

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

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1 Planning rainwater harvesting systems in a context of 2 uncertainty: from the building to the urban scale

3
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14 **Keywords:** rainwater harvesting; urban water management; water savings efficiency; urban water demand;
15 Monte Carlo simulations; first flush variability; rainfall time series variability

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17

18 **ABSTRACT**

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

23 The present work analyses the water saving efficiency of RWH for indoor use at the building and urban scales,
24 by assessing the variability of the performance estimations considering uncertainties on both the demand
25 and supply sides. We evaluated the variability of water consumption on the demand side, with reference to
26 both daily and multi-year scales, through Monte Carlo simulations that considered the statistical distribution
27 of the indoor, non-potable, water demand. Diversion of the first flush, which is required to ensure acceptable

28 water quality standards, is an important source of variability that has here been analysed considering both
29 the role of different set ups of the first flush device and the volume of the first flush that is diverted. We
30 evaluated the influence of the variability of rainfall patterns, considering different lengths and periods of the
31 used rainfall series, in order to establish the length of the minimum series that can guarantee reliable results.
32 The city of Turin (Italy) has been considered as a case study for the proposed approach. The obtained results
33 indicate which buildings are more sensitive to the considered variabilities and that the factor which impacts
34 RWH efficiency the most is the average, long-range, non-potable water demand, while daily variabilities have
35 shown no effects. Furthermore, the length and period of the rainfall series have been found to drive the
36 variability of the RWH efficiency on the supply side but, when the series is longer than 15 years, the variability
37 related to the first flush amount and set up has an even greater impact.

38 **PRACTICAL APPLICATIONS**

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

46 **1 INTRODUCTION**

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

53 al. 2021) and the need for incentives to promote RWH (Schuetze 2013), such as those that have been applied
54 in some countries, are crucial aspects for the implementation of RWH.

55 The estimation of the water savings efficiency of an RWH system for a building is relatively simple, when the
56 data on rainfall and water demand, as well as on the collection area of the buildings, are available. Analysis
57 tools have already been developed for this purpose (e.g., Jenkins et al. 1978; Fewkes and Butler 2000; Palla
58 et al. 2011; Imteaz and Shadeed 2022; Carollo and Butera 2025), and some methods have been included in
59 national and/or regional regulations and guidelines (e.g., DIN 2002; ANQUIP 2007; RF 2009; UNI 2012; BS
60 2013; Aqua España 2016). Loper et al. (2024) have recently developed a GIS tool that integrates precipitation
61 and evapotranspiration data which can be used to target the locations in the USA that are the most suitable
62 for rainwater harvesting.

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

75 The spatial variability of rainfall may be somewhat limited at a city scale, depending on the size of the city,
76 but certain local aspects, such as the orography, can induce spatial variability, even at a small spatial scale.
77 The data available on rainfall are limited to the locations of the meteorological stations. Moreover, satellite
78 data have spatial resolution limitations and, being indirect measurements, some differences may not be
79 accurately captured at a city scale. Accounting for time variations implies the use of sufficiently long historical

80 precipitation records, usually recorded at a daily scale. Several works have studied the effects of the duration
81 of rainfall series (e.g., Liaw and Tsai, 2004; Mitchell, 2007; Geraldi and Ghisi, 2017) in different areas of the
82 world, and they have revealed differences between the lengths of the minimum rainfall series required to
83 obtain results that are independent of the length of the series. This type of evaluation is somewhat limited
84 for the Italian territory (e.g., Palla et al., 2011) and non-existent for the considered case study, that is, the
85 Turin area. In addition, fewer studies have addressed the issue of the time frame of the precipitation series
86 in regions already affected by climate changes (Santos et al., 2020), although this may be an important issue,
87 as shown in this work.

88 The first flush is the amount of rainwater that is discharged into the sewerage system at the beginning of a
89 rainfall event to minimise the risk of contamination of the water in the RWH tank due to the washout of dust
90 and other substances that may have accumulated on the catchment surfaces (e.g., roofs). A diversion of the
91 first flush can be realised in different ways. The simplest first flush devices are volumetric systems, which
92 simply divert a fixed volume of water when it rains. More sophisticated systems resort to water quality
93 sensors, such as turbidity sensors, to decide whether the water quality is adequate for storage or not. The
94 amount of first flush depends on the degree of contamination of the collection surfaces, which, in turn, is a
95 function of the existing contamination sources (e.g., air pollution; birds) and the length of the antecedent dry
96 weather period (Farreny et al., 2011; Campisano et al., 2017). Some guidelines and rules of thumb for RWH
97 suggest that a first flush of 0.4 mm - 0.8 mm is adequate (Texas Water Development Board, 2005; Eslamian
98 and Eslamian, 2021), while others suggest discharging at least 1 mm (e.g., Cabell Brand Center, 2009; Amin
99 et al., 2013; Lay et al., 2024). Silva and Ghisi (2016), who considered the Brazilian Standards (ABNT, 2007),
100 adopted a 2 mm first flush, while the “2 mm rule” was considered not to be sufficient for Charlebois et al.
101 (2023). Kus et al. (2010) found that a 5 mm first flush allowed the rainwater to meet all the drinking water
102 requirements in Australia, including those concerning the lead concentration and turbidity. Finally, according
103 to Thomas and Martinson (2007), first flush values ranging from 1 mm to 8.5 mm should be chosen, on the
104 basis of both the initial turbidity of the water and the desired one.

