parameters τ_m (interarrival time) and i_m (intensity) by 60% and 55%, respectively. Following this approach, S2 is characterized by less frequent and more intense events. Although the IPCC climatic projections foresee a general decrease of the average annual rainfall in Mediterranean areas, S_2 preserve the average annual rainfall, with the aim to evaluate the MBGR performance under critical conditions (intense rainfall events).

The last generated time series, S3, provides a climate projection which leads to a lower mean annual precipitation than S1 and S2. S3 presents an increase of τ_m (interarrival times) and i_m (intensity) by 95% and 55%, respectively. As matter of facts, S3 leads to a lower average annual precipitation than S1, according to the IPCC future projection with RCP (Representative Concentration Pathways) 8.5, which correspond to the most critical scenario (Mascaro et al., 2018; IPCC et al., 2019; Shukla et al., 2019). Table 1 summarizes the main differences among the three generated rainfall time series.

Besides the rainfall time series, temperature time series are also required as input for the ecohydrological model. The characterization of the near-future temperature time series, used in correspondence of the rainfall time series S2 and S3, has been achieved with the support of climatic modelling (CM) outputs. Within the EUROCORDEX project (Jacob et al., 2014), the MPI-ESM-LR-r2 coupled with the regional model REMO2009 at EUR-11 resolution and daily time scale has been selected. Surface temperature output has been bias-corrected and then used to generate (by identical replication) the temperature time series. Two scenarios have been used: historical and RCP 8.5 scenario, that reproduce temperature time series under current conditions (used in correspondence of S1) and in the near future (used in correspondence of S2 and S3), respectively.

2.5. Management goals and performance indices

MBGR management rules should be shaped on the specific goals that the user wants to achieve. In this work, we will focus on three main MBGR goals. With the installation of MBGRs in urban areas we could aim (i) to mitigate the pluvial flood, (ii) to ensure a water storage for different domestic purposes, while (iii) limiting the load on the rooftop. Increasing the water storage can have multiple benefits, especially if a

Table 1
Generated rainfall time series characteristics.

Series	Interarrival times τ_m [day]	Duration d_m [day]	Intensity i_m [mm/day]	Mean annual precipitation [mm/year]
S1	τ_m	d_m	i_m	413.15
S2	1.6 τ_m	d_m	1.55 i_m	417.66
S3	1.95 τ_m	d_m	1.55 i_m	349.98

large-scale installation of MBGR over an entire city or extended neighborhood is planned. If properly treated and stored, rainwater can be utilized for many non-drinkable urban uses, such as, for example, garden irrigation or street cleaning, and in more complex system it can be used for flushing the toilets. Moreover, the stored water constitutes a large support for the increase of soil moisture in the soil layer: due to different ecohydrological processes, such as evaporation, condensation and capillarity rise, a fraction of the collected water moves to the soil layer. This phenomenon reduces the water stress, ensuring better growing conditions for the MBGR vegetation and reducing the costs and water resources needed for irrigation. Finally, we must consider that this tool has been developed to be placed above the roofs. If the water storage is situated at a reasonable height, it can be used to irrigate lower MBGRs. However, it is important to guarantee a low load over the roof, especially for old buildings, which might be able to carry a lower load than new constructions.

The achievement of the three proposed goals has been quantified by five indices, as summarized in Table 2. The flood mitigation is evaluated through three indices: two focuses on extreme rainfall events, defined in terms of highest return period (G1. RP) and total volume (G1. V), while the third one investigates the average percentage reduction of the annual outflow (G2). In the first case (G1. RP), for each rainfall event, intensity and duration are identified and referred to the intensity-duration curves available for Cagliari, to estimate the correspondent return period. For each year, the event with the highest return period is considered in this analysis. G1. V, the second index, evaluates the annual event with the highest total volume, calculated as the product of rainfall intensity and duration.

These three indices are based the index of retention, IOR, defined as:

$$IOR = 1 - \frac{O_i}{R_i} \tag{8}$$

where O_i is the total outflow of the *i-th* event, while R_i indicates the total rainfall of the *i-th* event. The five indices focus on the *IOR*, expressed in percentage, of rainfall events with different characteristics.

The goal of ensuring water storage is evaluated through the daily average annual stored volume (G3), while the goal of limiting the roof load is investigated with the average annual load over the rooftop (G4).

Table 2
Proposed management goals and related indices.

