Potential reduction in potable water consumption by reusing rainwater in urban centers

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Abstract

Rainwater harvesting systems (RWHS) have been used in many countries as an alternative to potable water, in order to minimize water availability problems. This paper evaluates the amount of water that is consumed in a house and its non-potable uses, like washing machine and toilet flushing. In the city perspective, the uses considered were street washing and gardening. Two analyses were made, one at the city point of view and another at the building level. In the first, the conclusion was that in almost every area, the collected water is enough for the housing uses, and there is still remaining water for the outside ones. At the building level, the savings obtained were not that high, being 0,86 the maximum value, in comparison with the non-potable consumption. This study was made in the city of Lisbon, although, the developed methodology can be used in other cities or areas.

Key-words: Rainwater harvesting systems, water consumption, non-potable uses, precipitation regime, Lisbon

1. Introduction

Due to the climatic changes observed around the world [1] [2] and the fast rate of population growth [3], water has become a resource at risk and some countries are already facing some problems related to water scarcity or will have them in a near future [4] [5].

The amount of water consumed everyday per capita, is different around the globe, and generally is higher in developed countries. For instance, in Spain the consumption is 320 L per capita per day while in Kenya it is only 46 L per capita per day [6]. Different studies also showed that in a house, the water consumed in non-potable uses is around 35% of the total water consumption [7] [8] [9] [5] [10]. In the scope of water efficiency, rainwater has been considered as an alternative source for non-potable water uses and several studies were done in order to know the potential water savings when installing a RWHS. In Brazil, for example, in the southeastern region the results obtained were between 29% and 42% [11], while in the south the value was 69% [12]. This indicates that a specific analysis should be performed in the area where the system is to be installed, in order to achieve more reliable results.

The main objective of this paper is to evaluate the city of Lisbon potential for using rainwater for non-potable uses and comparing the results of performing the analysis at a city level and at a building level. The influence of the precipitation variability is also evaluated at a city level.

2. Methodology

The methodology developed in this work (Figure 1) is based in three characterizations: i) water consumption, ii) urban area and iii) precipitation regime.

