A scale-adaptive method for urban rainwater harvesting simulation

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Abstract

At a building or dwelling scale, accurate evaluation of the water savings potential from rainwater harvesting (RWH) can be achieved by simulating the performance of the RWH system using a balance equations model. At an urban scale, water savings potential is usually estimated from the balance between the annual rainfall and annual water consumption. This approach has limited accuracy since it assumes an infinite storage capacity and it disregards the variability of the ratio between the water collected and water consumed in each building. This paper presents a methodology to evaluate rainwater harvesting potential at an urban level taking into consideration buildings' characteristics and consumption pattern. The complexity of the model is balanced with the format and detail of the information available to allow fast and easy implementation with few resources. The proposed methodology is applied to the city of Lisbon, Portugal, located on the Atlantic coast of the Mediterranean climate region. The results demonstrate water savings potential ranging from 16 to 86% depending on the buildings and occupancy characteristics. The spatial variability of the rainfall in the city of Lisbon was found to be negligible for rainwater harvesting potential evaluation.

Keywords Rainwater harvesting systems simulation · Accuracy/data requirements balance · Urban planning · Water savings potential · Parametric water savings potential functions

Introduction

Due to population growth (UN 2015), water consumption increase (UNEP 2002), pollution of water sources (UNEP 2002), and, more recently, climate changes around the world (IPCC 2007; Lehner et al. 2006), water has become a resource at risk. Several countries are already facing problems related to water scarcity or will face them in the near future (Abdulla and Al-Shareef 2009; Ghisi 2006).

In the scope of water efficiency, rainwater has been considered an alternative source usually for non-potable uses in buildings. Research focusing on estimating water savings potential from RWH in buildings can be organized into three broad categories: (i) studies considering only a balance between rainfall and water consumption over a region or country (e.g., Abdulla and Al-Shareef (2009) in Jordan; Ghisi (2006) in Southern Brazil; Aladenola and Adeboye (2010) in Abeokuta, Nigeria); (ii) studies considering the simulation of RHW systems in a specific or typified building or set of buildings (e.g., multi-unit building in Sydney, Newcastle, and Wollongong (Eroksuz and Rahman 2010); single and multi-family buildings in Barcelona, Spain (Domènech and Saurí 2011); single family building in Almada and Porto, Portugal (Silva et al. 2015)); and (iii) studies considering the simulation of RWH systems in a neighborhood (e.g., Ringdansen neighborhood in Norrköping, Sweden (Villarreal and Dixon 2005); neighborhood in Granollers, Spain (Farreny et al. 2011a)) or a city (Drancy and Colombes, France (Belmeziti et al. 2013); 62 cities in Santa Catarina, Brazil (Ghisi et al. 2006); Morelia, Mexico (Bocanegra-Martínez et al. 2014)). A fourth group could be identified evaluating RWH water savings potential for specific end-uses (Basinger et al. 2010) or without considering a specific building configuration (Campisano and Modica 2012; Mun and Han 2012; Palla et al. 2012, 2011; Rahman et al. 2012; Mehrabadi et al. 2013). These studies show a substantial variability of water savings potential

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from RWH depending on the specific context of the analysis and the adopted design method. To achieve reliable results, a daily simulation of the RWH performance taking into consideration the local climate (namely the rainfall), the water consumption pattern per end-use, and the RWH system configuration (in particular the collection area and loses) is required (e.g., Campisano and Modica 2014; Ghisi et al. 2007; Imteaz et al. 2015; Silva and Ghisi 2016).

Studies evaluating the potential savings associated with a generalized implementation of RWH in a city are important when planning municipality policies in an integrated water management framework. Most of these studies at an urban level focus on few of the problem variables. Several studies account for the spatial variation of the precipitation (e.g., Imteaz et al. 2015), some emphasize the real collection area derived from the building roof area (e.g., Lange et al. 2012) but the link to the buildings demographics to determine the water consumption is only found in the studies by Belmeziti et al. (2013, 2014). It is essential to understand and quantify the expected RWH savings potential at an urban level taking into consideration the spatial variation of the rainfall, the characteristics of the buildings, their occupancy, and the end-use pattern, namely in the Mediterranean region. Consequently, the goals of the present paper are twofold. First, develop a methodology to evaluate rainwater harvesting potential at an urban level that takes into consideration the rainfall and buildings spatial variability and also accounts for the buildings geometric and demographic characteristics. Second, apply the methodology to the city of Lisbon, Portugal, that is located in the on the Atlantic coast of the Mediterranean climate region.

Proposed methodology

The simulation of a rainwater harvesting system performance requires a set of information at different scales: (i) local scale, (ii) building scale, and (iii) system scale. At the local scale, the rainfall is the most relevant, but other climate information influencing evapotranspiration could be included. At the building scale, it is required to characterize the collection area and the water consumption pattern. The tank capacity and optional first-flush devices are the system features that need to be defined.

The information technology advances during the last years empowered the individuals and organizations to perform more complex analysis in many fields. Still, there are information limitations and integration gaps for rainwater harvesting systems simulation at an urban scale. If geographical information systems (GIS) with the detailed land use are available for most cities in the more developed countries, the data on the type (e.g., residential, commercial) and geometry (e.g., number of floors number and characteristics of the apartments in each

floor) of the buildings presents a lower level of detail and, usually, is not integrated in the GIS. The same is applicable to the information regarding the building occupancy and corresponding water consumption. In practice, nowadays, it is possible to identify the roof area of every building from a GIS, but the remaining information required for the simulation of a rainwater harvesting system performance is only available at a larger scale (e.g., civil parish, zone, city).

The proposed methodology (Fig. 1) aims at balancing the complexity of simulating the performance of rainwater harvesting systems for every building in a city with the lack of accuracy when estimating the water savings potential based on the balance between annual rainfall and water consumption. Considering the information limitations regarding the buildings characteristics, namely the number of floors and the number of apartments per floor, and the occupancy, the methodology adopts equivalent buildings as representative of a certain city building stock and uses them to estimate the performance of a RWH system in a delimited area. The approach is, to some extent, similar to the methodology developed by Belmeziti et al. (2013), but conceptually distinct in terms of the spatial evaluation and RWH system simulation.

Scope definition includes (i) the definition of the spatial boundaries of the study (area delimitation) and (ii) the potential uses for the harvested rainwater (considered uses). The proposed methodology may be applied to a country, municipality, city, civil parish, or even a neighborhood. The adopted urban area should be defined depending on the purpose of the analysis, expected accuracy of the results, and available information about the characteristics of the rainfall and the building's geometry and occupancy. The proposed methodology also considers the possibility of using rainwater in buildings and/or in public spaces. In buildings, rainwater uses vary depending on the level of demand of the target population. One may assume rainwater to be suitable for potable uses, both in residential and service buildings, but in most developed countries, only non-potable uses are acceptable, typically indoor uses such as cloth washing and flushing and outdoor uses such as washings (e.g., car, garage, driveways, and walkways) and watering. In public spaces, rainwater may be used for street washing and garden watering.