Goal		Index	Description	Variability range
1°	Mitigate Pluvial Flood	*G1.RP [%]*	Reduction (IOR) of the annual rainfall events with the highest return period	0%–100%: 0% when none of the considered event is mitigated, 100 when all considered events are fully retained/detained
		G1.V [%]	Reduction (IOR) of the annual rainfall events with the highest volume	0%–100%: 0% when none of the considered event is mitigated, 100 when all considered events are fully retained/detained
		G2 [%]	Annual average rainfall reduction (IOR at annual scale)	0%–100%: 0% when none of the considered event was mitigated, 100% when all considered events are fully retained/detained
2°	Ensure water storage	*G3 [m^3]*	Average annual stored volume at daily scale	0 m^3–1.28 m^3: 0 m^3 when no water is stored, 1.28 m^3 when the storage layer is always full
3°	Limit the roof load	*G4 [kg/ m^3]*	Average annual load over the rooftop	131 kg/m3–259 kg/m3:131 kg/m3 is the MBGR weight without water, 259 kg/m3 is the weight when soil is saturated and storage layer full.

2.6. Management rules

The MBGR performance goals, defined in Section 2.5, are evaluated in relation to several management rules, which set the opening and closing of the gate. In this way, it is possible to identify the most efficient management rule that enables to achieve a specific goal. In this work, ten different management rules have been proposed and analyzed: the selected rules are summarized in Table 3 with a detailed description and a list of instruments required for their correct application.

The first rule R1 represents the behavior of a traditional green roof, which does not have the storage layer: in this case the gate is always open and the water that percolates from the soil layer is not stored in the additional layer, and it directly generates runoff. The second management rule R2 simulates the opposite condition: the gate always closes,

Table 3
Investigated management rules.

ID	Management rule	Description	Required Sensor
R1	Gate always open	Reference condition	None
R2	Gate always closed	All rainwater is stored, and it is available for different purposes	None
R3	Gate closed when rainfall is higher than zero, open when it is not raining	Simple condition based only on the rainfall measurements	Rain gauge
R4	Gate closed when rainfall is higher than zero. Gate open when there was no rainfall in the previous 2h	Assuming that the lag time for urban catchment is lower than 1 h, this condition ensures that the sewer system is empty when the gate is open	Rain gauge
R5	Gate open from October to March if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h. Gate closed from April to September	Gate is closed during the dry season to store water, which could be reused for the green roof irrigation. During the rainy season, the gate overflow is avoided.	Rain gauge Weather forecasts
R6	Gate open if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h; c) $h > 1/4\ h_{lim} = 0.02$ m.	A least the 75% of the storage layer is always available to mitigate the rainfall event	Rain gauge Weather forecasts Water level
R7	Gate open if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h; c) Rainfall expected after 3h	This rule aims to empty the water storage, before a rainfall event.	Rain gauge Weather forecasts
R8	Gate open if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h; c) $h > 1/4\ h_{lim} = 0.02$ m. Gate closed between April to September	Combination of R5 and R6	Rain gauge Weather forecasts Water level
R9	Gate partially open (gate height = 0.03 m) if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h; c) $h > 3/8\ h_{lim} = 0.03$ m	A small amount of water is always stored, and it is ready to be reused (about 37% of the storage volume).	Rain gauge Weather forecasts Water level
R10	Gate closed if rainfall >5.6 mm/d Gate open if: a) No rainfall in the previous 2 h; b) No rainfall expected in the following 2 h	This rule assumes that medium-intensity rainfall events (<5.6 mm/d, corresponding to 0.0389 mm/10min) are retained by the soil layer. The chosen rainfall threshold, represents the 75%-ile of the rainfall time series without zeros.	Rain gauge Weather forecasts

enabling to store a large amount of water. These two conditions do not require any measurements or remote control, are not affected by the meteorological events, and represent the reference conditions.

The other rules, summarized in Table 3, require some instruments to measure rainfall depth and water height in the storage layer and some of them need weather forecasts. To define the management rules, the standard instruments installed for the prototype located in Cagliari, described in section 2.1, have been considered: in particular, the rain gauge and the water level sensor. In this work we proposed multiple rules that requires different measurements and observations, with the aim to provide flexible solutions that can be applied to different case studies, where a specific sensor might or not be available. The rule R4 relies only on the rainfall measurements and does not require any water level measurements nor weather forecasts: it establishes to close the gate when it rains and to open it 2 h after the end of a rainy event.