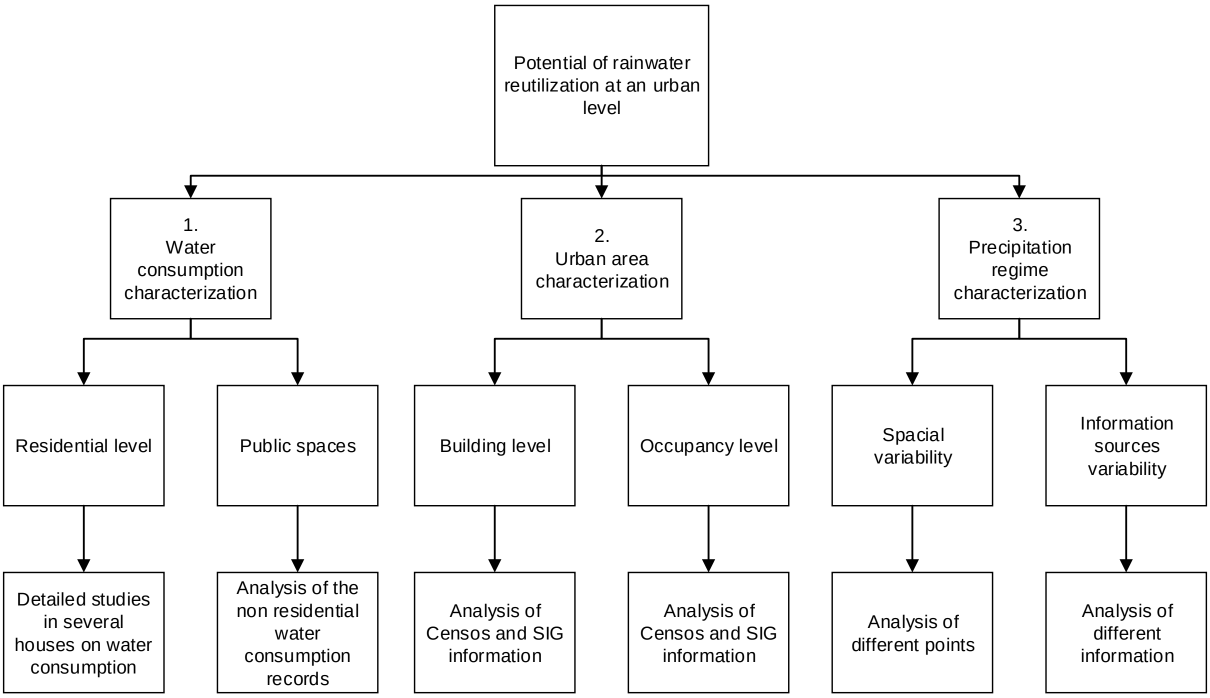

Figure 1 – Flowchart of the developed methodology.

The water consumption characterization was done through inquiries with the participation of residents. The participants were requested to measure the water consumption by end-use in order to identify the non-potable uses susceptible of being replaced by rainwater. In a first stage, the study focused only in one familiar house, in order to obtain the detailed proportion of the water consumption associated to each end-use. The second stage involved the participation of 15 houses where only the total water consumption and the non-potable water consumption (washing machines and toilet flushing) were measured. Although the more direct application of a RWHS is in a house, it can be applied as well at an urban level, namely for street washing and gardens irrigation. The water consumption in these end-uses at an urban level were obtained from the municipality of Lisbon records (Câmara Municipal de Lisboa – CML) [13].

Through information available in the 2011 Censos [14] it was possible to define different areas in Lisbon, according to the most typical number of floors of the buildings. The Centro de Informação Urbana de Lisboa (CIUL) provided the Lisbon plot plan, with the roof area of the all buildings in the city. Then, with the information of the total number of residents and families in each areas, the average number of people per house in the area was estimated [15].

In the first stage, the precipitation regime was characterized with data from SNIRH [16], Sacavém de Cima station, which had values from 1980/81 to 2001/02. Due to its reduced temporal representativeness, a study available in IPMA was also consulted [17]. This study provides a series of 53 years of daily precipitation records in a 2º grid covering all Portuguese mainland. For characterizing the precipitation regime in the city of Lisbon, 5 points were selected, namely P173, P174, P175, P185 and P186. A comparison between SNIRH and IPMA values was made, obtaining a correlation of 0,87, which means the study of IPMA is close to the reality, so its values were used.

The spatial analysis of the precipitation at the city level was performed using the ArcGis software, more specifically the Geostatistical Analyst tool, with the Geostatistical Wizard – Inverse Distance Weighting option. In this way, having the information about the five points around Lisbon, the precipitation in each area of Lisbon was calculated.

In a more detailed analysis, the particular building perspective, daily data was used. It was not possible to use the ArcGis program for this study, so an inverse distance weighting equation was determined to calculate the daily precipitation in each area.

The evaluation of the RWHS potential for Lisbon was made at the city level, considering the annual precipitation of each area and the respective total area of buildings, and at the building level perspective, considering the daily precipitation and adopting buildings with representativeness in each area.

3. Lisbon Database

From the water consumption characterization, it was estimated an average per capita daily water consumption of 0,146 m^3, from which around 28% can be replaced by rainwater (0,041 m^3). Consulting the Matriz de Lisboa 2014 [13], the CML used 4 400 x 10^3 m^3 for gardening and 1 700 x 10^3 m^3 for street washing, which is around 75% of all the yearly water consumption made by CML.

According to the buildings number of floors in Lisbon, six areas were defined (Figure 2).