105 As far as the non-potable water demand is concerned, the water demand of each household can change
106 substantially, for many different reasons, in both time and space (e.g., Mazzanti and Montini, 2006; Statzu

107 and Strazzer, 2009; Sauri et al., 2013; Romano et al., 2014; March et al., 2012; Liao and Chang, 2002). The
108 fluctuation of the water demand over time and, in turn, of the non-potable water demand, occurs at different
109 scales, that is, from sub-daily to annual or multi-year scales. The water demand at a sub-daily scale depends
110 on the categories of people who live inside a house: young, workers, or retired and elderly. A pattern in the
111 water demand that follows the temperature, due to an increase in the frequency of showers and, above all,
112 irrigation of green spaces, is often visible at an annual scale (Butera et al., 2021). The effects of holidays (which
113 means different degrees of occupancy of the building) are also visible at an annual scale, and either a decrease
114 or increase of the consumption may be observed, depending on the location (e.g., Souriau, 2011). Water
115 consumption at a multi-year scale can change as a result of variations in the number of people present in a
116 house, of long-term changes in the water consumption habits, and/or of a change in the use of the building
117 (for example from residential apartments to offices). Nevertheless, few studies have explicitly analysed the
118 effects of the variability or uncertainty of a non-potable water demand for domestic use (e.g., Silva and Ghisi,
119 2016).

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

134 2 PROPOSED APPROACH

135 2.1 SIMULATION OF A RAINWATER HARVESTING SYSTEM

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

140 The storage capacity (S) of an RWH tank can be designed using simplified approaches (e.g., National
 141 guidelines, such as UNI (2012) or BS (2013)), probabilistic approaches (e.g., Guo and Baetz, 2007; Raimondi
 142 and Becciu, 2014; Pelak and Porporato, 2016) or continuous mass balance simulations, the so-called
 143 behavioural models (e.g., Jenkins et al., 1978; Fewkes and Butler, 2000; Palla et al., 2011; Imteaz and Shadeed,
 144 2022). The latter approach has been used in the present work. This approach is based on the simulation of
 145 the dynamics of inflows and outflows using the “time history” of both the rainfall at the location and the non-
 146 potable water demand of a building. We carried out the simulation considering a daily time-step, as the
 147 majority of studies that have applied this method have done (e.g., Mitchell, 2007; Campisano et al., 2017),
 148 and which has been demonstrated to provide accurate results, compared to operation data from existing
 149 RHW systems (e.g., Sousa et al., 2018), whenever the ratio of the capacity S , to the annual inflow of water
 150 Q , is greater than 1% (e.g., Fewkes, 1999; Fewkes and Butler, 2000; Mitchell, 2007). However, Imteaz and
 151 Boulimyitis (2022) and Zhang et al. (2020) reported differences between hourly and daily time scales for their
 152 simulations. The water saving efficiency E_{ws} is given by:

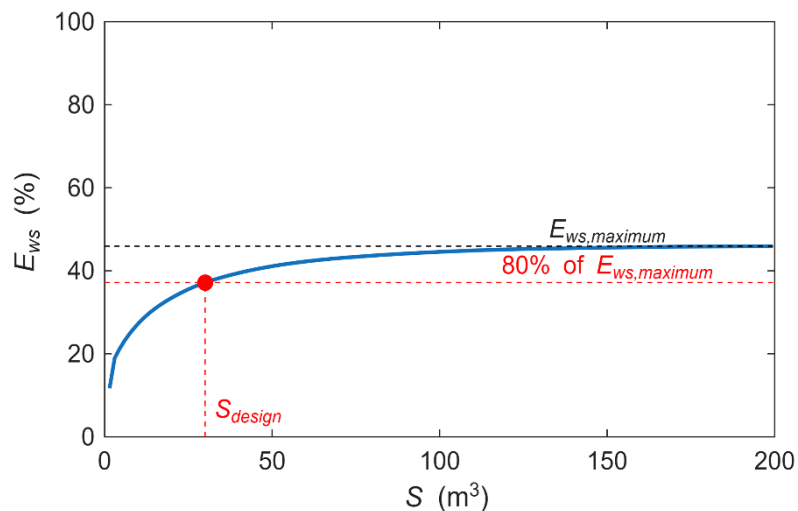
$$153 \quad E_{WS} = \frac{\sum_{t=1}^T Y_t}{\sum_{t=1}^T D_t} \cdot 100 \quad (1)$$

154 where Y_t is the rainwater supplied to a building in one day, and D_t is the non-potable water demand. As can
 155 be seen in eq. (1), E_{ws} provides an overall estimation of the percentage of the satisfied non-potable water
 156 demand over the entire analysis period, from $t=1$ to $t=T$ days, for a building. The analysis period should be
 157 long enough to make the results independent from its duration, and different suggestions can be found in the

158 relevant literature: 30 years for Palla et al. (2011), 25 years for Agudelo-Vera et al. (2013), 10 years for Mitchell
 159 (2007) and Geraldi and Ghisi (2017).

