The combined performance of green roof and rainwater harvesting: retention capacity and water saving

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The combined performance of green roof and rainwater harvesting: retention capacity and water saving

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ABSTRACT

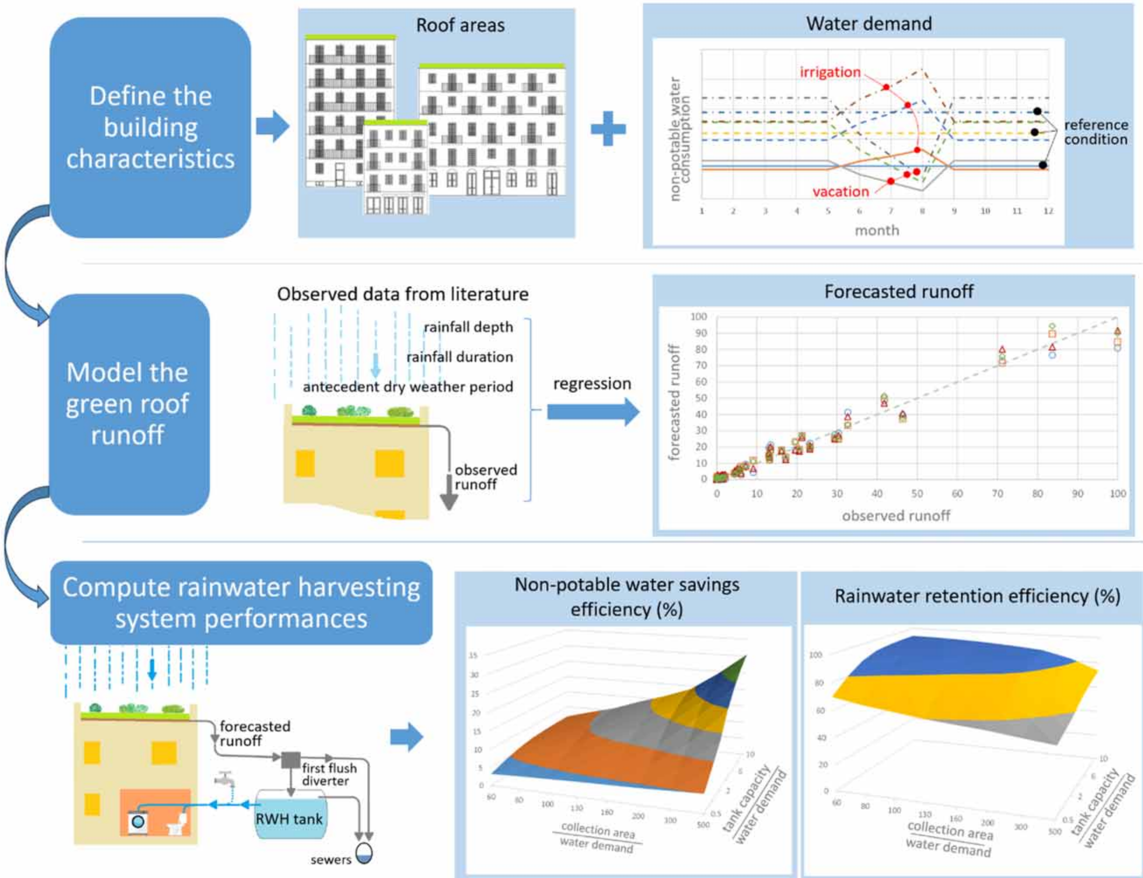
Population growth and migration to urban spaces are influencing the management of the urban water cycle, both in terms of supply and drainage, driving a more holistic management of the urban water cycle, combining hard centralized engineering infrastructures with soft decentralized nature-based solutions. Among the latter, rainwater harvesting (RWH) and green roofs are solutions that have been most encouraged by some municipalities around the globe at the building level. The present study describes a methodology to assess the combined performance of RWH and green roofs in terms of water savings and rainwater retention. The methodology can be easily applied and is compatible with the format in which the required data are usually available. The methodology is applied to the city of Turin, in Italy, and is used to develop generalized relations that allow estimating the performance of RWH systems with traditional and green roofs, based on two ratios that contain all the relevant characteristics of the rainwater harvesting system (water consumption, collection area and tank capacity).

Key words: green roofs, rainwater harvesting, rainwater retention, water savings

HIGHLIGHTS

- Urban water saving is reachable through rainwater harvesting (RWH).
- Combining green roofs with RWH increases the rainwater retention capacity.
- The best performances of the combination are reached with small and low-cost RWH tanks.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Historically, mankind resorted to rainwater harvesting (RWH) to tackle water shortages, either due to limitations of other water sources or to temporal constraints of water availability. Nowadays, this is still the main motivation underlying the implementation of RWH in many developing regions, regardless of the water resources available (e.g., Africa, South America, Southeast Asia), and in developed regions with limited water resources (e.g., California, Australia).

However, another driver emerged in highly urbanized areas in developed regions: the need to minimize the rainwater discharge into the stormwater drainage system. In the 1960s, roughly two-thirds of the world's population (2 billion) lived in rural areas, but since 2007, more than half of the world's population lives in urban areas (7.95 billion in 2022) (Ritchie *et al.* 2024). One of the consequences of urban growth that has already taken place, more noticeably in the developed regions, is the increase in impervious surfaces. These impervious areas are forecasted to increase further throughout the globe with population and urbanization growth, and this implies reductions in surface retention, infiltration and evapotranspiration. This results in an increase in the volumes and peak discharges into the sewers, which, combined with their limited capacity and difficulty in intervening in the existing drainage infrastructures, increase the risk of combined sewer overflows and urban floods. Adding the frequency and magnitude of extreme rainfall events due to climate changes to this situation, it is understandable that there is increased interest in sustainable rainwater management (Wilderer 2004), also referred to as Best Management Practices (Griffiths *et al.* 2020), Water Sensitive Design (Mguni *et al.* 2022), Integrated Water Management (Mitchell 2006), Low Impact Development (Griffiths *et al.* 2020), Sustainable Urban Drainage Systems (Ferrans *et al.* 2022) or Sponge City (Hamidi *et al.* 2021) in the literature.

Sustainable rainwater management relies, to a large extent, on the promotion of decentralized solutions to complement/alleviate the existing stormwater drainage system. At the building level, this has been done through incentives to implement solutions such as green roofs and RWH systems. These incentives range from financial support to stormwater fee reduction (Liberalesso *et al.* 2020). For instance, the city of Hamburg grants a 50%

rebate in the water fee for green roofs with a thickness of more than 5 cm and an impervious surface reduction of 20 m^2 per cubic metre of storage volume for RWH systems with tanks of at least 2 m^3. Some cities/regions/countries (e.g., New Delhi, Indore, Kanpur and other locations in India; New Zealand) promoted RWH, making it mandatory for new buildings (Gabe *et al.* 2012). In others, it is the green roofs that are mandatory (e.g., Saint Laurent, Toronto, in Canada; Tokyo, in Japan; Los Angeles, Portland, San Francisco, in USA; Recife, Porto Alegre, São Paulo, in Brazil; Córdoba, in Argentina; Zurich, Basel, in Switzerland; Copenhagen, in Denmark; Stuttgart, Munich, Hannover, in Germany; Turin, Bolzano, in Italy) (Wilkinson *et al.* 2022). In most cases, the main motivation underlying the policies towards promoting green roofs and RWH is reducing stormwater volume and peak discharge, but there are other motivations. In India and Brazil, water shortages were the more relevant drivers, whereas in Tokyo, it was the heat island effect reduction that motivated its green roof policy.

The literature on RWH is extensive (e.g., see Silva *et al.* 2022 for a review; Younos & Parece 2016; Campisano *et al.* 2017), but it has mainly focused on water savings. Water saving entails a quantitative and a qualitative dimension, since the rainwater needs to meet some minimal quality standards for it to be used. This is logical from the building owner/investor perspective since the financial viability of a RWH system is driven by the relation between the savings associated with the reduction of public water supply consumption and the investment and operation costs of the system. In addition to the RWH potential in each specific case, the water cost plays a key role in financial viability. In fact, higher RWH system performance in terms of water saving may not imply financial viability because water is, in most regions of the globe, an inexpensive commodity.

Green roofs, on the other hand, have been extensively studied (see Zheng *et al.* 2021 for a review) in terms of their hydrological performance, both in terms of rainwater detention (peak discharge reduction) and retention (volume reduction). Despite the generalized conclusion that green roofs contribute to reducing the rainwater discharged into the urban drainage networks, their performance is extremely variable. This variability is not only due to the location climate (e.g., see Voyde *et al.* 2010; Stovin *et al.* 2012; Viola *et al.* 2017) and the green roof characteristics but also to the specific temporal pattern of the rainfall (Zheng *et al.* 2021).

However, despite the various studies on the hydrologic performance of green roofs, physical modelling requires a range experimental data for calibration, which, even in the case of their availability from weather stations, are site-specific and may not be representative of each possible location of green roof (e.g., radiation due to shading; wind velocity due to building roughness; temperature due to heat island effect).

Also, the studies on the combined performance of RWH systems and green roofs are limited (e.g., Almeida *et al.* 2023). In this research effort, the performance of combining a green roof with an RWH system in the city of Turin, Italy, is explored, resorting to (i) an empirical model to estimate the green roof runoff and (ii) a simulation model to mimic the RWH system operation. The goal is to provide a planning-level tool that is easy to implement and use by both academia and industry, and requires only information that is either a design parameter (e.g., rainwater collection area; water consumption) or generally accessible data (e.g., daily rainfall series). The comparison with the performance achieved with a traditional roof is also presented, considering that a traditional roof encompasses a variety of possible impervious roofing solutions (e.g., clay tiles, metal sheets, polymeric membranes).

2. DATA AND METHODS

2.1. Case study

The present research uses the city of Turin as a case study to demonstrate the tool, providing continuity to past research on the topic (e.g., Carollo *et al.* 2022). The city of Turin is the administrative centre of the Piemonte Region and is located in the north of Italy, about 240 m above sea level. The climate is Cfa (humid subtropical), according to the Köppen-Geiger classification (Beck *et al.* 2023). The city extends over an area of 130 km^2, having 871,850 inhabitants distributed over 36,158 residential buildings (Istat 2011).

In and around Turin, there are eight rain gauge stations in the databases of the Regional Agency for the Environment Protection (ARPA Piemonte 2024) and the National Institution for Environment Protection and Research (SCIA-ISPRA 2024) with data, until at least 2022. The length of the daily rainfall series of records in these stations ranges from 18 to 70 years. However, it is important to notice that there are some days missing in several years. Considering only years with at least 350 days with data, the maximum series length is 69 years. The annual rainfall of the years with more than 350 days of data from each station is presented in Figure 1.