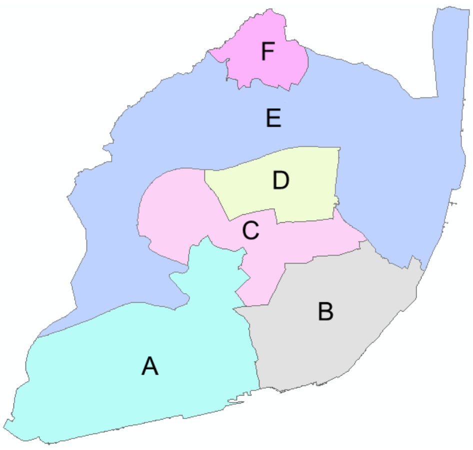

Figure 2 – Definition of the six areas in Lisbon.

As zone E was too big, it was divided into two areas, E.1 and E.2. The proportion of buildings according to the number of floors in each area is detailed in Table 1.

Table 1 – Characterization of the areas according to the number of floors.

Zone	1 floor	2 floors	3 floors	4 floors	5 floors	6 floors	7 or more floors
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 %

In order to calculate the water needs in each defined area, a study about the occupancy was made, which is summarized in Table 2 and represented in Figure 3.

Table 2 – Number of residents in each area.

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	8 684	2,6
Lisbon	552 700	245 894	2,2

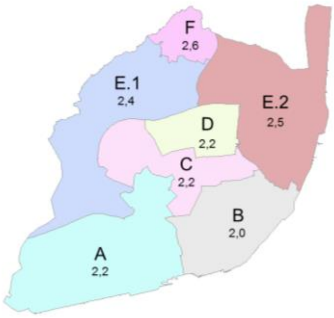

Figure 3 – Spatial representation of the average family dimension.

Once the seven different urban areas in the city of Lisbon were defined, the precipitation regime characterization was performed. Figure 4 shows the precipitation distribution along the year in each of the defined areas and it was observed that the total amount of rain is practically the same in all zones, for each month. From October to April, wet period, the median is always between 50 and 100 mm. Between May and September this value is below 50 mm, and in July and August, it is about 2 mm, being these two considered the dry months. It was concluded that, in the city of Lisbon, the temporal variability of the precipitation is far more relevant than the spatial variability.

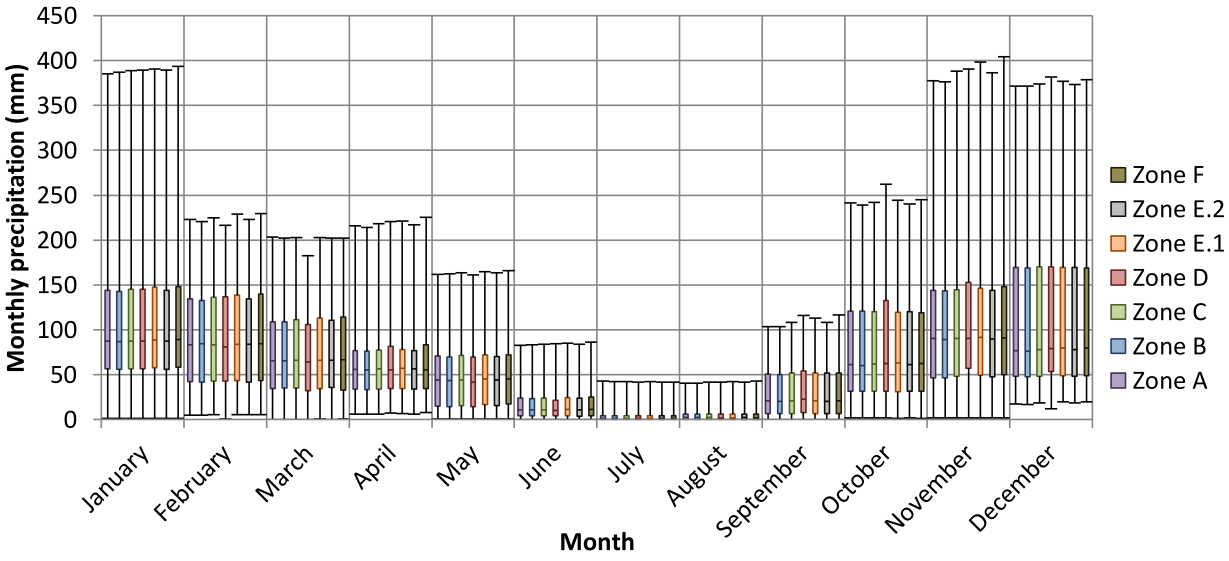

Figure 4 – Precipitation distribution along the year in the different areas of Lisbon.