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

168



169

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

171

172 An analysis of the RWH performance, at an urban scale, should start from an analysis of the RWH performance
 173 at the building scale. In this way, the complexity of the city is simplified and the heterogeneity of the buildings
 174 is managed through the representative building concept (Lúcio et al., 2020). Thus, we chose a small ensemble
 175 of representative buildings for each municipal district, from statistical and geographical data, in such a way
 176 that each representative building corresponded to a number, n_k , of buildings in the district that had identical
 177 RWH system characteristics and performances. We then optimized the size of the tank for each representative

178 building, and used the resultant water savings to compute the overall water savings efficiency of the district,
 179 assuming the following weighted sum of the performance of each representative building:

$$180 \quad E_{WS} = \frac{\sum_{k=1}^K n_k \cdot \sum_{t=1}^T Y_{t,k}}{\sum_{k=1}^K n_k \cdot \sum_{t=1}^T D_{t,k}} \cdot 100 = \frac{\sum_{k=1}^K E_{WSk} \cdot D_k \cdot n_k}{\sum_{k=1}^K D_k \cdot n_k} \cdot 100 \quad (2)$$

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

189 **2.2 SOURCES OF RWH PERFORMANCE VARIABILITY**

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

197

198 **Rainfall variability**

199 Rainfall can vary in both time and space. However, this work has mainly focused on the time variability of
 200 rainfall. This is usually accounted for in RWH studies by using a long rainfall series. Herein, the influence of
 201 the time variability of rainfall has been explored as it concerns: i) the length of the rainfall series; and ii) the
 202 period of the rainfall series. This was done by considering various sub-series extracted from the long rainfall
 203 series used for the Base Case. Time windows of different durations were considered (1, 2, 3, 4, 5, 10, 15, 20,

204 25, 30, 40, 50 years) to capture the effect of the length of the rainfall. The time windows were moved on in
205 one-yearly time steps, starting from the first year of observation, to capture the effect of the used sub-period
206 of the rainfall series. Data from different rain gauge stations located in or close to the city were used to
207 evaluate the impact of the spatial variability of the rainfall on the RWH performance.

208

209 **First flush**

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

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

219 The first method is the one that is most frequently found in the literature, with most authors considering a
220 fixed runoff coefficient that accounts for the first flush, regardless of the number of consecutive rainy days.

221 The second method assumes that a precipitation event within 24 hours large enough to clean the collection
222 surface is necessary, after which all the rainwater can be collected. The latter method assumes that, after a
223 minimum rainfall amount has gathered over consecutive days, the contamination of the collection surface
224 has been washed away and all the remaining rainwater from the event can be collected.

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

231 **Non-potable water demand**

232 The impact of the temporal variability of the non-potable water demand for indoor uses has been investigated
233 for all the representative buildings of the city through Monte Carlo simulations considering four scenarios. In
234 each scenario, there are sub-periods of equal duration in which the non-potable water demand (constant in
235 the sub-period) differs from the value used to size the tank of the RWH system. The duration of the sub-
236 periods in which the non-potable water demand is constant, but variable from one sub-period to another and
237 from one simulation to the another, differs for the four scenarios. Scenarios 1 and 4 refer to opposite
238 conditions: in Scenario 1, the non-potable water demand of a building is constant for the entire simulation
239 period and reproduces an overall change in the water demand, from that of the initial design phase, due to
240 cultural or technological changes. Instead, in Scenario 4, the non-potable water demand changes daily. The
241 other two scenarios are intermediate: in Scenario 2, the non-potable water demand remains constant over
242 50% of the analysis period (two sub-periods, that is, two values of non-potable water demand are considered
243 in each simulation); in Scenario 3, the water demand remains constant over about 10% of the analysis period.
244 Overall, 30000 simulations were performed for all the Scenarios and for each representative building to
245 accurately model the variability of the non-potable water demand and obtain the relative frequency
246 distribution of the water saving efficiency for all the representative buildings.

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

$$257 \quad f(x) = \frac{(x-a)^{\alpha-1}(c-x)^{\beta-1}}{B(\alpha,\beta)(c-a)^{\alpha+\beta-1}} \quad a \leq x < c \quad (3a)$$

$$258 \quad \alpha = 1 + \frac{4(b-a)}{c-a}; \quad \beta = 1 + \frac{4(c-b)}{c-a} \quad (3b)$$