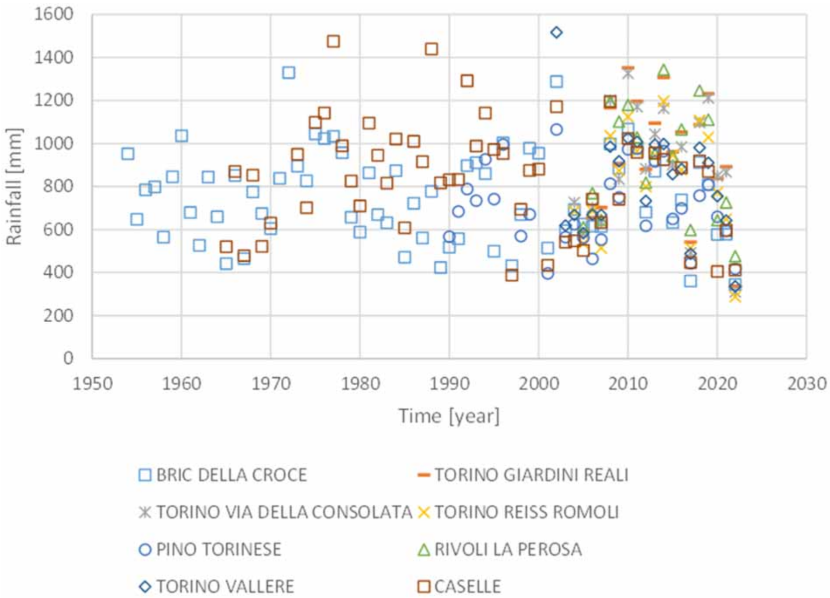


Figure 1 | Annual rainfall depth for locations with at least 350 days of data within a year.

Most of the stations are located at elevations identical to Turin (239–368 m), but two are located at higher elevations (Bric della Croce, 710 m, and Pino Torinese, 608 m). These latter stations recorded a lower average annual rainfall (731 mm) than the stations at lower elevations (870 mm), so they were not considered as data sources. Among the remainder, data from the Caselle station was chosen to conduct the study, because it has the longest record series (54 years between 1973 and 2022) and the Pearson correlation with the remaining stations is always above 0.842 (Table 1), meaning that there are no important differences in the rainfall regime over the city of Turin. The length of the rainfall series affects the results of the RWH simulation. In the present case study, the length of the chosen rainfall series, 54 years, is even longer than what is generally suggested for RWH performance analysis (e.g., 30 years, according to Palla *et al.* 2011). Nevertheless, other authors used rainfall series shorter than 30 years for RWH simulation (e.g., 25 years – Agudelo-Vera *et al.* 2013; 10 years – Mitchell 2007 and Geraldi & Ghisi 2017).

2.2. Methodology

The general methodology for assessing the combined performance of green roof and RWH is depicted in Figure 2.

According to the Turin public water utility, the annual potable water consumption in 2022 was 7.5×10^7 m^3 (SMAT Torino 2023). Considering the residential population, the average per capita water consumption is 241

Table 1 | Pearson correlation of the annual rainfall between the Caselle station and the remaining stations located at elevations under 400 m

Station	Torino giardini reali	Torino via della consolata	Torino reiss romoli	Rivoli la perosa	Torino vallere
Caselle	0.848	0.865	0.842	0.879	0.874

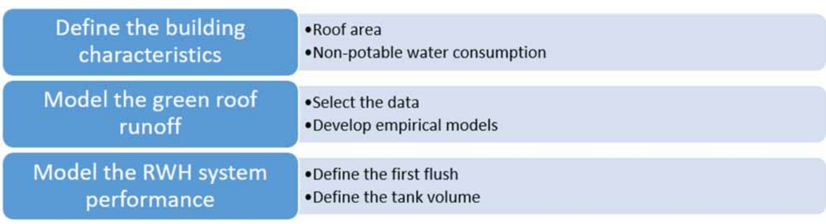


Figure 2 | Proposed methodology.

litres per day per person (l/(day.person)). However, this amount includes all water consumption within the city of Turin, both for residential and non-residential uses and for the residents and visitors (i.e., commuters and tourists). Studies specifically on the domestic water demand at the building level in Piemonte Region (e.g., Busca 2018; Salvatico 2020) estimate a mean water consumption of 150 l/(day.person), varying between 144 and 158 l/(day.person) on weekdays and weekends, respectively. The non-potable water fraction was estimated to be one-third of the total consumption (Carollo *et al.* 2022).

Based on previous research on RWH carried out in Turin (Carollo *et al.* 2022), the following characteristic buildings were selected to capture the RWH system's performance differences:

- Type 1 – roof area = 240 m^2; number of individuals = 11 (non-potable water consumption = 0.55 m^3/day).
- Type 2 – roof area = 460 m^2; number of individuals = 22 (non-potable water consumption = 1.10 m^3/day).
- Type 3 – roof area = 600 m^2; number of individuals = 29 (non-potable water consumption = 1.45 m^3/day).

Complementary to assuming a constant per capita water consumption, two scenarios were considered to model seasonality:

- Scenario 1 aims to capture households in which non-potable water consumption increases during the summer months (June, July and August), namely motivated by irrigation needs and the occupants spending more time at home (e.g., children on vacation while parents work).
- Scenario 2 pretends to capture the alternative situations, in which the occupants are outside the household during the summer (e.g., vacations outside Turin).

The monthly non-potable water consumption patterns assumed to model potential seasonality effects are presented in Figure 3. Regarding scenario 1, it was assumed that irrigation represents a water consumption increase of 15, 30 and 50% in June, July and August, respectively. Since irrigation is a non-potable use, this proportion of non-potable water end-use during these months is also higher than during the rest of the year. In scenario 2, a water consumption reduction of 25, 50 and 75% was assumed in June, July and August, respectively. The underlying reasoning was assuming that during June and July, the children in the households start their summer school vacations and go outside of Turin (e.g., friends' or family houses) for 1 week and 2 weeks, respectively. During August, it was assumed that all occupants were outside of Turin for at least 2 weeks.

The proposed empirical model for green roof, which transforms rainfall into runoff, has to be calibrated with observations of green roofs with structure (e.g., thickness of the soil layer) and geographic location that are coherent with the case study, located in Turin, Italy. Therefore, a literature review was conducted to obtain data on rainfall and runoff from green roofs in Italy using the following combination of keywords in Scopus: 'green roof' and 'Italy' and 'runoff', resulting in 47 publications (13 in conference proceedings/book series and 34 in international journals). Some studies, despite the keywords being present, were not focused on the hydrological

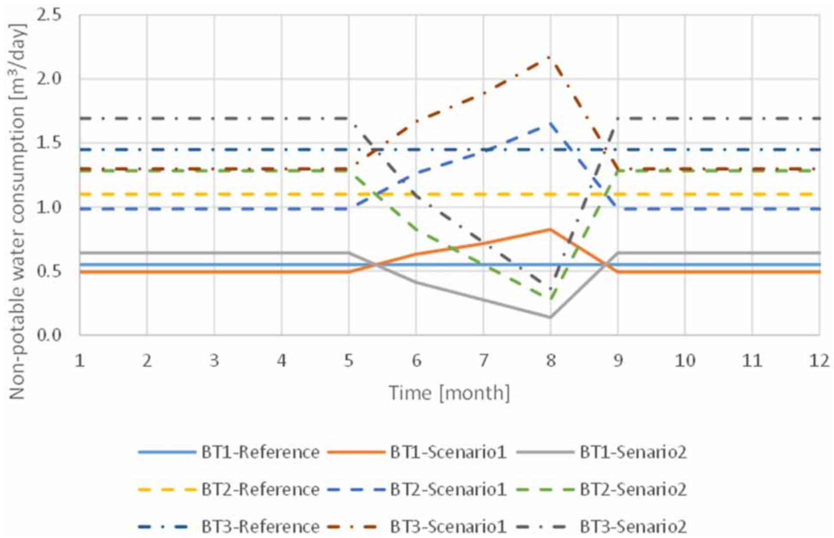


Figure 3 | Seasonal pattern of the non-potable water consumption considered for the various building types.

performance of green roofs, but rather on other aspects (e.g., greenhouse gas emissions – Lugo-Arroyo *et al.* 2024; thermal performance – Cirrincione *et al.* 2021). Several of the references focused on modelling runoff from green roofs with physical models (e.g., Palla & Gnecco 2019; Pugliese *et al.* 2022; Mobilia *et al.* 2023; Pampaloni *et al.* 2024). Still, various studies report experimental research on green roofs, but the vast majority do not disclose the data or just present it in a graphical or aggregated form (e.g., Mobilia & Longobardi 2020; Raimondi *et al.* 2023). From the few studies disclosing the data at the rainfall event level (e.g., Longobardi *et al.* 2019; D'Ambrosio *et al.* 2022; Pumo *et al.* 2023), the study by Palermo *et al.* (2019) was selected since it has the largest (in terms of the number of rainfall events) and most complete (in terms of the number of variables) dataset. In the present work, linear and non-linear multiple regression analysis were used to develop empirical models to estimate the runoff from green roofs using SPSS, version 29. The models were developed to estimate directly the runoff or indirectly the runoff coefficient (runoff/rainfall). The best subsets and Akaike Information Criterion were used to select the variables to include in the models.

The typical mass balance model (e.g., Silva *et al.* 2015) was used to simulate the RWH system performance, only changing the way in which the first flush is accounted for. First flush diversion is an important part of the RWH process regarding the quality of the collected water. Typically, the first millimetres of rainwater that are collected from the roof during a rainfall event are the most polluted and should be discarded before entering the RWH tank. From a computational viewpoint, however, the first flush is just a volume of water that is not conveyed to the rainwater tank; thus it can possibly be considered as an 'initial loss' and aggregated to the other real initial losses (e.g., evaporation/evapotranspiration and retention due to roof type – traditional or green roof, materials and slope). Most research efforts, in fact, either account for the first flush in an overall constant runoff coefficient (e.g., Bashar *et al.* 2018; Geraldi & Ghisi 2018, 2019; Khan *et al.* 2021) or discount a constant first flush amount every day (e.g., Carollo *et al.* 2022). Herein, the first flush was modelled at the rainfall event scale, because (i) assuming an overall constant runoff coefficient is not compatible with the variable runoff from the green roof and (ii) it is reasonable to assume that during rainfall events lasting for several days, there is no need to discharge the first flush every day. In this context, rainfall events were considered independent if there was an antecedent dry weather period (ADWP) of at least 24 h. Other authors (e.g., Stovin *et al.* 2012) use a 6 h interval to identify independent rainfall events when studying green roofs, but the rainfall data is only available at a daily resolution in the gauge stations that are selected. This is a very common restriction of the rainfall data available from most official sources of information, particularly when looking at long record series. Nevertheless, the use of daily rainfall data is not a limitation, given that computations refer to a large-scale analysis. A wide range of suggested values for the first flush diversion can be found in the scientific literature, from 0.4 to 8.5 mm (e.g., Texas Water Development Board 2005; Thomas & Martinson 2007), depending on the initial and desired turbidity of water. For instance, Kus *et al.* (2010) found that a 5 mm first flush diversion leads to a quality of water that meets the standards for drinking water. In the present work, the collected rainwater does not have to comply with drinking water standards, and a first flush that corresponds to the first 2 mm of runoff from the roof, in each rainfall event, has been adopted according to Silva & Ghisi (2016).

