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Planning rainwater harvesting systems in a context of uncertainty: from the building to the urban scale

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ABSTRACT

Rainwater harvesting (RWH) can be a useful way of obtaining multiple benefits for the sustainable management of urban water. Among such benefits, the reduction of the consumption of potable water has been widely analysed in the scientific literature, but the effects of different sources of uncertainty have often been neglected.

The present work analyses the water saving efficiency of RWH for indoor use at the building and urban scales, by assessing the variability of the performance estimations considering uncertainties on both the demand and supply sides. We evaluated the variability of water consumption on the demand side, with reference to both daily and multi-year scales, through Monte Carlo simulations that considered the statistical distribution of the indoor, non-potable, water demand. Diversion of the first flush, which is required to ensure acceptable water quality standards, is an important source of variability that has here been analysed considering both the role of different set ups of the first flush device and the volume of the first flush that is diverted. We evaluated the influence of the variability of rainfall patterns, considering different lengths and periods of the used rainfall series, in order to establish the length of the minimum series that can guarantee reliable results. The city of Turin (Italy) has been considered as a case study for the proposed approach. The obtained results indicate which buildings are more sensitive to the considered variabilities and that the factor which impacts RWH efficiency the most is the average, long-range, non-potable water demand, while daily variabilities have shown no effects. Furthermore, the length and period of the rainfall series have been found to drive the variability of the RWH efficiency on the supply side but, when the series is longer than 15 years, the variability related to the first flush amount and set up has an even greater impact.

PRACTICAL APPLICATIONS

This study presents a methodology that can be used to estimate the potential for rainwater harvesting at the city scale level, while considering building scale effects. This is of particular relevance for policy makers when making decisions on regulations and/or incentives regarding rainwater harvesting in the context of the sustainable management of urban water cycles. This study also assesses the impact of uncertainty on the results, and it reveals that the most relevant impacts are: i) changes in the rainfall pattern along with the natural interannual rainfall variability; ii) the first flush design; and iii) the choice of the long-run average non-potable water demand.

1 INTRODUCTION

Rainwater harvesting (RWH) is a practice that, since antiquity, has allowed mankind to settle in areas with limited and/or time-constrained water resources (Beckers et al. 2013; Iliopoulou et al., 2022). RWH for non-potable use now plays an important role in achieving a more sustainable world, with several benefits that allow mankind's environmental footprint to be reduced (Campisano et al. 2017; de Sá Silva et al. 2022, Semaan et al. 2021). Among the most relevant direct benefits of RWH are the reduction of potable water consumption and the contribution towards decreasing stormwater runoff. A cost-benefit analysis (Dallman et al. 2021) and the need for incentives to promote RWH (Schuetze 2013), such as those that have been applied in some countries, are crucial aspects for the implementation of RWH.

The estimation of the water savings efficiency of an RWH system for a building is relatively simple, when the data on rainfall and water demand, as well as on the collection area of the buildings, are available. Analysis tools have already been developed for this purpose (e.g., Jenkins et al. 1978; Fewkes and Butler 2000; Palla et al. 2011; Imteaz and Shadeed 2022; Carollo and Butera 2025), and some methods have been included in national and/or regional regulations and guidelines (e.g., DIN 2002; ANQUIP 2007; RF 2009; UNI 2012; BS 2013; Aqua España 2016). Loper et al. (2024) have recently developed a GIS tool that integrates precipitation and evapotranspiration data which can be used to target the locations in the USA that are the most suitable for rainwater harvesting.

The evaluation of the RWH performance at the urban scale is, instead, less frequent, although it is desirable because it makes policymakers and city planners aware of the potentiality of using RWH to manage the urban water cycle. However, some problems can arise in this type of analysis at an urban scale, due to the heterogeneous nature of cities, that is, in defining: i) the number of buildings that have to be analysed; ii) the differences in the water consumption of the population; and iii) the possible variation of the rainfall regime in the different zones of the city. An RWH analysis for residential use at an urban scale requires the same data that are needed for individual buildings: i) the collection area (e.g., the roof area of the buildings); ii) the water demand pattern; iii) the rainfall pattern; and iv) other parameters, such as the runoff coefficient and the first flush. Apart from the collection area, that can be regarded as constant over time (as the variability due to the construction of new buildings and changes in the existing ones are limited in consolidated urban settlements), these data are variable, and this introduces uncertainty in the planning of urban actions and incentives for RWH systems.

The spatial variability of rainfall may be somewhat limited at a city scale, depending on the size of the city, but certain local aspects, such as the orography, can induce spatial variability, even at a small spatial scale. The data available on rainfall are limited to the locations of the meteorological stations. Moreover, satellite data have spatial resolution limitations and, being indirect measurements, some differences may not be accurately captured at a city scale. Accounting for time variations implies the use of sufficiently long historical precipitation records, usually recorded at a daily scale. Several works have studied the effects of the duration of rainfall series (e.g., Liaw and Tsai, 2004; Mitchell, 2007; Geraldi and Ghisi, 2017) in different areas of the world, and they have revealed differences between the lengths of the minimum rainfall series required to obtain results that are independent of the length of the series. This type of evaluation is somewhat limited for the Italian territory (e.g., Palla et al., 2011) and non-existent for the considered case study, that is, the Turin area. In addition, fewer studies have addressed the issue of the time frame of the precipitation series in regions already affected by climate changes (Santos et al., 2020), although this may be an important issue, as shown in this work.

The first flush is the amount of rainwater that is discharged into the sewerage system at the beginning of a rainfall event to minimise the risk of contamination of the water in the RWH tank due to the washout of dust and other substances that may have accumulated on the catchment surfaces (e.g., roofs). A diversion of the first flush can be realised in different ways. The simplest first flush devices are volumetric systems, which simply divert a fixed volume of water when it rains. More sophisticated systems resort to water quality sensors, such as turbidity sensors, to decide whether the water quality is adequate for storage or not. The amount of first flush depends on the degree of contamination of the collection surfaces, which, in turn, is a function of the existing contamination sources (e.g., air pollution; birds) and the length of the antecedent dry weather period (Farreny et al., 2011; Campisano et al., 2017). Some guidelines and rules of thumb for RWH suggest that a first flush of 0.4 mm - 0.8 mm is adequate (Texas Water Development Board, 2005; Eslamian and Eslamian, 2021), while others suggest discharging at least 1 mm (e.g., Cabell Brand Center, 2009; Amin et al., 2013; Lay et al., 2024). Silva and Ghisi (2016), who considered the Brazilian Standards (ABNT, 2007), adopted a 2 mm first flush, while the “2 mm rule” was considered not to be sufficient for Charlebois et al. (2023). Kus et al. (2010) found that a 5 mm first flush allowed the rainwater to meet all the drinking water requirements in Australia, including those concerning the lead concentration and turbidity. Finally, according to Thomas and Martinson (2007), first flush values ranging from 1 mm to 8.5 mm should be chosen, on the basis of both the initial turbidity of the water and the desired one.