4. Results and discussion

4.1. City level analysis

The city level analysis was performed using the information depicted in Table 3, and the 53 years record of annual precipitation [17]. This analysis considered all the rainwater and building area in the city of Lisbon.

Table 3 – Information for the city level analysis.

Zone	Building area (m^2)	Residents	Average daily consumption (m^3)/person	Average annual consumption (m^3)/person	Average annual consumption (m^3)/zone
A	3 759 745	103 796	0,041	15,0	1 553 307
B	4 258 210	125 398	0,041	15,0	1 876 581
C	2 325 885	74 799	0,041	15,0	1 119 367
D	1 250 356	31 812	0,041	15,0	476 067
E.1	2 525 321	101 808	0,041	15,0	1 523 557
E.2	2 846 148	92 607	0,041	15,0	1 385 864
F	505 670	22 480	0,041	15,0	336 413

Equation (4.1) was used to calculate the potential of savings in a house (Residential savings – RS). The collected rainwater is the result of multiplying the building area (m^2) by the annual precipitation in the area (mm x 10^{-3}). The value 0,8 is the runoff coefficient, that takes into account several losses that may occur during rainwater harvesting. These losses can be due to the material texture of the collecting area, evaporation or absorption by the collecting surface, losses in the gutter pipe or tank, inefficiencies in the collecting process and water that is not used due to the first flush device [4] [18]. This first flush device diverges the initial portion of rainwater in the beginning of a rainfall event, because it tends to transport pollutants that accumulate in the collecting surface.

$$RS = \frac{Collected\ rainwater \times 0{,}8\ (m^3)}{Average\ annual\ consumption\ (m^3)/zone} \tag{4.1}$$

Figure 5 displays the histograms with the number of years, by intervals of potential savings in the different zones. Practically every area has many years where the potential savings are equal or higher than 1, which means that the collected rainwater is enough or exceeds the non-potable uses. Because there is more water than needed for the residential uses, it can also be used for gardening and street washing. In Matriz da Água de Lisboa 2014 the water consumption for these uses is for the entire city. The amount in each area was estimated has a proportion of the total based on the corresponding public area, which was calculated from the difference between the total area and the building area of each region.

