Simplified method for rainwater harvesting tank sizing using long day-resolution rainfall time series

Méthode simplifiée de dimensionnement des réservoirs pour la réutilisation des eaux pluviales à partir de séries de pluies prolongées à résolution journalière

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RÉSUMÉ

La présente étude a pour objectif de développer une méthode simplifiée pour le dimensionnement de réservoirs pour la réutilisation des eaux de pluies, en utilisant des séries prolongées de pluie à résolution journalière. La méthode développée considère aussi des bassins versants hétérogènes et des débits d'eau nécessaires pour la réutilisation. De manière à estimer la capacité volumétrique des bassins, il est proposé d'utiliser la probabilité nécessaire pour satisfaire le volume d'eau requis, ainsi que le pas de temps le plus probable nécessaire et leurs respectives variabilités. Cette méthode a été appliquée à un cas d'étude particulier (dimensionnement du bassin de réutilisation des eaux pluviales du campus de l'université Pontificia Universidad Javeriana –PUJ– à Bogotá), avec 73 années de données de pluie à résolution journalière (entre 1936 et 2010, sans les années 1969 et 1988 par manque de données). La méthode a été appliquée pour des différentes périodes de la base de données en obtenant les résultats suivants : (i) pour la série de pluie complète – 76 années : 395 m^3 (28 jours, probabilité : 78%); (ii) pour les dix dernières années : 494 m^3 (35 jours, probabilité : 89%); (iii) pour les cinq dernières années : 346 m^3 (25 jours, probabilité : 84%); (iv) pour la dernière année : 155-198 m^3 (11-14 jours, probabilité : 89-90%).

ABSTRACT

This work aims to develop a simplified method for rainwater harvesting tank sizing using long day-resolution rainfall time series. The developed method, also considers heterogeneous contributing catchments and water demand flow rates. In order to estimate the tank capacities it is proposed to take into account the probability to supply the water demand, as well as the most probable time step needed and their respective variabilities. This method was applied to a specific case study (campus of the Pontificia Universidad Javeriana, Bogota –PUJ– university rainwater harvesting tank sizing), with 73 years of daily-resolution rainfall information (between 1936 and 2010, without years 1969 and 1988 with no data). The method was applied using different time periods from data-set and the results obtained are: (i) for the whole data series - 76 years: 395 m^3 (28 days, probability: 78%); (ii) for the last ten years: 494 m^3 (35 days, probability: 89%); (iii) for the last five years: 346 m^3 (25 days, probability: 84%); (iv) for the last year: 155-198 m^3 (11-14 days, probability: 89-90%).

KEYWORDS

Rainwater harvesting system, Rainwater tank, Tank sizing, Time series, Urban water management, Water demand

1 INTRODUCTION

Nowadays it exists an increasing attention on the rainwater harvesting (RWH) as an alternative source of water (Hatt *et al.*, 2006) for non-potable uses (Fewkes, 1999; Herrmann and Schmida, 1999; Appan, 2000; Coombes *et al.*, 2000; Li and Gong, 2002; Handia *et al.*, 2003; Marinoski *et al.*, 2004; US EPA, 2004; Coombes and Mitchell, 2006; Wong, 2006; Ghisi *et al.*, 2009), which is aditionnaly recognized as one of the specific adaptation strategies that the water sector should implement to deal with climate changes (Pandey *et al.*, 2003; Muller, 2007; Mukheibir, 2008; Aladenola and Adeboye, 2010; Kahinda *et al.*, 2010; Rozos *et al.*, 2010; Boelee *et al.*, 2012). This technique have been successfully implemented as alternative water source in some countries such as China (Li *et al.*, 2000), South Korea (Song *et al.*, 2003), Malaysia (Lariyah *et al.*, 2011), Australia (Duan *et al.*, 2008) and Brazil (Ghisi *et al.*, 2009). Typically, today's questions which have to be answered through research and engineering studies about the use of RWH are (Mitchell *et al.*, 2008): "How much stormwater can be harvested? How reliable is this supply source? (Farreny *et al.*, 2011) and How large a storage is required?"