Area characterization includes (i) water consumptions pattern, (ii) mapping land use and occupancy, and (iii) spatial and time rainfall regimes. The daily water consumption per capita on residential buildings varies around the globe and is generally higher in developed countries. For instance, in Spain, the daily water consumption is 320 L per capita while in Kenya, it is only 46 L per capita (UNDP 2006). Different studies also show that the non-potable water consumption of an average household in developed countries represents about 35% of the total indoor water consumption (Ghisi 2006; Villarreal and Dixon 2005; Fewkes 1999; Environment Agency 2010; Cheng and Liao 2009). Outdoor uses and water consumption
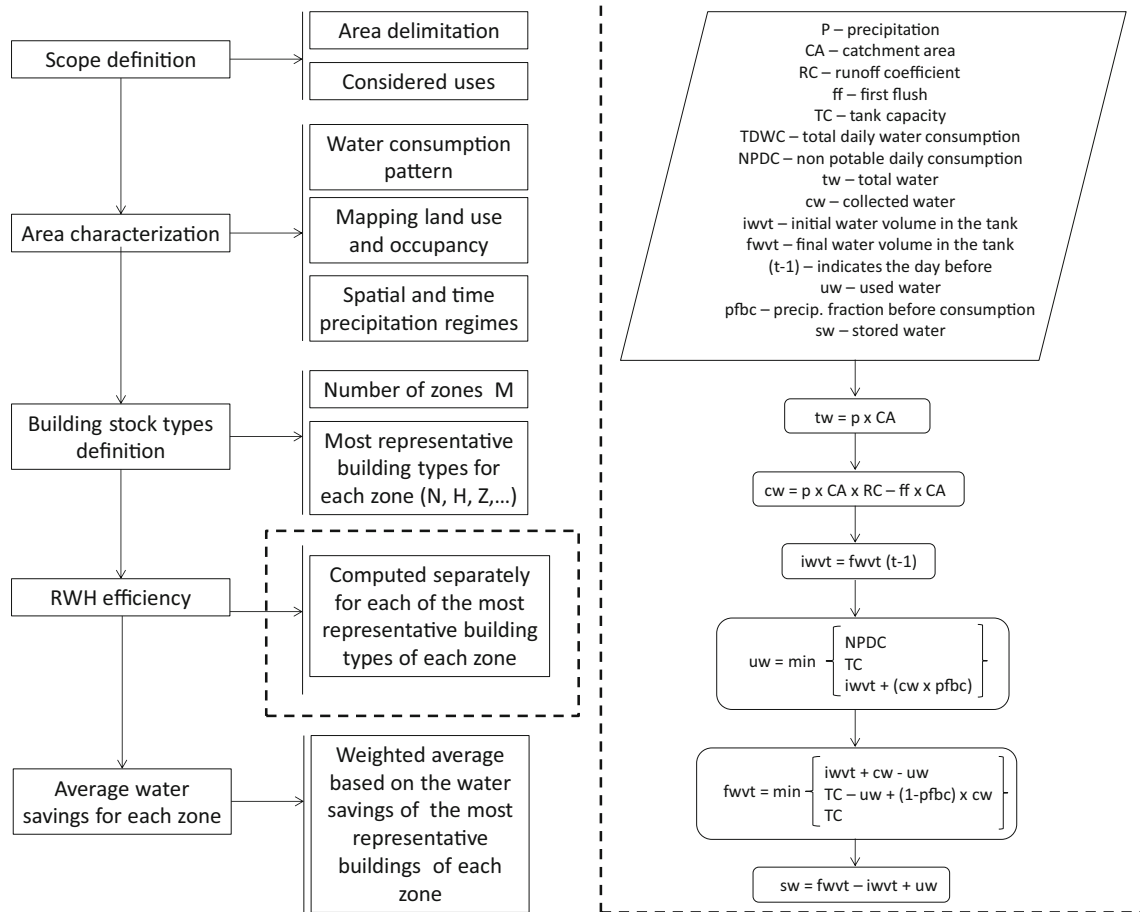
Fig. 1 Methodology flowchart

in public spaces can be even more variable depending on the country and community. The characterization of the urban area involves analyzing information from statistical studies, geographical information systems, and local observations, in order to identify city zones that are distinct in terms of (i) land uses proportions, for instance, roads, gardens and building areas; and (ii) building characteristics and occupancy, due to different number of floors, number of households per floor, and number of occupants per household. Rainfall is variable both in time and space around the globe. In order to characterize the hydrologic regime, it is important to identify the available sources of information and select the most adequate. For rainwater harvesting systems simulation, Mitchell et al. (2008) recommend the use of rainfall series with a minimum of 10 years of records. Distinct rainfall series should be defined for different zones since there can be significant spatial variability of the rainfall depending on the climate and area under analysis (Imteaz et al. 2013).

Water consumptions pattern, land use and occupancy, and rainfall regimes are balanced to determine, simultaneously, the adequate number of zones that should be considered in the analysis and the most representative building types of each zone. It is not adequate to map the area into zones considering

only one or two of the three variables. For instance, similar buildings in distinct locations of an urban center may show different performances due to the rainfall regimes, as different buildings in the same zone due to differences in the water consumption pattern or occupancy. After this procedure, each zone is characterized by a certain rainfall (P) and a number of building types with more representativeness. The number of buildings with more representativeness may be different for each zone. The goal set herein for illustration purpose is to cover at least 40–50% of the total building stock in each zone, but the methodology could be applied using different limits. This option is made to restrict the analysis of each zone to two or three building types (the more representative ones), balancing the effort required to characterize each building type with the accuracy of the results. Nowadays, it became relatively easy to accurately estimate the roof area of all the buildings using geographical information systems (GIS) tools with adequate maps. However, given the limitations in identifying the use of each and every building and the corresponding occupancy and water consumption end-use pattern, this would be only an apparent accuracy increase. Within each zone, the RWH potential is assessed for each building type considered representative of the zone.

The RWH system is evaluated for each building type by simulating its performance on a daily basis considering (i) the daily rainfall amount (mm); (ii) the collection area (m^2); (iii) the total daily water consumption of the building (m^3/day) as well as its non-potable fraction; (iv) the tank capacity (m^3); and (v) the first flush and losses. The daily rainfall amount can be obtained from direct observations (records of meteorological stations), indirect observations (satellite images), or monitoring local rainfall. Building roof area of each building type representative of each zone should be characterized since it directly defines the collection area of the RWH system. This information can be obtained from GIS. The average daily water consumption per building type can be obtained based on the number of residents (occupancy) times the daily water consumption per capita. Occupancy should be estimated as the roundup integer computed from the number of dwellings per floor and the number of floors of each building type in each zone and also the average family dimension in that zone. This information can be estimated consulting statistical studies and performing visits on site to characterize each building stock under analysis. Consumption pattern of each zone, including its non-potable fraction, should be assessed consulting previous studies eventually complemented by monitoring campaigns. The dashed box in Fig. 1 presents a simplified representation of the model used to simulate the performance of a RWH system. A daily scale was chosen to estimate approximately the real RWH potential because it limits the influence of the temporal variability between the rainfall and consumption. The pfbc represents the fact that the precipitation can take place before or after the consumption. If the consumption is constant, the results will be similar regardless if the consumption takes place before or after the consumption for long series simulation. However, in the case of variable water consumption that is no longer the case, if the water consumption is variable from day to day, having the rainwater available before or after the consumption will interact with the amount of water consumed in each day and the differences between the approaches will increase. Other parameters such as tank capacity and losses are defined according to users' requests. Typically, for evaluating RWH systems potential in unconstrained scenarios, several tank capacities are tested in order to identify the optimum point. The losses are frequently quantified by a constant first-flush diversion and a runoff coefficient. The runoff coefficient may vary depending on the antecedent number of dry days, roof slope, material, orientation, and rainfall intensity (Farreny et al. 2011b).