In the case of the RWH system combined with a green roof, the runoff was estimated at the rainfall event scale, and it was assumed that the retention takes place at the start of the event and is not uniformly distributed over the event duration (i.e., the net-rainfall approach was used). For instance, if the runoff of a rainfall event is estimated to be 90% of the rainfall amount, the rainfall retained in the green roof is the first 10% of the rainfall amount. This implies that, for rainfall events that last for several days, after the retention amount is discounted, the runoff will be equal to the rainfall.

The performance assessment of the combined green roof-RWH system was evaluated using the following indicators:

(1) Non-potable water savings efficiency (E_{NPWS})

$$E_{NPWS} = \frac{\sum NPWS}{\sum NPWC}$$

with

$$NPWC = CPC \times NI \times NPWF$$

(2) Rainwater retention efficiency (E_{RR})

$$E_{RR} = \frac{\sum RR}{\sum RC}$$

with

$$RR = GRR + NPWS$$

$$RC = \frac{CA \times RA}{1000}$$

where *NPWS* is the non-potable water savings (m^3/day); *NPWC* is the non-potable water consumption (m^3/day); *CPC* is the consumption per capita (m^3/(day.person)); *NI* is the number of individuals (persons); *NPWF* is the non-potable water fraction (%); *RR* is the rainfall retained (m^3/day); *GRR* is the green roof retention (m^3/day); *RC* is the rainfall collected (m^3/day); *CA* is the collection area (m^2); and *RA* is the rainfall amount (mm/day). The *NPWS* is determined by simulating the RWH system operation and represents the portion of the roof runoff that is not discharged to the sewers as first flush or as overflow from the rainwater tank.

Concerning the replication of this study under different climates, two design parameters need to be defined: RWH catchment area and water demand of the building. Then, the regression equation for the green roof runoff estimation should be calibrated based on data for the specific location, which are climate and technology dependent, since green roof solutions are distinct in different regions of the globe (e.g., substrate thickness tends to be bigger as the climate becomes drier). As a last step, the well-known mass balance simulation for RWH has to be applied.

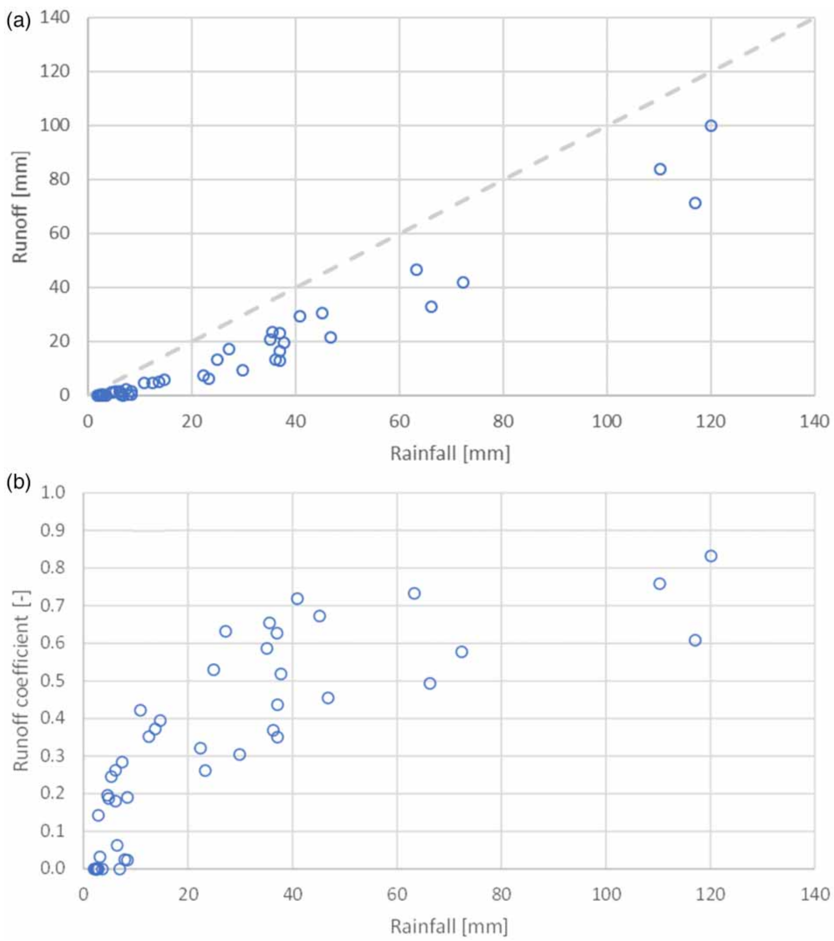


Figure 4 | Relation between rainfall and runoff (a) and runoff coefficient (b).

Table 2 | Regression models of the runoff and runoff coefficient of the green roof

Model	Unstandardized coefficients		Standardized coefficients			95.0% Confidence interval for B	
	B	Std. Error	Beta	*t*	Sig.	Lower bound	Upper bound
Linear models							
Runoff							
(constant)	1.654	1.701		0.972	0.337	−1.781	5.088
P	0.757	0.024	1.020	31.986	0.000	0.709	0.804
D	−3.462	1.016	−0.109	−3.408	0.001	−5.514	−1.410
LnADWP	−1.677	0.685	−0.072	−2.449	0.019	−3.060	−0.294
Runoff coefficient							
(constant)	−0.059	0.040		−1.498	0.142	−0.139	0.021
LnP	0.185	0.011	0.889	16.516	0.000	0.163	0.208
LnADWP	−0.068	0.014	−0.259	−4.820	0.000	−0.097	−0.040
Non-linear models							
Runoff							
(constant)	15.354	5.263		2.917	0.006	4.726	25.983
P^1.255	0.227	0.006	1.019	38.785	0.000	0.216	0.239
D^0.258	−14.298	5.076	−0.074	−2.817	0.007	−24.548	−4.047
LnADWP^2.035	−0.597	0.158	−0.091	−3.777	0.001	−0.916	−0.278
Runoff coefficient							
(constant)	0.064	0.033		1.941	0.059	−0.003	0.130
ln*P*^1.427	0.087	0.005	0.892	17.088	0.000	0.077	0.097
lnADWP^1.026	−0.070	0.013	−0.275	−5.269	0.000	−0.097	−0.043

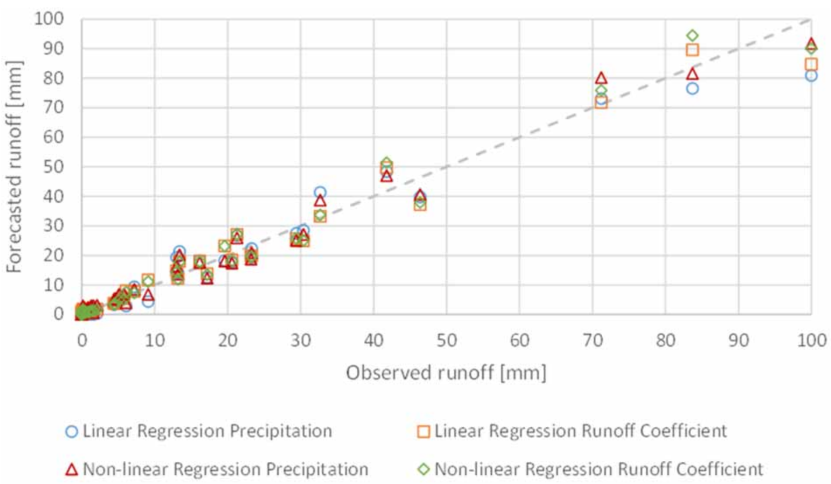


Figure 5 | Observed versus forecasted runoff.

3. RESULTS AND DISCUSSION

3.1. Green roof runoff

The rainfall-runoff data from Palermo *et al.* (2019) are available with a time resolution of minutes, which is incompatible with the rainfall data available from the gauge stations. As such, the event duration and ADWP were rounded up to a number of days. As a consequence, the efficiency values resulting from the RWH simulations have to be considered suitable for daily-scale analysis. Also, to be compatible with the rainfall events