One of the most widely studied options for saving the rainwater harvested is the use of rainwater tanks. Typically, the studies about rainwater tanks focus on the design optimization (Imteaz *et al.*, 2011; Seo *et al.*, 2011; Imteaz *et al.*, 2012; Campisano and Modica, 2012) and the performance of rainwater tanks considering the annual rainfall at a specific geographic location, homogeneous catchment area (only one type of surface – e.g. roofs – are considered) and water demand patterns (Fewkes, 1999; Jenkins, 2007; Khastagir and Jayasuriya, 2010). Other studies focus on the effect that produces the use of rainwater tanks on the sewer system design (Vaes and Berlamont, 2001). More recently, Youn *et al.* (2012) developed a methodology that establishes a probabilistic relationship between the storage capacity and the deficit rate of a rainwater harvesting system considering climate change.

In Colombia some researches about RWH have been developed for potable (Sánchez and Caicedo, 2003) and non-potable uses (Ballén *et al.*, 2006; Lara-Borrero *et al.*, 2007; Ramírez, 2009; Castañeda, 2010; Torres *et al.*, 2011a). Ballén *et al.* (2006) concluded that the feasibility of RWH depends on five variables: Precipitation of the area, house cover's area, water availability to supply, price per cubic meter of water and investment needed for the systems' construction and maintenance. On the other hand, in Colombia some sizing methodologies based on maximum intensities, and hence more adapted to flooding control, have been developed and implemented (Galarza and Garzón, 2005; Velez *et al.*, 2004; Navarro and Saldarriaga, 2008; Mora *et al.*, 2011; Torres *et al.*, 2012b). This paper presents a tank sizing simplified methodology specifically for RWH purposes and adapted to developing countries (low and medium hydrological data resolution) for non-potable uses of rainwater runoff from heterogeneous catchments.

2 MATERIALS

The study case is the Pontificia Universidad Javeriana Bogotá (PUJB) RWH project. The PUJB campus includes 18.4 ha and almost 200000 m^2 of constructions where academic, administrative, parking areas, chapels, banks, meeting and other service buildings, as well as sport fields and green zones can be found. Every day, approximately 30000 people enter the campus, whose some buildings are up to 70 years old, but mostly around 40 years and several are recent constructions. It is located at the north-east of Bogota's centre (Torres *et al.*, 2011c).

The RWH project in the PUJB was born within the framework of the PUJB Environmental Management Plan. A first project was proposed with the objective of assess economic and technical feasibilities of RWH as an alternative for irrigation and washing hard areas and buildings' facades. This project was leaded by the Research Group *Ciencia e Ingeniería del Agua y el Ambiente* (from the same university) in order to determine the amount of water potentially usable. Results show the possibility of using rainwater for some uses, from the standpoint of the amount of water (Lara-Borrero *et al.*, 2007). As a result, measurement campaigns were conducted to know the quality of the stormwater on campus and to identify potential uses (Torres *et al.*, 2011d). Taking into account these results, Torres *et al.* (2011c) undertook a study to identify the infrastructure requirements for the sustainable use of rainwater on the university campus. They concluded that rainwater could supply a maximum demand of 14%, requiring large investments and a change in the cultural model of water use. Subsequently, a MCA (Multi Criteria Analysis) tool (called CRIDE: multiCRIteria DEcision support tool – it's a Celtic word that means heart (Davis, 2002)) for supporting the process of decision making for RWH in PUJB campus was developed (Galarza-Molina *et al.*, 2012). Six scenarios were proposed for RWH and, by applying CRIDE, the University's Physical Resources Division (PRD) chose the scenario number five. This scenario consists of the runoff collection on nine basins (Figure 1) (basins number 1, 2, 3, 4, 5, 9, 10, 11 and 12) for non-potables uses quality (floor cleaning, sanitary discharge and landscape irrigation) (as recommended by Torres *et al.*, 2011c) using SUDS (Sustainable Urban Drainage Systems) as basins, bioretention gardens, permeable pavings and constructed wetlands (CIRIA, 2007) for collection and treatment of the rainwater (Galarza-Molina *et al.*, 2012).

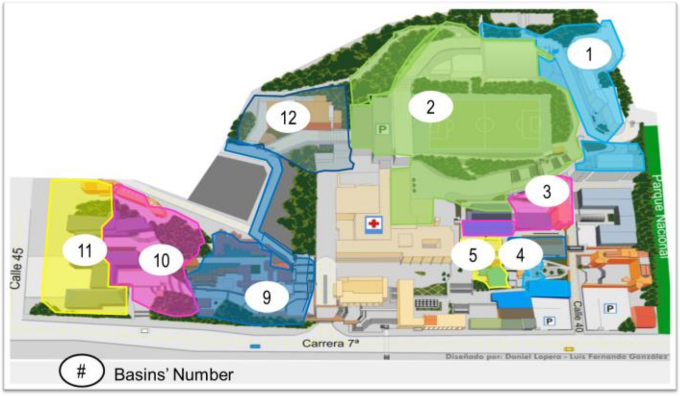

Figure 1. PUJ Campus. Basins defined for the scenario number five, base figure delivered by DPR.