Recent studies (Xu et al., 2020; Busker et al., 2022) have shown that

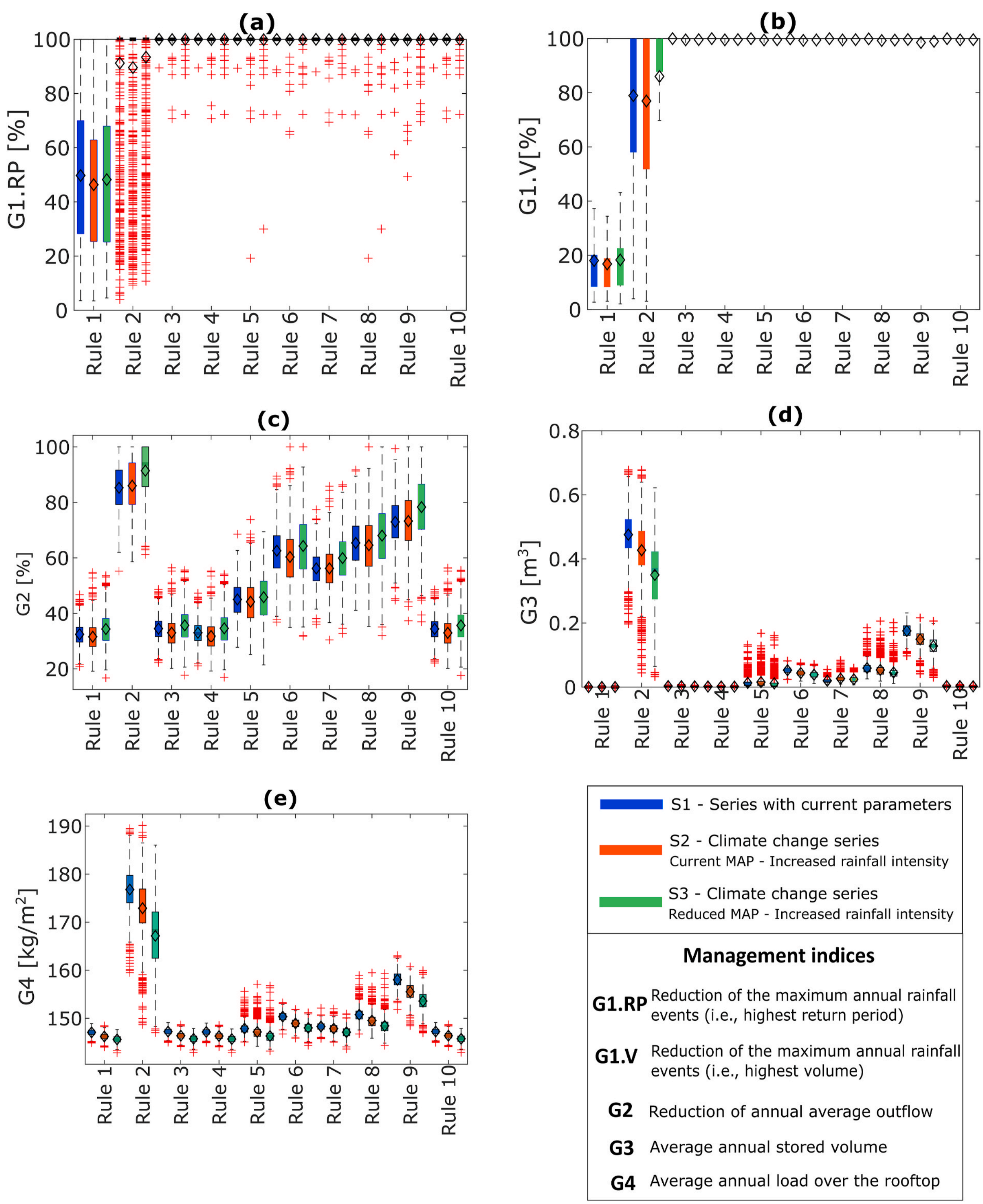

Fig. 4. Performance of each management rule in achieving the investigated goals for the series S1 (Blue), S2 (Orange) and S3 (Green), evaluated through the indices, as specified in the legend. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

including weather forecasts provide a valid support in the real time control of rainwater harvesting systems, and for this reason some rules also consider the rainfall forecasts. Due to the high level of uncertainty related to weather forecast, only near time 2 h-rainfall forecasts have been considered. Moreover, this study is based on generated weather time series, used to represent present and near future weather conditions: hence, the uncertainty related to the weather forecasts is not considered.

