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Green roof retention performance under extreme current and future climate conditions in Italy

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ABSTRACT

Due to the combination of intense urbanization and climate changes, cities are becoming more prone to pluvial floods. Among the different nature-based solutions proposed to ensure sustainable urban development, green roofs have shown high potential in mitigating the runoff generation during rainfall events. Beyond the design structure, the retention performance of these solutions is strongly influenced by the climate variability and could change when considering future climatic conditions. In this context, this work aims to evaluate the capacity of green roofs in mitigating runoff generation under current and future climate conditions in Italy, with a special focus on intense rainfall events. Three Italian cities (i.e., Cagliari, Palermo and Torino), characterized by different rainfall and temperature regimes, have been chosen as case studies. Two future scenarios have been investigated (RCP4.5 and RCP8.5), considering climate projections derived by dynamically downscaling the global climate model, proposed by the Euro-Mediterranean Research Center on Climate Changes, bias corrected with a quantile mapping approach. A standard extensive green roof has been modeled using a conceptual ecohydrological model at hourly scale, testing the performance variability across different design structures. Results confirm the full hydrological efficiency of green roofs under current climate conditions, with a median retention rate equal to 1 in all cities. Under future climate conditions, due to the foreseen intensification of rainfall events, the green roofs performance tends to slightly decline. The overall high retention capacity and the multiple benefits confirm green roofs as a key solution for the creation of sustainable and resilient cities.

1. Introduction

In recent decades, nature-based solutions (NbS) have gained increasing attention as effective strategies to mitigate the environmental impacts of rapid urbanization and support the development of sustainable and resilient cities[1,2]. NbS encompass a wide range of interventions that use natural processes to address urban environmental challenges, providing multiple co-benefits such as climate change adaptation and mitigation, biodiversity enhancement, and improved human well-being [3–5]. Among the most common NbS implemented in urban areas, green roofs (GRs) have been widely explored, demonstrating the multiple benefits that they can provide for the urban environment [6,7]. GRs, in fact, ensure high thermal insulation of the underneath buildings, reducing energy demand for heating and cooling systems [8,9]. In addition, GRs contribute to the urban heat island mitigation [10], to the biodiversity increase [11] and to the air quality improvement [12], and enhance the aesthetic value of built environment [13]. Beyond these multiple benefits, GRs have been widely recognized as effective NbS for urban stormwater management, as they can reduce runoff generation during rainfall events and increase the resilience of cities to pluvial flood risk [14,15]. Their hydrological performance mainly derives from the capacity of the substrate and vegetation layers to retain and temporarily store rainfall, thereby delaying runoff generation and reducing peak discharge from impervious roof surfaces [16].

The stormwater retention performance of GRs is influenced by several physical and design-related factors. Structural characteristics such as substrate type, porosity, and thickness determine the storage

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capacity and infiltration dynamics of the system. In general, thicker or highly porous substrates can retain larger volumes of water and thus enhance runoff mitigation [16–19]. For instance, soil layers characterized by high porosity or greater thickness consistently ensure better retention performance during rainfall events, as they increase both water storage capacity and infiltration potential [16,20]. Among green roofs, extensive systems (soil thickness < 20 cm) are widely adopted due to their lower structural weight and economic convenience, which make them suitable for retrofitting existing buildings [21,22]. Although extensive GRs generally provide lower retention capacity than intensive systems (soil thickness >20 cm), their widespread use makes them a relevant baseline for evaluating stormwater performance [23]. Vegetation characteristics, including plant species and coverage density, also play an important role by regulating evapotranspiration processes and soil moisture dynamics [24,25]. For example, while Sedum is often selected for its drought resistance and low maintenance, native grasses may enhance both stormwater retention and biodiversity [25,26]. In addition, the presence of drainage or storage layers can further influence the hydrological behavior of GR systems [27–30].

Alongside design characteristics, local climatic conditions strongly affect GR performance. Rainfall intensity, event duration, seasonality, and evapotranspiration rates determine both the amount of water retained during rainfall events and the recovery of storage capacity between consecutive storms [31]. Numerous studies have investigated the hydrological performance of GRs under different climatic regimes through experimental and modeling approaches [32–35]. For example, the large-scale review conducted by Zheng, Zou [20], which analyzed 2375 experimental studies from 21 countries between 2005 and 2020, reported an average retention rate of approximately 62 %. However, a considerable variability in retention performance is observable in the literature, depending on substrate depth, vegetation type, climatic conditions and seasonal patterns. Studies conducted in different climatic zones have shown that GR performance can vary significantly across regions, emphasizing the importance of considering local climate characteristics when evaluating their effectiveness [27,31].

Despite the extensive literature on GR performance under present climatic conditions, their long-term effectiveness under future climate scenarios remains insufficiently understood. Climate change is expected to alter precipitation regimes in many regions, with projections indicating an increase in short-duration, high-intensity rainfall events [36]. Such changes may reduce the retention efficiency of GRs by exceeding their storage capacity during extreme storms. Conversely, rising temperatures may enhance evapotranspiration and accelerate soil drying processes, potentially increasing the available storage capacity prior to subsequent rainfall events. However, this mechanism may also increase water stress for vegetation, potentially affecting the ecological stability of GR systems. Consequently, assessing the combined effects of these processes is essential for evaluating the resilience of GRs under future climatic conditions.

In this context, high-resolution climate modeling approaches, such as convective-permitting climate models (CPMs), are increasingly used to better represent precipitation dynamics at spatial and temporal scales relevant for urban hydrology [37–39]. Unlike traditional regional climate models, CPMs explicitly resolve atmospheric convection processes and therefore provide a more accurate representation of short-duration and high-intensity rainfall events. These features make CPM outputs particularly valuable for assessing the impacts of climate change on urban drainage systems and NbS performance. Recent studies have applied CPM simulations to investigate the response of urban stormwater infrastructures and NbS to future climate scenarios in several regions, demonstrating their potential to improve the reliability of hydrological impact assessments [40–43].

Within this framework, the present study investigates the variability of green roof hydrological performance under both current and future climate conditions. Climate projections derived from dynamically downscaled simulations produced by the Euro-Mediterranean Center on Climate Change are used to characterize future rainfall dynamics[44]. Three Italian cities, i.e., Cagliari, Palermo, and Torino, characterized by different climatic regimes, are selected as representative case studies. Despite the different climate characteristics, all three cities have experienced several pluvial floods in the past [45–47] and, for this reason, the implementation of GRs and other NbS could be beneficial for the sustainable development and creation of flood resilient urban environments. Overall, Italy provides an interesting context for climate impact assessments because projected changes in precipitation patterns are expected to vary considerably across the country. Northern regions are expected to experience relatively small variations in total annual precipitation, consistent with projections for Central Europe, whereas southern regions are expected to undergo a substantial reduction in rainfall, similar to projections for the broader Mediterranean basin. Nevertheless, precipitation is expected to become more intermittent throughout the country [48]. A conceptual model proposed by Viola, Hellies [16] has been used to investigate ecohydrological processes that characterize GRs and to estimate the retention capacity under both historical and future scenarios. The model is used to estimate retention performance under both historical and projected climate scenarios. In addition, different design configurations are explored by varying substrate thickness and vegetation characteristics to assess potential adaptation strategies. Specifically, this study aims to investigate how the GRs retention capacity may change under projected future climate scenarios compared to historical conditions. Particular attention is given to understanding how different climatic regimes influence the hydrological performance of green roofs and whether design modifications, such as variations in substrate thickness and vegetation characteristics, can enhance their resilience under changing climate conditions.