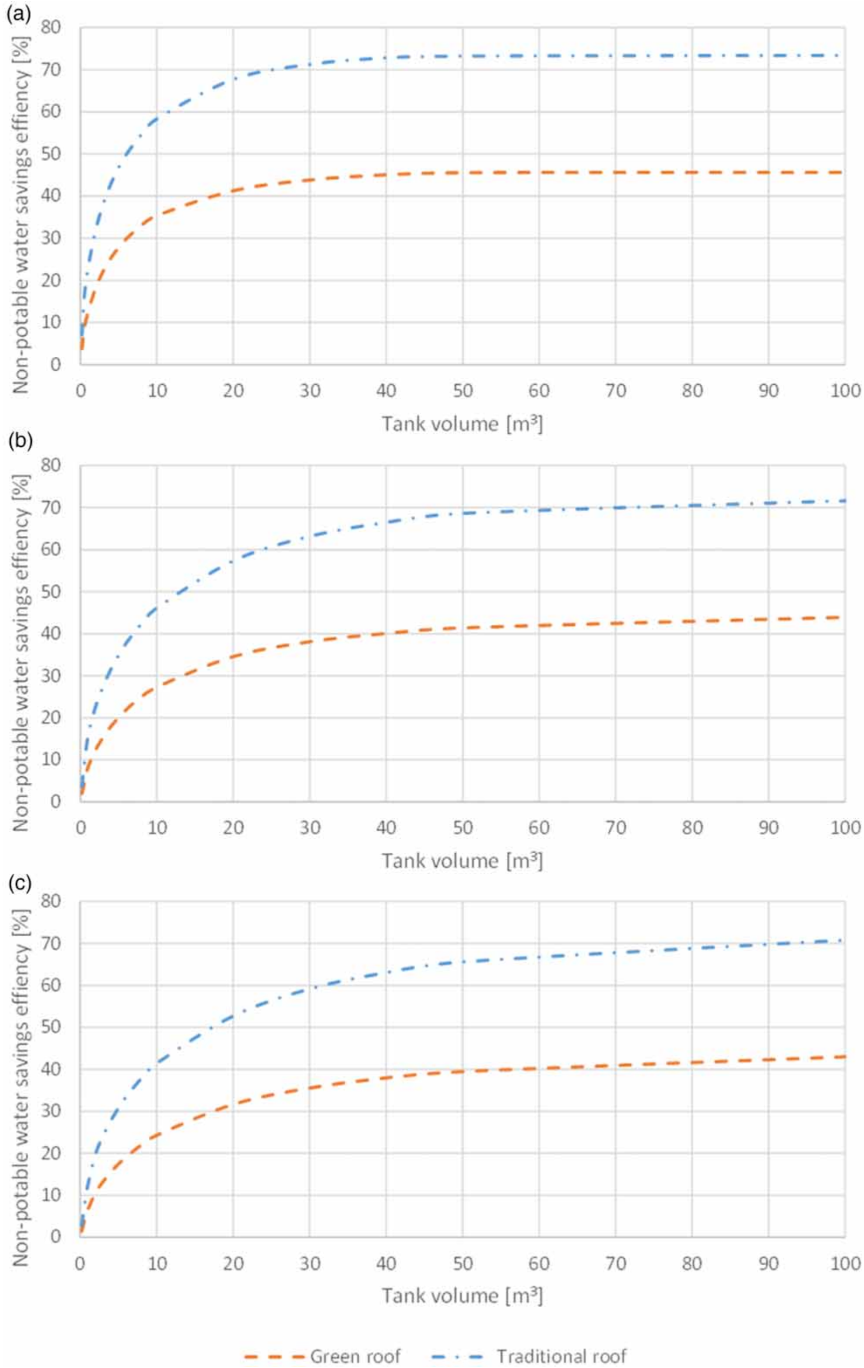


Figure 6 | Non-potable water savings efficiency of RWH for building types 1 (a), 2 (b) and 3 (c).

definition established to compute the first flush, the rainfall and runoff from consecutive days were summed in a single event. After these transformations, the initial 61 rainfall events were reduced to 45, of which 8 did not produce any runoff. Figure 4 relates the rainfall with the runoff (a) and runoff coefficient (b) of all the events at the daily scale.

From the information available in the original data, the maximum intensity was excluded since it is not available from the rainfall data series, remaining as potential predictors the (i) total rainfall amount during the event (*P* in mm); (ii) rainfall event duration (D in days); and (iii) ADWP in days. Additionally, the mean rainfall intensity (in mm/day) and the natural logarithms of P, D and ADWP were calculated. Table 2 presents empirical models developed for predicting the green roof runoff directly or the runoff coefficient. In the order of appearance of the models in the table, the Adjusted R^2 is 0.974, 0.873, 0.975 and 0.880, respectively, indicating a better fit of the models using the runoff as a dependent variable.

The sign of the regression coefficients is consistent with what was physically expected: (i) a positive sign for the precipitation implies proportionally more runoff as the total rainfall of the event increases; (ii) a negative sign for the duration, since the durations increase for the same total rainfall amount implies a lower rainfall intensity; and (iii) a negative sign for ADWP, since the moisture content of the soil decreases with the length of the dry period prior to a rainfall event.

Figure 5 depicts the observed versus predicted runoff of the different models. The Pearson correlation is similar for all the models and higher than 0.985, which means that the apparent lower fit of the models forecasting the runoff coefficient does not reflect in the forecast of the actual runoff. The empirical models developed contain fewer variables, and the fit is higher than the alternative models available in the literature for Italy (e.g., Pelorosso *et al.* 2024).

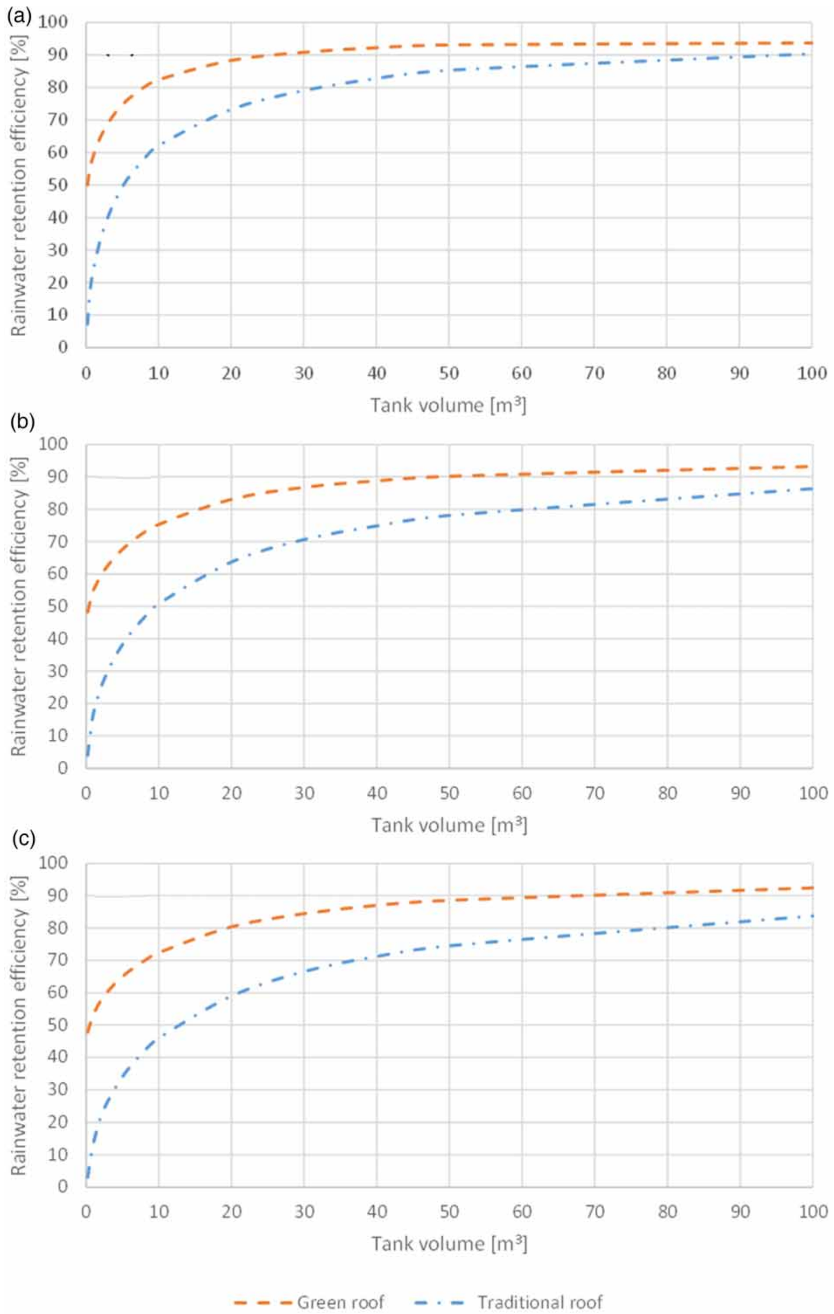


Figure 7 | Rainwater retention efficiency of RWH for building types 1 (a), 2 (b) and 3 (c).

For the simulations present below, the model of the linear regression of the runoff coefficient was used since (i) the correlation between the observed and forecasted runoff is identical to the models of the runoff; (ii) the model is simpler (parsimony principle); and (iii) it identifies more accurately the precipitation events with no runoff. Also, the runoff coefficient is physically bounded between 0 and 1, whereas the upper limit of the runoff is the rainfall, which is not a fixed value.

3.2. Performance assessment

The evolution of the non-potable water savings and rainwater retention efficiencies with tank volume for the three building types is presented in Figure 6 and Figure 7, respectively. These simulations were done with reference to non-potable water consumption (without seasonality). Although the efficiencies increase as the tank capacity increases, an important aspect is the distance between the blue and the orange lines in Figure 6 and Figure 7. Considering Figure 6, as the storage capacity of the RWH system increases, the non-potable water savings efficiency loss due to the green roof increases (distance between the two lines), while the gain in rainwater retention (Figure 7) decreases. These results indicate that the benefits of the green roof are higher for small tank volumes. The similarity of the results among the three building types is explained by the fact that they show a similar ratio between the roof area and the non-potable water consumption (ranging between 413 and 436 m^2 day/m^3). This implies that there is an almost proportional increase in the rainwater availability and the non-potable water demand. Rainwater retention efficiency is increased with respect to traditional roofs, especially for tank volumes smaller than 10 m^3.

From a financial perspective, the viability of the RWH system decreases when the slope of the relation between tank capacity and the non-potable water savings or rainwater retention efficiency decreases, because it shows that the benefit from investing in a larger tank delivers a smaller increase in benefit. Since a detailed cost-benefit analysis is outside of the scope of the present study, it is possible, simply by visual observation, to conclude

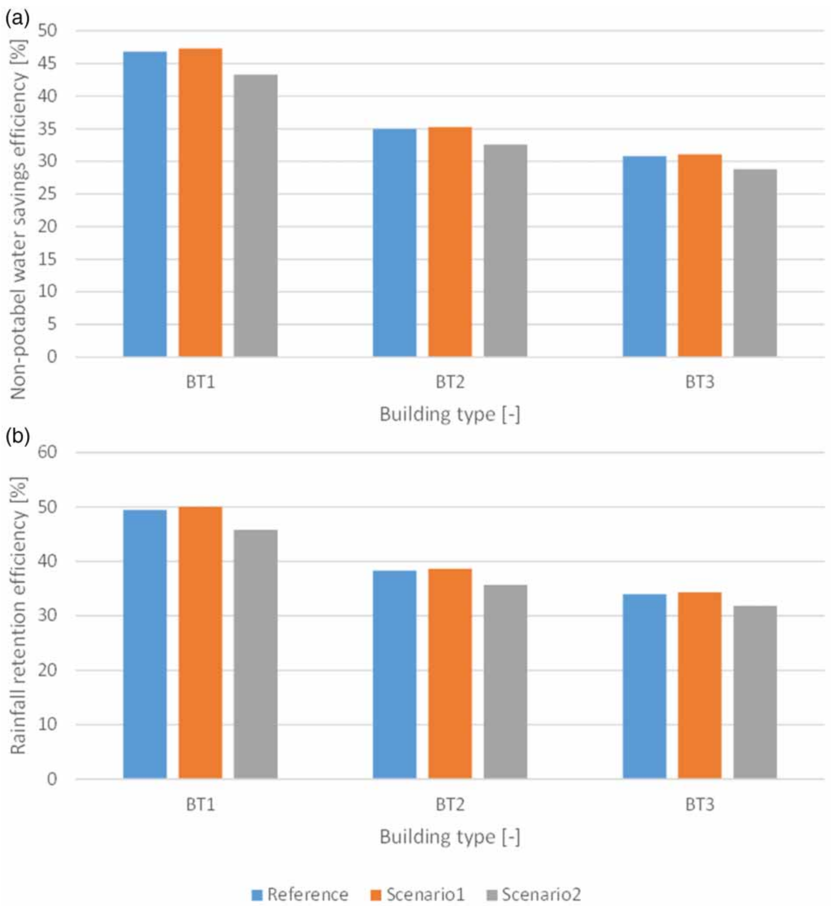


Figure 8 | Non-potable water savings (a) and rainfall retention (b) efficiency differences associated with different month water consumption pattern scenarios for a RWH system associated with a traditional roof (tank capacity = 5 m^3).

that the slope of the curves starts to decrease for a tank of roughly 5 m^3 in volume, for both the traditional and the green roof. This size of storage capacity corresponds to the non-potable water supply of 3 days (building type 3) to 10 days (building type 1), which is within the storage length recommended to prevent water quality degradation in the tank. For this tank capacity, the combination of green roof and RWH system would allow savings up to 30% of the non-potable water consumed and retain at least 65% of the rainwater precipitation on the roof of the building. On the other hand, a traditional roof would provide water savings above 35%, but would only retain up to 50% of the rainwater. It is worth noting that in Italy, there is a recommendation to select a tank capacity corresponding to 80% of the maximum water savings (Gnecco *et al.* 2013), which leads to a tank capacity over 10 m^3 in this case study. However, this would mean that the rainwater could be stored for up to 20 days, which might result in water quality issues.