Some rules are applied seasonally and foresee a different behavior during the warm months and the cold ones. Following the rule R5 the gate is closed during the warm months, when the water scarcity can be a serious issue, especially in Mediterranean areas: in this way, the stored water can be used for the irrigation of the MBGR itself. In winter, on the other hand, R5 establishes to open the gate when there were not rainfall events in the previous 2 h, and rainfall is not expected in the following 2 h: to apply R5, the availability of rain gauges and weather forecast model are, hence, required. Rule R6 relies also on the presence of a water level sensors, since it hypothesizes an open gate 2 h after a rain event, if it is not expected to rain in the following 2 h and only if more than the 25% of the storage layer is filled. In this way, at least the 75% of the storage volume is always available at the beginning of a new rainfall event. Rule R7 aims to empty the water storage, before a rainfall event: for this purpose, rainfall measurements and forecasts are required, and the gate is closed when it has not rained in the previous 2 h, it is not going to rain the following 2 h, but rain is expected after 3 h. A combination of R5 and R6 is presented in rule R8, where the conditions described in R6 are applied only in winter, while in summer the gate is always closed.

An option to keep a fraction of rainwater available for domestic purposes is to open the gate only partially: this is the case of rule R9, when the gate is open to a gate heigh of 0.03 m, when it has not rained in the previous 2 h and it is not going to rain the following 2 h.

The last rule, R10, focuses on the mitigation of medium-intense rainfall events, characterized by a rainfall intensity higher than the 75%-ile (equal to 5.6 mm/d for the Cagliari case study). The gate is, in fact, closed when rainfall intensity is higher than the 75%-ile and opened when it has not rained in the previous 2 h and it is not going to rain the following 2 h.

3. Results

In this section the MBGR performance of each management rule in achieving the management goals is evaluated through the five indices summarized in Table 2. Results, plotted in Fig. 4, are investigated for the three rainfall time series described in Section 2.3: the rainfall time series S1 (blue) is obtained using the historical parameters, while the other two time series S2 (orange) and S3 (green) represent possible future scenarios. The legend includes a summary of the main characteristics of the rainfall time series and of the proposed indices, described in Section 2.5.

3.1. *Reduction of the maximum annual rainfall events (G1.RP and G1.V)*

The first two management indexes focus on the mitigation of maximum annual events, which are identified either by the highest return period (G1. RP) or the highest volume (G1. V), as defined in Section 2.5. To evaluate the MBGR performance in achieving G1. RP and G1. V, the IOR, as defined in Section 2.5, has been estimated for the maximum annual rainfall events of S1, S2 and S3 time series.

Results regarding events with the highest return period, reported in Fig. 4a, have shown that the lowest performance is achieved applying rule R1 (gate always open), with an average outflow reduction that varies between 45% and 50%, depending on the evaluated rainfall time series. When the gate is closed (R2) the IOR rises up to 93%. The other rules allow to obtain an average reduction above 99% for all the investigated time series, since they ensure an empty storage layer before the beginning of intense rainfall events.

The MBGR performance in mitigating the maximum annual rainfall events with high volumes, reported in Fig. 4b, is generally lower than in the case of events with the high return period. When applying the management rule R1, in fact, the runoff reduction is lower than 20% for all investigated time series. R2 enables to increase the retention capacity above the 76% for S1 and S2 and up to 86% for S3. As for G1. RP, when applying the other management rules (R3 – R10), the MBRG performance for G1. V is about 99% for all rainfall time series, highlighting the importance of including the gate in the MBGR design and to regulate the opening/closing.

It is worth noticing that the outflow reduction in the case of high return period events is higher than for the events with high volume, since short-duration and high-intensity events, which have a high return period, present a total precipitation that is not sufficient to saturate the soil. Moreover, the average outflow reduction with both R1 and R2 is higher under the scenario S3, since events are less frequent: consequently, the antecedent soil water content is lower, and the retention capacity is higher than for the events of S1 and S2. The outflow reduction of critical events is, in fact, influenced by the combination of different aspects, such as soil moisture conditions, water level in the storage layer and gate opening.