2. Methodology

2.1. Ecohydrological green roof model

The conceptual ecohydrological streamflow model proposed by Viola, Hellies [16] has been used to simulate the GR outflow in response to climate forcings. The model is schematically represented by a soil bucket, regulated by soil moisture and active soil depth, defined as the product between the porosity n and the soil thickness Z_r. Although the framework proposed by Viola, Hellies [16] was originally developed at a daily scale, in this work the ecohydrological conceptual model was adapted to simulate GR dynamics with an hourly time step. When it rains, water infiltrates into the soil until the field capacity, s_{fc}, is reached; over this point, percolation begins. When the soil reaches saturation, the excess of water leaves the system via surface runoff SR. Soil moisture dynamics are expressed with the water mass balance equation (eq. 1):

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

where Δs is the variation of the relative soil moisture in the soil bucket, R the rainfall depth, ET the actual evapotranspiration, L the deep percolation and SR the surface runoff. Evapotranspiration and percolation are determined by the relative soil moisture s, which can vary between 0 (dry soil) and 1 (saturated soil). They can be estimated as:

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

$$L = \begin{cases} 0 & 0 < s \leq s_{fc} \\ (s - s_{fc})\ \mathrm{n}\ \mathrm{Z_r} & s_{fc} < s \end{cases} \tag{3}$$

where s_0 is the wilting point and s_{fc} the field capacity. ET_{max} is the maximum crop evapotranspiration, computed as the product of the crop coefficient K_c and the potential evapotranspiration, estimated with the Thornthwaite equation [49]. In particular, ET_{max} is estimated at daily time step and then divided by an average of 12 light hours. A schematic representation of the proposed model is illustrated in Fig.1.

The study focuses on the hydrological performance of a standard extensive green roof. A reference soil layer thickness of 10 cm was considered, with additional simulations exploring the effect of increasing the substrate thickness up to 20 cm. Sandy loam was selected as the substrate, characterized by a porosity of n equal to 0.43, a wilting point s_0 of 0.018, and a field capacity s_{fc} of 0.56 [50].

When designing a GR, vegetation is a key factor in regulating both evapotranspiration and runoff and ensuring high performance of the ecosystem services [51]. Depending on the main purpose of the GR, different vegetation choices could be made. *Sedum* is often considered an ideal choice as GR vegetation thanks to the high resistance without irrigation [52,53]. In this study, a common grass cover was assumed, with a crop coefficient (Kc) of 1, meaning that potential evapotranspiration corresponds to the maximum crop evapotranspiration [54]. The potential effects of alternative vegetation with a lower crop coefficient (Kc = 0.5, typical for Sedum) were also assessed and discussed.

The index of retention *IOR* (eq. (4)) is here proposed to evaluate the retention capacity of the GR (Cristiano et al., 2022). *IOR* can be written, for the generic time period i, as:

$$IOR_i = 1 - \frac{O_i}{R_i} \tag{4}$$

where O_i is the outflow from the system, estimated as the sum of deep percolation and surface runoff. The proposed index can vary between 1, when the rainfall event is fully retained by the GR structure, and 0, when the GR is already saturated and all rainfall is directly converted to outflow. The IOR can be estimated for each time step using the same temporal resolution of rainfall data or aggregated scales (frequently used scales are: daily, weekly, monthly, and annual), or it can be referred to an independent rainfall event with varying duration and thus including multiple timesteps. In this work, we considered two consecutive rainfall events as independent when their interarrival time is greater than 6 h, as commonly used in the literature for GR studies that investigate the retention capacity [17,30,55].

It is worth noticing that, for the proposed reference configuration, if a rainfall event occurs on dry soil ($s = s_0$), the total amount of rainfall that could infiltrate (i.e., maximum retention capacity of the soil) is equal to:

$$nZ_r(s_{fc} - s_0) = 0.43 * 100(0.56 - 0.018) = 23.3\ mm.$$

This value will be assumed as a threshold to identify extreme events, and the performance analysis will be focused only on those exceeding this value, which ensure outflow generation (IOR < 1). This threshold corresponds to the 91st, 85th and 86th percentile of the historical rainfall event series in Cagliari, Palermo and Torino (see Section 2.2), respectively, highlighting how this value actually represents extreme conditions for all the selected cities.

2.2. Study cases

Three Italian cities have been selected as case studies to investigate the GR retention performance under different climate conditions: Torino (TO, Piedmont), Cagliari (CA, Sardinia) and Palermo (PA, Sicily). These three cities are characterized by different climate regimes, as summarized in Table 1. Torino presents a higher annual precipitation compared to the other two cities, and rainfall is more uniformly distributed

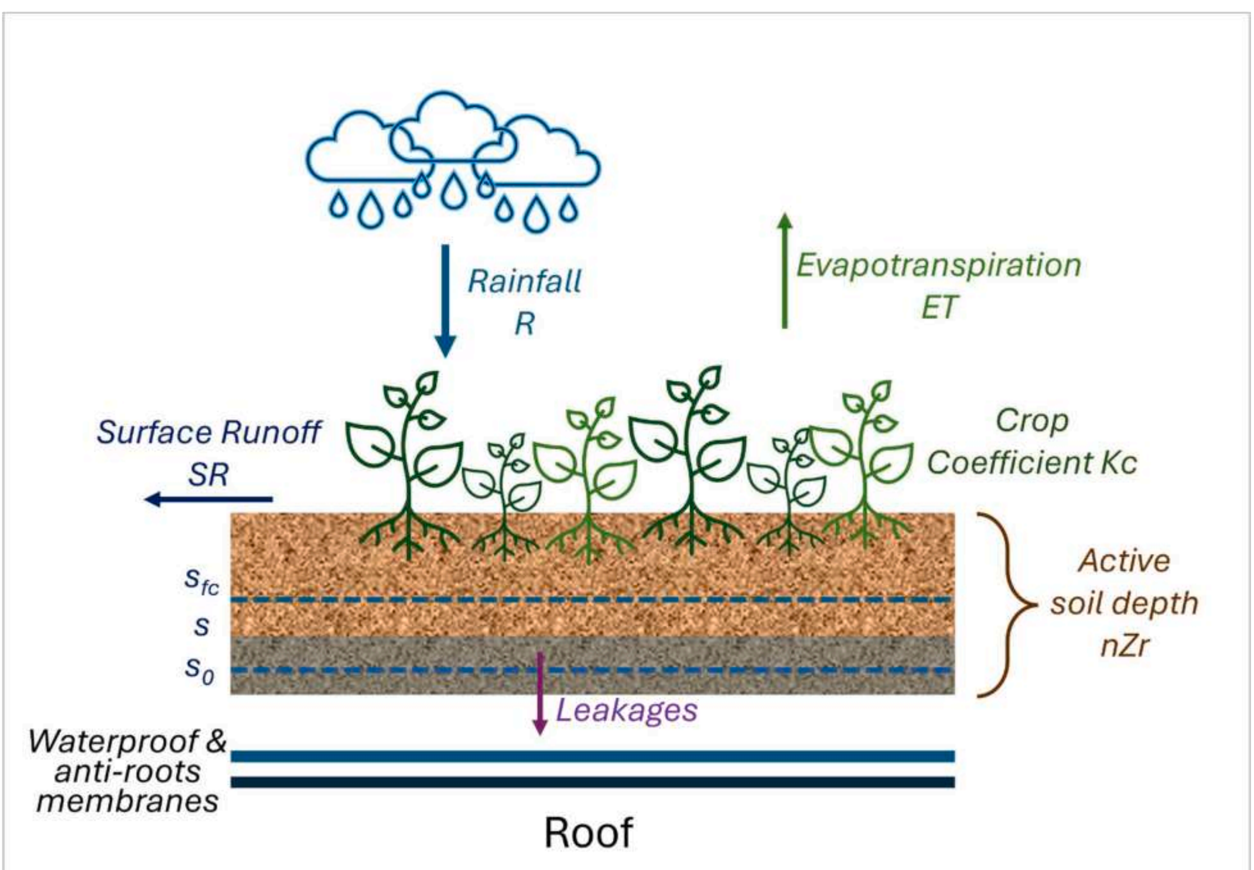

Fig. 1. Schematization of the ecohydrological model used in this study. Standard GR assumes Kc=1 and Zr=10 cm; scenarios with thicker soil layer (20 cm) and lower crop coefficient (0.5) are analyzed.

Table 1
Characterization of the 3 investigation locations.