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

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

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

269 **3 CASE STUDY**

270 **3.1 PRESENTATION**

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

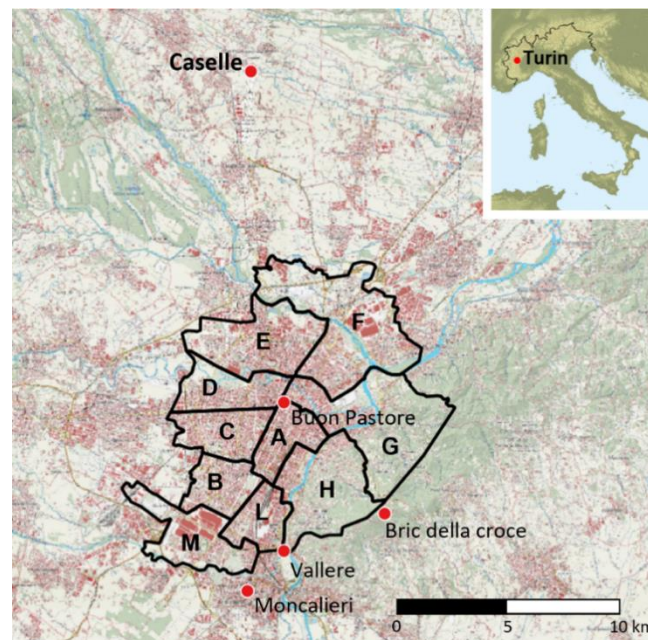
273 Turin is the administrative centre of the Piedmont Region, and it has a population of 871 850 residents,
 274 although a decreasing trend has been observed in the last few decades (since the 1980s). The population is
 275 distributed over an area of 130 km² with 36158 residential buildings (ISTAT 2011).

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

281 3.2 DATA SOURCES

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

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



295

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

298 Data about the total water consumption of the city of Turin in 2022 were provided by the municipal water
299 utility (Società Metropolitana Acque Torino - SMAT). The average daily consumption was around
300 204700 m³/day, and the distribution of the water demand over the year showed that the highest
301 consumption was in late Spring (+3% in May). Consumption was instead at its lowest during the Summer (-
302 4% in August). The decrease witnessed during the summer was due to the holiday period (which, in Turin, is
303 generally in August), when there was no consumption related to workers from outside the city and thousands
304 of residents were on holiday outside the city. The higher values observed during late spring instead are
305 probably related to both the higher frequency of showers resulting from the hot weather and to irrigation
306 (both private and public - most of the public parks are irrigated with potable water (Comune di Torino,
307 personal communication)). However, the fluctuation around the mean water consumption value was low. This
308 was probably due to a compensation effect, with the lower residential water consumption in the summer
309 being offset by a higher consumption for irrigation and for tourism (Osservatorio Turistico della Regione
310 Piemonte 2024).

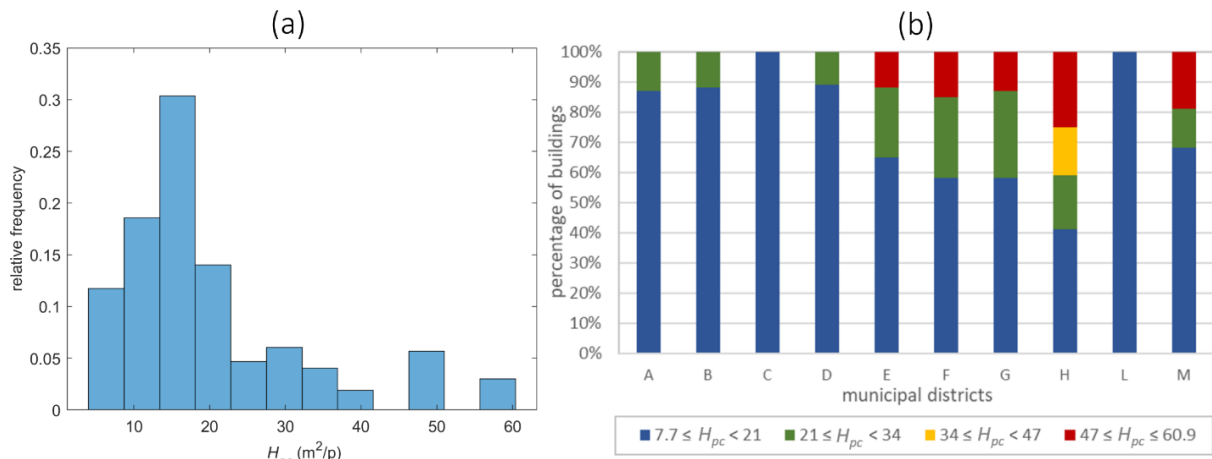
311 The minimum, maximum and most likely consumption values are needed to stochastically model the non-
312 potable water demand. Studies conducted specifically on the domestic water demand at the building level in
313 the Piedmont Region (e.g., Busca 2018; Salvatico 2020) estimated a mean water consumption of around 150
314 l/(d·p) (litres per day per capita). According to Busca (2018), the water consumption varies between 144 and
315 158 l/(d·p), depending on whether it is measured during the week or over the weekend. These estimates are
316 used to calculate the most likely value of the Turin water demand. The minimum and maximum values are
317 calculated on the basis of other assumptions. It is assumed, as regards the minimum value of the water
318 demand, that it is unlikely that water will be consumed for less than one toilet flushing (9 litres) and one hand
319 wash per day (10 seconds with an 8 l/min discharge tap means a volume of 1.3 litres). Instead, when people
320 are at home all day, they can consume water for: i) about 4 toilet flushings (36 litres); ii) several hand washes
321 (10 l); iii) one shower (80 l); iv) one bidet (10 l); v) the washing machine (50 l); and vi) the hand-washing of
322 dishes (40 l). In short, as far as the city of Turin is concerned, the PERT distribution parameters for d are: i)
323 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);
324 and iii) the maximum, 226 l/(d·p).