As far as the non-potable water demand is concerned, the water demand of each household can change substantially, for many different reasons, in both time and space (e.g., Mazzanti and Montini, 2006; Statzu and Strazzera, 2009; Saurì et al., 2013; Romano et al., 2014; March et al., 2012; Liao and Chang, 2002). The fluctuation of the water demand over time and, in turn, of the non-potable water demand, occurs at different scales, that is, from sub-daily to annual or multi-year scales. The water demand at a sub-daily scale depends on the categories of people who live inside a house: young, workers, or retired and elderly. A pattern in the water demand that follows the temperature, due to an increase in the frequency of showers and, above all, irrigation of green spaces, is often visible at an annual scale (Butera et al., 2021). The effects of holidays (which means different degrees of occupancy of the building) are also visible at an annual scale, and either a decrease or increase of the consumption may be observed, depending on the location (e.g., Souriau, 2011). Water consumption at a multi-year scale can change as a result of variations in the number of people present in a house, of long-term changes in the water consumption habits, and/or of a change in the use of the building (for example from residential apartments to offices). Nevertheless, few studies have explicitly analysed the effects of the variability or uncertainty of a non-potable water demand for domestic use (e.g., Silva and Ghisi, 2016).

In this work, the effects of the uncertainty on the water saving efficiency of RHW systems for indoor non-potable uses, on both the supply side and the demand side, have been analysed from the building to the urban scale. We have studied the duration and period (time variability of the rainfall) of rainfall series and gauge stations (spatial variability of the rainfall) on the supply side, as well as the volume of the first flush that needs to be diverted to sewerage systems. We have also examined the time variability of the non-potable water demand on the demand side. Unfortunately, not enough data were available to model the spatial variability of the non-potable water demand at the urban scale, and we therefore considered two simplified, opposite scenarios: (i) the absence of spatial variability; and (ii) the total random variability. We then applied the proposed method to a case study, the city of Turin, which had already been analysed in a previous work (Carollo et al., 2022), from a deterministic perspective, where a constant water demand, a fixed duration of the rainfall series and a unique value of first flush had been considered. The innovative aspect of this study concerns the effects of the different sources of uncertainty on the water saving efficiency of RWH systems, from the building scale to the urban scale, which can be considered to help city planners and incentive policy makers define their priorities, develop guidelines and/or set up incentive systems.

2 PROPOSED APPROACH

2.1 SIMULATION OF A RAINWATER HARVESTING SYSTEM

The performance of an RWH system, at the building scale, depends on: i) rainfall pattern; ii) the roof area or, in general, the harvesting area, iii) the non-potable water consumption pattern, iv) the first flush amount when a device is applied, and v) the size of the tank used to store rainwater, as the storage capacity is the core aspect in the design of any RWH system.

The storage capacity (*S*) of an RWH tank can be designed using simplified approaches (e.g., National guidelines, such as UNI (2012) or BS (2013)), probabilistic approaches (e.g., Guo and Baetz, 2007; Raimondi and Becciu, 2014; Pelak and Porporato, 2016) or continuous mass balance simulations, the so-called behavioural models (e.g., Jenkins et al., 1978; Fewkes and Butler, 2000; Palla et al., 2011; Imteaz and Shadeed, 2022). The latter approach has been used in the present work. This approach is based on the simulation of the dynamics of inflows and outflows using the “time history” of both the rainfall at the location and the non-potable water demand of a building. We carried out the simulation considering a daily time-step, as the majority of studies that have applied this method have done (e.g., Mitchell, 2007; Campisano et al., 2017), and which has been demonstrated to provide accurate results, compared to operation data from existing RHW systems (e.g., Sousa et al., 2018), whenever the ratio of the capacity *,S,* to the annual inflow of water *,Q,* is greater than 1% (e.g., Fewkes, 1999; Fewkes and Butler, 2000; Mitchell, 2007). However, Imteaz and Boulimytis (2022) and Zhang et al. (2020) reported differences between hourly and daily time scales for their simulations. The water saving efficiency E_{ws} is given by:

$$E_{WS} = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t} \cdot 100 \qquad (1)$$

where Y_t is the rainwater supplied to a building in one day, and D_t is the non-potable water demand. As can be seen in eq. (1), E_{ws} provides an overall estimation of the percentage of the satisfied non-potable water demand over the entire analysis period, from *t*=1 to *t*=*T* days, for a building. The analysis period should be long enough to make the results independent from its duration, and different suggestions can be found in the relevant literature: 30 years for Palla et al. (2011), 25 years for Agudelo-Vera et al. (2013), 10 years for Mitchell (2007) and Geraldi and Ghisi (2017).

The performance of an RWH system is usually simulated for several tank sizes, and the results are then used to identify the optimal tank. In the present work, which was based on the works of Gnecco et al. (2013) and Carollo and Butera (2025), we assumed the optimal storage capacity to be a tank that leads to a water savings efficiency equal to 80% of its maximum. The underlying logic behind this choice is that, above this threshold, a water savings efficiency increase would require a substantial increase in the size of the tank (Fig. 1), thereby compromising the financial feasibility of the system. This criterion was defined for Italy as a whole, but it also seemed reasonable for regions that experience rainfall throughout the year, such as the city of Turin. However, it may not necessarily be applicable everywhere.

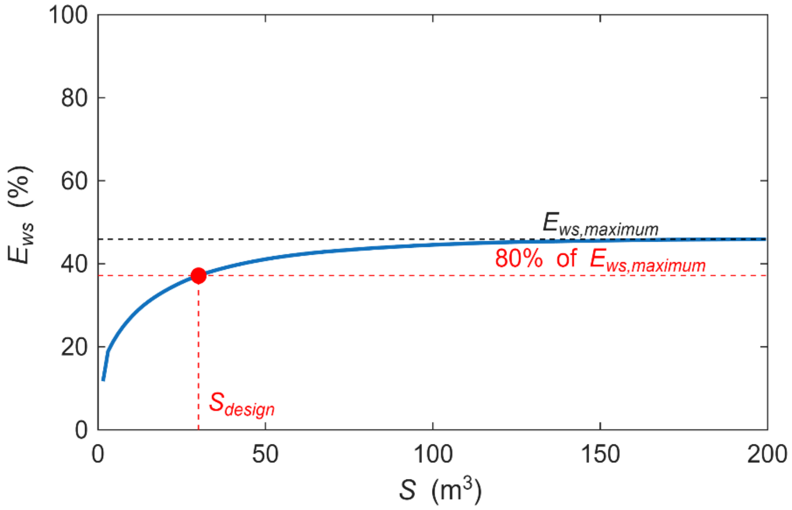

Fig. 1. Example of water saving efficiency behaviour as a function of the storage capacity. Identification of the optimal storage capacity.

An analysis of the RWH performance, at an urban scale, should start from an analysis of the RWH performance at the building scale. In this way, the complexity of the city is simplified and the heterogeneity of the buildings is managed through the representative building concept (Lúcio et al., 2020). Thus, we chose a small ensemble of representative buildings for each municipal district, from statistical and geographical data, in such a way that each representative building corresponded to a number, n_k, of buildings in the district that had identical RWH system characteristics and performances. We then optimized the size of the tank for each representative building, and used the resultant water savings to compute the overall water savings efficiency of the district, assuming the following weighted sum of the performance of each representative building:

$$E_{WS} = \frac{\sum_{k=1}^{K} n_k \cdot \sum_{t=1}^{T} Y_{t,k}}{\sum_{k=1}^{K} n_k \cdot \sum_{t=1}^{T} D_{t,k}} \cdot 100 = \frac{\sum_{k=1}^{K} E_{WS_k} \cdot D_k \cdot n_k}{\sum_{k=1}^{K} D_k \cdot n_k} \cdot 100 \qquad (2)$$

where *K* is the number of representative buildings in the district, D_k is the cumulative demand of the *k-th* representative building over the entire analysis period, $Y_{t,k}$ is the rainwater volume supplied to the *k-th* representative building in day *t,* and *T* is the length of the simulation period, expressed in days. Eq. (2) can easily be expanded from the district to the city scale just by summing the rainwater supplied in all the districts in the numerator and summing the demand in all the districts in the denominator. The total volume of the tanks at a city scale, S_{city}, is computed by multiplying the optimal storage capacity of each representative building by the number of buildings in that group. Complete details of the approach can be found in Carollo et al. (2022).