	Cagliari	*Palermo*	*Torino*
Coordinates	39.2237° N, 9.1217° E	38.1157° N, 13.3615° E	45.0703° N, 7.6869° E
Köppen-Geiger Climate Classification	Csa - warm temperate climate with dry and hot summer	Csa - warm temperate climate with dry and hot summer	Cfa - warm temperate climate, fully humid hot summer
Mean annual precipitation [mm/y]	408	742	906
Average minand maxdaily Temperature [°C]	12.4 - 22.6	15.5 - 22.2	8 - 18.4
Length of the recoded time series	20 years (2005 to 2024)	21 years (2002 to 2022)	37 years (1989 to 2004: Buon Pastore + 2004 to 2024: Giardini Reali)
Rainfall observation resolution	1-min	10-min	10-min

throughout the year, with slightly higher peaks in May and November. Cagliari and Palermo, instead, are denoted by dry summers and rainfall peaks in spring and autumn. Overall, Cagliari exhibits the lower mean annual precipitation. Following the classification proposed by Kottek, Grieser [56], Cagliari and Palermo can be classified as “warm temperate climate with dry and hot summer” (Csa), while Torino as “warm temperate climate, fully humid hot summer” (Cfa).

As reported in Table 1, at least 20 years of measured hourly precipitation and temperature data are available for the three investigated cities. For Cagliari, rainfall and temperature time series were recorded from the weather station network managed by the Regional Agency for the Protection of the Environment of Sardinia (*Agenzia Regionale di Protezione Ambientale, ARPAS*). For Palermo, 10-min resolution rainfall and temperature data from 2002 to 2022 recorded at the gauge station *ID276 - Uditore* managed by the regional agency SIAS (*Servizio Informativo Agrometeorologico Siciliano*) have been used. For the city of Torino, two complementary weather stations (*Buon Pastore* and *Giardini Reali*), managed by the regional agency ARPA (*Agenzia Regionale di Protezione Ambientale*), located less than 1.7 km apart, have been considered, to ensure a long time series of available data. To ensure homogeneity among the collected data and coherency with the ecohydrological model described in Section 2.1, rainfall data has been aggregated at hourly scale. Recorded data have been used to bias correct the historical and future climate scenarios, following the approach described in Section 2.3.

2.3. Climate scenarios and bias correction

Future climate scenarios have been derived by dynamically downscaling the global climate model proposed by the Euro-Mediterranean research Center on Climate Changes at hourly scale (CMCC—CM) [44]. This model has been selected since it is convection-permitting and therefore reproduces the extreme rainfall characteristics in the Mediterranean region more accurately.

Two greenhouse concentration scenarios, RCP4.5 and RCP8.5, have been investigated, considering an historical time series from 1981 to 2005 and a future time series from 2006 to 2070 [44]. In order to remove potential systematic errors from the climate models [57,58], rainfall data have been bias-adjusted following a two-step approach that aims to correct, at monthly scale, number of events and rainfall depth. The bias correction, based on the historical time series at the three cities, has been developed using 80 % of records for calibration and the remaining 20 % for validation. The rainfall timeseries from climate models also include very small values (i.e. likely numerical noise) which do not have a counterpart in the observed time series, because too low to be detected due to the limitations in the instrument’s sensitivity and precision.

To guarantee better conceptual correspondence, a minimum threshold of 0.01 mm hourly rainfall was introduced. Whenever a modelled rainfall value fell below this threshold, it was accumulated together with the consecutive values until the cumulative sum reached or exceed 0.01 mm. Once this condition was met, the total was assigned to the time step where the threshold was reached, and all the individual values that contributed to the sum were set to zero.

Prior to applying any correction to the probability distribution, the first step of the adjustment procedure aims to align the number of hourly rainfall events of the modelled time series with the observed one. In particular, the average number of hourly events for each month in the observed time series is kept in the modelled time series, by randomly removing the exceeding events. Ensuring that the number of events matches the observed climatology allows the following corrections to focus on adjusting rainfall intensities rather than compensating for differences in occurrence frequency.

Subsequently, a quantile mapping bias correction of monthly rainfall was applied. The monthly correction was selected to preserve rainfall seasonality and to accurately represent soil-moisture dynamics. Only in this way can the retention effect be explicitly assessed, accounting for the fact that winter precipitation is greater but occurs on already moist soils, whereas the opposite holds during summer. Correction coefficients have been estimated for each month separately, from the comparison of the cumulative distribution of the non-zero values of the modeled (historical) and observed values. The percentiles were set based on the distribution of the observed timeseries and, for each of them a multiplier coefficient has been estimated and used to correct the modelled historical time series. This approach corrects biases across the whole range of monthly rainfall ensuring, for a given month, an improved reproduction of the full distribution of values, and consequentially of its statistics (mean, variance, skewness and extremes).

The application of this two-step bias correction, hence, ensures the correct match of number of events and rainfall intensity distribution at hourly time scale within 12 months between observed data and the time series derived from climate model. Once the monthly quantile mapping functions and number of events to remove per each month are determined from the comparison with the historical period, they have been finally applied to future projections of rainfall time, series for both scenarios, to reduce bias while preserving trends.

Temperature data, which are required for the estimation of the potential evapotranspiration, instead, have been adjusted at monthly scale via a linear correction approach, using an additive factor as expressed in eq. (5). For each month, the mean bias was calculated as the difference between the monthly average of the recorded data $\overline{x}_{obs}$ and the monthly average of the historical model $\overline{x}_{hist}$. This difference was then added to the daily model data x_i to obtain the bias - corrected temperature:

$$x'_i = x_i + (\overline{x}_{obs} - \overline{x}_{hist}) \quad (5)$$

The estimated additive factors have been finally used to bias correct the two future temperature projections.

3. Results

3.1. Bias corrected rainfall and temperature

Following the approach described in Section 2.3, the bias correction procedure has been carried out by randomly selecting 80 % of the years of the historical data for calibration and using the remaining 20 % for validation. Figs. 2a, 2c and 2e illustrate the monthly average total rainfall depth of the historical model in the three cities, before and after the application of the bias correction, for both calibration and validation. The observed rainfall data are also plotted, showing the