Along with the raw data from the simulations, the outputs of the program include the following parameters:

- Full use of rainwater efficiency (FURE) = $\frac{\text{Stored rainwater}}{\text{Total rainwater}}$
- Non-potable water savings (NPWS) = $\frac{\text{Consumed rainwater}}{\text{Non−potable water consumption}}$
- Total water savings (TWS) = $\frac{\text{Consumed rainwater}}{\text{Total water consumption}}$

After assessing the water savings of each building type, it is possible to estimate an average water savings value of each urban zone according to Eq. (1).

$$\text{Non−potable savings}_{\text{zone } j}$$

$$= \frac{\sum \text{Quant.buildings}_i \times \text{Non−potable water savings}_i}{\sum \text{Quant.buildings}_i} \quad (1)$$

The "$\sum$Quant. buildings$_i$" symbolizes the representativeness that a building type has in the zone (in percentage). The "Non − potable savings$_{\text{zone } j}$" is the final output expected for the program, since the goal is to map a certain area, being able to reproduce different RWH efficiencies in a heterogeneous city.

## Application to the city of Lisbon, Portugal

The proposed methodology was applied to the city of Lisbon, Portugal, considering only residential buildings and non-potable water uses in toilet flushing and laundry ("Water consumption" section). The city was divided into seven different zones depending on the buildings characteristics and occupancy ("Urban area" section) and possible spatial variability of the rainfall ("Hydrologic regime" section). Specific RWH evaluation values obtained for each of the most representative building types of each city zone are detailed in the "RWH evaluation" section.

The case study of Lisbon encompasses several information limitations, and the implementation presented herein presents a possible solution. Other options in terms of assumptions and simplifications could have been made and the methodology would still be applicable.

Water consumption

In Portugal, the average daily residential water consumption is 61 L per capita according to the official statistics (Pordata 2015). However, according to a study from the largest water supplier in Portugal, EPAL (Empresa Pública das Águas Livres), the national average daily residential water consumption is 152 L per capita (Associação Portuguesa de Distribuição e Drenagem de Águas 2011). Other sources are consistent with the results from the EPAL study (Amado and Barroso 2013; Matos et al. 2013; Silva et al. 2015). The few and limited studies regarding the residential water consumption end-use pattern in Portugal estimate the proportion of non-potable uses ranging from 25 to 40% of the total water consumption. Given the limitations (namely water end-use distribution) and dispersion (due to the location and context of the households) of the available consumption data in Portugal, a rough water end-use consumption characterization

Fig. 2 Results of the first stage of the inquiries for each end-use (top) and potable and non-potable consumption (bottom)
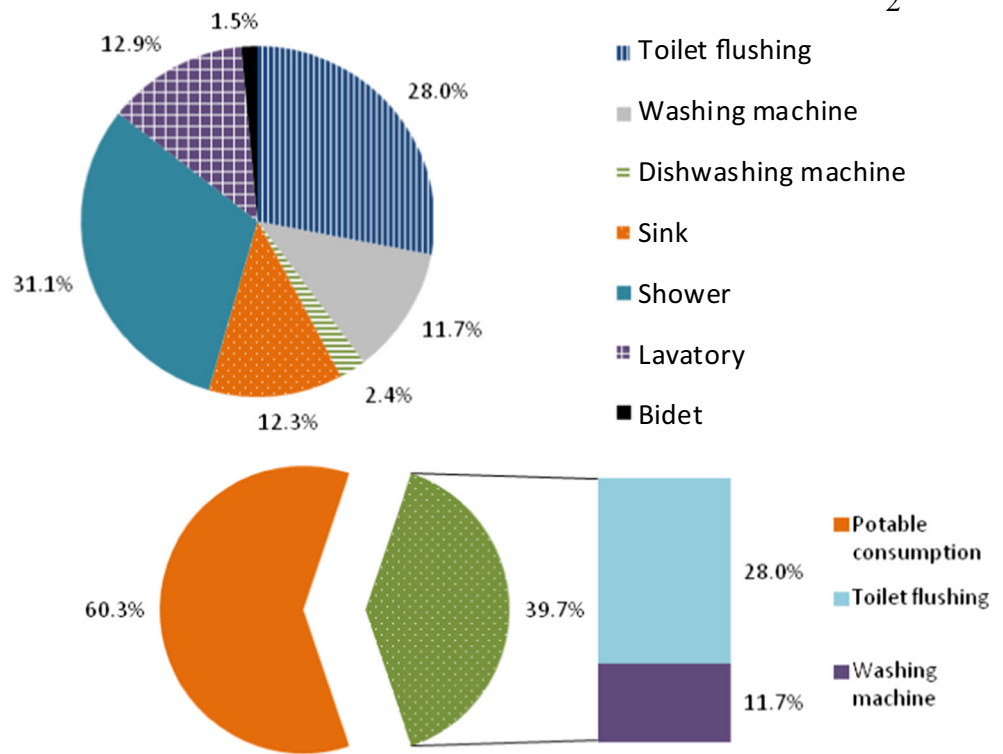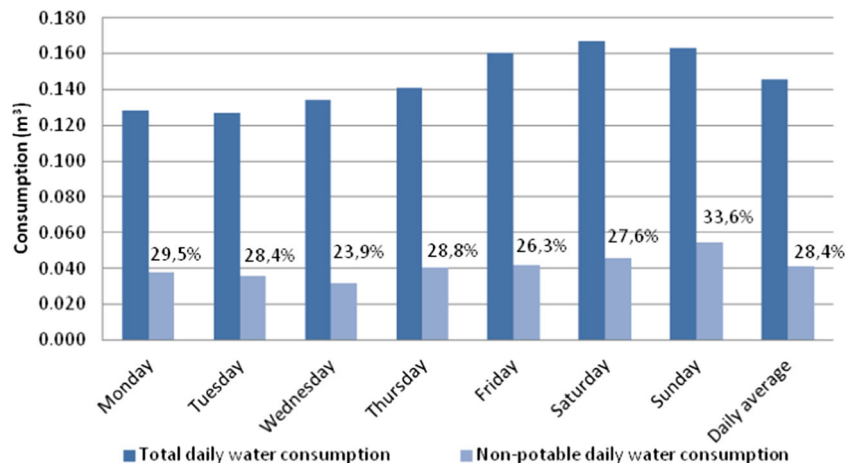