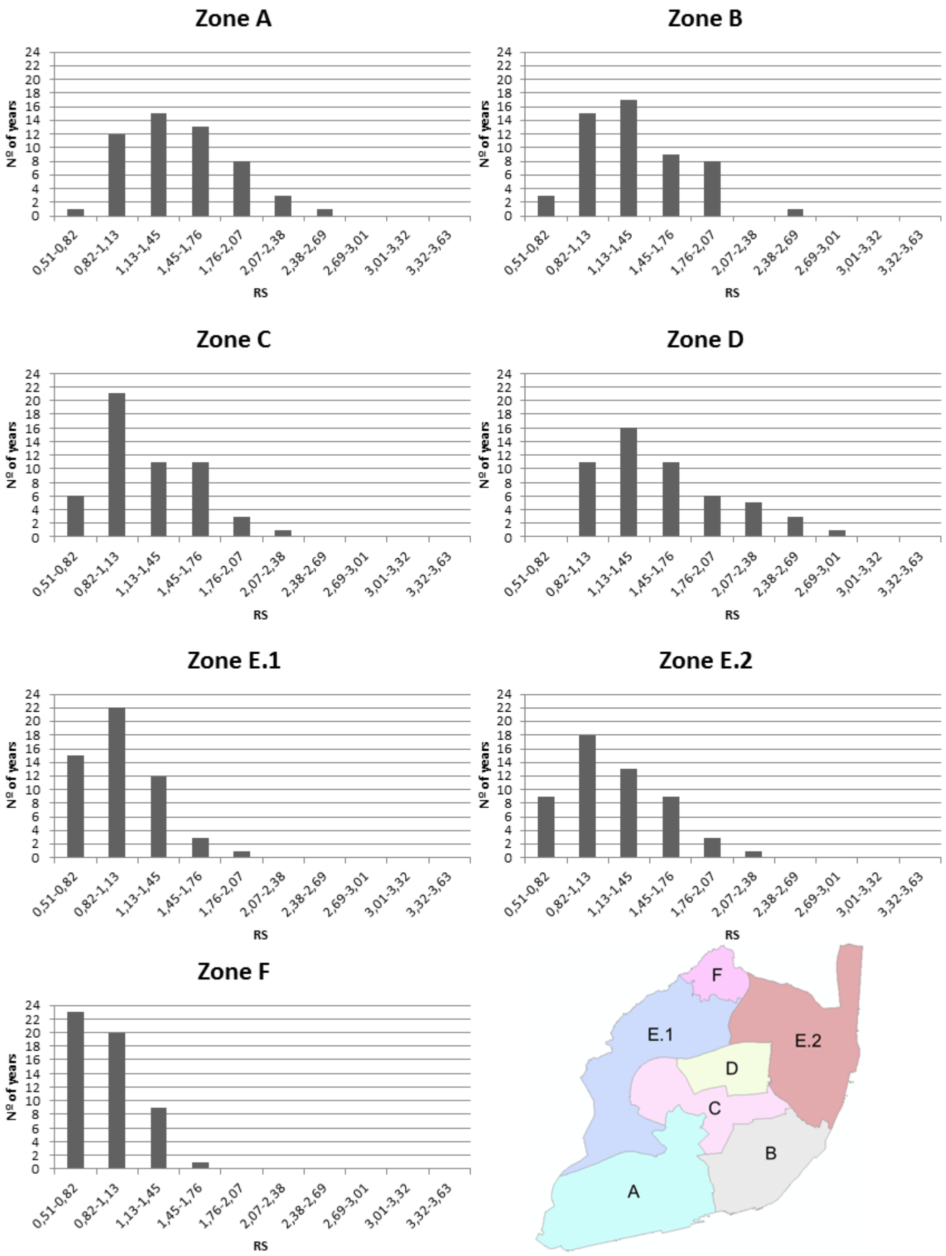

Figure 5 – Residential savings in the different zones.

Then, it was calculated de percentage of the public area in relation to the all city, and this percentage was multiplied by the CML reported consumption for street washing and gardening (Table 4).

Table 4 – CML consumption distribution in each zone.

Zone	Total area (ha)	Building area (ha)	Public area (ha)	% Zone	CML consumption (m^3)
A	2 028	376	1 652	23,9	1 459 148,5
B	1 138	426	712	10,3	629 179,7
C	903	233	670	9,7	592 354,6
D	534	125	409	5,9	361 409,1
E.1	1 829	253	1 576	22,8	1 392 411,3
E.2	1 885	285	1 600	23,2	1 413 764,6
F	336	51	285	4,1	251 732,2
Lisbon	8 653	1 747	6 906	100	6 100 000,0

Based on these values it was possible to estimate the urban potential savings (US) using the equation (4.2). The histograms with the number of years, by intervals of potential savings, for the CML consumption in the different zones are presented in Figure 6.

$$US = \frac{Remainder\ water\ in\ houses/zone\ (m^3)}{CML\ consumption\ (m^3)/zone} \tag{4.2}$$

As it is possible to observe from Figure 6, the collected water can, almost every time, replace at least half of the potable water consumption. Therefore, in the first analysis, the conclusion was that almost every time the collected water is enough for the housing uses, and there is still remaining water for the outside ones.