3.3. Sensitivity analysis

Assuming that the optimal tank capacity is around 5 m^3, the impact of the water consumption seasonality represented by Scenarios 1 and 2 defined in Section 2 was assessed. The results are presented in Figure 8 for a RWH system with a traditional roof and for a RWH system with a green roof in Figure 9. The results indicate that the seasonality has a limited impact on the RWH system performance, regardless of the combination with the green roof or not. The results highlight that the building type has a higher impact than the non-potable water consumption seasonality. The higher performance of building type 1 is explained by the higher rainwater collection area to non-potable water consumption ratio (436 m^2 day/m^3, against 418 m^2 day/m^3 for building type 2 and 413 m^2 day/m^3 for building type 3). This implies that for the same non-potable water consumption, more rainwater can be collected in building type 1 (since the area available is larger and the rainfall is the same). This also indicates that the rainfall pattern is distributed over time and, for this tank capacity, an increase in the amount of rainwater collected does not result only in tank overflow.

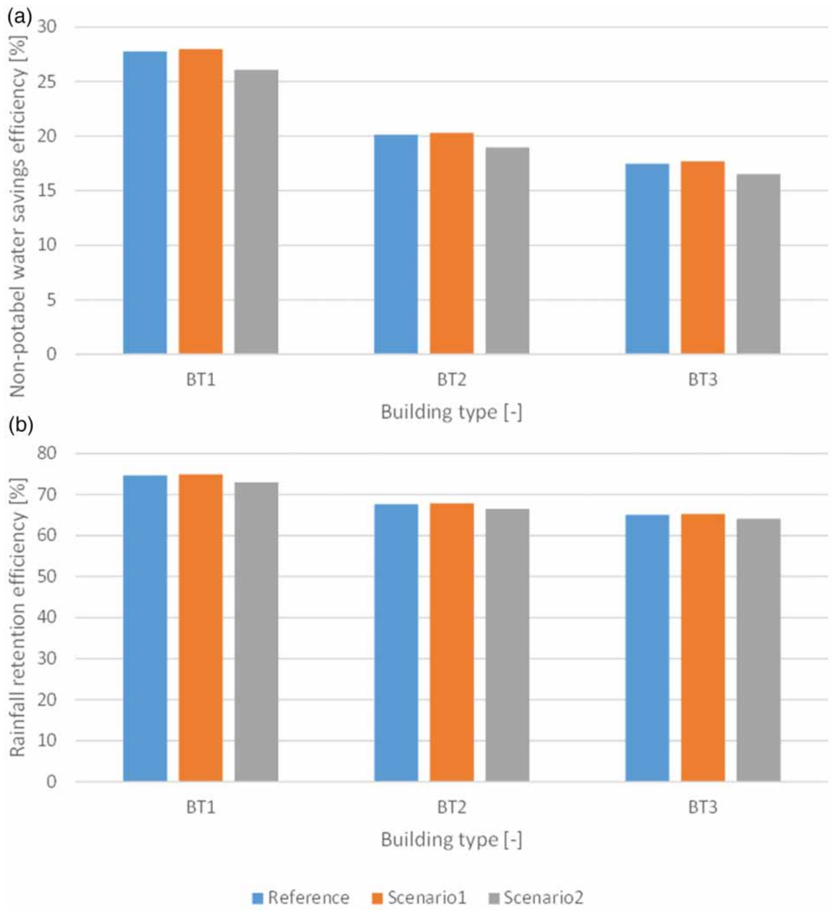


Figure 9 | Non-potable water savings (a) and rainfall retention (b) efficiency differences associated with different month water consumption pattern scenarios for a RWH system associated with a green roof (tank capacity = 5 m^3).

The lower performance associated with Scenario 2, with or without a green roof, is explained by the fact that the rainfall amount during the summer months is larger than during the winter months in Turin. Consequently, in Scenario 2, there is less rainwater available when the non-potable water consumption is higher, explaining the performance difference obtained. This also implies a seasonal variation of the performance of the RWH system, both with traditional (Figure 10) and green (Figure 11) roofs.

As expected, the wetter months allow for higher non-potable water savings, but lower rainfall retention. The performance differences between traditional and green roofs are according to the annual performance results. However, it is noticeable that there is a greater variability in the rainwater retention efficiency when the RWH system is associated with a green roof. This is explained by the fact that the retention of the green roofs decreases, in percentage, with the rainfall. When the retention capacity of the green roof is exhausted, all remaining rainfall will be converted into runoff, which is more likely to occur when the rainfall event is intense. Additionally, in

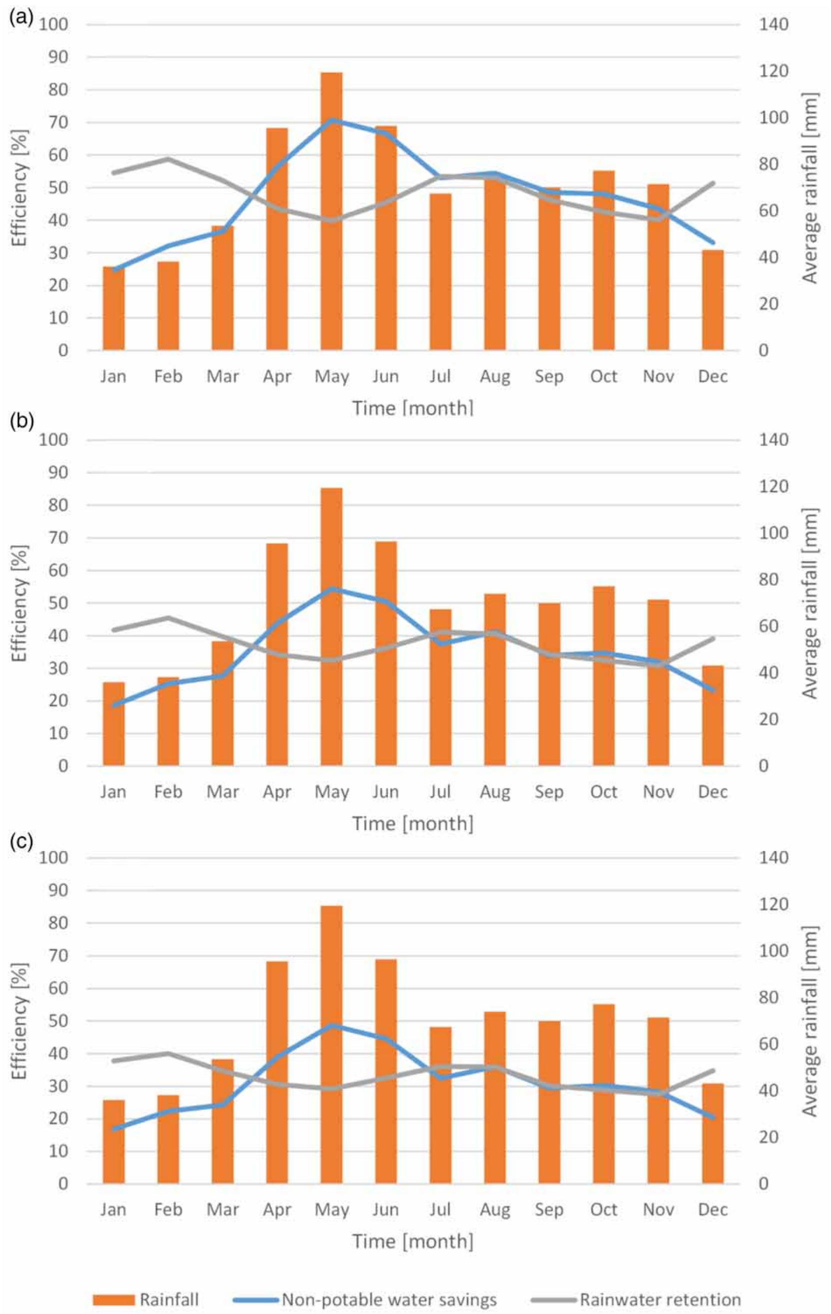


Figure 10 | Monthly variability of the efficiency of the RWH system associated with a traditional roof for building types 1 (a), 2 (b) and 3 (c) (tank capacity = 5 m^3).