study was done. This was not intended to be statistically significant, but rather to provide an estimation of water consumption end-use pattern in Lisbon with a level of detail compatible with the implementation of the proposed methodology and an indication of the magnitude of its variability.
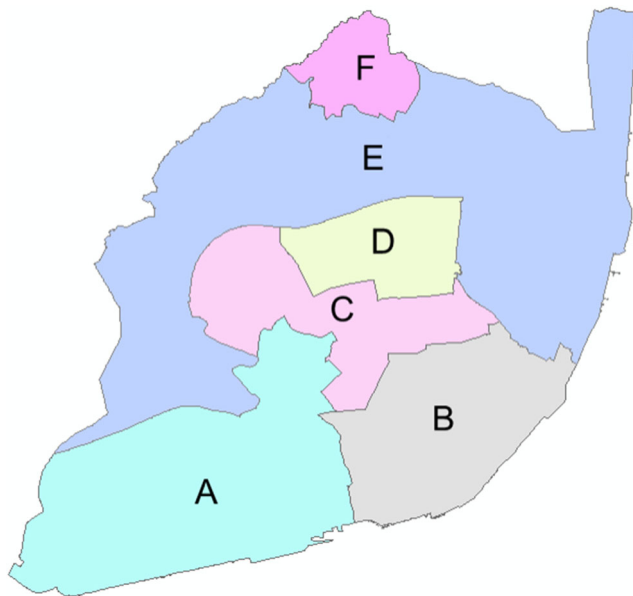
The study was based on inquiries requesting the participants to measure the water consumption by end-use in order to identify the non-potable uses susceptible of being replaced by rainwater. In the first stage, the study focused on a single household in order to obtain the detailed proportion of the water consumption associated with each end-use. The second stage involved the participation of 15 households, where only the total water consumption and non-potable water consumption (washing

machines and toilet flushing) were measured. The household selection covered a wide range of occupancy typologies, including households of families with children of different ages, couples, single people, pensioners, and students.

The first stage of the water consumption characterization study involved a detailed record of the water consumed in each end-use in a family household with three occupants. The record was carried out during 2 weeks, outside vacation or holiday periods. Both washing and laundry machines consumptions were calculated using the manufacturer reported consumption available in the technical specification of the machines models and the number of uses. For the toilet flushing consumption, the unit discharge was determined by

Fig. 3 Water consumption per capita: potable and non-potable daily consumptions

Fig. 4 Definition of the six zones in Lisbon

Table 1 Building characterization in each city zone

Zone	Floors percentage (%)						
	1	2	3	4	5	6	≥ 7
A	*30*	*23*	17	14	8	3	5
B	15	15	*19*	*22*	16	7	6
C	9	7	9	*19*	17	11	*28*
D	8	16	*25*	*21*	11	5	15
E.1	16	*31*	6	6	8	6	27
E.2	14	*30*	11	10	11	5	20
F	*35*	*24*	8	10	7	4	12

GIS with the roof area of all the buildings in the city. The 2011 national census (Instituto Nacional de Estatística 2011) and the Lisbon municipality (Câmara Municipal de Lisboa 2012) provided information regarding the number of buildings organized by groups depending on the number of floors, households, and residents. This enabled identifying six zones in the city of Lisbon with distinct relative proportions of buildings in terms of number of floors and estimating the average number of occupants in each dwelling type. The six zones were designated from A to E (Fig. 4) and each one represents a homogenous area of the city different from the surrounding areas. Since zone E spreads over a large area of the city, it was divided into two zones, E.1 and E.2, to allow considering potential spatial variability of the rainfall. Building characterization in terms of the number of floors is detailed in Table 1 for each zone.

The most representative types of buildings in each zone are in italic in Table 1. Except for zones E.1 and E.2, defined due to potential spatial rainfall variability, it is noticeable that the most representative buildings of any adjacent zones are different in terms of the number of floors.

The municipality of Lisbon website (Câmara Municipal de Lisboa 2012) provides information about the number of residents and families in each civil parish. The average family dimension was estimated for each zone dividing the number

consulting the water meter before and after flushing, then it was multiplied by the number of uses. For the shower and other tap devices, the associated consumption was calculated knowing the unit discharge as well as their average usage time. The unit discharge was determined by measuring the time needed to fill a 5-L tank. The measurements were carried out at three different hours and with and without other appliances in use to account for the variability due to pressure variation. At the end of the day, the estimated water consumption was compared with the value recorded by the water meter and an error of less than 10% was observed in all days. The daily water consumption per capita by each end-use and organized by potable and non-potable water consumption is presented in Fig. 2.

In order to have a general idea of the potential variability of the water consumption end-use distribution, a second stage was conducted, with the participation of two student houses (with two and three occupants) and 13 family houses (ranging from one to four occupants). The evolution of the water consumption per capita during 1 week is presented in Fig. 3.

The results obtained are consistent with Silva et al. (2015), EPAL (Associação Portuguesa de Distribuição e Drenagem de Águas 2011), and Amado and Barroso (2013), namely in terms of the total water consumption and toilet flushing. Therefore, the evaluation of the RWH savings potential in Lisbon computed in this work assumed a total daily water consumption of 0.146 m^3 per capita, of which roughly 28% (0.041 m^3 per capita) is used in non-potable end-uses.

Urban area

The Lisbon Urban Information Center (CIUL—Centro de Informação Urbana de Lisboa) provided the Lisbon plan in

Table 2 Number of residents in each city zone

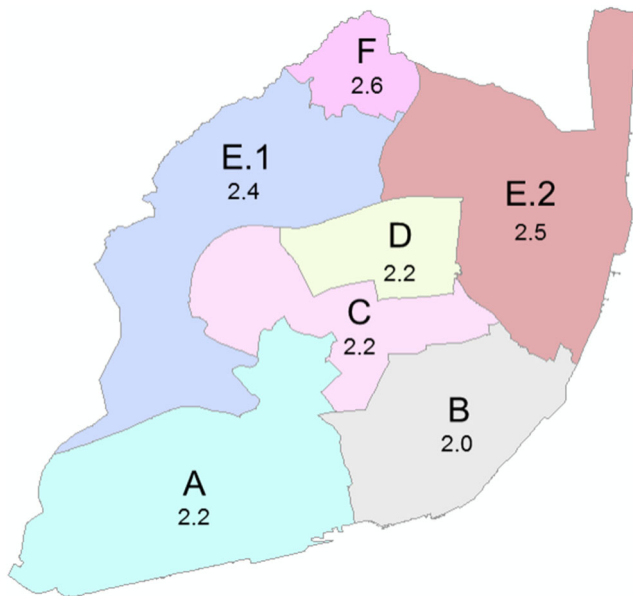| Zone	Residents	Families	Average family dimension
A	103,796	47,308	2.2
B	125,398	61,419	2.0
C	74,799	34,135	2.2
D	31,812	14,403	2.2
E.1	101,808	43,121	2.4
E.2	92,607	36,824	2.5
F	22,480	8684	2.6
Lisbon	552,700	245,894	2.2

Fig. 5 Average family dimension in each zone

of residents by the number of families of all the civil parishes within the zone (Table 2). It is possible to observe that the average family dimension increases from the city center to the city periphery (Fig. 5). This is consistent with the municipality urban rehabilitation initiatives to revitalize and attract young couples to the city center that is mainly inhabited by older people.