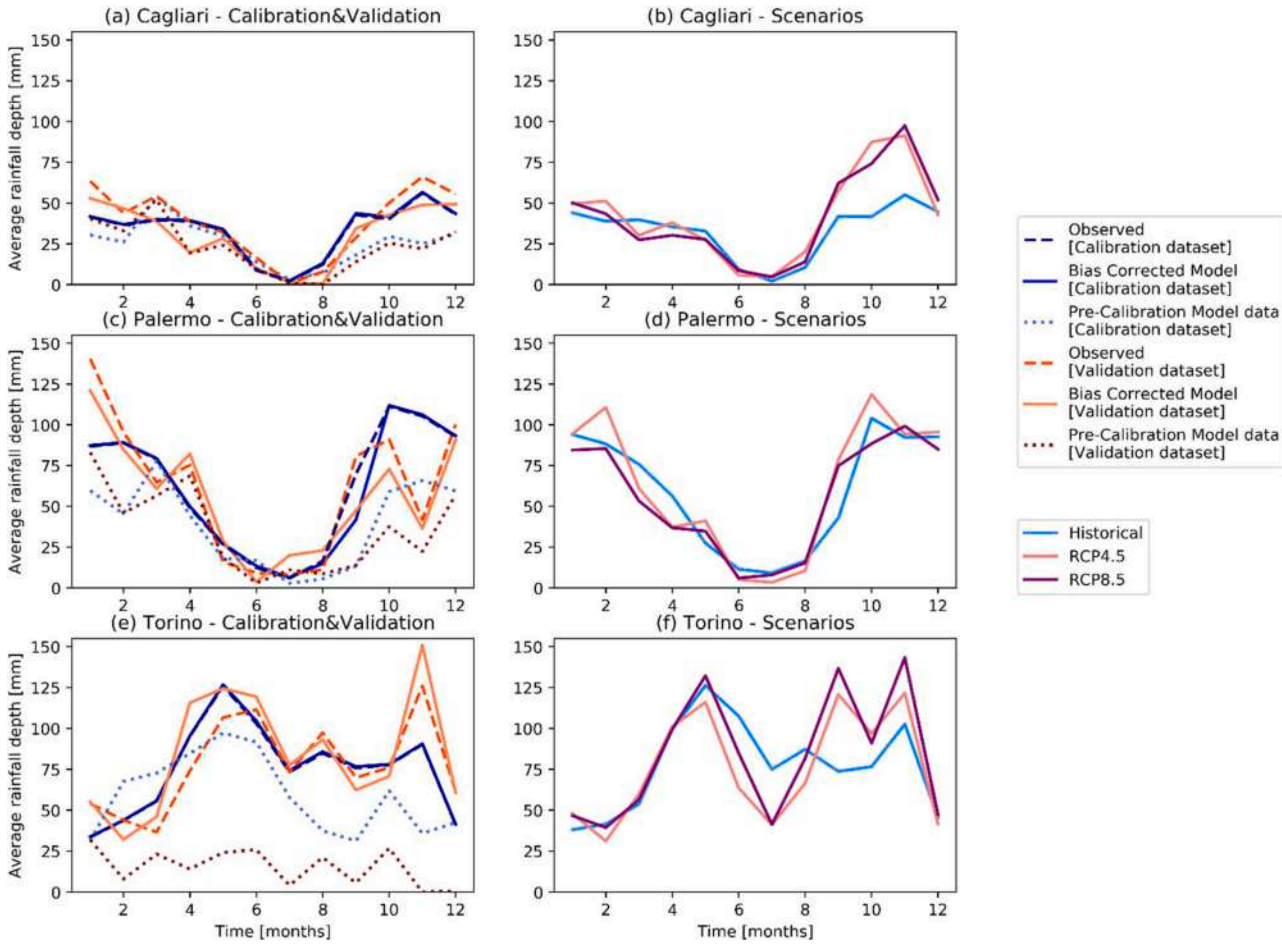

Fig. 2. Monthly average of the bias-corrected rainfall data. (a, c, e) Calibration and validation data set, before (dashed lines) and after (solid lines) bias correction. (b, d, f) Bias-corrected historical and future scenarios.

improvement achievable with the two-step bias correction and highlighting the importance of this approach. While in the cases of Cagliari and Palermo the proposed procedure is mostly needed to correct the monthly average in Autum and Winter, in Torino the error adjustment is required for each month. Figs. 2b, 2d and 2f show monthly averages of the bias-corrected datasets for historical and future scenarios. In Cagliari (Fig. 2b), a general increase of mean annual precipitation is expected, varying from the observed 408 mm (Table 1) to 506 mm (+24 %) and 492 mm (+20 %) for the RCP4.5 and RCP8.5 scenarios, respectively. The increase of rainfall is mostly observed in Autumn (September, October and November), while a slightly lower monthly average is expected in February and March. In Palermo, on the other hand, only slight variations of mean annual precipitation are projected, with a variation from the observed 741 mm to 750 mm (+1 %) and 671 mm (−9 %) for the RCP4.5 and RCP8.5 scenarios, respectively. Also in this case study, the mean annual precipitation projected for RCP8.5 is expected to be lower than for RCP4.5 scenario. A similar trend is modeled for Torino, where the observed mean annual precipitation (906 mm), is projected to stay constant (907 mm; +0 %) in RCP4.5 and to slightly increase (1000 mm; +10 %) in RCP8.5.

A general rise in intense rainfall events is expected in all three cities and under both future climate scenarios. For example, considering events with an intensity above 2.8 mm/h (the average 95th percentile of historical events across the three cities), their share in Cagliari is projected to increase from 3 % of all events to 7 %. Similarly, in Palermo the proportion of intense events is expected to rise from 4 % to 8 %, while in Torino the increase is slightly smaller, going from 6 % to about 7–8 %.

Temperatures, illustrated in Fig. 3, are projected to increase in both future scenarios, in all three cities, without significant differences between RCP4.5 and RCP8.5. For the average monthly temperature, indicated as solid line, this increase is most severe for the month of January, ranging from 2.3 °C for Cagliari and Palermo to 2.7 °C for Torino. Moreover, the average annual temperature is expected to rise from 18.1 °C, 18.7 °C and 14.2° to 20.1 °C, 20.7 °C and 16.3 °C, for Cagliari, Palermo and Torino, respectively. Looking at the average maximum monthly temperatures, marked as dotted lines, the highest future temperatures can be observed for all three cities in July, reaching values of about 40 °C. Simultaneously, the increase in maximum temperatures between the historical and future period peaks in July, with a value of around 3 °C.

3.2. *Green roof retention performance*

To analyze the retention capacity of GRs in the three selected cities under current and future climate conditions, the IOR index (eq. (4)) has been estimated for each rainfall event. To analyze the retention capacity of GRs in the three selected cities under current and future climate conditions, the IOR index (Eq. (4)) was computed for each rainfall event. In Cagliari, 2047 rainfall events were identified in the historical scenario, increasing to 4307 and 4286 under the RCP4.5 and RCP8.5 scenarios, respectively. Among these, 77 (3.8 %), 290 (6.7 %), and 300 (7.0 %) events are classified as intense, i.e., characterized by a rainfall depth exceeding 23.3 mm, as detailed in Section 2.1. In Palermo, 2046 events are simulated for the historical scenario, rising to 4643 and 4479 in the future projections. Of these, 219 (10.7 %), 569 (12.3 %), and 495 (11.0 %) events are intense. The proportion of extreme events in Palermo is

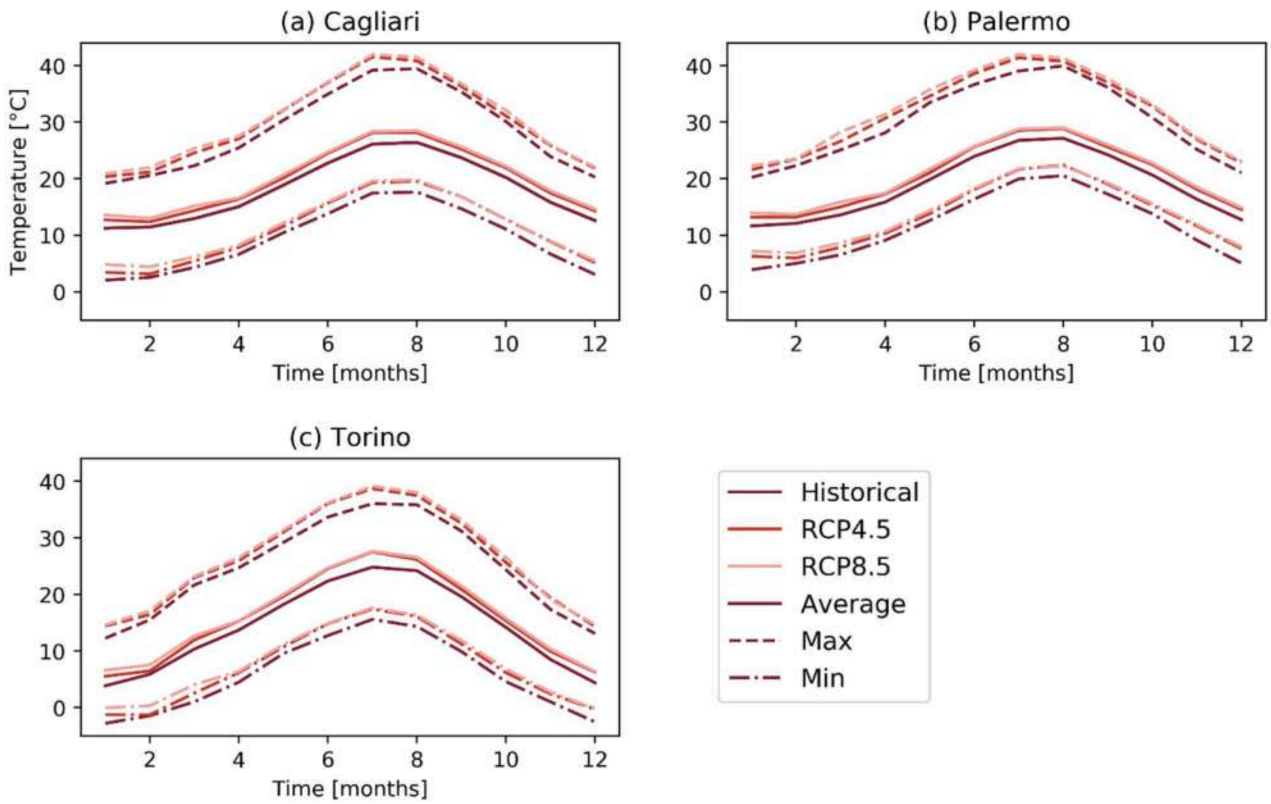

Fig. 3. Monthly average, minimum and maximum temperature for the three investigated cities and climatic scenarios.

higher than in Cagliari across all scenarios, indicating a greater relative occurrence of high-intensity rainfall events. Torino exhibits a higher total number of independent events, with 3007 in the historical scenario and 6918 and 6794 under RCP4.5 and RCP8.5, respectively. Among these, 252 (8.4 %), 636 (9.2 %), and 703 (10.3 %) events are intense. Although Torino experiences more events overall, the share of extreme events remains lower than in Palermo but higher than in Cagliari, highlighting differences in the relative intensity of rainfall across the three cities.