2.2 SOURCES OF RWH PERFORMANCE VARIABILITY

The variations in the water saving efficiency induced by various sources of variability have been examined in this work, namely: i) rainfall variability; ii) the first flush amount; and iii) the time variability of the non-potable water demand. All these aspects were treated separately for the representative buildings and for the whole city of Turin, and the results were then compared with a Base Case, which was grounded on common hypothesis (constant water demand, long rainfall series). The tank capacity of the RWH system of each representative building was that of the Base Case and did not change when a source of variability was introduced.

Rainfall variability

Rainfall can vary in both time and space. However, this work has mainly focused on the time variability of rainfall. This is usually accounted for in RWH studies by using a long rainfall series. Herein, the influence of the time variability of rainfall has been explored as it concerns: i) the length of the rainfall series; and ii) the period of the rainfall series. This was done by considering various sub-series extracted from the long rainfall series used for the Base Case. Time windows of different durations were considered (1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 40, 50 years) to capture the effect of the length of the rainfall. The time windows were moved on in one-yearly time steps, starting from the first year of observation, to capture the effect of the used sub-period of the rainfall series. Data from different rain gauge stations located in or close to the city were used to evaluate the impact of the spatial variability of the rainfall on the RWH performance.

First flush

The impact of the variability of the first flush amount (*ff*) was assessed considering values from 0.4 mm to 5 mm, according to the indications of the relevant literature. Three methods were considered here to model first flush:

1) Method 1 - the *ff* diversion was applied to each rainy day, independently of the number of antecedent wet or dry days;
2) Method 2 - the *ff* diversion was applied to all the rainy days but, in the case of consecutive rainy days, it was made equal to zero after a daily rainfall depth equal or greater than *ff* was reached;
3) Method 3 - the *ff* diversion was applied to rainy days, and in the case of consecutive rainy days when the cumulative rainfall depth was equal to *ff*, the *ff* diversion was no longer applied.

The first method is the one that is most frequently found in the literature, with most authors considering a fixed runoff coefficient that accounts for the first flush, regardless of the number of consecutive rainy days. The second method assumes that a precipitation event within 24 hours large enough to clean the collection surface is necessary, after which all the rainwater can be collected. The latter method assumes that, after a minimum rainfall amount has gathered over consecutive days, the contamination of the collection surface has been washed away and all the remaining rainwater from the event can be collected.

Considering that most first flush devices are of a volumetric type, their real performances are probably somewhere in between methods 1 and 3, depending on how long the emptying time lasts. Longer emptying times lead to results that are closer to method 3, while shorter times will have a performance that can be represented by method 1. Method 2 is aimed at simulating a system with a water quality probe, where it is assumed that smaller events than the first flush do not have a cumulative cleaning effect, and this method requires a 24 hour precipitation event of at least the first flush to effectively clean the collection surface.

Non-potable water demand

The impact of the temporal variability of the non-potable water demand for indoor uses has been investigated for all the representative buildings of the city through Monte Carlo simulations considering four scenarios. In each scenario, there are sub-periods of equal duration in which the non-potable water demand (constant in the sub-period) differs from the value used to size the tank of the RWH system. The duration of the sub-periods in which the non-potable water demand is constant, but variable from one sub-period to another and from one simulation to the another, differs for the four scenarios. Scenarios 1 and 4 refer to opposite conditions: in Scenario 1, the non-potable water demand of a building is constant for the entire simulation period and reproduces an overall change in the water demand, from that of the initial design phase, due to cultural or technological changes. Instead, in Scenario 4, the non-potable water demand changes daily. The other two scenarios are intermediate: in Scenario 2, the non-potable water demand remains constant over 50% of the analysis period (two sub-periods, that is, two values of non-potable water demand are considered in each simulation); in Scenario 3, the water demand remains constant over about 10% of the analysis period. Overall, 30000 simulations were performed for all the Scenarios and for each representative building to accurately model the variability of the non-potable water demand and obtain the relative frequency distribution of the water saving efficiency for all the representative buildings.

The water demand variability was modelled by varying two parameters: i) the daily domestic water consumption (d); and ii) the non-potable volume fraction, f_{np} (0-100%), i.e., the fraction of daily water consumption that is used for non-potable use. The probabilistic distribution of the non-potable water demand, given by the product $d \cdot f_{np}$, was defined resorting to the Monte Carlo simulation method. Considering that no data were available to fit the real probability distribution function (p.d.f.) that represents these parameters, the most commonly used distributions (triangular and PERT) were considered. The PERT distribution was adopted in this work for both d and f_{np}, because: i) it only requires three values (maximum, minimum and most likely) as defined by the user; ii) it allows skewness to be considered; and iii) the probability density function (p.d.f.) at the extremes is inferior to the triangular distribution. The p.d.f. of the Pert distribution is nil at each point, except in the [a,c] interval:

$$f(x) = \frac{(x-a)^{\alpha-1}(c-x)^{\beta-1}}{B(\alpha,\beta)(c-a)^{\alpha+\beta-1}} \quad a \le x < c \tag{3a}$$

$$\alpha = 1 + \frac{4(b-a)}{c-a};\ \beta = 1 + \frac{4(c-b)}{c-a} \tag{3b}$$

where a is the minimum value, b the most likely value, c is the maximum value, and B is the beta function.

When scaling at the urban scale, the relative frequency of the E_{ws} values was computed, considering the temporal variability of the non-potable water demand, for the four above mentioned scenarios, and the spatial variability of the demand was computed for the two opposite simplified cases: (i) the absence of spatial variability; and (ii) the total random spatial variability. In the former, it was assumed that all the buildings had the same per capita non-potable water demand value for each sub-period, although it could vary from one simulation to another. In the latter, each building had a different, per capita, non-potable, water demand in each sub-period, which was varied in each simulation.

The effect of the seasonality of the water demand on the performance of RWH was modelled using monthly multipliers of the mean water demand derived from the water consumption pattern of the city.

3 CASE STUDY

3.1 PRESENTATION

The approach presented in the previous section was applied to Turin, a city in northern Italy, which is located at an altitude of about 240 m above sea level (a.s.l.).

Turin is the administrative centre of the Piedmont Region, and it has a population of 871 850 residents, although a decreasing trend has been observed in the last few decades (since the 1980s). The population is distributed over an area of 130 km^2 with 36158 residential buildings (ISTAT 2011).

According to the Köppen-Geiger classification (Beck et al., 2023), the climate is Cfa, Humid subtropical, with a mean annual rainfall of about 850 mm (as elaborated on data from ARPA Piemonte, 2022). On average, there are 94 rainy days per year, with an average value of consecutive rainy days of 2.1 and a maximum number of consecutive rainy days equal to 15. Moreover, on average, there are 6 dry consecutive days and a maximum number of consecutive dry days equal to 163.

3.2 DATA SOURCES

Rainfall data is available on the databases of the Regional Agency for the Environment Protection (ARPA Piemonte, 2022) and the National Institution for Environment Protection and Research (ISPRA, 2023). Fig. 2 indicates the stations around Turin.