Hydrologic regime

Imteaz et al. (2013) observed considerable variability of the RWH systems performance in Melbourne, Australia, due to spatial variability of the rainfall. As such, in order to account for possible spatial variability of the rainfall, the hydrologic regime was characterized separately for each city zone defined on Fig. 5.

Unfortunately, the stations in Lisbon area with daily rainfall data do not have data from the same period of time. Alternatively, to evaluate the influence of the rainfall in the RWH performance, the 53-year daily rainfall series dataset (1950/51 to 2002/03) in a 2° grid covering all Portuguese
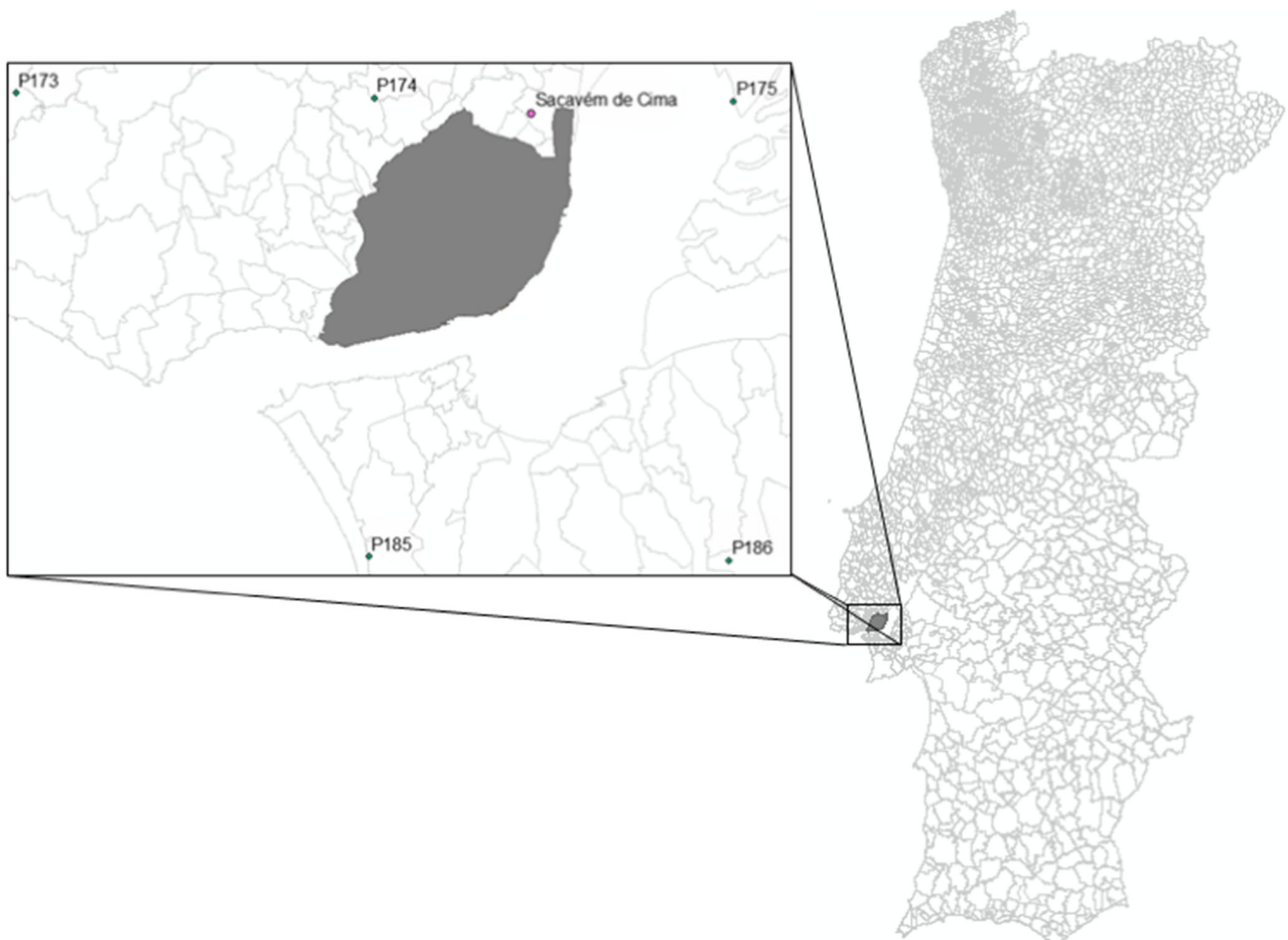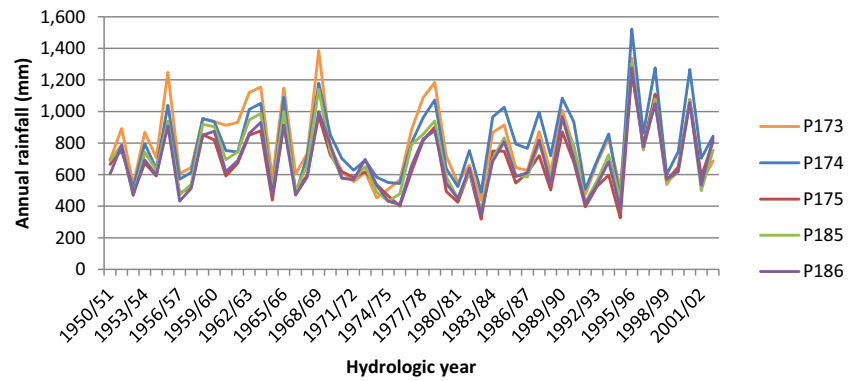

Fig. 6 Location of P173, P174, P175, P185, P186, and the Sacavém de Cima meteorological station

Fig. 7 Annual rainfall in the five grid points of Lisbon from 1950 to 2001

mainland developed by Belo-Pereira et al. (2011) was used. The city of Lisbon is limited by five grid points, namely P173, P174, P175, P185, and P186 (Fig. 6) that were selected to characterize the hydrologic regime of each city zone. Since the dataset was developed resorting to several sources and involved interpolation and gap filling, its consistency was checked against the rainfall records of the Sacavém de Cima meteorological station (Sistema Nacional de Informação de Recursos Hídricos 2003). The length of the rainfall records of the Sacavém de Cima meteorological station extends from 1980/81 to 2001/02 and the correlation between both data sources is of 0.87. Given the high correlation, it was considered that the Belo-Pereira et al. (2011) dataset is a good approximation of the real rainfall regime and is suitable to be used in the present study.

The total annual rainfall between 1950/51 and 2002/03 is presented in Fig. 7, and no statistical evidence of any trend was found. In that way, although some studies show that there will be a variation in the hydrologic regime due to climate changes (e.g., IPCC 2007; Lehner et al. 2006; Frich et al. 2002; Klein Tank et al. 2002), in the present research, these values were considered to represent the hydrologic regime in the near future and no climate changes scenarios are taken into account.