Fig. 4 illustrates the IOR variability for the three investigated climate scenarios (historical, future RCP4.5 and RCP8.5), considering the entire dataset (Fig. 4a, 4c and 4e) and focusing only on intense rainfall events (Fig. 4b, 4d and 4f). Despite the high variability, the median IOR (orange line in Fig. 4) is equal to 1 in all the locations and under all scenarios, underlining the overall high runoff mitigation capacity that characterizes this NbS. The IOR variability is higher in Torino and Palermo than in Cagliari, suggesting a more variable hydrological response of the GR with increasing depth of the rainfall events, which are not always fully retained by the GRs. In both Cagliari and Palermo, a slight reduction in performance is expected across the two future scenarios, reflected in a decrease in the mean IOR. Specifically, in Cagliari the mean IOR decreases by approximately 5 % under both RCP4.5 and RCP8.5 scenarios, while in Palermo the decrease is about 8 % under RCP4.5 and 3 % under RCP8.5. In Torino, by contrast, no significant differences are observed among the three climate scenarios, as confirmed by Welch's *t*-test ($p = 0.088$ and $p = 0.754$ for the comparisons of the two future scenarios with the historical one), indicating that the mean IOR remains statistically unchanged.

From the analysis of a subset of events including only extreme events (i.e. >23.3 mm, see Section 2.1) (Fig. 4b, 4d and 4f), a drop in the estimated IOR values is observed in all three locations, as expected, with mean values for the historical period around 0.46 in Cagliari, 0.25 Torino and 0.36 in Palermo, i.e., less than half of the values resulting from the analysis of all rainfall events. The better performance observed in Cagliari is caused by a lower frequency of intense rainfall events in this location, along with the higher temperature, that favor evapotranspiration between events. However, when the context of climate changes with the associated increase of intense rainfall events is addressed, a decrease in the GR performance can be observed for Cagliari. In Palermo and Torino, on the other hand, the IOR variability and median values remain constant, with a slight increase when considering future climatic conditions.

3.3. *Factors influencing the retention capacity: rainfall events characteristics*

In this section, the effects of rainfall characteristics, such as event depth, duration, intensity and interarrival time are discussed. The double heat maps in Fig.4 illustrate, for different values of event duration and total depth, the average IOR and the percentage of events falling into each class. The average IOR is reported in the lower-right corners of the heat map cells, highlighted with green shades, while the percentage of events is plotted in the upper-left corners, colored with orange shades. The figure shows the three investigated scenarios (i.e., historical, RCP4.5 and RCP8.5) for Cagliari (Fig. 5a–c), Palermo (Fig. 5d–F) and Torino (Fig. 5g–i), plotting event duration and depth on a logarithmic scale.

Results show high IOR, close to 1, in correspondence of low event depth and duration and indicate that the retention capacity decreases with increasing rainfall duration and depth. In all three cities, the majority of the events present low depth and duration, with more than 60% of the events showing a rainfall depth lower than 9 mm and duration lower than 13 h. For these ordinary events (i.e., rainfall depth < 9 mm and shorter than 13 h), the average IOR across all cities and scenarios remains consistently above 0.7, supporting the effectiveness of this NbS. In contrast, for deeper (>9 mm) and longer (>13 h) rainfall events, which represent on average 13 % of the total events, the average IOR does not exceed 0.59.

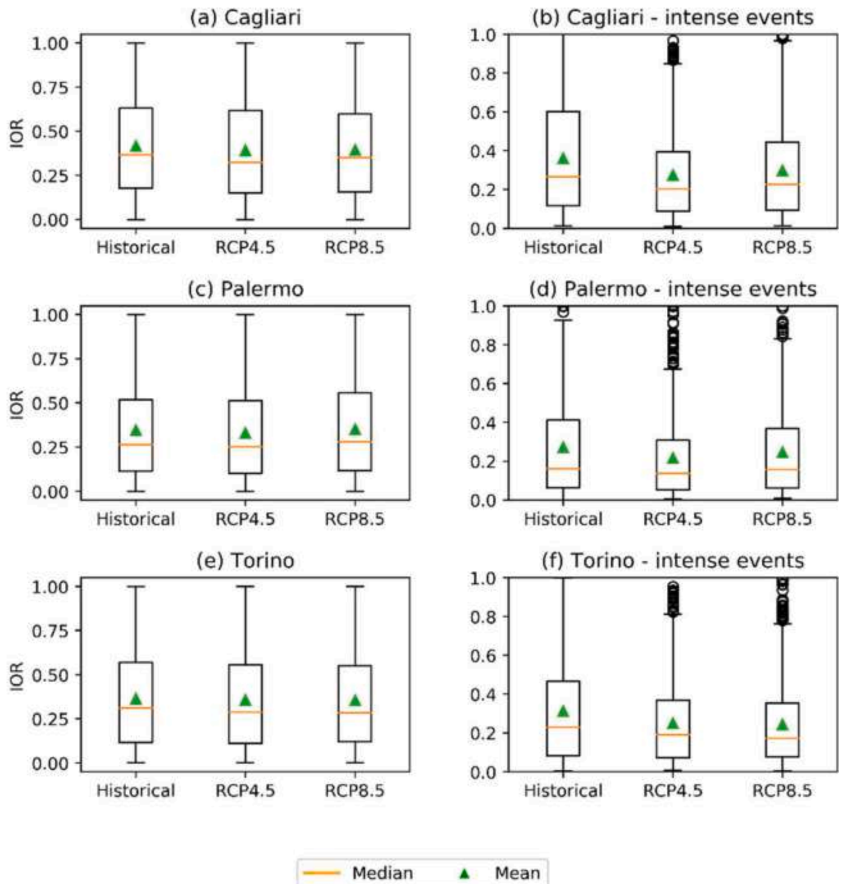

Fig. 4. IOR variability estimated for each event in the historical and future scenarios for the three cities: (a, c, e) all events, (b, d, f) intense events with total depth above 23.3 mm. Median values are highlighted with an orange line, while average values are represented with a green triangle.

In the context of future scenarios, a slight increase of short but intense rainfall events is expected in all three cities, with a few events with rainfall depth between 79 mm and 530 mm, and duration lower than 13 h. In correspondence of these events, the expected average IOR is generally lower than 0.15, underlying potential decrease of performance under future climate conditions.

Another important influencing factor that affects the retention capacity of GRs is the interarrival time, occurring between two separate events. As expected, the average IOR generally increases with the increase of the interarrival time, due to the drier soil and consequent higher volume available into the soil to collect rainwater.

Fig. 6 illustrates with a double heatmap the average IOR variability with respect to the interarrival time and the average event intensity, defined as the ratio between event depth and duration. The lower-right corner (green shades) of each cell of the heatmaps illustrates the average IOR, while the upper-left corner (orange shades) represents the percentage of event with these specific characteristics. Event intensity and interarrival time are plotted on a logarithmic scale.

The heatmaps confirm how the retention capacity increases with the increase of the interarrival time, while presenting lower values for higher event intensity. Although the majority of the events, that are characterized by short interarrival time and low rainfall intensity, present a good retention capacity (i.e., IOR above 0.66), the IOR reaches values close to 1 only for light events characterized by both an intensity lower than 0.75 mm/h and an interarrival time higher than 74 h.