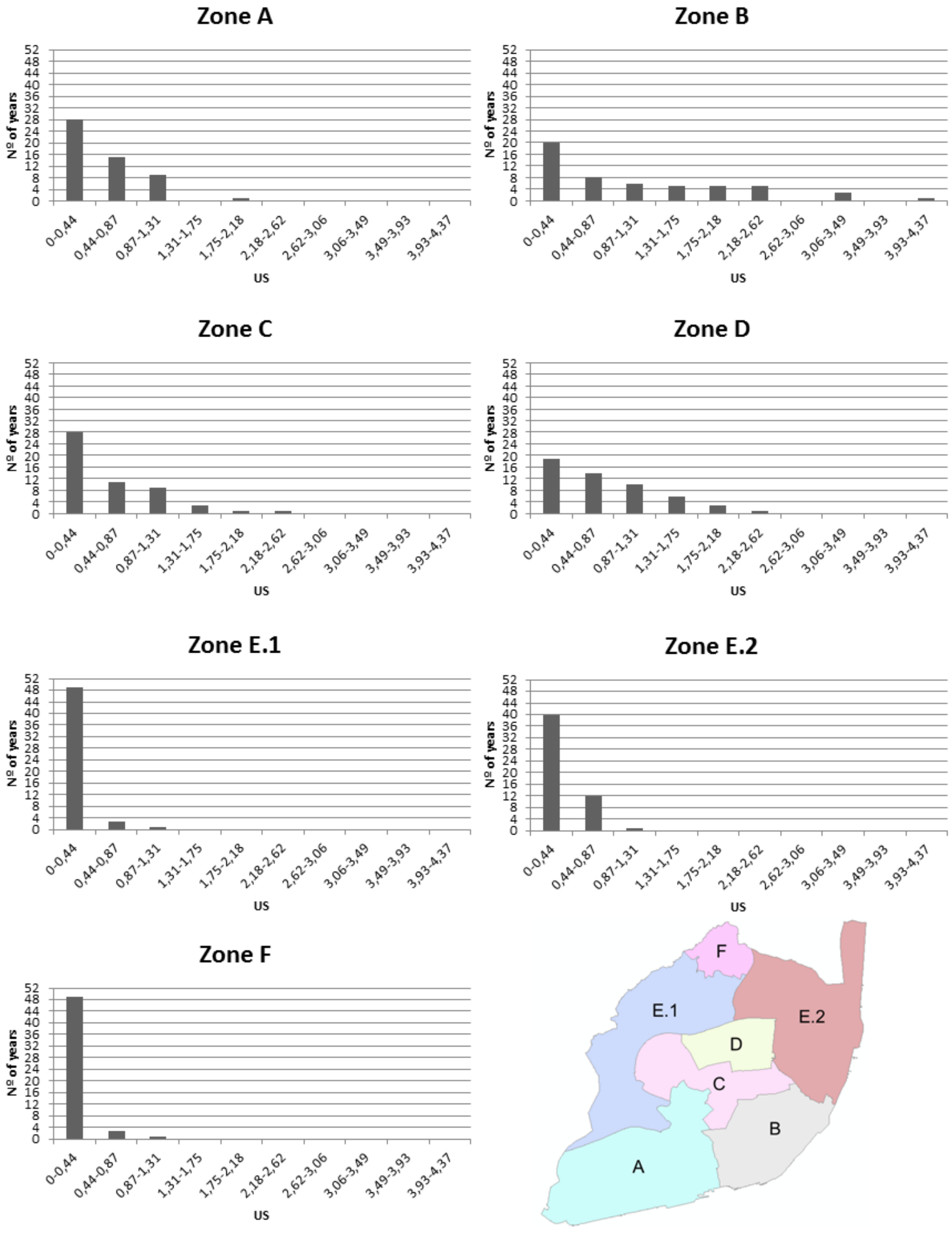

Figure 6 – Urban savings in the different zones.