The rainfall in the centroid of each city zone was determined by interpolating from the five grid points using an inverse distance weighting method. Figure 8 shows the boxplot of the monthly rainfall in each of the city zones. It is possible to observe that the amount and variability of the rainfall in each month are similar in all zones. From October to April, the wet period in Portugal, the median monthly rainfall is always between 50 and 100 mm. Between May and September, the dry season, this value is below 50 mm and around 2 mm in July and August. It can be concluded that, in the city of Lisbon, the temporal variability of the rainfall is far more relevant than the spatial variability.

RWH evaluation

Table 3 synthesizes the roof area of the most representative buildings in each city zone and also the respective estimated number of residents. The representative building is intended to represent the most common building typology of each representative building type. As such, it has a specific number of floors, number of apartments, and number of residents. Visits to each zone allowed the identification of the average number of dwellings per floor in each building type. This information

Fig. 8 Rainfall distribution along the year in the different zones of Lisbon
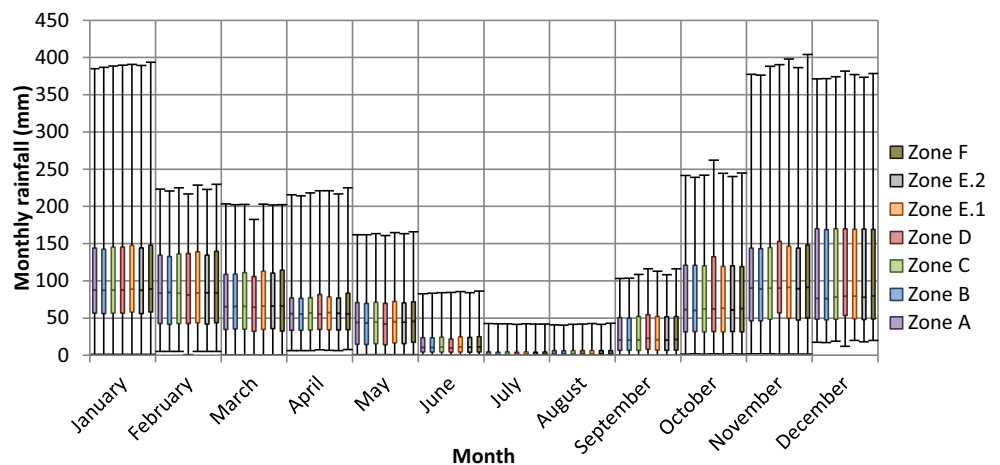
Table 3 Roof area and number of residents of the most representative buildings in each city zone

Zone	Roof area (m²)	Number of floors	Number of dwellings/floor	Number of families	Average family dimension	Estimated number of residents	Number of residents
A	32	1	–	1	2.2	2.2	3
A	159	2	2	4	2.2	8.8	9
B	126	3	2	6	2.0	12	12
B	229	4	2	8	2.0	16	16
C	152	4	2	8	2.2	17.6	18
C	228	8	2	16	2.2	35.2	36
D	127	3	2	6	2.2	13.2	14
D	265	4	2	8	2.2	17.6	18
E.1	25	2	–	1	2.4	2.4	3
E.1	199	9	2	18	2.4	43.2	44
E.2	55	2	–	1	2.5	2.5	3
E.2	421	8	–	23	2.5	57.5	58
F	55	1	–	1	2.6	2.6	3
F	103	2	–	1	2.6	2.6	3

was then used to estimate the total occupancy of the buildings and, consequently, the water demand in each case (Table 4).

The buildings without value for the number of dwellings per floor are houses with only one family, excluding the eight floors' building in zone E.2 which has two dwellings per floor in the ground level and three dwellings per floor in the remaining floors.

RWH system performance was evaluated separately for each building type defined in Tables 3 and 4, through the calculation of three parameters defined in the "Proposed methodology" section: (i) full use of rainwater efficiency, (ii) non-potable water savings, and (iii) total water savings.

The collection area adopted for the RWH system corresponds to the building roof area and was obtained directly from CIUL. Following Farreny et al. (2011b), the relation between the pitched roofs orientation and the wind direction was neglected and a runoff coefficient of 0.80 was adopted. Considering the events with rainfall height over 1 mm, it was observed that only 30% of the total water precipitated occurs in events with a rainfall height up to 5 mm. Therefore, since the large majority of the buildings in Lisbon have pitched clay tile roofs, a 0.80 runoff coefficient can be regarded conservative based on the runoff equations developed by Farreny et al. (2011b). The first flush was assumed to be 1 mm based on the findings by Amin et al. (2013).

Tank capacities of 0.1 m³, 0.5 m³, 3 m³, 5 m³, 7.5 m³, 15 m³, 30 m³, 50 m³, 65 m³, and 75 m³ were tested for all cases.

Results and discussion

The evolution of the RWH system performances with the tank capacity for the most representative buildings of each city zone

is presented in Fig. 9. The results show a similar pattern for all buildings of the different zones, with an increase of the performance with the tank capacity until a maximum is reached. The maximum value for the full use of rainwater efficiency is 70%, which represents the fraction of the total rainwater that is not lost in the collection and first flush. The differences between each building type include the optimum tank capacity, which corresponds to the minimum tank capacity that achieves the maximum RWH systems performance. Each building type also leads to distinct non-potable and total water savings.