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

333 The residential buildings in Turin were characterised, on the basis of the representative building concept
334 (Lúcio et al. 2020; Carollo et al. 2022), for the analysis. Overall, 47 representative buildings were identified for
335 Turin for the analysis of the RWH efficiency, by using land use maps and census data about population and
336 buildings. A table of the characteristics of all the representative buildings can be found in Carollo et al. (2022).

337 The total collection area was 12.2 km² at the city scale. Four typical buildings that had the characteristics
338 presented in Table 1 were selected from among the 47 representative buildings to indicate the response of
339 the different buildings to the sources of variability (where D is the average, annual, non-potable, water
340 demand and Q is the average annual volume of collected rainwater and S is the optimal tank capacity). The
341 four buildings of Table 1 were selected to represent the whole interval of the roof area per capita (H_{pc} , in
342 m²/p), that is the ratio of the rain collection area (the roof) to the number of people living in a building.

343 The relative frequency of the buildings is shown in Fig. 3a as function of H_{pc} , with H_{pc} varying between 7.7
344 m²/p (tall buildings) and 60.9 m²/p (villas). The composition of the buildings in the districts, which was
345 obtained by dividing the buildings into four H_{pc} classes, is shown in Fig. 3b. It can be observed that there is a
346 prevalence of small H_{pc} values, except in the hilly eastern zone, where there are more villas.



347

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

350 3.3 BASE CASE

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

356 4 RESULTS AND DISCUSSION

357 The Base Case resulted in a non-potable water savings efficiency of 36% for a total city-wide storage volume
 358 of $513 \times 10^3 \text{ m}^3$ (50% of the buildings has a tank between 3 and 11 m^3 , 28% between 11 and 19 m^3 and 22%
 359 between 19 and 35 m^3). The effect of the variability of the water demand, rainfall series and first flush amount
 360 were studied separately and compared with the Base Case, and the results are presented hereafter. In each
 361 case, the rainwater collection area and the storage volume are those of the Base Case.

362 As far as the effects of the temporal variability on the water demand are concerned, the seasonality effects
 363 are presented and examined in Section 4.1, and those related to variations of the non-potable water demand
 364 are shown in Section 4.2. Concerning the rainfall series, the influence of the length of the rainfall series, the
 365 period and its location are examined in Section 4.3. The effect of the first flush variability is analysed in Section
 366 4.4.

367 4.1 SEASONALITY

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

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

381 4.2 NON-POTABLE WATER DEMAND VARIABILITY

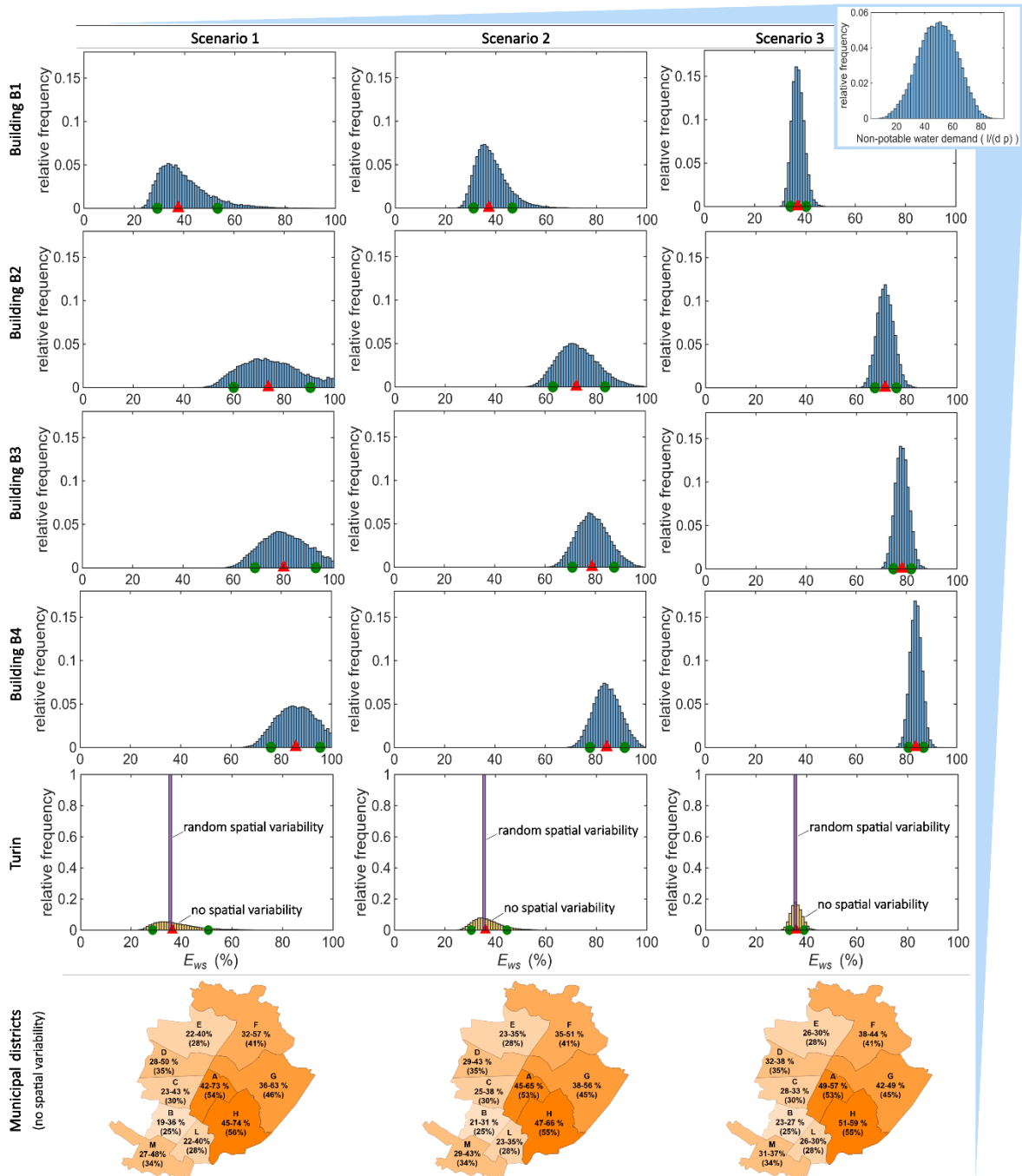
382 The effects of the variability of the non-potable water demand are considered in this section for the
383 representative buildings and for the whole town. For brevity reasons, the results obtained at the building
384 scale are only shown for the four representative buildings indicated in Table 1.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