The Caselle station was selected as a reference since: i) it is close to Turin (15 km to the north); ii) it has a similar elevation to Turin (287 m a.s.l.); and iii) it has the longest rainfall series (58 years, between 1965 and 2022, with a percentage of 5.2% of missing data). Bric della Croce was not selected because, despite having a longer available series (69 years, between 1952-2022, with 1 missing year) and being closer, it is located upon a hill (710 m a.s.l.) at a very different elevation from Turin. Three other stations exist in the region, two of which are within the city limits (Vallere and Buon Pastore; average elevation 240 m a.s.l.), but they have shorter rainfall series. Moncalieri (240 m a.s.l.; 31 years, between 1951-86, with 4 missing years) was excluded because it was deactivated almost 40 years ago. Vallere and Buon Pastore series were merged into a 32 years long series (between 1990 and 2021) to create a second dataset which was used to assess the spatial variability (see Carollo et al. 2022).

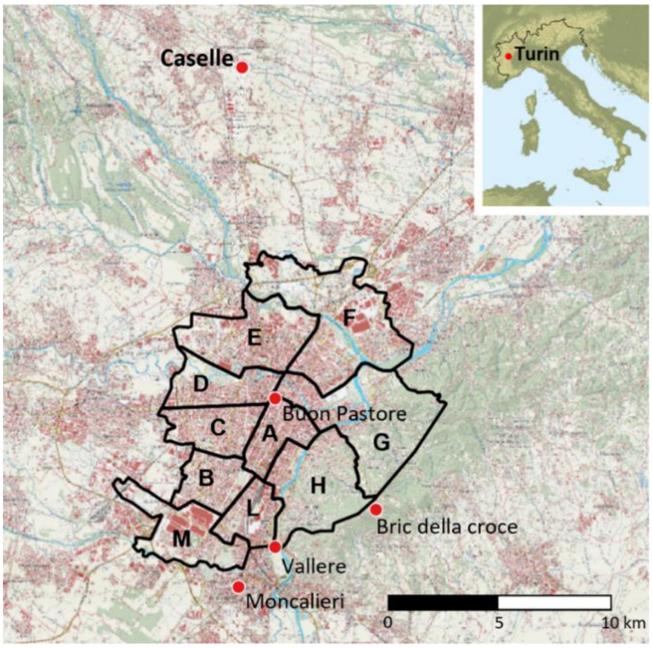

Fig. 2. Location of the rain gauges in the Turin area, as based on the BDTRE map (Regione Piemonte, 2024). The municipal district division (from A to M) is also shown.

Data about the total water consumption of the city of Turin in 2022 were provided by the municipal water utility (Società Metropolitana Acque Torino - SMAT). The average daily consumption was around 204700 m^3/day, and the distribution of the water demand over the year showed that the highest consumption was in late Spring (+3% in May). Consumption was instead at its lowest during the Summer (-4% in August). The decrease witnessed during the summer was due to the holiday period (which, in Turin, is generally in August), when there was no consumption related to workers from outside the city and thousands of residents were on holiday outside the city. The higher values observed during late spring instead are probably related to both the higher frequency of showers resulting from the hot weather and to irrigation (both private and public - most of the public parks are irrigated with potable water (Comune di Torino, personal communication)). However, the fluctuation around the mean water consumption value was low. This was probably due to a compensation effect, with the lower residential water consumption in the summer being offset by a higher consumption for irrigation and for tourism (Osservatorio Turistico della Regione Piemonte 2024).

The minimum, maximum and most likely consumption values are needed to stochastically model the non-potable water demand. Studies conducted specifically on the domestic water demand at the building level in the Piedmont Region (e.g., Busca 2018; Salvatico 2020) estimated a mean water consumption of around 150 l/(d·p) (litres per day per capita). According to Busca (2018), the water consumption varies between 144 and 158 l/(d·p), depending on whether it is measured during the week or over the weekend. These estimates are used to calculate the most likely value of the Turin water demand. The minimum and maximum values are calculated on the basis of other assumptions. It is assumed, as regards the minimum value of the water demand, that it is unlikely that water will be consumed for less than one toilet flushing (9 litres) and one hand wash per day (10 seconds with an 8 l/min discharge tap means a volume of 1.3 litres). Instead, when people are at home all day, they can consume water for: i) about 4 toilet flushings (36 litres); ii) several hand washes (10 l); iii) one shower (80 l); iv) one bidet (10 l); v) the washing machine (50 l); and vi) the hand-washing of dishes (40 l). In short, as far as the city of Turin is concerned, the PERT distribution parameters for d are: i) the minimum, 10.3 l/(d·p); ii) the most likely, 151 l/(d·p), corresponding to averages of 144 and 158 l/(d·p); and iii) the maximum, 226 l/(d·p).

Two sources of data were considered for the non-potable fraction of the indoor water demand in Turin: i) data from the Italian Ministry of the Environment, which suggests a value of 42%; and ii) according to Italian Regulations (UNI, 2012), which suggest a value of up to 55 l/(d·p). The minimum f_{np} value was computed as the ratio of the non-potable water consumption (55 l/(d·p)), as provided by the Italian regulations) to the water demand (241 l/(d·p) - data from the Turin water utility). The same approach was used to compute the most likely value, referring to the water demands observed by Busca (2018), and two values of f_{np} were computed (38% and 35%). In short, the PERT distribution parameters for f_{np} were: i) the minimum, 23%; ii) the most likely, 36.5%, corresponding to the average of 35% and 38%; and iii) the maximum, 42%.

The residential buildings in Turin were characterised, on the basis of the representative building concept (Lúcio et al. 2020; Carollo et al. 2022), for the analysis. Overall, 47 representative buildings were identified for Turin for the analysis of the RWH efficiency, by using land use maps and census data about population and buildings. A table of the characteristics of all the representative buildings can be found in Carollo et al. (2022). The total collection area was 12.2 km^2 at the city scale. Four typical buildings that had the characteristics presented in Table 1 were selected from among the 47 representative buildings to indicate the response of the different buildings to the sources of variability (where D is the average, annual, non-potable, water demand and Q is the average annual volume of collected rainwater and S is the optimal tank capacity). The four buildings of Table 1 were selected to represent the whole interval of the roof area per capita (H_{pc}, in m^2/p), that is the ratio of the rain collection area (the roof) to the number of people living in a building.

The relative frequency of the buildings is shown in Fig. 3a as function of H_{pc}, with H_{pc} varying between 7.7 m^2/p (tall buildings) and 60.9 m^2/p (villas). The composition of the buildings in the districts, which was obtained by dividing the buildings into four H_{pc} classes, is shown in Fig. 3b. It can be observed that there is a prevalence of small H_{pc} values, except in the hilly eastern zone, where there are more villas.