Table 4 Water consumption of the most representative buildings in each city zone

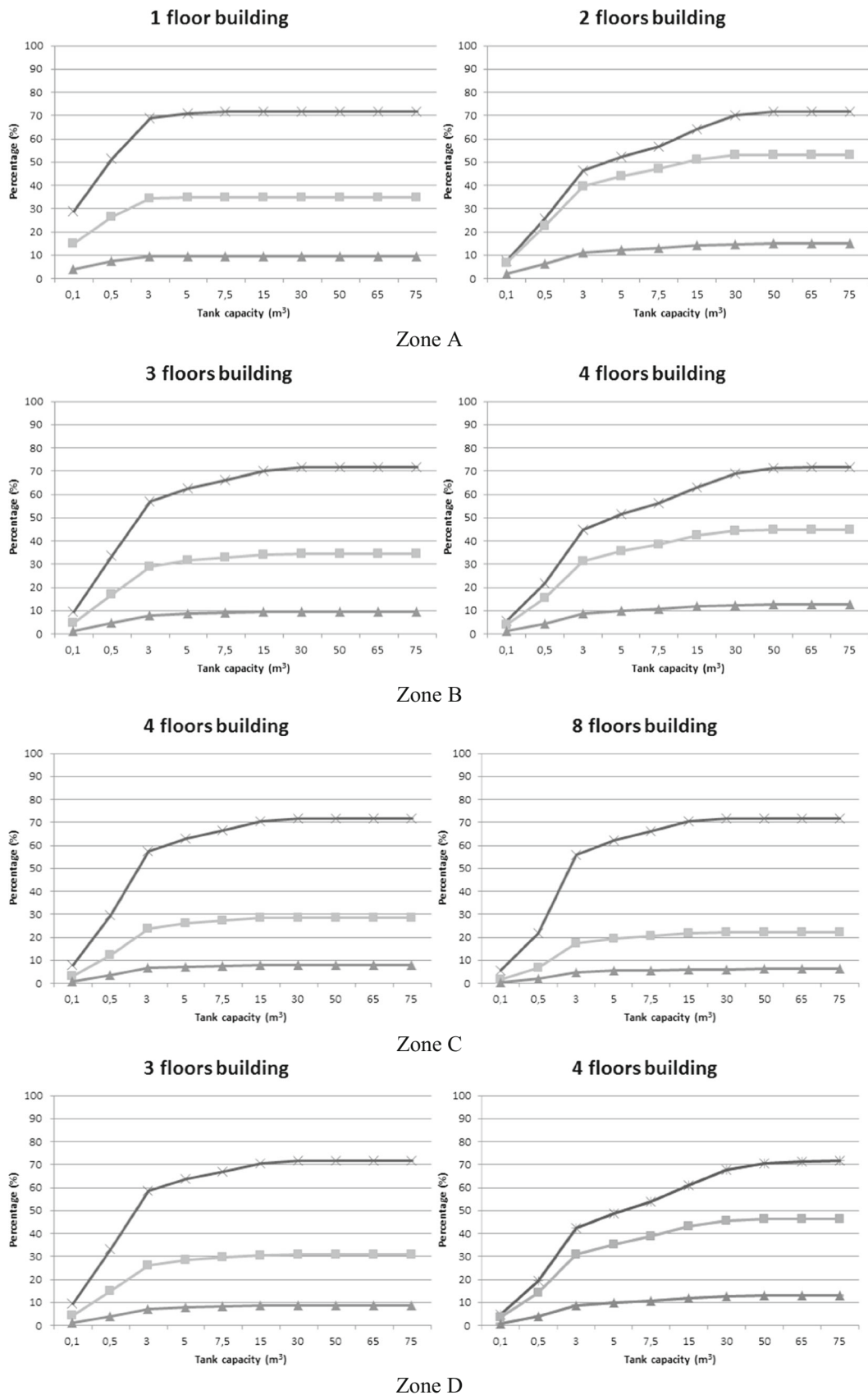| Zone	Number of residents	Average daily water consumption (m³)/building	Average daily non-potable water consumption (m³)/building
A	3	0.438	0.123
A	9	1.314	0.369
B	12	1.752	0.492
B	16	2.336	0.656
C	18	2.628	0.738
C	36	5.256	1.476
D	14	2.044	0.574
D	18	2.628	0.738
E.1	3	0.438	0.123
E.1	44	6.424	1.804
E.2	3	0.438	0.123
E.2	58	8.468	2.378
F	3	0.438	0.123
F	3	0.438	0.123

Fig. 9 RWH system performance for different tank capacities for the most representative buildings of each zone of Lisbon

Zone E.1

Zone E.2

Zone F

—✕—Full use of rainwater efficiency (%)　　—■—Non-potable water savings (%)　　—▲—Total water savings (%)
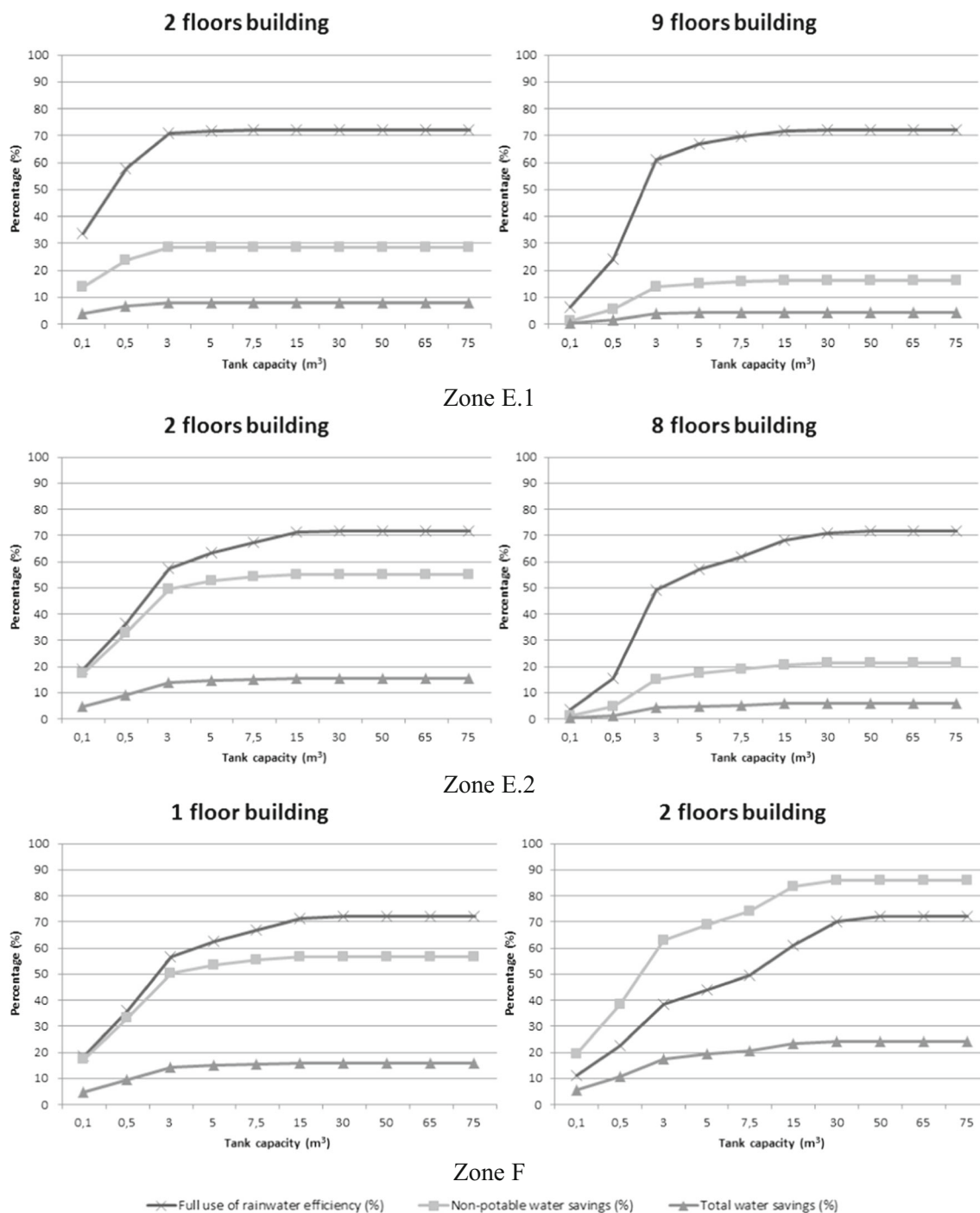
Fig. 9 (continued)

The optimum tank capacity varies from 3 to 50 m³. Equation (2) was developed based on the relation between the roof area, the number of occupants, and the maximum potential performance of the RWH system, to enable an easy approximation of the optimum tank capacity. The maximum potential performance was defined as the tank capacity for which an increase would result in less than 5% improvement on the three parameters used to assess the RWS potential (defined in the "Proposed methodology" section). Equation (2) was determined using the

least squares method and is valid for Lisbon or a case with identical rainfall and water consumption patterns.