The design and construction of the scenario number five will begin with the RWH of one of the nine basins (basin number 2), using a constructed-wetland / reservoir-tank system. Basin number 2 represents 15% (2.73 ha) of the total campus area, with a contributing catchment of 2.20 ha and with a weighted runoff coefficient of 0.51.

The inventory of water uses was taken from Torres *et al.* (2011c). Scenario number five considers the use of non-potable water uses. These monthly water uses range between 7.02 m^3/day and 14.11 m^3/day (Figure 2 - right).

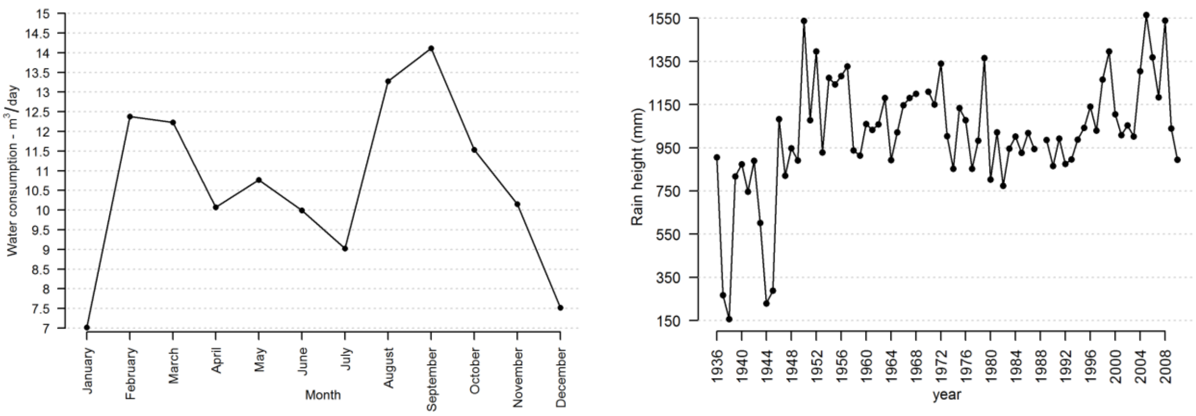

Figure 2. Monthly water uses in m^3/day for floor cleaning, sanitary discharge and landscape irrigation in PUJB (right). Evolution of total rain height per year for 73 years from San Luis station (left).

3 METHODOLOGY

A script based on Rational Method was developed in R (R Development Core Team, 2012) considering daily rainfall, contributing catchment and water uses. The input data were the 73 years of inter-monthly precipitation information between 1936 and 2010 (without years 1969 and 1988 with no data) (Figure 2 - left) and the water uses (demand). The rainfall data-set was collected from a daily rain gauge near the university campus (San Luis - type: Pluviograph station; latitude: 4°38'; longitude: 74°02'; elevation: 3000 m). The water demand was calculated from water bills (October 2003 - March 2010) delivered by PRD. The contributing catchment has a surface of 22026.20 m^2. It is composed by a sport centre, a parking structure, a sport field and green zones and roads, with a weighted runoff coefficient of 0.51.

The maximum value of storage H_{max} needed to supply the water demand is calculated using: (i) the amount of water used per month: demand volume(V_{dem}), (ii) the contributing catchment characteristics (area (A) and runoff coefficient (C)) and (iii) the estimated time between events (te_j).

For the estimation of te_j (for j=1) is necessary the following procedure (see Figure 3):

(i) The first te_j (for j=1) is taken as a time seed (ts) needed to begin the iterative procedure explained below, the script is executed for ts from 1 day to 100 days.

(ii) For consecutive starting days i, by screening the data-set from the first (i=1) to the last day (i=n), the cumulative daily rainfall height (H_i) is computed until H_i is greater than H_{max}. For H_{max} the corresponding time is called "ending day".

(iii) When $H_i > H_{max}$, the number between starting and ending days (time in days needed to supply H_{max}) is recorded as Δt_i, and the procedure is undertaken again with the next consecutive starting day (i+1) (see Figure 4).