3.2. *Average reduction of annual average outflow (G2)*

The second management index, G2, analyses the average annual outflow reduction: by reducing this index, the first goal can be pursued and the pressure on the sewer system is limited. The annual total outflow from the MBGR is influenced by the evapotranspiration and evaporation phenomena, that characterize the soil and storage layer. Results are illustrated in Fig. 4c, where the boxplots represent the variability of the annual outflow reduction for the three time series. The management rules that guarantee the highest performance in terms average annual outflow reduction are the R2, R9, R8 and R6 which are characterized by an outflow reduction percentage above 56% for S1 and S2, and above 59% for S3. The analysis shows how the management rules that ensure long periods with the gate closed are more efficient in reducing the annual average outflow, since they guarantee high evapotranspiration from the soil and vegetation layer and evaporation from the storage layer.

On the other hand, the other management rules, which are characterized by the gate open for long periods, present an average outflow reduction percentage between 32% and 45% for all the investigated time series. The differences among the three rainfall time series are negligible, confirming, also in a context of climate changes, the high potential of a MBGR, which can ensure an average outflow reduction above the 80% when with an optimized management of the gate, compared to a traditional GR (represented by R1), which provides an average outflow reduction of 32% with the same rainfall conditions.

3.3. *Maximization of the average annual stored volume (G3)*

To pursue the second goal (i.e., to ensure the highest water storage), the third index, G3 (i.e., daily average annual volume of water in the storage layer) should be maximized, guaranteeing a large amount of water available for different domestic purposes, such as garden irrigation. Moreover, the collected water can be used for the self-irrigation of the MBGR, ensuring the sustainability of the vegetation installed. The maximum volume of water that can be physically stored in the prototype located in Cagliari is equal to 1.28 m^3.

The maximum daily average annual storage volume in correspondence of the three time series, plotted in Fig. 4d was obtained by simulating the behavior of the green roof according to rule R2, when the gate is always closed, and is around 0.4 m^3. When R2 is applied, the volume in the water storage is reduced only by evaporation.

The management rules R9, R8 and R6 allow to accumulate an average annual volume in the case of S1 of 0.176 m^3, 0.059 m^3 and

0.053 m^3, respectively and similar performances are guaranteed for S2 and S3. In these cases, the stored volume is limited since the gate is open when the water level reaches a fixed level. Lower storage capacities are achieved when the other management rules are applied, since the gate is open for several days.

3.4. Minimization of the average annual load over the rooftop (G4)

The last index G4 is the weight of the MBGR system: the minimization of this index allows to achieve the third goal, limiting the rooftop load. This aspect is particularly relevant for the installation of MBGR on