$$\text{Tank capacity} = 2.791 + 0.220 \times \text{roof area} - 1045$$
$$\times \text{number of occupants} \qquad (2)$$

The relation obtained reveals what was expected. A larger roof area requires bigger tanks to increase water storage and reduce overflow. A higher number of occupants imply a

Fig. 10 Relation between the roof area per occupant and the maximum potential non-potable water savings in Lisbon
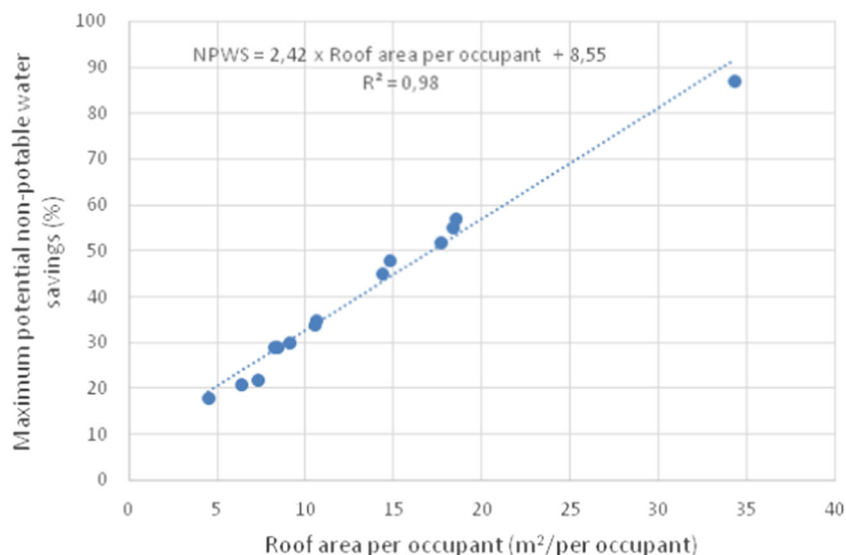
higher consumption, reducing the water storage requirements since the water is consumed faster and the tank becomes available to store more rainwater.

The non-potable water savings vary from less than 20% to nearly 90% depending on the relation between the total non-potable water consumption in the building (number of floors and average family dimension) and rainwater available (collection area and tank capacity). Based on this balance, the buildings with less floors and larger roof areas present the highest non-potable water savings. This unveils the relation between the maximum potential non-potable water savings and the roof area per occupant of the building, and Fig. 10 was developed to enable a quick way of estimating the maximum potential non-potable water savings in Lisbon. Physically, the regression presented in Fig. 11 has a limit of 100%.

Combining Eq. (2) with Fig. 10, we can obtain an approximation of the minimum tank capacity and the corresponding maximum non-potable water savings. It should be taken into consideration that this approximation is based on hydraulic optimization and not financial optimization. From a financial perspective, the optimum tank size may be smaller than the one forecasted with the proposed formulas.

Since there is a relation between the non-potable water consumption and the total water consumption, the potential total water consumption savings corresponds to 28% of the potential non-potable water consumption.

Table 5 resumes the optimum tank capacity chosen for each building type of each city zone and the corresponding non-potable water savings that were used to compute an average value of non-potable water savings for each city zone (Fig. 11). The non-potable water savings in each zone only consider the buildings with more representativeness. These values were calculated applying Eq. (1), presented in the "Proposed methodology" section, based on the non-potable water savings obtained in each building type per zone. As these values are a

weighted average of the values obtained per building, they are lower than the maximums shown in Table 5.

The results obtained encompass a high level of uncertainty considering the number of assumptions and simplifications that had to be done due to the information limitations (e.g., buildings characteristics—number of floors, number of apartments per floor, number of residents per apartment, and the corresponding roof area of each building had to be approximated; water consumption and end-use patterns—variability of the total water consumption and end-use distribution between households, variability of the total water consumption, and end-use distribution over time were not accounted for). Bearing this in mind, it is possible to state that the non-potable water savings obtained in this analysis should be taken into account in new buildings because in several cases, almost
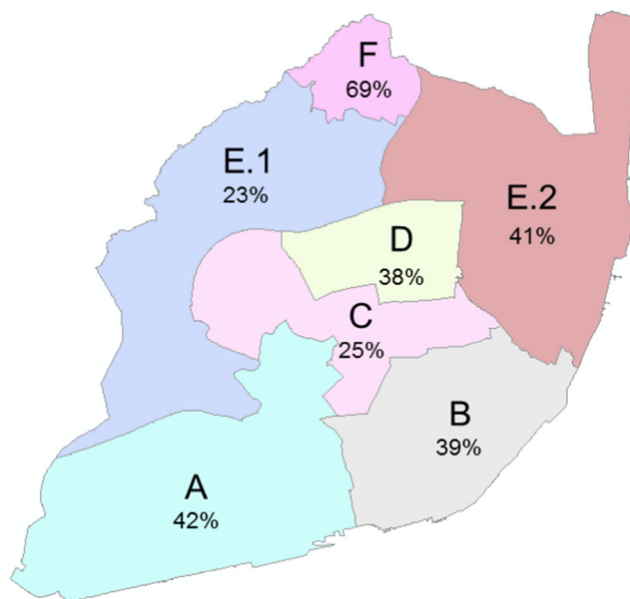
Fig. 11 Average non-potable savings in each city zone

Table 5 Non-potable water savings per building

Zone	Num. floors	Tank capacity (m^3)	Non-potable water savings (%)
A	1	3	34
A	2	30	53
B	3	15	34
B	4	30	44
C	4	15	29
C	8	15	22
D	3	15	31
D	4	50	46
E.1	2	3	29
E.1	9	7.5	16
E.2	2	7.5	54
E.2	8	30	26
F	1	15	57
F	2	30	86

50% of the non-potable water consumption can be replaced by rainwater. Despite the uncertainty in the results, the order of magnitude of the non-potable water consumption that can be replaced by rainwater indicates it as a promising option, at least in terms of potable water savings.

Conclusions

This paper presents a methodology to evaluate the potential of rainwater harvesting in heterogeneous urban areas by taking into consideration differences in the rainfall regime, building characteristics, occupancy, and water use pattern. The practical application of the methodology was demonstrated through its application to the city of Lisbon.

The potential reduction in potable water consumption by using rainwater was evaluated for Lisbon using the proposed methodology and limiting the scope to residential buildings. Since the rainfall regime was found to be roughly uniform throughout the city of Lisbon, the definition of zones with possible different potential performance of the RWH system was conducted based on the building characteristics and occupancy.

In none of the zones was it possible to collect all the rainwater required for the non-potable consumption, being 86% the maximum value obtained. This implies that, after discounting the losses and first flush, the rainwater collected at the buildings roofs is not sufficient to meet the non-potable water demand. When calculating the weighted potential non-potable water savings, this value reduces to 69%. Nevertheless, there is the potential for at least half of the non-potable water needs to be replaced by rainwater, which is encouraging for a large scale installation of a RWH system in the city.

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