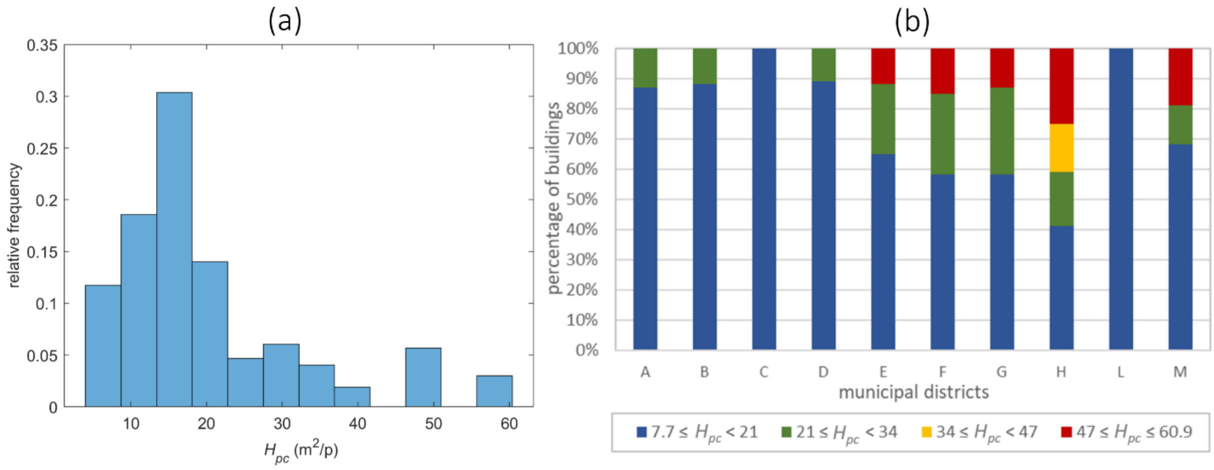

Fig. 3. Relative frequency of the collection area per capita in Turin (side a) and the proportion of the building categories in each municipal district (side b).

3.3 BASE CASE

A Base Case was assumed to assess the impact of uncertainty on the RWH system performance estimate considering: i) the longest available rainfall series (58 years, as collected at the Caselle station); ii) a first flush of 1 mm; and iii) a constant non-potable water demand of 50 l/(d·p). The Base Case was used to calculate the optimal storage capacity (that is to reach 80% of the maximum water savings efficiency) of the RWH system of each representative building, which was kept constant when the sources of variability were considered.

4 RESULTS AND DISCUSSION

The Base Case resulted in a non-potable water savings efficiency of 36% for a total city-wide storage volume of 513x10^3 m^3 (50% of the buildings has a tank between 3 and 11 m^3, 28% between 11 and 19 m^3 and 22% between 19 and 35 m^3). The effect of the variability of the water demand, rainfall series and first flush amount were studied separately and compared with the Base Case, and the results are presented hereafter. In each case, the rainwater collection area and the storage volume are those of the Base Case.

As far as the effects of the temporal variability on the water demand are concerned, the seasonality effects are presented and examined in Section 4.1, and those related to variations of the non-potable water demand are shown in Section 4.2. Concerning the rainfall series, the influence of the length of the rainfall series, the period and its location are examined in Section 4.3. The effect of the first flush variability is analysed in Section 4.4.

4.1 SEASONALITY

The seasonality of the water demand was analysed by modulating the non-potable water demand according to the changes in the pattern of the total potable water consumption in Turin. Twelve monthly multipliers were derived from the water consumption values, at the urban scale, provided by the water utility of Turin. These multipliers, or coefficients, reflected how much the monthly water demand was compared to the mean annual water demand. The sub-annual variation in Turin is weak, and the multipliers varied from a maximum of 1.03 (May) to a minimum of 0.96 (August).

When the reference water consumption for non-potable uses, 50 l/(d·p), was considered, the seasonality produced variations of between 52 and 48 l/(d·p). The simulation results confirmed that, due to these negligible differences between the highest and the lowest water demand values, the computed water savings were not different from what had been estimated for the Base Case. It is important to acknowledge that this is an approximation, since the seasonal pattern of the domestic water demand cannot be accurately derived from water utility data. The available data included all the water end-uses within the city, and not only the domestic uses. As such, seasonality may have had a different impact on each specific household.

4.2 NON-POTABLE WATER DEMAND VARIABILITY

The effects of the variability of the non-potable water demand are considered in this section for the representative buildings and for the whole town. For brevity reasons, the results obtained at the building scale are only shown for the four representative buildings indicated in Table 1. The relative frequency of the non-potable water demand obtained from the Monte Carlo simulations is shown in Fig. 4 (top right corner): it can be seen that it is almost symmetrical (mean=49.2 l/(d·p); median=49.5 l/(d·p)), given the weak asymmetry of the distribution of water consumptions and of the non-potable volume fraction.

The results of the simulations for Scenarios 1, 2, 3, defined in Section 2.2, are shown in Fig. 4. The results for Scenario 4 are depicted in Fig. 5a. It can be noted that when the rainfall data of the Caselle gauge station are considered, the duration of the sub-periods of Scenario 2 is roughly 27 years and that of Scenario 3 is roughly 5 years. The relative frequency of E_{ws} is shown for the 4 buildings indicated in Table 1, for the districts and for the whole town. The bins have a width equal to 1% in all the figures, thus, the relative frequency values can be considered comparable. The red triangles in Figs. 4 and 5 represent the median value, the green dots the 10% and 90% quantiles, while the values are reported in Table 2.

The obtained results show that buildings with a high H_{pc} (i.e., the B4 and B3 buildings) reach high water saving efficiency values, since E_{ws} is directly proportional to H_{pc} (Carollo and Butera, 2025). As far as the distribution of the relative frequency of E_{ws}, in Scenario 1 (first column in Fig. 4) for the B1 building is concerned, the distribution is clearly asymmetrical, even though the non-potable water demand distribution is almost symmetrical (top right corner in Fig. 4). This result shows that any deviations of the water demand from the design value do not linearly affect the variations of E_{ws}. This fact is less evident for buildings B2, B3 and B4, whose distribution of E_{ws} is limited by the 100% value. When the scenarios are compared, the distribution of the E_{ws} relative frequency becomes more symmetrical and narrower, from Scenario 1 to Scenario 4, that is, when the non-potable water demand varies over shorter time scales. This reveals that the daily variability of the water demand (Scenario 4) has a very limited impact on the performance of the RWH system for a large time scale. On the other hand, periodic (Scenarios 2 and 3) or permanent (Scenario 1) changes of the average water demand have more influence on the performance of the RWH system.

The results for the urban scale are shown in the fifth row of Fig. 4, where the colour yellow refers to the absence of spatial variability, while purple refers to random spatial variability, that is, for each sub-period, each one of the 36158 building has a water demand that is extracted from the distribution shown in Fig. 4. These results show that, in the absence of spatial variability, since most of the buildings in the city fall into category B1 or into similar categories, the relative frequency of E_{ws} for Turin is close to that of building B1 for all the scenarios. When a spatial random variability of the water demand is considered, no variability of E_{ws} can be observed for any of the scenarios or among the scenarios because the spatial mean of the non-potable water demand values is constant. The results of the analysis at the district scale are also shown in Fig. 4 for the absence of spatial variability of the water demand: the water saving efficiency is higher in districts A, G and H, due to the presence of buildings with a greater H_{pc} value. When focusing on the urban scale, it can be seen that the median value of E_{ws} is almost constant for all the scenarios, with a minimum value of 35.9%, for Scenario 3, and a maximum of 36.4%, for both Scenarios 1 and 4. The Base Case has an E_{ws} value of 36%.