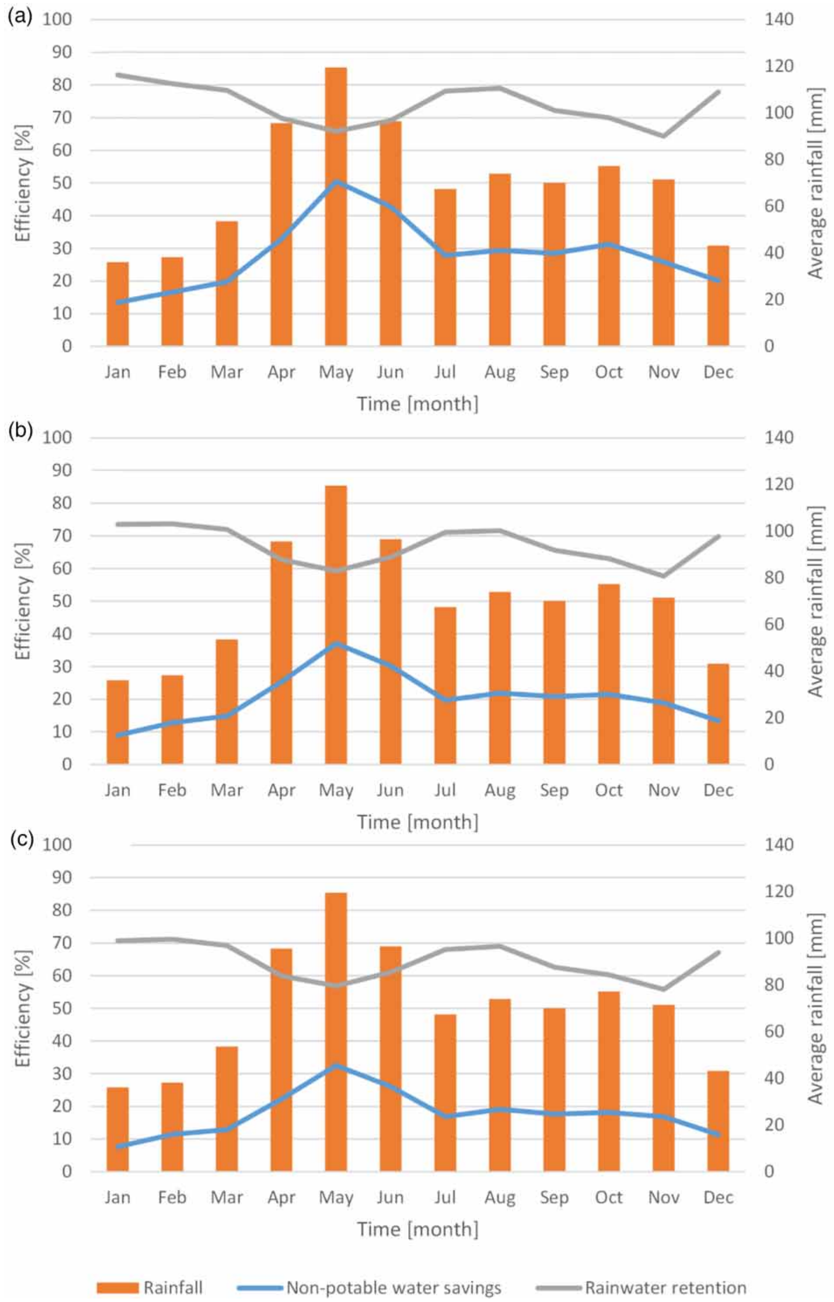


Figure 11 | Monthly variability of the efficiency of the RWH system associated with a green roof for building types 1 (a), 2 (b) and 3 (c) (tank capacity = 5 m^3).

wetter months, the initial retention capacity tends to be reduced, since the green roof may not have time to dry between rainfall events.

Lastly, the influence of the rainfall series was assessed by comparing the results obtained with the data from the Pino Torinese station. Not only is this station located at a much higher altitude, but the average annual precipitation recorded is the lowest (709 mm) from any rain gauge station near Turin and presents the biggest absolute difference to the Caselle station (on average, a difference of 129 mm per year). Despite the 15% difference in terms of annual rainfall, the performance estimates vary between 5 and 10%, for RWH systems associated with traditional roof (Figure 12) and with green roof (Figure 13) alike.

Overall, the most relevant variability results from the building type and the consumption pattern. The monthly variation is large, but expected, and does not affect the decision regarding investing in the RWH system from the perspective of the building owner. It does, however, influence the assessment of the potential contribution of

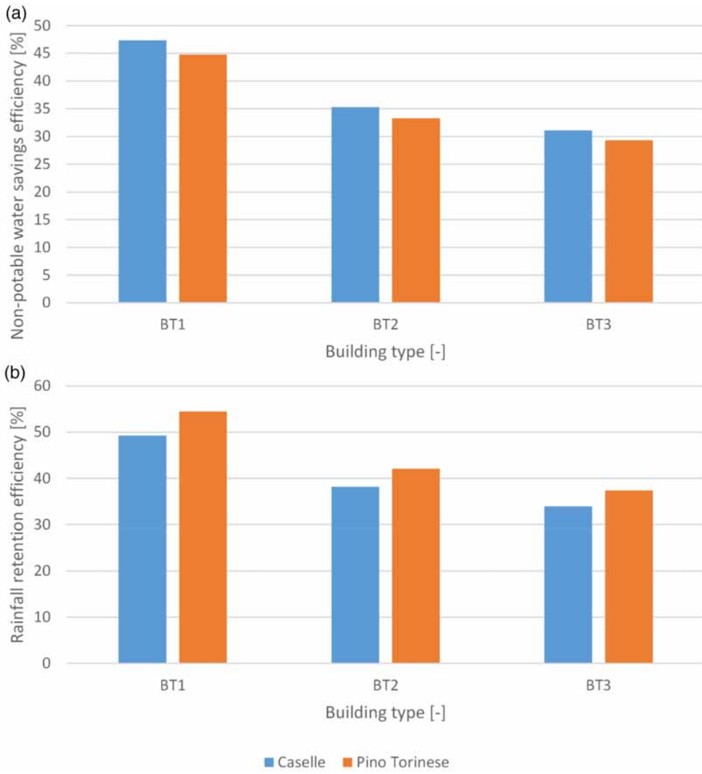


Figure 12 | Non-potable water savings (a) and rainfall retention (b) efficiency differences due to using rainfall data from different weather stations for a RWH system associated with a traditional roof (tank capacity = 5 m^3).

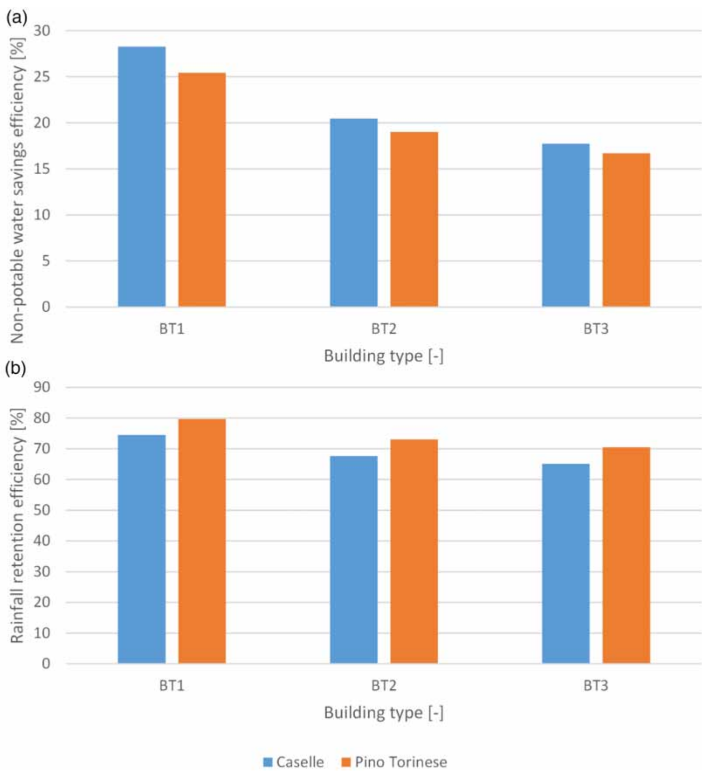


Figure 13 | Non-potable water savings (a) and rainfall retention (b) efficiency differences due to using rainfall data from different weather stations for a RWH system associated with a green roof (tank capacity = 5 m^3).

these solutions towards flood risk reduction since it was observed that their combined water retention efficiency decreases non-linearly with the magnitude of the rainfall event.

3.4. Generalized relations

To enable an estimate of the performance of a RWH system installed in Turin, associated with a traditional roof (Figure 14) or a green roof (Figure 15), generalized relations were established considering two parameters: (i) the ratio between the rainwater collection area and the non-potable water consumption; and (ii) the ratio between the rainwater tank capacity and the non-potable water consumption. The range of values selected aimed at covering the most common situations. The three building types identified by Carollo *et al.* (2022) have rainwater collection area to non-potable water consumption ratios of around 400. It was assumed that in residential buildings, it is more probable that smaller ratios would be associated with single-family houses or high-rise buildings. Higher ratios imply buildings with large garden areas and few residents, which are associated with high-value detached houses. Also, high-value detached houses tend to have gardens, pools and other features that increase the

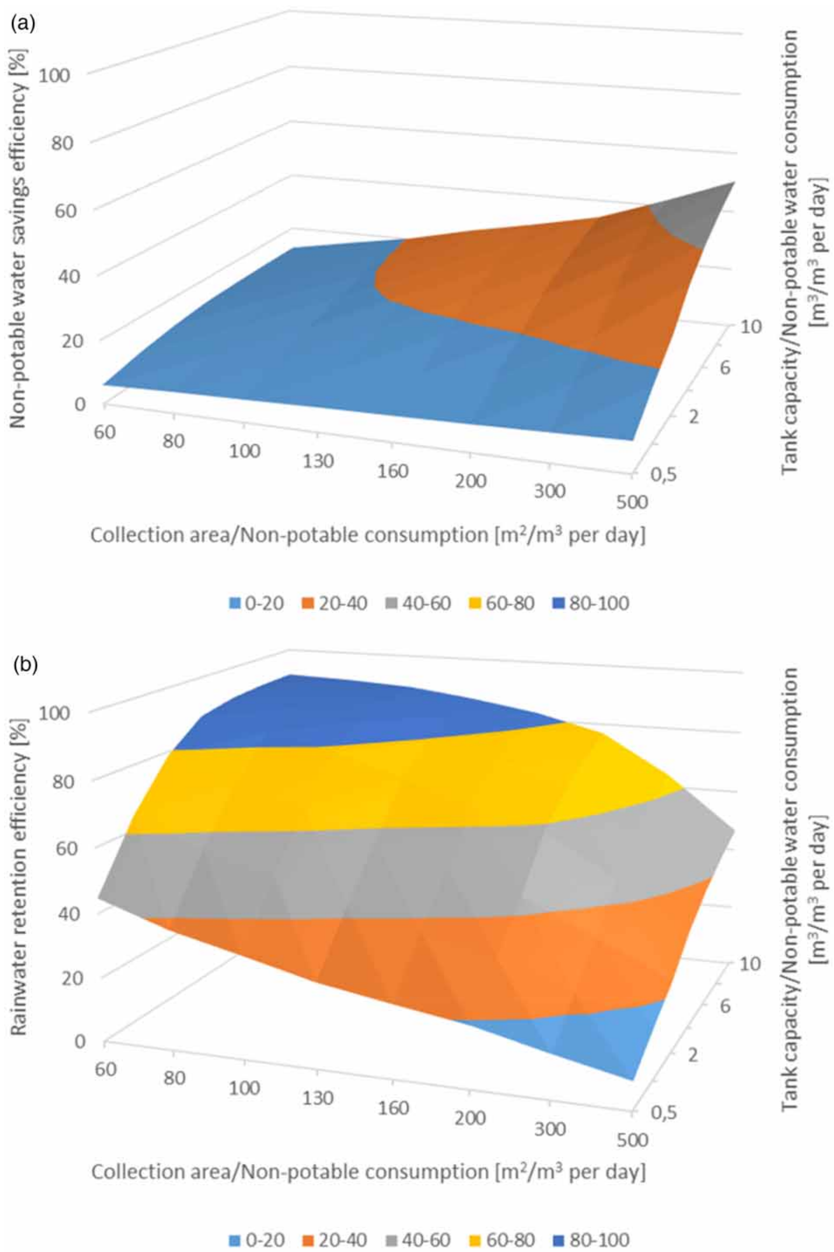


Figure 14 | Generalized relations to estimate the RWH system performance with traditional roof performance in terms of non-potable water savings efficiency (a) and rainwater retention efficiency (b).