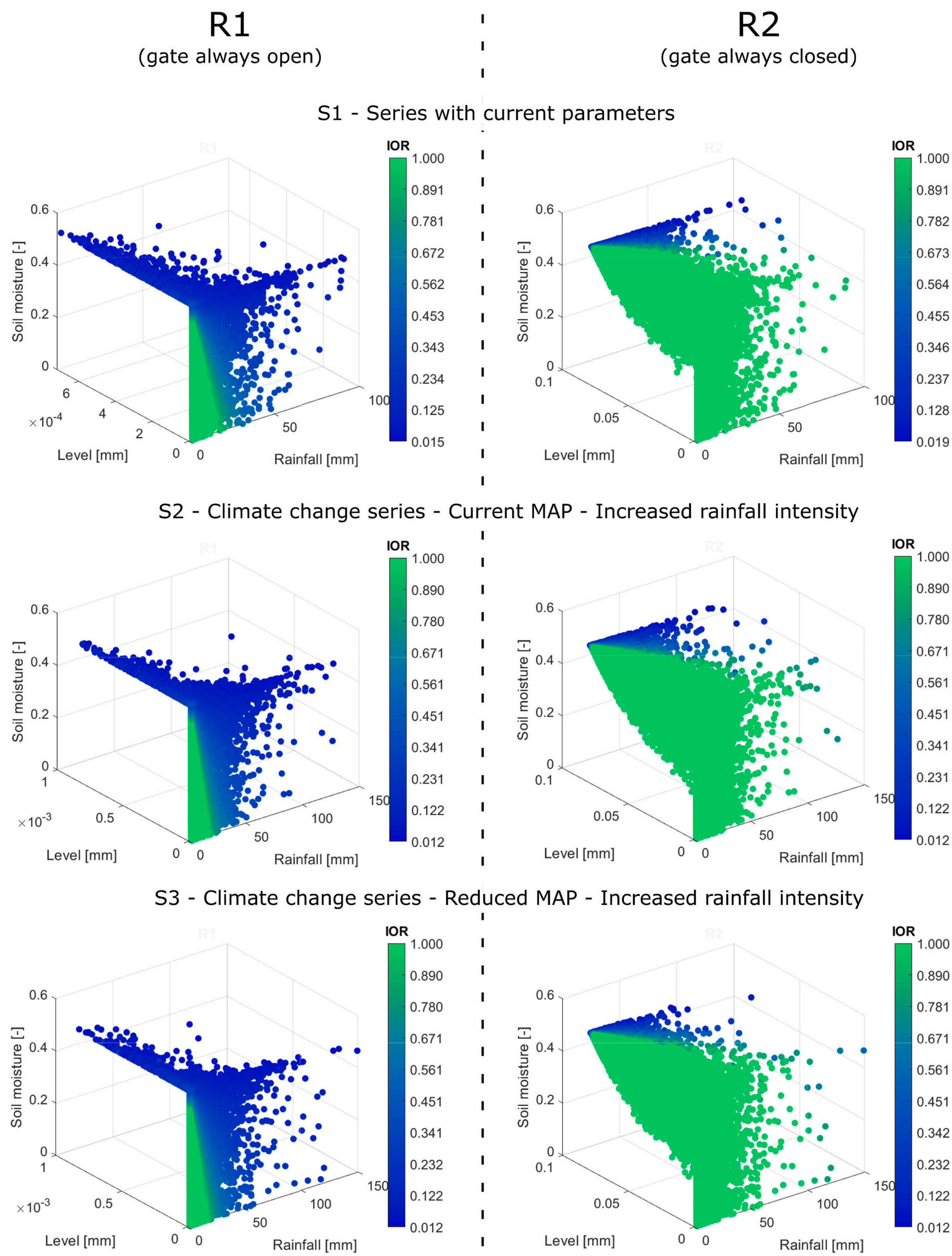

Fig. 5. Example of the roof load variability during a year (applying the rainfall time series S1), related to the different management rules.

existing buildings, which were not designed to carry this additional load. This index is not simply related to the storage layer volume (as G3), but it is also influenced by the soil moisture dynamics that characterize the soil layer.

The maximum weight of a MBGR with the same characteristics of the MBGR located in Cagliari is 259 kg/m^2, given by the sum of the various layers (illustrated in Fig. 1a), assuming that the soil layer is saturated, and the storage layer is completely full. On the other hand, when there is no water in the system and the soil is dry, the MBGR weighs 131 kg/m^2.

Fig. 4e illustrates the load variability estimated with the three investigated rainfall time series and highlights the average annual value. R1, R3, R4, R5, R7 and R10 guarantee the higher performance to reach the last goal, with an average annual load around 147 kg/m^2 for the three rainfall time series. The lower performance in minimizing the average load on the rooftop is achieved by management rule R2, that keeps the gate always closed, accumulating large amount of water. In this case, the average annual load reaches 175 kg/m^2 for S1 and for S2, while in correspondence of S3 the load is slightly lower (167 kg/m^2). Thanks to the rainfall characteristics, S2 and S3, which represent possible future climatic scenarios, guarantee higher performance in reaching the last management goal, confirming the importance of integrating MBGR in the urban planning for city development.

In order to deepen the above considerations, Fig. 5 illustrate the MBGR weight variability during a generic year, applying all the investigated management rules. As expected, R1 (gate always open) and R2 (gate always closed) represent the two extreme conditions, with the minimum and maximum weight, respectively.

4. Discussion

Analyzing the results presented in Section 3, it is clear that it is not possible to find a management rule that allows to reach all the proposed goals simultaneously and optimally. This is due to the fact that the second and third management goals are in contrast: it is not possible to achieve simultaneously the maximization of the water volume in the storage layer and the minimization of the load on the rooftop.

Focusing only on the runoff mitigation capacity, the obtained results confirms the findings presented by Busker et al. (2022), that investigated the performance of a MBGR installed in the Netherlands in retaining extreme events with different management rules. They found that if the gate is always open, the runoff generation is reduced up to 12% and it rises to 59% if the gate is always closed. On the other hand, when the gate is regulated accordingly to the weather forecasts, the performance increases, varying between 70% and 95%. Although the retention capacity of the Dutch prototype presents similar behavior to the Sardinian MBGR under different management rules, the performance in mitigating rainfall extremes higher in Cagliari, suggesting the high potential of this nature-based solution in Mediterranean climate.