In the historical scenario for all three cities, the majority of the events (23 %, 23 % and 26 % in Cagliari, Palermo and Torino, respectively) presents interarrival time lower than 21 h and rainfall intensity lower than 0.75 mm/h, with corresponding IOR higher than 0.66. For slightly higher values of rainfall intensity, ranging from 0.75 mm/h and 6 mm/h, combined with low interarrival times (below 21 h), the IOR drastically drops to values lower than 0.62 Similar trends are foreseen for both future scenarios, where a slight increase in the interarrival times can be noticed in all cities, that is also accompanied by an overall increase in rainfall intensity for the case of Palermo.

3.4. Factors influencing the retention capacity: green roof design

The last analysis assesses the influence of the GR design on retention capacity, evaluating how different soil thicknesses and vegetation types could affect the performance of this NbS. This aspect is particularly relevant in the context of climate changes, since good design choices for these elements are fundamental to ensure high performance not only in the present but also in the long term and under varying conditions.

The mitigation performance achievable with a GR characterized by a thicker active soil depth (i.e., 86 mm, corresponding to a soil depth of 20 cm) is illustrated in Fig. 7, for the three investigated cities and for each investigated scenario, comparing it with the standard GR design (i.e., active soil depth equal to 43 mm, corresponding to a soil depth of 10 cm). The double heatmaps show in the upper-left corner the average IOR for the thicker soil layer, and in the lower-right corner the average IOR for the standard design. From the comparison, it is clear that the thicker soil layer leads to a general increase of the retention capacity, especially in correspondence of events characterized by high rainfall depth.

For events with depth lower than 9 mm and duration lower than 47 h, the GR performance, characterized by IOR values higher than 0.66, does not present any significant differences with varying soil depth, highlighting how the standard GR design was already leading to the maximum achievable performance for the majority of the events. On the other hand, in correspondence of events with high depth and duration,

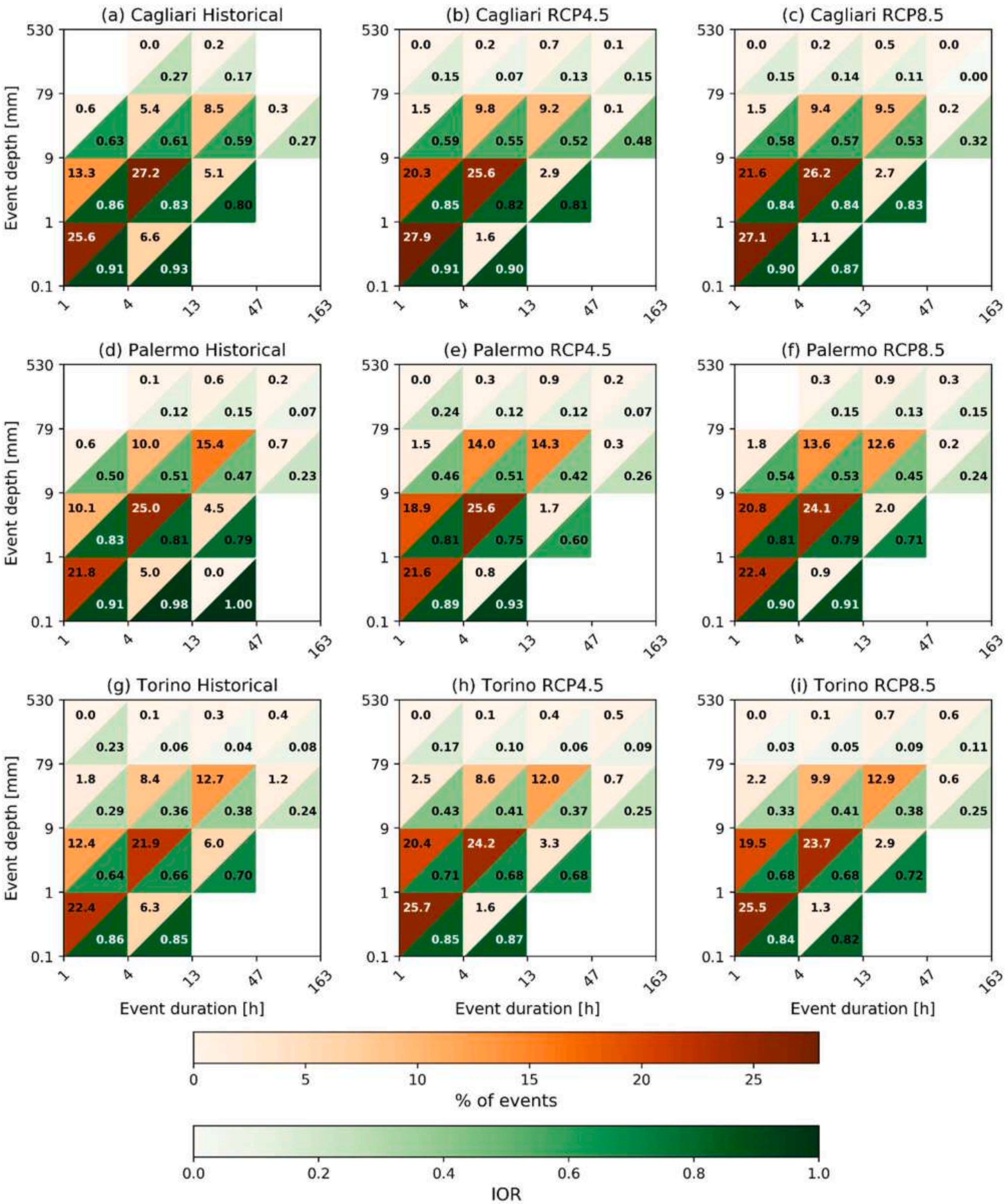

Fig. 5. Influence of rainfall event depth and duration on the IOR. The lower right corner of each cell of the heatmaps illustrates the average IOR in the range (green shades), while the upper left corners indicate the % of events that falls in that range (orange shades). Event depth and duration are plotted on logarithmic scale.

the thicker soil layer enables to increase the retention capacity, up to a two-fold factor.

Additionally, the influence of the vegetation type is investigated considering a lower crop coefficient, set equal to 0.5, as representative of Crassulacean Acid Metabolism (CAM) vegetation, commonly used in arid and semiarid regions. Fig. 8 shows, for all investigated cities and climatic scenarios, the variability of the IOR index in relation to event length and duration, comparing the GR design response in the case of CAM vegetation (upper-left corner of the double heat map cells) with the one considering the standard configuration (grass) with a unit value for the crop coefficient (lower-right corners). For this analysis the soil depth is assumed to be equal to 10 cm (reference configuration).

The retention capacity of the investigated NbS decreases passing from grass to CAM vegetation in all scenarios due to reduced