It was also studied the influence of the spatial variability of the precipitation in the RS, either if the precipitation is considered equal in all Lisbon, or if it is different in each zone, as presented before. The conclusion was that the differences are minimum, being the maximum value of error between the two cases 5,5%. The influence of the consumption pattern was also analyzed. If instead of the average daily consumption, the correspondent to the percentile 25 was considered, the RS would increase 18%. On the other hand, if it was the percentile 75 to be considered, the RS would decrease 5,8%.

Figure 7 presents the value for RS in the different zones considering the average annual precipitation of the 53 years in the study.

Average values should be used with caution. In Figure 7, only zone F has a RS lower than 1. However, in every zone there are years where the RS is lower than 1, but this is not perceptible when using average values.

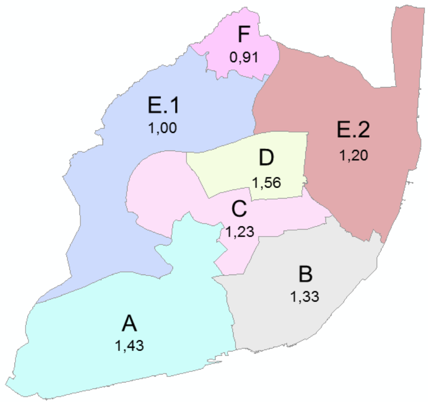

Figure 7 – Residential savings in the different zones considering the average annual precipitation.

4.2. Building level analysis

For this analysis, it was important to define the buildings with more representativeness in each area, being this information presented in Table 5.

Table 5 – Percentage of buildings with 1 to 7 or more floors, in each zone.

Zone	1 floor	2 floors	3 floors	4 floors	5 floors	6 floors	7 or more floors
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 %

It was also important to know the number of dwellings per floor. Through visits in each area, it was possible to define, in the buildings with more representativeness, the number of dwellings per floor. The corresponding roof area, which represents the collecting surface, was provided by CIUL. Also considering the information in Table 2, the number of residents in each building was calculated (Table 6) and consequently, the associated average water consumption, which is shown in Table 7.

Table 6 – Building area and number of residents.

Zone	Building area (m^2)	Number of floors	Number of dwellings/floor	Number of families	Average family dimension	Estimated number of residents	Number of residents
A	31,68	1	-	1	2,2	2,2	3
A	158,60	2	2	4	2,2	8,8	9
B	125,90	3	2	6	2,0	12	12
B	229,35	4	2	8	2,0	16	16
C	151,63	4	2	8	2,2	17,6	18
C	227,90	8	2	16	2,2	35,2	36
D	127,19	3	2	6	2,2	13,2	14
D	264,97	4	2	8	2,2	17,6	18
E.1	24,76	2	-	1	2,4	2,4	3
E.1	198,55	9	2	18	2,4	43,2	44
E.2	55,00	2	-	1	2,5	2,5	3
E.2	420,68	8	-	23	2,5	57,5	58
F	55,48	1	-	1	2,6	2,6	3
F	102,81	2	-	1	2,6	2,6	3

Note: The buildings without value for the number of dwellings per floor are housings with only one family, excluding the 8 floors' building in zone E.2 which has 2 dwellings per floor in the ground level and 3 dwellings per floor in the remaining.

Table 7 – Water consumption per building.

Zone	Number of residents	Average daily water consumption (m^3)/building	Average daily non-potable water consumption (m^3)/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

For this analysis, the precipitation values were on a daily scale. To calculate the volume of the tank that best fits each building and the associated potential savings, comparing to the non-potable consumption, a program was used [19]. The volumes tested were: 0,1 m^3, 0,5 m^3, 3 m^3, 5 m^3, 7,5 m^3, 15 m^3, 30 m^3, 50 m^3, 65 m^3 and 75 m^3. Table 8 presents the tank capacity chosen for each building and the potential non-potable savings obtained.

Table 8 – Potential non-potable savings per building.