(iv) The result of this screening is a list of days needed to supply H_{max}: Δt_i, Δt_{i+1}, Δt_{i+2}, …, Δt_n, where i denotes the starting day.

(v) By using a frequency analysis, $\Delta t_{mp(j)}$ (the most probable time Δt_i) is calculated, and is compared with te_j. If they are equal, $\Delta t_{mp(j)}$ is taken as the time needed to obtain the demand volume.

(vi) Otherwise the previous proceeding is repeated with $\Delta t_{mp(j)}$ as te_{j+1} until there is no difference between te_{j+k} and $\Delta t_{mp(j+k)}$.

The script was executed four times using different parts of the data-set: with all the data, with the last ten years, with the last five years and the last year. For the analysis of these results it was constructed a confidence interval graph with equations 1 and 2, using the first (Q_1) and the third quartiles (Q_3) to define the confidence intervals bound.

(1) $Upper\_bound = Q_3 + 1.5*(Q_3 - Q_1)$

(2) $Lower\_bound = Q_1 - 1.5*(Q_3 - Q_1)$

To support the selection of Δt_{mp} two variability indexes (VI_i) are calculated using equation 3 and 4: the relation between the minimum Δt_{mpi} and maximum Δt_{mpi}; and the relation between the minimum (min $P(\Delta t_{mpi})$) and maximum (max $P(\Delta t_{mpi})$) probability which each Δt_{mp} would have.

(3) $VI_{i\Delta tmp} = \min(\Delta t_{mpi}) / \max(\Delta t_{mpi})$

(4) $VI_{iProbability} = \min P(\Delta t_{mpi}) / \max P(\Delta t_{mpi})$

Δt_{mp} is chosen taking into account three criteria: higher values of $VI_{i\Delta tmp}$ and $VI_{iProbability}$ (difference between upper and lower bounds), lower values of Δt_{mp} to avoid oversized tank and high retention times (number of days are proportional to the amount of stored water) and higher values of probability of Δt_{mp}.

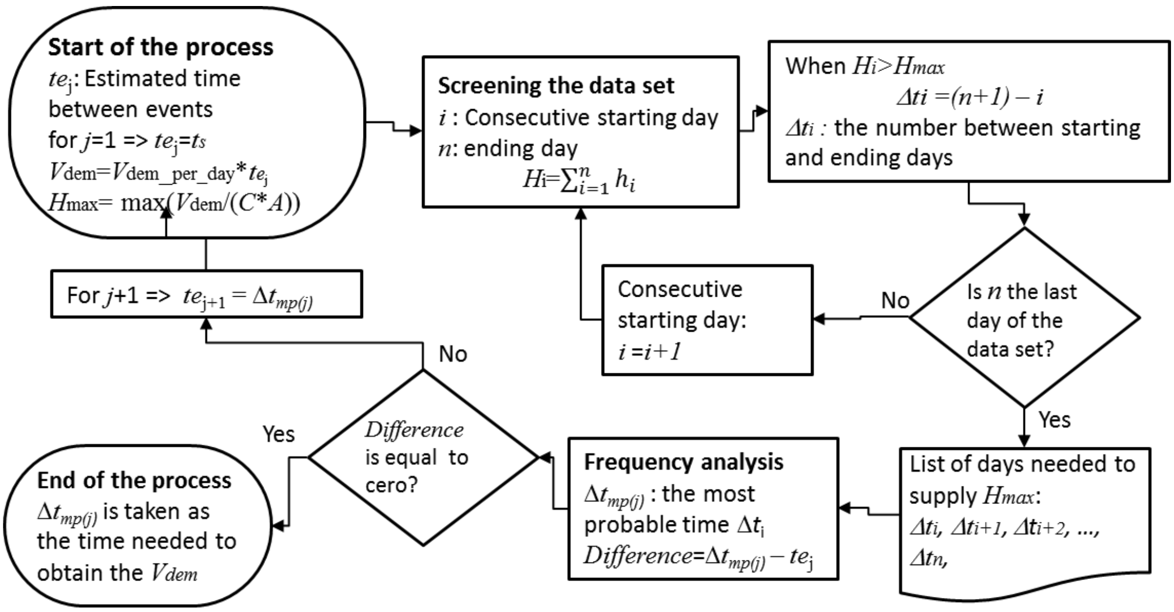

Figure 3. Procedure proposed to estimate the time between events (te_j).