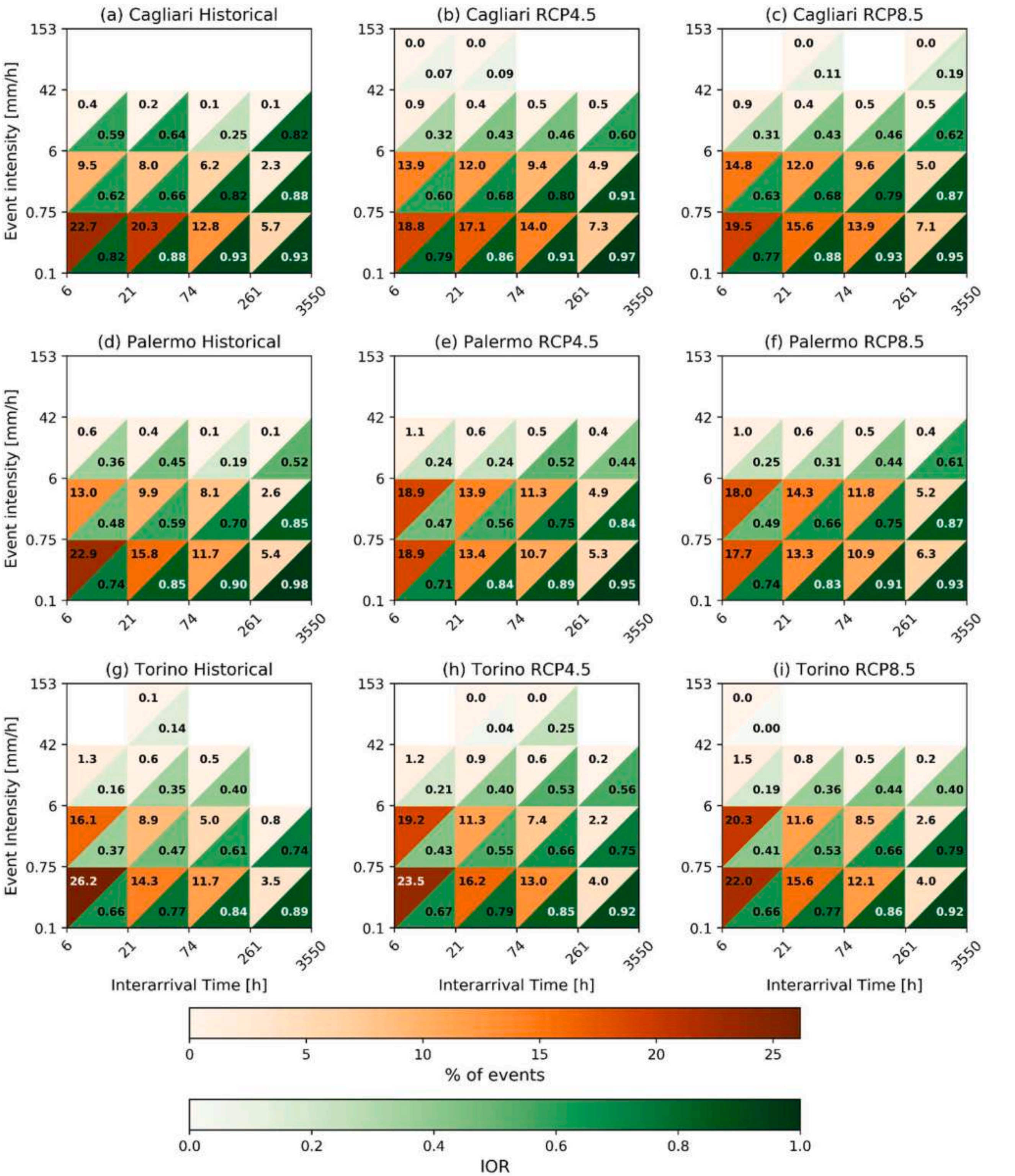

Fig. 6. Influence of rainfall intensity and interarrival time on the IOR. The lower right corner of each cell of the heatmaps illustrates the average IOR in the range (green shades), while the upper left corners indicate the % of events that falls in that range (orange shades). Event depth and duration are plotted on logarithmic scale.

evapotranspiration activity. The reduction in IOR (up to 50 %) is more intense for events with high depth and duration, while for events with rainfall depth lower than 1 mm and duration shorter than 13 h, the performance decline is almost negligible. These results highlight the importance of carefully selecting vegetation types according to the specific objectives of the NbS. In particular, when the goal is to minimize outflow and reduce flood risk, achieving high retention performance requires considering the species' ability to establish, grow and adapt to the local climate conditions, including projected climate change.

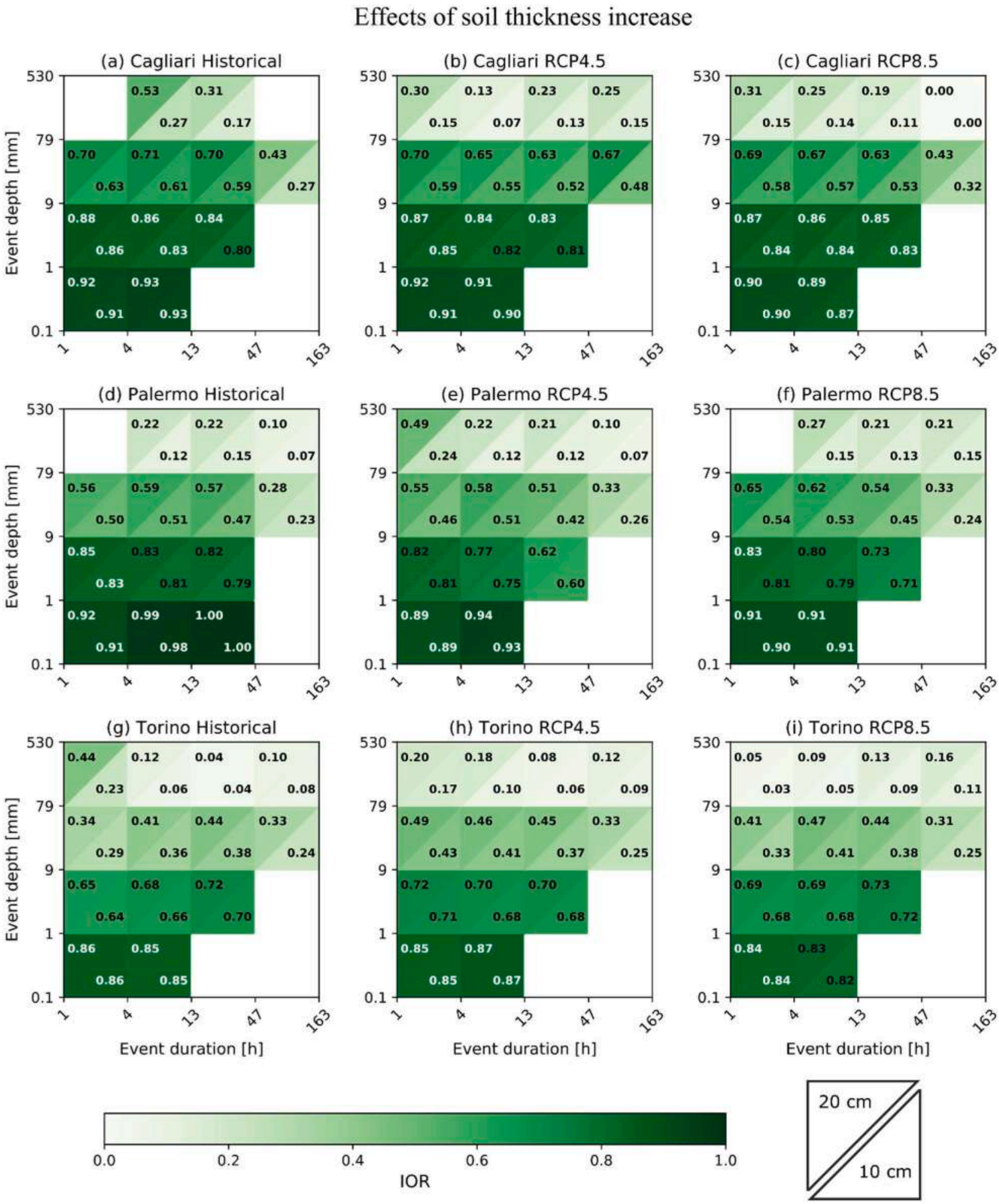

Fig. 7. Influence of the event depth and duration on the retention capacity, comparing a GR with a soil thickness of 20 cm (upper left corners, with the standard green roof depth of 10 cm (lower right corners) for the three investigated cities under historical and future climate scenarios.