The IOR, as defined in eq. (8), has been analyzed in relation to the total rainfall, antecedent soil moisture and water level in the storage layer following the different management rules. Results related to R1 and R2 are plotted in Fig. 6. The three rainfall generated time series S1, characterized by current parameters, S2, with same mean annual rainfall (MAP) as S1, but higher rainfall intensity, and S3 (higher MAP and rainfall intensity than S1) have been evaluated. Although not considered in this study. It is worth noticing that a certain level of uncertainty is always associated to any investigation under future climate scenarios, including natural climate variability, model and scenario uncertainty, and the incomplete knowledge of the Earth System dynamics (Latif, 2011; Wu et al., 2022). In this work, we focused on the influence of different management rules, under current climate conditions and possible critical future scenarios, without an explicit account for related uncertainty. Future research can be addressed to a comprehensive evaluation of the potential of MBGR in a context of climate changes, also including the influence of the main sources of uncertainty in climate projections.

Results obtained under rule R1 in the case of the three climatic series, suggest how the outflow reduction is maximum when precipitation occurs with low soil water content. When the soil is saturated, the MBGR performance in terms of outflow reduction decreases. In this case, since the gate is always kept close, the outflow reduction only depends on the antecedent soil moisture conditions.

When applying R2, on the other hand, the outflow reduction is not only influenced by the antecedent soil water content, but also by the water level in the storage layer. If the soil is dry and the storage layer is empty, the MBGR prototype can retain 94.78 mm of water, 15% in the

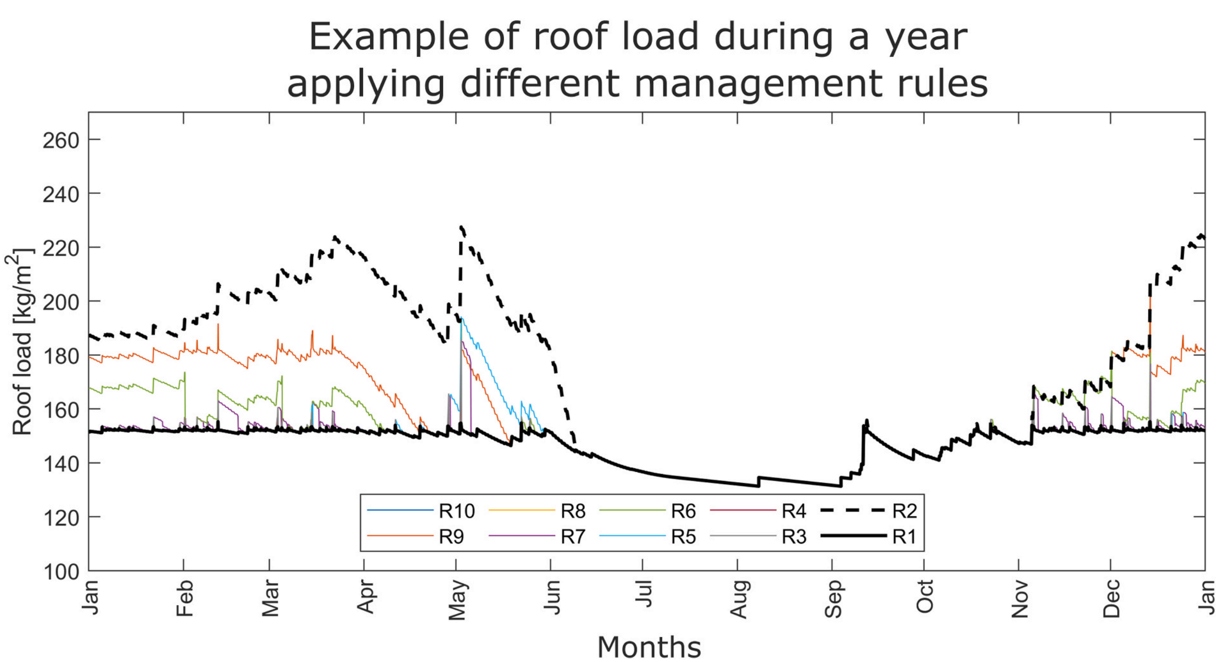

Fig. 6. Influence of rainfall depth, antecedent soil moisture conditions and water level in the storage layer on the IOR, when applying the R1 (Open Gate, left column) and R2 (Closed Gate, right column) management rules. The three rainfall time series S1 (current parameters), S2 (same MAP as S1 and increased rainfall intensity) and S3 (increased MAP and rainfall intensity) are evaluated.

soil and 85% in the storage layer. However, these conditions are not easy to achieve and, in most cases, if the gate is close the soil is partially wet, and the storage layer is partially full.