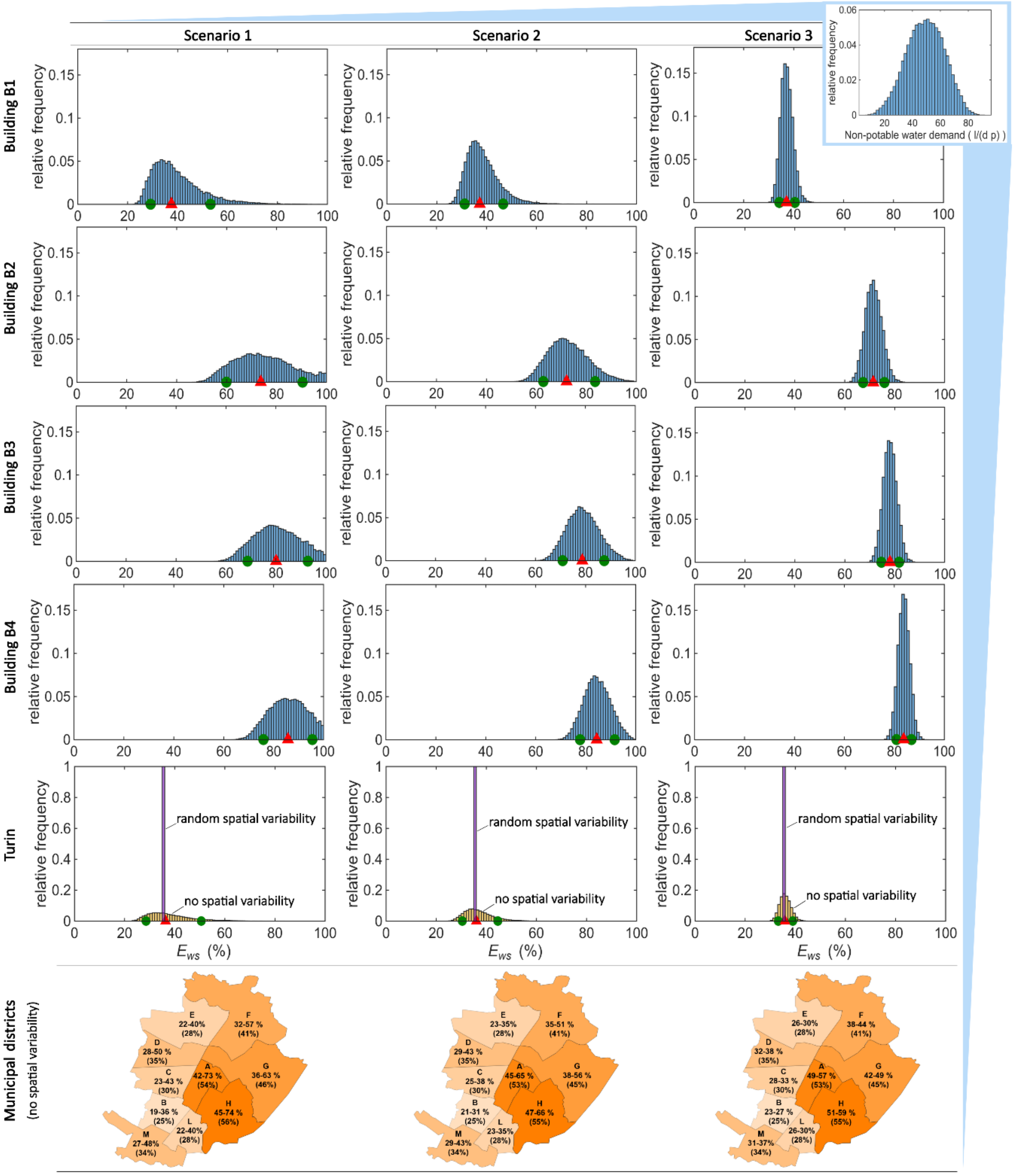

Fig. 4. Relative frequency of the water saving efficiency (bin width equal to 1%) for Scenarios 1, 2, and 3, for Buildings B1, B2, B3, B4 and for the city of Turin. The red triangles indicate the median values, while the green dots indicate the 10th and 90th percentiles (for Turin, the markers refer to the non-spatial variability case). The results for the Turin districts are indicated in the lowest row: the E_{ws} interquartile 10%-90% range and the median values, in brackets, are shown. The distribution of the daily per capita demand of the non-potable water is shown at the top right of the figure.

When comparing the different scenarios at the building scale, Table 2 shows that the median value of E_{ws} is almost constant for each building, while the interquartile range decreases when the period in which the non-potable water demand is constant decreases, that is, from Scenario 1 to Scenario 4. Instead, the median E_{ws} value increases for a fixed scenario as the H_{pc} of the building increases, while the interquartile value is higher for the B2 building. This result can be explained by considering Fig. 5b, where the dimensionless optimal storage capacity *S/Q* is shown for the Turin case, as a function of the dimensionless non-potable water demand, *D/Q*. The B2 building, with *D/Q* near to 1, is located where the curve is steep and the optimal storage capacity varies a great deal for a small variation of the non-potable water demand, so that, when the non-potable water demand *D* is different from the value used to size the tank, E_{ws} can change more than for other buildings. This is not evident for buildings B3 and B4, which are also located where the curve is steep, and this is because E_{ws} cannot exceed 100% when *D* is smaller than the value used to design the tank.

For completeness, the results of a sensitivity analysis are shown in Table 3 for the four buildings indicated in Table 1 and for the whole city of Turin. The values of E_{ws} obtained for a variation of the non-potable water demand from the design value of ± 20% are shown for Scenario 1.

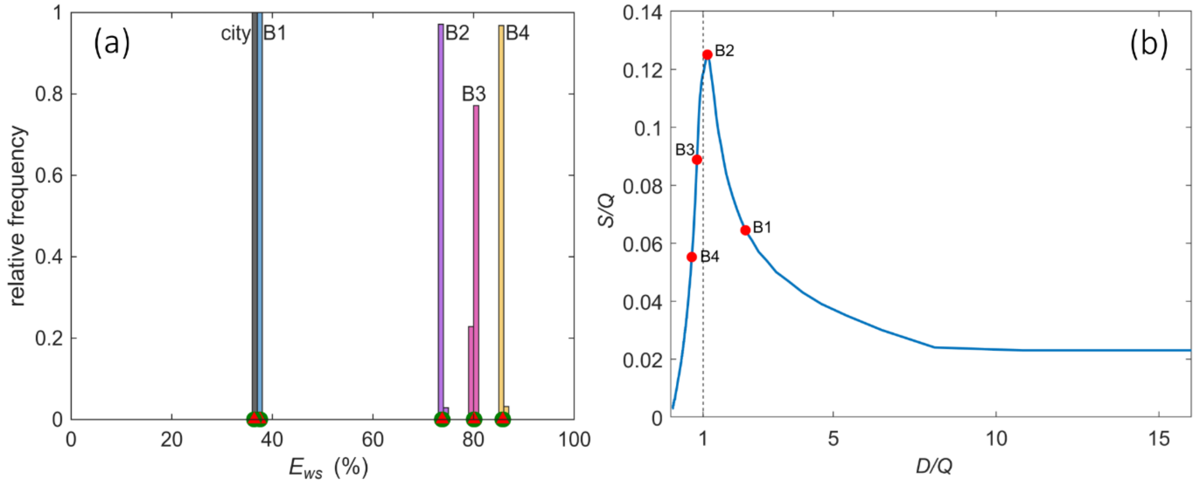

Fig. 5. Side a: relative frequency of the water savings efficiency (bin width equal to 1%) for Scenario 4 (non-potable water demand constant at a daily scale**).** The red triangles of the medians overlap the green dots of the 10th and 90th percentiles. In the city case, the histogram without any spatial variability of the water demand overlaps the histogram with a total random spatial variability of the water demand. Side b: the optimal storage capacity, *S,* is indicated as a function of the average non-potable water demand, *D*. The quantities are dimensionless with respect to the average net rain volume *Q*. The curve refers to the city of Turin.