388 The results of the simulations for Scenarios 1, 2, 3, defined in Section 2.2, are shown in Fig. 4. The results for
389 Scenario 4 are depicted in Fig. 5a. It can be noted that when the rainfall data of the Caselle gauge station are
390 considered, the duration of the sub-periods of Scenario 2 is roughly 27 years and that of Scenario 3 is roughly
391 5 years. The relative frequency of E_{ws} is shown for the 4 buildings indicated in Table 1, for the districts and for
392 the whole town. The bins have a width equal to 1% in all the figures, thus, the relative frequency values can

393 be considered comparable. The red triangles in Figs. 4 and 5 represent the median value, the green dots the
394 10% and 90% quantiles, while the values are reported in Table 2.

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

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



419

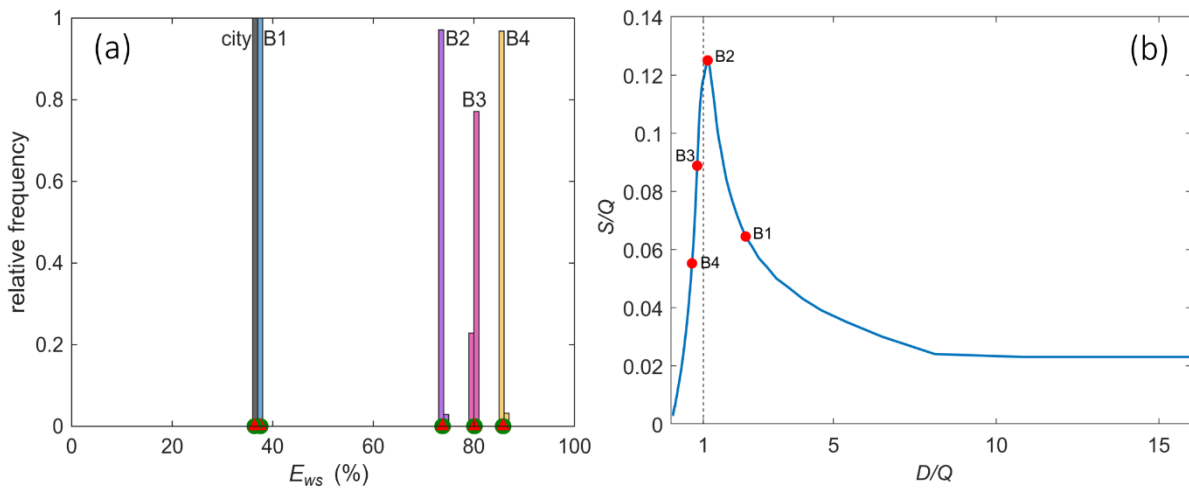
420 Fig. 4. Relative frequency of the water saving efficiency (bin width equal to 1%) for Scenarios 1, 2, and 3, for Buildings B1, B2, B3, B4
 421 and for the city of Turin. The red triangles indicate the median values, while the green dots indicate the 10th and 90th percentiles (for
 422 Turin, the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

425

426 When comparing the different scenarios at the building scale, Table 2 shows that the median value of E_{ws} is
 427 almost constant for each building, while the interquartile range decreases when the period in which the non-

428 potable water demand is constant decreases, that is, from Scenario 1 to Scenario 4. Instead, the median E_{ws}
 429 value increases for a fixed scenario as the H_{pc} of the building increases, while the interquartile value is higher
 430 for the B2 building. This result can be explained by considering Fig. 5b, where the dimensionless optimal
 431 storage capacity S/Q is shown for the Turin case, as a function of the dimensionless non-potable water
 432 demand, D/Q . The B2 building, with D/Q near to 1, is located where the curve is steep and the optimal storage
 433 capacity varies a great deal for a small variation of the non-potable water demand, so that, when the non-
 434 potable water demand D is different from the value used to size the tank, E_{ws} can change more than for other
 435 buildings. This is not evident for buildings B3 and B4, which are also located where the curve is steep, and
 436 this is because E_{ws} cannot exceed 100% when D is smaller than the value used to design the tank.
 437 For completeness, the results of a sensitivity analysis are shown in Table 3 for the four buildings indicated in
 438 Table 1 and for the whole city of Turin. The values of E_{ws} obtained for a variation of the non-potable water
 439 demand from the design value of $\pm 20\%$ are shown for Scenario 1.