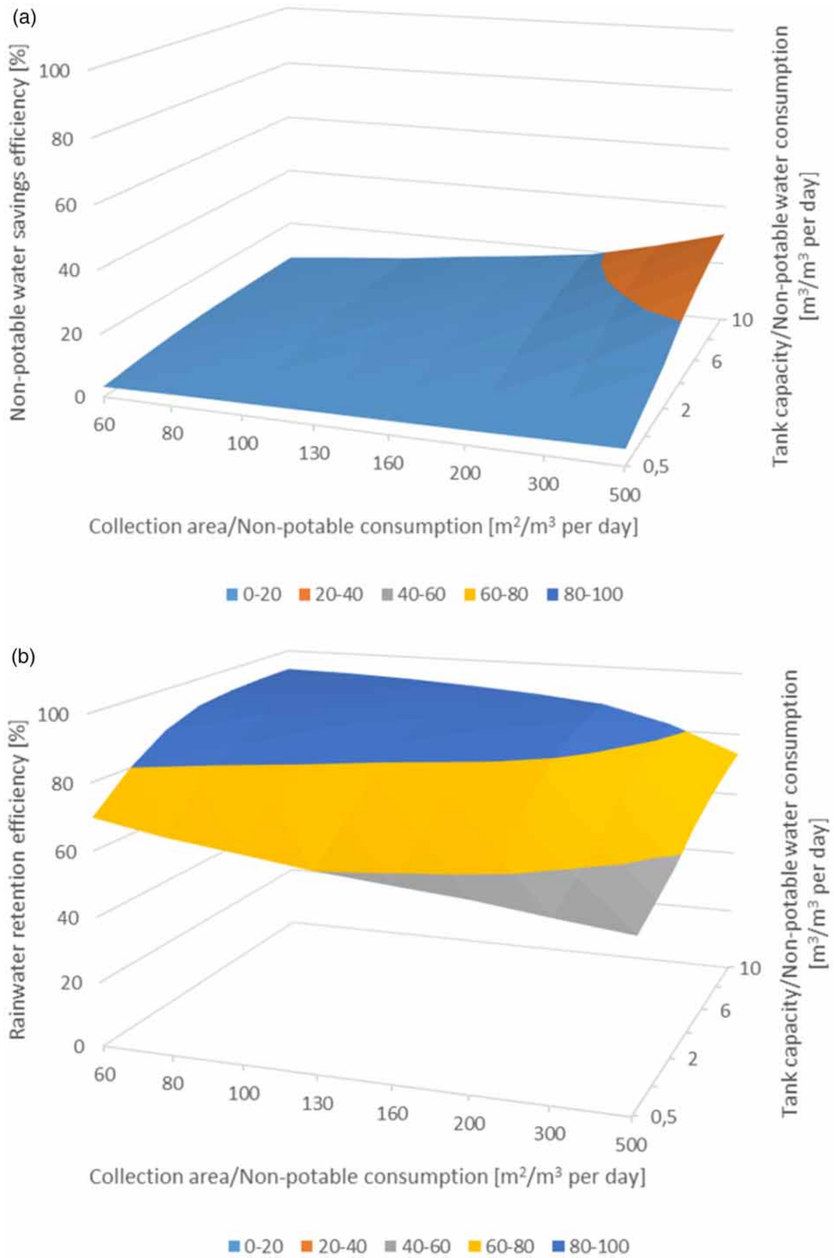


Figure 15 | Generalized relations to estimate the RWH system performance with green roof performance in terms of non-potable water savings efficiency (a) and rainwater retention efficiency (b).

proportion of non-potable water consumption. Regarding the rainwater tank capacity to the non-potable water consumption ratio, a value of 0.5 represents the capacity to store rainwater to supply 50% of the daily non-potable water demand, and a value of 10 represents the capacity to store rainwater for 10 days. Below a ratio of 0.5, the results of a daily simulation may be prone to error and storing rainwater for 10 days may lead to water quality issues. These ratios enable the identification of combinations that yield identical performances.

4. CONCLUSIONS

The growth of population and urban spaces is increasing the pressure on the public water infrastructure, both for water supply and stormwater drainage. This led decision makers to adopt more holistic approaches, integrating both centralized and decentralized solutions. Two common decentralized solutions at the building level that are being promoted by municipalities throughout the globe are RWH and green roofs. These solutions have been extensively studied from multiple perspectives (e.g., financial performance, environmental performance, technical performance – hydrologic and thermal), but in most cases, these perspectives have been considered in isolation.

Since the water supply and stormwater management are the most common drivers for the implementation of RWH, the present research aims at assessing the combined performance of RWH and green roofs in these two dimensions, providing a planning-level tool useful for policymakers. The city of Turin was used as a case study, but the approach proposed is applicable in other contexts. Still, it has a limitation which is the need for data from monitored green roofs to develop an appropriate empirical model to estimate the runoff from the green roof. However, the large majority of the green roofs tend to be of the extensive type, due to their lower implementation and operation cost, but mostly to their lower weight. The additional weight of the green roof plays a decisive role in the decision-making process, considering the impact that it may have on the structure of the building, particularly in seismically active regions. For this type of green roof, there are already numerous experimental studies in many climate contexts (e.g., see Zheng *et al.* 2021 for an extensive review) that allow for, at least, a crude approximation in most contexts.

In Turin, the analysis of a group of typical buildings shows that the advantages of the combination of RWH and green roofs decrease with the increase of the RWH system storage capacity. This is a positive result for the combination of these two solutions, considering that RWH tanks are the most expensive component of the RWH system, and large rainwater retention periods may induce water quality issues.

The sensitivity analysis shows that both the seasonality of water consumption and the use of rainfall data from different weather stations have a limited impact on the RWH system performance, regardless of the combination with the green roof or not. Furthermore, the monthly variation of performance is large, but expected, and does not affect the decision regarding investing in the RWH system from the perspective of the building owner.

Using the non-potable water consumption to calculate two ratios with the other two governing parameters of a RWH system, generalized relations were developed to enable a simple estimation of a RWH system in Turin with either a traditional or a green roof.

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AUTHOR CONTRIBUTIONS

Conceptualization: VS; Data curation: VS, MC, IB, IM; Methodology: VS, IM; Models and simulations: VS, IM; Supervision: IB; Validation: MC; Visualization: IM; Writing – original draft: VS, IM; Writing – review and editing: MC, IB; Funding: VS, IB. The final version was approved by all co-authors.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Agudelo-Vera, C. M., Keesman, K. J., Mels, A. R. & Rijnaarts, H. H. M. (2013) Evaluating the potential of improving residential water balance at building scale, *Water Research*, **47** (20), 7287–7299. http://dx.doi.org/10.1016/j.watres.2013.10.040.

Almeida, A. P., Liberalesso, T., Silva, C. M. & Sousa, V. (2023) Combining green roofs and rainwater harvesting systems in university buildings under different climate conditions, *Science of The Total Environment*, **887**, 163719. https://doi.org/10.1016/j.scitotenv.2023.163719.

ARPA Piemonte (2024) Agenzia Regionale per la Protezione Ambientale Piemonte [Regional Agency for the Environment Protection Piemonte], Turin, Italy: Banca dati storica - rete meteorologica [Historical database - meteorological network]. Available at: https://www.arpa.piemonte.it/rischi_naturali/snippets_arpa_graphs/map_meteoweb/?rete=stazione_meteorologica [Accessed May 2024].

Bashar, M. Z. I., Karim, M. R. & Imteaz, M. A. (2018) Reliability and economic analysis of urban rainwater harvesting: a comparative study within six major cities of Bangladesh, *Resources, Conservation and Recycling*, **133**, 146–154. https://doi.org/10.1016/j.resconrec.2018.01.025.

Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A. I. J. M. & Miralles, D. G. (2023) High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections, *Scientific Data*, **10**, 724. doi: 10.1038/s41597-023-02549-6.
Busca, F. (2018) *Bilancio idrico a scala di edificio*. *MSc Thesis*, Politecnico di Torino, Turin, Italy.
Campisano, A., Butler, D., Ward, S., Burns, M. J., Friedler, E., DeBusk, K., Fisher-Jeffes, L. N., Ghisi, E., Rahman, A., Furumai, H. & Han, M. (2017) Urban rainwater harvesting systems: research, implementation and future perspectives, *Water Research*, **115**, 195–209. https://doi.org/10.1016/j.watres.2017.02.056.
Carollo, M., Butera, I. & Revelli, R. (2022) Water savings and urban storm water management: evaluation of the potentiality of rainwater harvesting systems from the building to the city scale, *PLoS ONE*, **17** (11), e0278107. https://doi.org/10.1371/journal.pone.0278107.
Cirrincione, L., Marvuglia, A. & Scaccianoce, G. (2021) Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: methodology proposal and application, *Building and Environment*, **205**, 108198. https://doi.org/10.1016/j.buildenv.2021.108198.
D'Ambrosio, R., Longobardi, A. & Mobilia, M. (2022) Temporal Changes of Green Roofs Retention Capacity. In: Gervasi, O., Murgante, B., Hendrix, E. M. T., Taniar, D. & Apduhan, B. O. (eds.) *Computational Science and Its Applications – ICCSA 2022. ICCSA 2022. Lecture Notes in Computer Science*, Vol. 13376, Cham: Springer. https://doi.org/10.1007/978-3-031-10450-3_24.
Ferrans, P., Torres, M. N., Temprano, J. & Sánchez, J. P. R. (2022) Sustainable Urban Drainage System (SUDS) modeling supporting decision-making: a systematic quantitative review, *Science of The Total Environment*, **806** (2), 150447. https://doi.org/10.1016/j.scitotenv.2021.150447.
Gabe, J., Trowsdale, S. & Mistry, D. (2012) Mandatory urban rainwater harvesting: learning from experience, *Water Science and Technology*, **65** (7), 1200–1207. https://doi.org/10.2166/wst.2012.955.
Geraldi, M. S. & Ghisi, E. (2017) Influence of the length of rainfall time series on rainwater harvesting systems: a case study in Berlin, *Resources, Conservation and Recycling*, **125**, 169–180. http://dx.doi.org/10.1016/j.resconrec.2017.06.011.
Geraldi, M. S. & Ghisi, E. (2018) Assessment of the length of rainfall time series for rainwater harvesting in buildings, *Resources, Conservation and Recycling*, **133**, 231–241. https://doi.org/10.1016/j.resconrec.2018.02.007.
Geraldi, M. S. & Ghisi, E. (2019) Short-term instead of long-term rainfall time series in rainwater harvesting simulation in houses: an assessment using Bayesian network, *Resources, Conservation and Recycling*, **144**, 1–12. https://doi.org/10.1016/j.resconrec.2019.01.017.
Gnecco, I., Palla, A. & Lanza, L. G. (2013) Sistemi per la raccolta ed il recupero delle acque meteoriche–Verso la definizione della normativa [Rainwater harvesting systems–Towards the definition of legislation], *L'Acqua.*, **1**, 9. (*in Italian*).
Griffiths, J., Chan, F. K. S., Shao, M., Zhu, F. & Higgitt, D. L. (2020) Interpretation and application of Sponge city guidelines in China, *Philosophical Transactions of the Royal Society A*, **378**, 20190222. http://dx.doi.org/10.1098/rsta.2019.0222.
Hamidi, A., Ramavandi, B. & Sorial, G. A. (2021) Sponge city – an emerging concept in sustainable water resource management: a scientometric analysis, *Resources, Environment and Sustainability*, **5**, 100028. https://doi.org/10.1016/j.resenv.2021.100028.
ISTAT (2011) *Dati censimento popolazione e abitazioni 2011 [2011 Population and Houses Census Data]*. Rome, Italy: Istituto Nazionale di Statistica (ISTAT) [National Institute of Statistics]. Available at: http://daticensimentopopolazione.istat.it/Index.aspx Italian [Accessed July 2024].
Khan, Z., Alim, M. A., Rahman, M. M. & Rahman, A. (2021) A continental scale evaluation of rainwater harvesting in Australia, *Resources, Conservation and Recycling*, **167**, 105378. https://doi.org/10.1016/j.resconrec.2020.105378.
Kus, B., Kandasamy, J., Vignesvaran, S. & Shon, H. (2010) Analysis of first flush to improve the water quality in rainwater tanks, *Water Science and Technology*, **61** (2), 421–428. https://doi.org/10.2166/wst.2010.823.
Liberalesso, T., Cruz, C. O., Silva, C. M. & Manso, M. (2020) Green infrastructure and public policies: an international review of green roofs and green walls incentives, *Land Use Policy*, **96**, 104693. https://doi.org/10.1016/j.landusepol.2020.104693.
Longobardi, A., D'Ambrosio, R. & Mobilia, M. (2019) Predicting stormwater retention capacity of green roofs: an experimental study of the roles of climate, substrate soil moisture, and drainage layer properties, *Sustainability*, **11** (24), 6956. https://doi.org/10.3390/su11246956.
Lugo-Arroyo, A., Zanin, G., Thompson, A., Borin, M. & Maucieri, C. (2024) Diurnal greenhouse gas emissions and substrate temperatures from blue-green roofs in north-eastern Italy during a dry-hot summer season, *Scientia Horticulturae*, **324**, 112560. https://doi.org/10.1016/j.scienta.2023.112560.
Mguni, M., Abrams, A., Herslund, L. B., Carden, K., Fell, J., Armitage, N. & Dollie, A. (2022) Towards water resilience through nature-based solutions in the global south? scoping the prevailing conditions for water sensitive design in Cape Town and Johannesburg, *Environmental Science & Policy*, **136**, 147–156. https://doi.org/10.1016/j.envsci.2022.05.020.
Mitchell, V. G. (2006) Applying integrated urban water management concepts: a review of Australian experience, *Environmental Management*, **37**, 589–605. https://doi.org/10.1007/s00267-004-0252-1.
Mitchell, V. (2007) How important is the selection of computational analysis method to the accuracy of rainwater tank behavior modelling?, *Hydrological Processes*, **21**, 2850–2861. https://doi.org/10.1002/hyp.6499.
Mobilia, M. & Longobardi, A. (2020) Impact of rainfall properties on the performance of hydrological models for green roofs simulation, *Water Science and Technology*, **81** (7), 1375–1387. https://doi.org/10.2166/wst.2020.210.
Mobilia, M., Longobardi, A., Amitrano, D. & Ruello, G. (2023) Land use and damaging hydrological events temporal changes in the Sarno river basin: potential for green technologies mitigation by remote sensing analysis, *Hydrology Research*, **54** (3), 277–302. https://doi.org/10.2166/nh.2023.036.

Palermo, S. A., Turco, M., Principato, F. & Piro, P. (2019) Hydrological effectiveness of an extensive green roof in Mediterranean climate, *Water*, **11**, 1378. https://doi.org/10.3390/w11071378.

Palla, A. & Gnecco, I. (2019) A continuous simulation approach to quantify the climate condition effect on the hydrologic performance of green roofs, *Urban Water Journal*, **17** (7), 609–618. https://doi.org/10.1080/1573062X.2019.1700287.

Palla, A., Gnecco, I. & Lanza, L. G. (2011) Non-dimensional design parameters and performance assessment of rainwater harvesting systems, *Journal of Hydrology*, **401**, 65–76. https://doi.org/10.1016/j.jhydrol.2011.02.009.

Pampaloni, M., Sordo-Ward, A., Lompi, M., Pacetti, T., Zubelzu, S., Rodríguez-Sinobas, L., Bianucci, P., Caporali, E. & Garrote, L. (2024) Performance of Low impact development on peak flow reduction in an urban system, *JAWRA Journal of the American Water Resources Association*, **60** (2), 427–441. https://doi.org/10.1111/1752-1688.13188.

Pelorosso, R., Petroselli, A., Cappelli, F., Noto, S., Tauro, F., Apollonio, C. & Grimaldi, S. (2024) Blue-green roofs as nature-based solutions for urban areas: hydrological performance and climatic index analyses, *Environmental Science and Pollution Research*, **31**, 5973–5988. https://doi.org/10.1007/s11356-023-31638-7.

Pugliese, F., Gerundo, C., De Paola, F., Caroppi, G. & Giugni, M. (2022) Enhancing the urban resilience to flood risk through a decision support tool for the LID-BMPs optimal design, *Water Resources Management*, **36**, 5633–5654. https://doi.org/10.1007/s11269-022-03322-x.

Pumo, D., Francipane, A., Alongi, F. & Noto, L. V. (2023) The potential of multilayer green roofs for stormwater management in urban area under semi-arid Mediterranean climate conditions, *Journal of Environmental Management*, **326** (Part A), 116643. https://doi.org/10.1016/j.jenvman.2022.116643.

Raimondi, A., Sanfilippo, U., Marchioni, M., Di Chiano, M. G. & Becciu, G. (2023) Influence of climatic parameters on the probabilistic design of green roofs, *Science of The Total Environment*, **865**, 161291. https://doi.org/10.1016/j.scitotenv.2022.161291.

Ritchie, H., Samborska, V. & Roser, M. (2024) *Urbanization*. Available at: https://ourworldindata.org/urbanization' [Accessed June 2024].

Salvatico, F. (2020) *RainWater Harvesting a scala di edificio: confronto tra diversi approcci per la determinazione del volume ottimale di stoccaggio*. *MSc Thesis*, Politecnico di Torino, Turin, Italy.

SCIA-ISPRA (2024) *Sistema Nazionale per l'elaborazione e diffusione di dati climatici (SCIA) [National System for the Elaboration and Diffusion of Climatic Data]*. Rome, Italy: Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) [National institute for environmental protection and research]. Available at: http://www.scia.isprambiente.it/wwwrootscia/Home_new.html# [Accessed May 2024].

Silva, A. S. & Ghisi, E. (2016) Uncertainty analysis of daily potable water demand on the performance evaluation of rainwater harvesting systems in residential buildings, *Journal of Environmental Management*, **180**, 82–93. https://doi.org/10.1016/j.jenvman.2016.05.028.

Silva, C. M., Sousa, V. & Carvalho, N. V. (2015) Evaluation of rainwater harvesting in Portugal: application to single-family residences, *Resources, Conservation and Recycling*, **94**, 21–34. https://doi.org/10.1016/j.resconrec.2014.11.004.

Silva, A. C. R. S., Bimbato, A. M., Balestieri, J. A. P. & Vilanova, M. R. N. (2022) Exploring environmental, economic and social aspects of rainwater harvesting systems: a review, *Sustainable Cities and Society*, **76**, 103475. https://doi.org/10.1016/j.scs.2021.103475.

SMAT Torino (2023) *Data on Monthly Water Consumption*. Turin, Italy: Società Metropolitana Acque Torino S.p.A. (SMAT Torino).

Stovin, V., Vesuviano, G. & Kasmin, H. (2012) The hydrological performance of a green roof test bed under UK climatic conditions, *Journal of Hydrology*, **414–415**, 148–161. https://doi.org/10.1016/j.jhydrol.2011.10.022.

Texas Water Development Board (2005) *The Texas Manual on Rainwater Harvesting*, 3rd edn. Austin, Texas: Texas Water Development Board.

Thomas, T. H. & Martinson, D. B. (2007) *Roofwater Harvesting: A Handbook for Practitioners*. The Netherlands: IRC International Water and Sanitation Centre, Delft.

Viola, F., Hellies, M. & Deidda, R. (2017) Retention performance of green roofs in representative climates worldwide, *Journal of Hydrology*, **553**, 763–772. https://doi.org/10.1016/j.jhydrol.2017.08.033.

Voyde, E., Fassman, E. & Simcock, R. (2010) Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand, *Journal of Hydrology*, **394**, 384–395. https://doi.org/10.1016/j.jhydrol.2010.09.013.

Wilderer, P. A. (2004) Applying sustainable water management concepts in rural and urban areas: some thoughts about reasons, means and needs, *Water Science and Technology*, **49** (7), 7–16. https://doi.org/10.2166/wst.2004.0403.

Wilkinson, S. J., Ghosh, S. & Pelleri, N. (2022) Mandatory or voluntary approaches to green roof implementation: a comparative study among some global cities, *Journal of Environmental Planning and Management*, **67** (2), 334–355. https://doi.org/10.1080/09640568.2022.2113768.

Younos, T. & Parece, T. E. (2016) chapter: Modern Urban Rainwater Harvesting Systems: Design, Case Studies, and Impacts. In: Younos, T. & Parece, T. (eds) *Sustainable Water Management in Urban Environments*, Vol. 47. Cham, Switzerland: Springer. doi:10.1007/978-3-319-29337-0_7.

Zheng, X., Zou, Y., Lounsbury, A. W., Wang, C. & Wang, R. (2021) Green roofs for stormwater runoff retention: a global quantitative synthesis of the performance, *Resources, Conservation and Recycling*, **170**, 105577. https://doi.org/10.1016/j.resconrec.2021.105577.

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