4.3 INTER-ANNUAL RAINFALL VARIABILITY

The influence of the rainfall variability has been analysed by evaluating the performance of the RWH system using sub-series of 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 40 and 50 consecutive years from the full Caselle rainfall series (1965-2022). Each sub-series is moved on by 1 year, thereby multiple sub-series of equal length are created and different periods in time are created. The storage capacity of each RWH system is that of the Base Case.

The E_{ws} value is shown in Fig. 6, as function of the sub-series, for the selected representative buildings and for the whole city of Turin; the green dashed lines represent the 10% and 90% percentiles. The results reveal that both the length of the series and their period influence the RWH performance results. As the series is 58 years long (with 5.2% of missing data), the results for the larger sub-periods (40-50 years) are less robust because they include fewer sub-periods, which overlap to a great extent.

As expected (and already explored by such authors as Geraldi and Ghisi (2017)), the variability of the performance decreases, at both the building scale and the city scale, as the length of the rainfall series increases (Fig. 6). The B2 building, with D/Q close to 1, shows the greatest variability, as it is the most sensitive to variations of Q. For a 30-year long time series, as suggested in the Italian Standards (UNI, 2012), E_{ws} variability is limited to 5% at both the building and urban scale.

However, the results reveal that the specific series of years used in the simulations can also be a source of variability. Furthermore, the differences due to the specific years of the sub-series are not random and show a visible decreasing trend for the RWH system performance estimate when rainfall data from the most recent years are used. For instance, the average annual rainfall depth during the first 20 years of the series (1973-1992) is 976 mm, but it is only 705 mm over the 20 years from 2003 to 2022. The effect of the decreased annual rainfall is highlighted by the different coloured markers in Fig. 6. The blue triangles represent the efficiencies that result from using the first half of the sub-series (the oldest precipitation records), while the red squares refer to the second half of the sub-series (the most recent precipitation records).

Thus, on the basis of these considerations, it is possible to state that more in-depth analysis is advisable. Estimating the future performance on the basis of the current methodologies may not be the most efficient way, in the context of decreasing (or increasing) total annual rainfall amounts. Instead, it is advisable to consider the effects of climate change, and some adjustments to the Standard recommendations may thus be required.

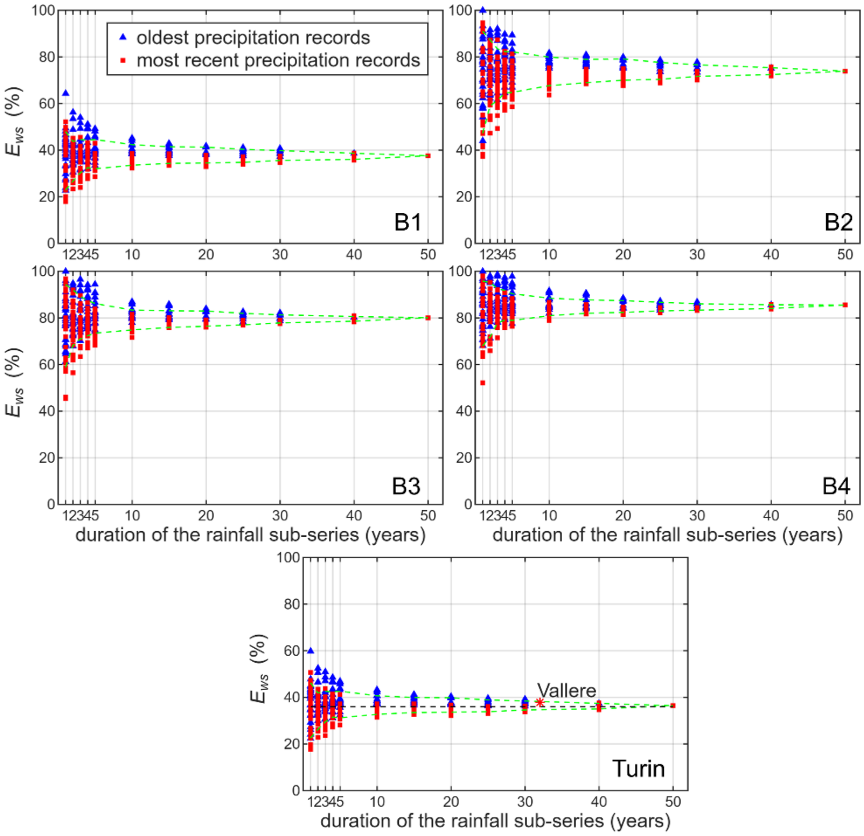

Fig. 6. Water savings efficiency (E_{ws}) as a function of the duration of the rainfall series. The green dashed lines represent the 10th and 90th percentiles; the grey dashed line for the Turin case indicates the efficiency estimated for the total rainfall series (Base Case), while the red asterisk shows the result for the Vallere-Buon Pastore rainfall series.

The water saving efficiency, at an urban scale, is also presented in Fig. 6 (red asterisk E_{ws} = 37.8%) for another rainfall series (Vallere-Buon Pastore). It can be observed that the result is within the range of the estimates obtained when the Caselle data series of a similar length was used. Considering that the stations are located in opposite directions to the city of Turin (Caselle to the north and Vallere and Buon Pastore to the south), it is reasonable to assume that it is highly improbable that there exists a spatial variability of the rainfall that significantly affects the water saving efficiency estimations of the city of Turin.

4.4 FIRST FLUSH VARIABILITY

The amount of the first flush in an RWH system depends on the device that is used and on its set up. The effect of the method (Methods 1, 2 and 3) and the amount (0.4 mm - 5 mm) used to model the first flush of the RWH performance are depicted in Fig. 7 for each representative building and for the city as a whole. The red points represent the results obtained for the Base Case.

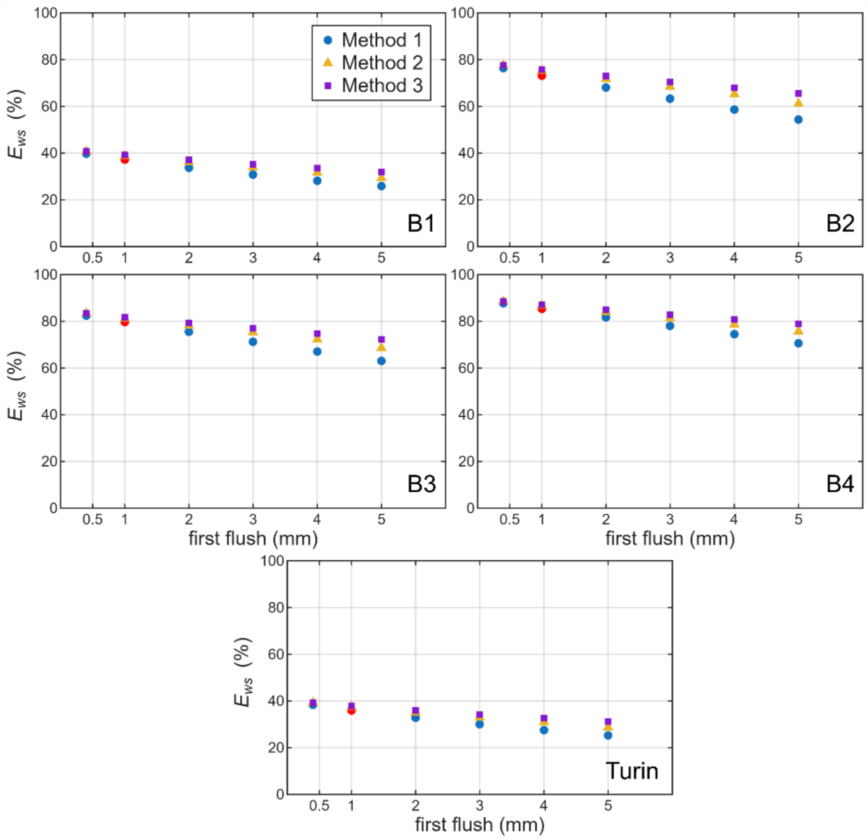

Fig. 7. The water saving efficiency (E_{ws}) as a function of the first flush. The red points show the results for the Base Case.