440



441

442 Fig. 5. Side a: relative frequency of the water savings efficiency (bin width equal to 1%) for Scenario 4 (non-potable water demand
 443 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
 444 histogram without any spatial variability of the water demand overlaps the histogram with a total random spatial variability of the
 445 water demand. Side b: the optimal storage capacity, S , is indicated as a function of the average non-potable water demand, D . The
 446 quantities are dimensionless with respect to the average net rain volume Q . The curve refers to the city of Turin.

447

448 4.3 INTER-ANNUAL RAINFALL VARIABILITY

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

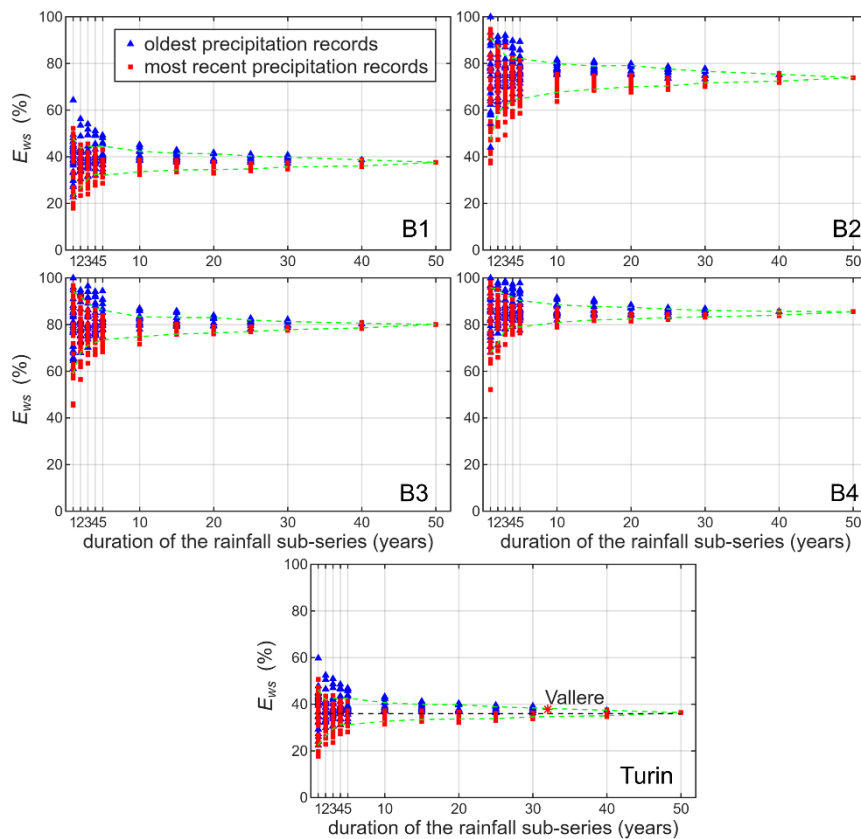
454 The E_{ws} value is shown in Fig. 6, as function of the sub-series, for the selected representative buildings and
455 for the whole city of Turin; the green dashed lines represent the 10% and 90% percentiles. The results reveal
456 that both the length of the series and their period influence the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

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

464 However, the results reveal that the specific series of years used in the simulations can also be a source of
465 variability. Furthermore, the differences due to the specific years of the sub-series are not random and show
466 a visible decreasing trend for the RWH system performance estimate when rainfall data from the most recent
467 years are used. For instance, the average annual rainfall depth during the first 20 years of the series (1973-
468 1992) is 976 mm, but it is only 705 mm over the 20 years from 2003 to 2022. The effect of the decreased
469 annual rainfall is highlighted by the different coloured markers in Fig. 6. The blue triangles represent the
470 efficiencies that result from using the first half of the sub-series (the oldest precipitation records), while the
471 red squares refer to the second half of the sub-series (the most recent precipitation records).

472 Thus, on the basis of these considerations, it is possible to state that more in-depth analysis is advisable.
473 Estimating the future performance on the basis of the current methodologies may not be the most efficient
474 way, in the context of decreasing (or increasing) total annual rainfall amounts. Instead, it is advisable to

475 consider the effects of climate change, and some adjustments to the Standard recommendations may thus
 476 be required.



477

478 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
 479 90th percentiles; the grey dashed line for the Turin case indicates the efficiency estimated for the total rainfall series (Base Case),
 480 while the red asterisk shows the result for the Vallere-Buon Pastore rainfall series.