Zone	Num. floors	Building area (m^2)	Num. resid.	Average daily water consump. (m^3)/build.	Average daily non-potable water consump. (m^3)/build.	Tank capacity (m^3)	Potential non-potable savings (-)
A	1	31,68	3	0,438	0,123	3	0,34
A	2	158,60	9	1,314	0,369	30	0,53
B	3	125,90	12	1,752	0,492	15	0,34
B	4	229,35	16	2,336	0,656	30	0,44
C	4	151,63	18	2,628	0,738	15	0,29
C	8	227,90	36	5,256	1,476	15	0,22
D	3	127,19	14	2,044	0,574	15	0,31
D	4	264,97	18	2,628	0,738	50	0,46
E.1	2	24,76	3	0,438	0,123	3	0,29
E.1	9	198,55	44	6,424	1,804	7,5	0,16
E.2	2	55,00	3	0,438	0,123	7,5	0,54
E.2	8	360,00	58	8,468	2,378	30	0,26
F	1	55,48	3	0,438	0,123	15	0,57
F	2	102,81	3	0,438	0,123	30	0,86

In this analysis, the maximum value of savings was 0,86 in comparison with the non-potable consumption, which is lower than the average value obtained in the first analysis.

With the values in Table 8, it is possible to calculate the potential non-potable savings for each area. The weighted potential non-potable savings is calculated according to (4.3):

$$Non\ potable\ savings_{weighted} = \frac{\sum Quant.buildings_i \times \text{Non potable savings}}{\sum Quant.buildings_i} \quad (4.3)$$

The variable "Quant. buildings$_i$" corresponds to the percentage of building types, from 1 to 7 or more floors, in each area of the study, as presented in Table 5. The results are presented in Figure 8.

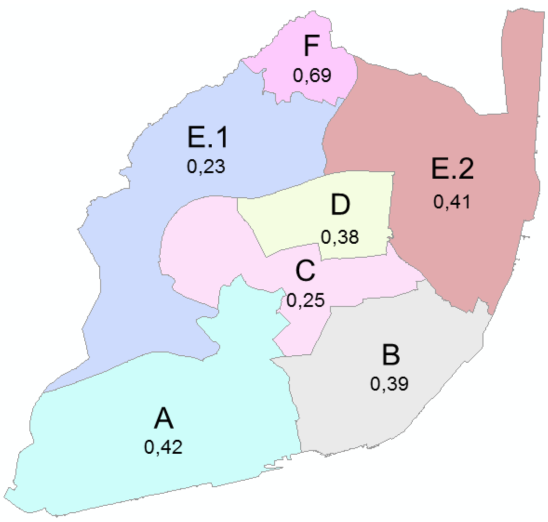

Figure 8 – Non-potable savings in each zona, based on the buildings with more representativeness.

Figure 8 shows the non-potable savings in each zone, only considering the buildings with more representativeness. These values are a weighted average of the values obtained per building, and so, they are lower than the maximums shown in Table 8. Zone F is still the one with the higher non-potable savings, but instead of 0,86, this value is now 0,69.

5. Conclusion

This paper evaluates the potential reduction in potable water consumption by reusing rainwater in the city of Lisbon, having made two different analyses: city level and the particular building perspective.

At the city level, comparing the spatial variability of precipitation, in other words, assuming one value for each zone or one value to the all city, the differences obtained were minimum, 5,5%. The variation in the consumption pattern was also analyzed, and the conclusions were that the RS would be more affected if the consumption, instead of the daily average, was the one correspondent to the percentile 25, in which the savings would increase 18%. If the scenario was the percentile 75, the savings would decrease 5,8%. Finally, in almost every zone it is possible to collect enough water to the non-potable uses in a house and there is still remaining water for uses like gardening and street washing.

At a building level, the savings were significantly lower than in the city level analysis. In none of the cases was possible to collect all the water required for the non-potable uses, being 0,86 the maximum value obtained, when comparing with the non-potable consumption.

This study allowed concluding that the city of Lisbon presents a significant potential in savings of potable water by reusing rainwater.

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