3.5. Recommendations

GRs are widely recognized for their high retention capacity at building scale [21,34,59], which makes them a reliable NbS to mitigate urban runoff and to create resilient cities, especially in Mediterranean areas [25,26,60]. Results presented in this study for the three Italian cities of Cagliari, Palermo and Torino, generally confirm these findings, showing a median index of retention equal to 1. However, the retention capacity presents a generally high variability (Torino and Palermo), and the GR performance can easily decrease in correspondence of intense, frequent or prolongated events. These conditions are likely to become more common in the near future, leading to a variation of the foreseen performance, as underlined also by Pons, Benestad [61]. It is hence fundamental to design GRs capable of ensuring high performances now

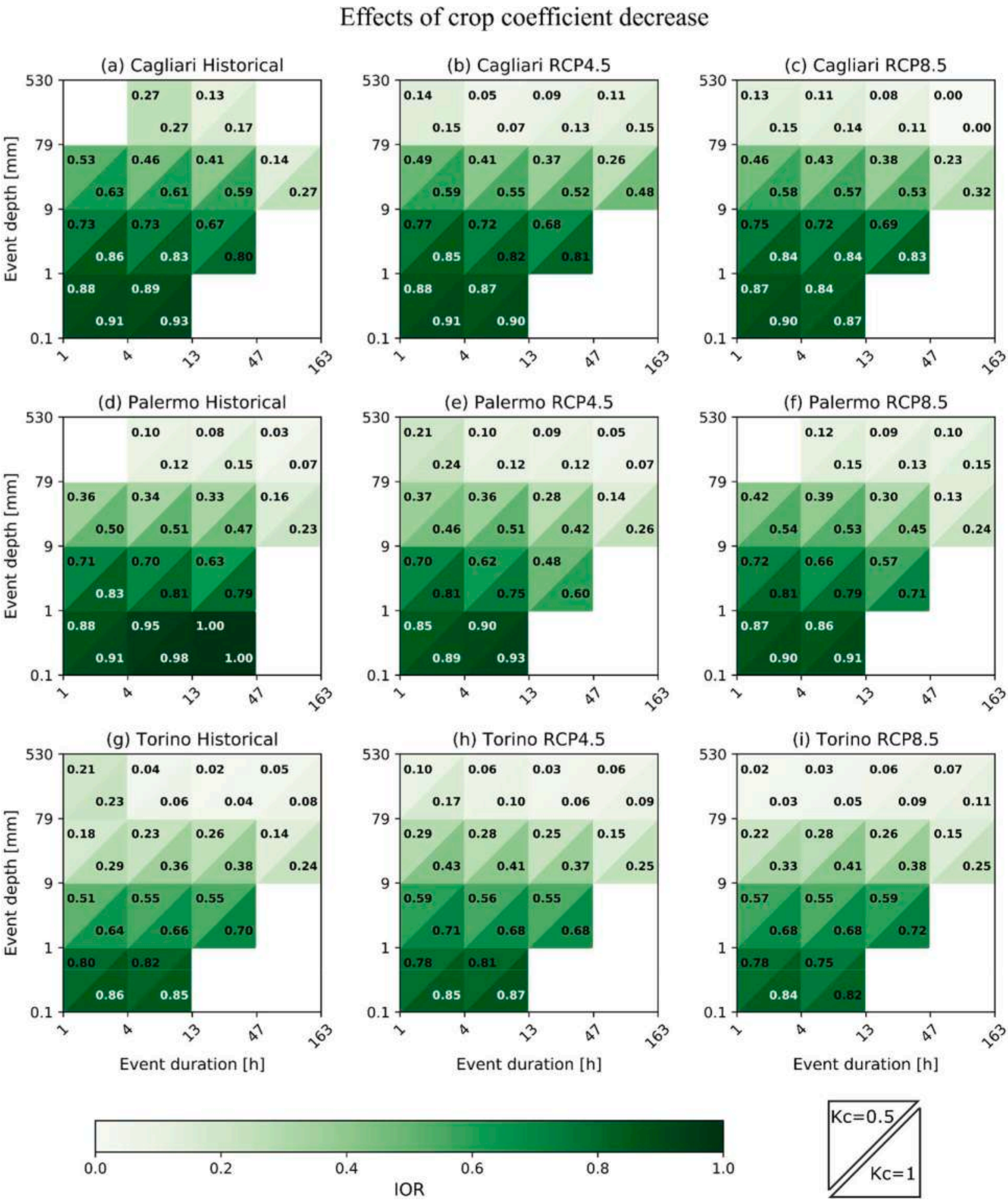

Fig. 8. Influence of the event depth and duration on the retention capacity, comparing a GR with a vegetation characterized by a low crop coefficient (Kc=0.5) in the upper left corners with the standard GR design in the lower right ones for the three investigated cities under historical and future climate scenarios.

and in the next decades.

Even in cities like Cagliari where, under current climate conditions, GRs can fully retain most of the rainfall events, the efficiency of these NbS is expected to slightly decrease in correspondence with future climatic scenarios, due to the increased frequency of intense rainfall events. A GR design that considers a thick soil layer and vegetation with high crop coefficient (e.g., grass) could ensure better performance, also in the context of climate changes, enhancing the potential of this solution in mitigating the runoff generation in urban Mediterranean areas. Conversely, the use of herbaceous vegetation with crop coefficients close to one may be hindered by rising temperatures in the future. The adoption of CAM species, such as the widely used *Sedum*, could be a more suitable option [25]. However, as shown in our analyses, this choice may lead to a slight reduction in the hydrological performance of GRs. When choosing the vegetation to be installed in the GR, it is fundamental to evaluate not only the performance in terms of retention capacity but also to consider the other multiple benefits that this structure provides to the building and more in general to the urban environment. A carefully balanced mix of native and selected species can ensure an increase of biodiversity, enhancing ecological functioning and ecosystem services [51,62].

Moreover, the vegetation choice can influence GR thermal performance in terms of both building insulation and of urban heat island reduction. Previous studies, for example, highlighted how a highly dense vegetation cover can increase the GR capacity of thermically insulating the underneath building [63]. In the same way, the vegetation installed in the GRs [64–66] strongly influences the extent of the reduction of the surrounding temperature, consequently limiting the urban heat island phenomenon. These aspects are particularly relevant for GR installation in cities like Cagliari, Palermo and Torino, where an increase of the mean annual temperature of 2 °C is foreseen. In a future climatic context, where temperatures are expected to increase, the key role of GR installations in urban areas (and in general of all NbS) can not be neglected. Furthermore, these types of intervention need to be carefully evaluated by policy makers and urban designers and included in a sustainable urban development planning, that aims to adapt to future climatic scenarios.

4. Conclusions

Among all the potential benefits of green roofs (GRs) for the sustainable urban development, this study assessed the runoff reduction capacity in three Italian cities (i.e., Cagliari, Palermo and Torino), under current and future climatic conditions. The conceptual ecohydrological model proposed by Viola, Hellies [16] was adapted to simulate the hydrological performance of standard GRs, using bias-corrected climatic input at hourly scale (i.e., rainfall and temperature). The proposed two-step bias correction procedure ensures the correction of event number and rainfall depth at monthly scale.

Results highlight an overall high retention capacity under both current and future climatic conditions in all three cities, with a median index of retention (IOR) equal to 1. Cities characterized by higher mean annual precipitation, such as Palermo and Torino, exhibit greater variability in retention performance and lower mean IOR values (0.75 and 0.65, respectively) compared to Cagliari (0.83). In Palermo and Torino the impact of future climate conditions is limited, while in Cagliari the variability of IOR increases under both future scenarios. For intense events (rainfall depth>23.3 mm), the performance drops significantly, with an average IOR of 0.36 (Cagliari), 0.3 (Palermo) and 0.2 (Torino). Retention performance is strongly influenced by the event characteristics, and it decreases with the increase of rainfall depth and duration: for events with duration lower than 13 h and depth lower than 9 mm an efficient IOR higher than 0.64 is ensured in all investigated cities and climatic scenarios. Other event characteristics that are essential to understand the potential GR performance are the intensity and the interarrival time, which are expected to increase in the future climatic projections in all three cities. On one hand, the increase of rainfall intensity reduces the retention capacity of GRs, on the other hand, the longer interarrival time mitigates this effect, leading to a very small decrease in IOR under future scenarios. Given the projected changes in rainfall characteristics, evaluating potential design adaptations is essential. Increasing the substrate thickness from 10 cm to 20 cm, for example, doubles the average IOR for very intense rainfall events (>79 mm), which are expected to become more frequent in the future.

These findings highlight the importance of assessing GR performance under future climatic scenarios to support urban planning and policy decisions. Appropriate design choices, including substrate thickness and vegetation type, are essential to maintain the effectiveness of these NbS, which remain a key strategy for sustainable urban development despite the slight performance decrease projected under future conditions.

CRediT authorship contribution statement

Elena Cristiano: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Malin Grosse-Heilmann:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Dario Pumo:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Fulvio Boano:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Matteo Ippolito:** Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Francesco Viola:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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Data availability

Data will be made available on request.

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