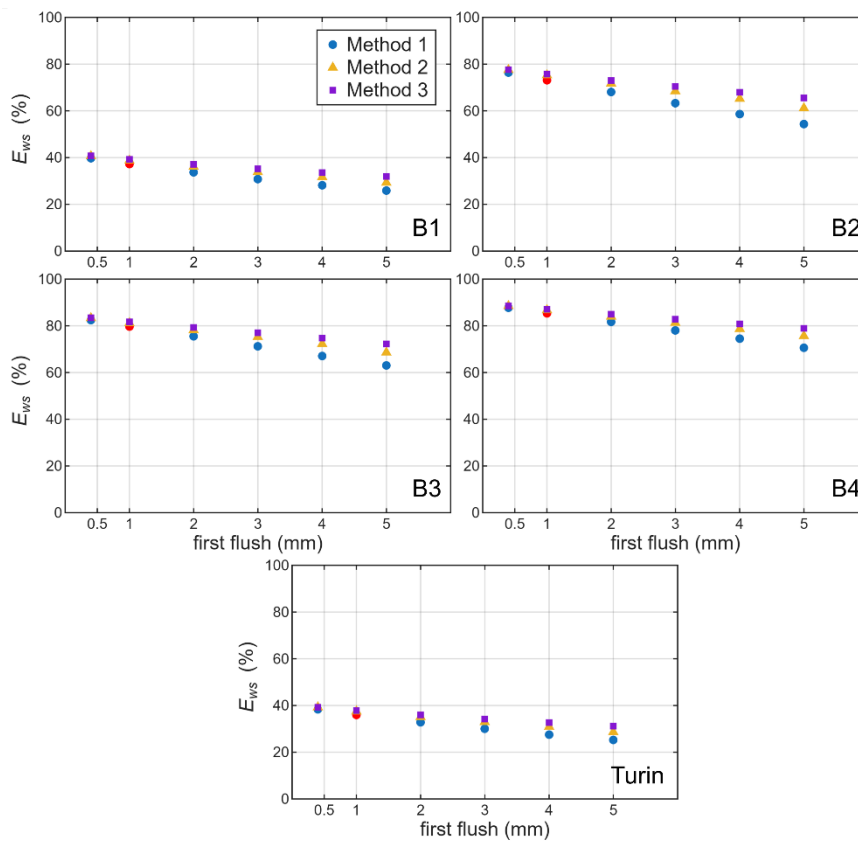
481

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

488 4.4 FIRST FLUSH VARIABILITY

489 The amount of the first flush in an RWH system depends on the device that is used and on its set up. The
 490 effect of the method (Methods 1, 2 and 3) and the amount (0.4 mm - 5 mm) used to model the first flush of

491 the RWH performance are depicted in Fig. 7 for each representative building and for the city as a whole. The
 492 red points represent the results obtained for the Base Case.



493

494 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.

495

496 It can be noted that E_{ws} decreases almost linearly when the first flush depth increases, with the greatest
 497 reduction of saved volumes being obtained when method 1 is used. A higher water saving efficiency is
 498 reached for all the buildings for a first flush diversion which, in the case of consecutive days, discards a rainfall
 499 cumulative depth equal to the ff (Method 3). Building B2 is the most sensitive, even with respect to the first
 500 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,
 501 the percentage change is not negligible for either the other buildings or for the whole city. Although the used
 502 first flush range (0.4 mm – 5 mm) could be considered somewhat limited, in Turin the water saving efficiency
 503 decreases considerably: from 38% to about 25% when a daily first flush diversion (Method 1) is used. If we
 504 consider that the average number of consecutive rainy days is just 2.1 days in Turin, the influence of the
 505 method to account for the first flush is limited. However, it could have a great impact on the water saving
 506 efficiency of an RWH system for areas with long rainy periods.

507 The difference between the average annual volume per capita of water saved when adopting an ff equal to
508 0.4 mm and an ff equal to 5 mm is shown in Table 4 for the considered representative buildings and for the
509 whole city. Once again, it is interesting to note that the B2 building is more sensitive, in terms of average
510 saved annual volumes per capita.

511 **5 CONCLUSIONS**

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

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

527 As expected, the length of the rainfall series shows an impact on the RWH performance estimations, as several
528 authors also observed in the past and is included in the recommendations for the minimum series lengths.
529 Moreover, the climate changes in the last 50 years have also resulted in an impact on the water saving
530 efficiency, and more in-depth analysis are therefore necessary to upgrade Standard recommendations. The
531 first flush has emerged to be a very important issue in the water saving efficiency of RWH systems, at both
532 the building scale and at the city scale: the type of diversion (volume-based or quality-based) and the first

533 flush value are very important. For instance, increasing the first flush amount from 1 mm to 5 mm resulted in
534 a decrease in the RWH water savings efficiency of roughly 10%, under the assumption that the same fixed
535 amount of the first flush occurred on each rainy day.

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

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

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

548 **DATA AVAILABILITY STATEMENT**

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

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554 **AUTHORS' CONTRIBUTIONS**

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

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 716

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

717

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 (Scenario 1)	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

718

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

719

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

720