Comparing the management rules R1 (which represents the behavior of a traditional green roof) and R2 (which represents a MBGR without the possibility to regulate the gate), it is possible to evaluate the potential impacts that the additional storage layer has on the runoff mitigation, on the storage capacity and on the total weight of the structure. Applying R2, instead of R1, ensures higher performance in terms of flood mitigation and storage capacity. This highlights the potential benefits that can be achieved installing a MBGR instead of a traditional one. However, the absence of the gate (or keeping it always closed) leads to a high total weight of the structure, which might not be easily supported, especially by old buildings. This fact underlines the importance of a gate to regulate the water level and the necessity of management rules to achieve the proposed goals.

Among the several management rules (described in section 2.6), rules R3, R4, R5 and R10 are characterized by a higher efficiency than the one achievable with R2, in the outflow reduction associated with the maximum annual values of rainfall and a lower efficiency in the reduction of the annual average outflows. These four rules are set to accumulate the water mainly during all meteoric events or only during the most intense ones, ensuring the release of the stored volume after the end of the event. Under these conditions, there is a reduction in the average volumes over the long term and a load content on the floor. On the other hand, rules R2, R6, R7, R8 and R9 are characterized by an excellent efficiency in the outflow reduction associated with the maximum annual values of rainfall and average annual outflows. These rules are thought to accumulate the water resource for very long periods. As a result, in these cases there is an increase in accumulated volumes and an increase in load in the floor in the long term.

5. Conclusions and future works

An ecohydrological model has been proposed and calibrated to simulate the behavior of the Multilayer Blue-Green Roof (MBGR) prototype located in Cagliari (Sardinia, Italy), and in particular to evaluate the performance of 10 different management rules in achieving three different goals, i.e., mitigate the outflow generation, maximize the water storage and limiting the load over the roof. The potential MBGR impacts has been analyzed using as input of the model three generated rainfall time series: the first one represents the current climatic conditions in terms of average annual precipitation and interarrival time, duration, and intensity of the events, and the other two hypothesize future climatic scenarios according to the IPCC projections.

Results suggest that it is not possible to identify one single management rule that optimizes all the proposed goals. However, some rules enable to reach very high performance in achieving specific goals, highlighting the potential benefits of the MBGR installation for the creation of resilient cities.

- If the goal is to mitigate the runoff generation during extreme rainfall events, choosing a management rule that integrates weather forecasts and enable to empty the storage layer before an extreme event, guarantees high performance, both under current weather conditions and future climate scenarios.
- To increase the storage capacity, keeping the gate always closed (R2) is the most efficient solution. However, a partial opening enable to ensure both good storage capacity and good performance also in mitigating the urban flood.
- Following similar considerations, if the goal is limiting the load on the building roof, as in the case of MBGR installation over existing buildings, keeping the gate always open (R1) guarantee the lowest load. However, if a small increase of MBGR weight can be admitted, management rules which close the gate partially, and only when it is raining, ensure a high performance in the urban flood mitigation with a limited roof overload.

Retention capacity is strongly influenced by the rainfall depth, antecedent soil water content and water level in the storage layer: however, in Mediterranean climate, such as the Cagliari case study, with an adequate gate management, it is possible to fully retain extreme events, confirming the strong potential of MBGRs.

Results also underline the importance of an automatic management of the MBGR, which should include a reliable weather forecast system, to increase the performance of MBGR in achieving the selected goal. Although the uncertainties related to the future climate scenario estimations have not been deeply discussed and evaluated in this work, it is clear that these uncertainties can impact on the performance of management rules and will be investigated in future studies.

Moreover, future works should include the evaluation of a large-scale installation of MBGRs, involving all the suitable building of a large neighborhood or entire city, with the aim of creating an interconnected network, which will enable to increase the ecohydrological benefits for the sustainable development of the urban environment. The possibility not only to control a single MBGR, but also to coordinate a network of multiple MBGRs would be a strong motivation for policy and decision maker to invest in this nature-based solution.

Credit author statement

Elena Cristiano: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. Francesco Lai: Methodology, Investigation, Data curation, Visualization, Writing – review & editing. Roberto Deidda: Conceptualization, Methodology, Supervision, Writing – review & editing. Francesco Viola: Conceptualization, Methodology, Supervision, Writing – review & editing.

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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.

Data availability

Data will be made available on request.

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