It can be noted that E_{ws} decreases almost linearly when the first flush depth increases, with the greatest reduction of saved volumes being obtained when method 1 is used. A higher water saving efficiency is reached for all the buildings for a first flush diversion which, in the case of consecutive days, discards a rainfall cumulative depth equal to the *ff* (Method 3). Building B2 is the most sensitive, even with respect to the first flush, with E_{ws} varying by 22.1% in the case of daily *ff* and by 12.1% in the case of cumulated *ff*. Nevertheless, the percentage change is not negligible for either the other buildings or for the whole city. Although the used first flush range (0.4 mm – 5 mm) could be considered somewhat limited, in Turin the water saving efficiency decreases considerably: from 38% to about 25% when a daily first flush diversion (Method 1) is used. If we consider that the average number of consecutive rainy days is just 2.1 days in Turin, the influence of the method to account for the first flush is limited. However, it could have a great impact on the water saving efficiency of an RWH system for areas with long rainy periods.

The difference between the average annual volume per capita of water saved when adopting an *ff* equal to 0.4 mm and an *ff* equal to 5 mm is shown in Table 4 for the considered representative buildings and for the whole city. Once again, it is interesting to note that the B2 building is more sensitive, in terms of average saved annual volumes per capita.

5 CONCLUSIONS

Rainwater harvesting systems for indoor use are generally designed under certain assumptions: the rainfall series should be long enough for the past rainfall pattern to be captured, a constant water consumption is usually considered, and the amount of the first flush diversion is also often considered equal for each rainy day. However, all these factors may be variable during the operation of a real RWH system. The present research effort has been made to assess the impact of the variability of the aforementioned factors on the water saving efficiency of some typical buildings in the city of Turin and for the whole city to provide insights that could be used to plan urban actions and financing for water management purposes, at both a building and an urban scale.

The assessment of the non-potable water consumption variability, with respect to the design values, revealed that the daily variation (around the design value) had a negligible impact. However, the performance of RWH systems is affected by changes in the average non-potable water consumption per capita. The limited seasonality of the overall water consumption in the city of Turin has been found to have no impact on the performance of RWH systems. However, this result may vary to a great extent in households with a marked water consumption seasonality (e.g., empty households or those with large irrigation amounts during the summer).

As expected, the length of the rainfall series shows an impact on the RWH performance estimations, as several authors also observed in the past and is included in the recommendations for the minimum series lengths. Moreover, the climate changes in the last 50 years have also resulted in an impact on the water saving efficiency, and more in-depth analysis are therefore necessary to upgrade Standard recommendations. The first flush has emerged to be a very important issue in the water saving efficiency of RWH systems, at both the building scale and at the city scale: the type of diversion (volume-based or quality-based) and the first flush value are very important. For instance, increasing the first flush amount from 1 mm to 5 mm resulted in a decrease in the RWH water savings efficiency of roughly 10%, under the assumption that the same fixed amount of the first flush occurred on each rainy day.

The variability of the first flush amount showed a greater impact for rainfall series lengths of more than 15 years than the rainfall variability. Thus, despite the significant focus of past research efforts on discussing the impact of rainfall variability on the performance of RWH and different recommendations regarding the length of the minimum rainfall series that should be used, the uncertainty regarding the non-potable water consumption and the first flush amount showed a greater impact, in the city of Turin, on the estimation of the water saving efficiency.

The analysis showed that the water saving efficiency of buildings with an annual, mean, non-potable water demand (volume) almost equal to the annual mean collected rainwater (volume) is the most sensitive to variations of both the demand and supply data.

The analysis performed in this work has not exhausted this topic. Indeed, it could be interesting to investigate the impact of spatial variability of the water demand at the urban scale in more detail, if up to date databases become available.

DATA AVAILABILITY STATEMENT

All the data, models and codes that support the findings of this study are available from the corresponding author upon reasonable request.

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AUTHORS’ CONTRIBUTIONS

Conceptualisation: MC, VS, IB - Data curation: MC, VS, IB – Investigation: MC, VS, IB – Methodology: MC, VS, IB – Software: MC – Supervision: VS, IB – Validation: MC, VS, IB – Visualisation: MC, VS, IB - Writing – original draft: MC, VS, IB - Writing – review and editing: VS, IB.

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Table 1. The main characteristics of the 4 buildings selected from among the 47 representative ones.

Name of the building	Roof area - *H* (m^2)	no. of people	H_{pc} (m^2/p)	*D/Q*	*S* (m^3)
B1	800	56	14.3	2.3	30
B2	200	7	28.6	1.13	16.5
B3	240	6	40	0.81	12
B4	100	2	50	0.65	4.5

Table 2. The 10th, 50th and 90th percentiles of E_{ws} for four representative buildings for the different scenarios

	Building B1			Building B2			Building B3			Building B4		
	E_{ws} percentile			E_{ws} percentile			E_{ws} percentile			E_{ws} percentile		
Demand constant for	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
54 years (Scenario1)	28.9	37.7	53.5	59.4	73.9	90.7	68.2	80.2	92.9	75.5	85.9	95.6
27 years (Scenario 2)	31.4	37.3	47.0	63.0	72.3	84.0	71.1	78.9	88.0	77.9	84.5	91.9
5 years (Scenario 3)	34.3	37.1	40.3	67.5	71.5	75.8	74.8	78.1	81.5	81.0	83.8	86.7
daily (Scenario 4)	37.5	37.6	37.7	73.6	73.8	73.9	79.9	80.1	80.2	85.7	85.8	85.9

Table 3. Water saving efficiency for variations of the non-potable water demand. The optimal storage capacity tank has been sized for a demand equal to 50 l/(d p).

	Water saving efficiency E_{ws}				
non-potable water demand l/(d·p)	Building B1	Building B2	Building B3	Building B4	City
40	44.4	82.1	86.7	91.1	42.6
50	37.2	73.2	79.6	85.4	36.0
60	31.9	64.8	73.0	79.6	31.1

Table 4. Variation of the average annual volume per capita of water saved (m^3) from *ff*=0.4mm to *ff*=5mm.

The *ff* method (Section 2.2)	Building B1 (m^3/person)	Building B2 (m^3/person)	Building B3 (m^3/person)	Building B4 (m^3/person)	City (m^3/person)
Method 1	2.53	4.04	3.54	3.14	2.38
Method 2	2.07	2.99	2.69	2.34	1.92
Method 3	1.59	2.21	2.03	1.75	1.47