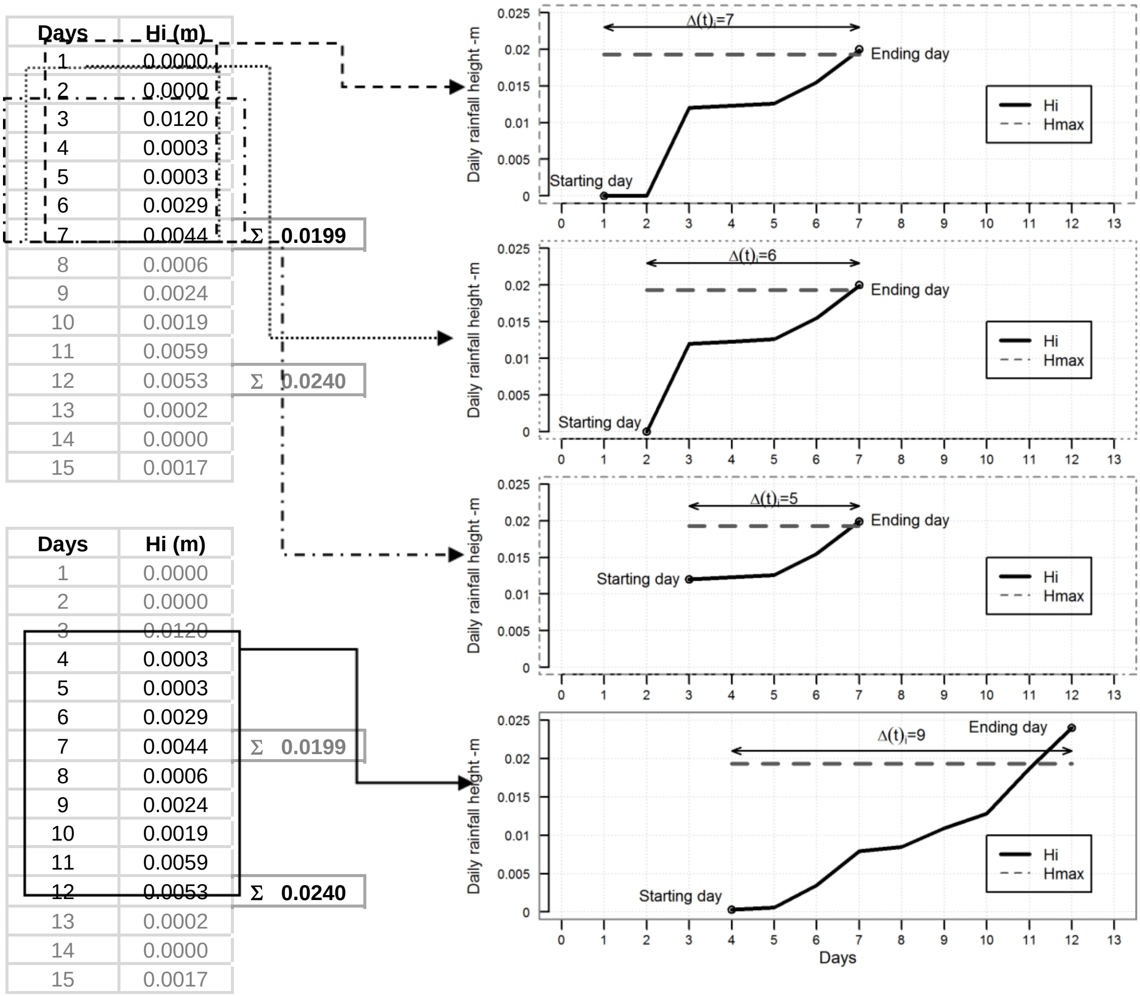

Figure 4. Rainfall data-set, the cumulative daily rainfall height (H_i) is computed until H_i is greater than H_{max}, for which the corresponding time is called "ending day"

4 RESULTS AND DISCUSSION

With the script described above, the rainfall data-set, the water uses (demand volume V_{dem}) and time seed (ts) from 1 to 100 days, the results were extracted from four executions: (i) with all the rainfall data-set, (ii) with the last ten years of the rainfall data-set, (iii) With the last five years of the rainfall data-set and (iv) with the last year of the rainfall data-set.

Taking into account the methodology for the selection of Δt_{mp}, the variability indexes ($VI_{i\Delta tmp}$ –using the most probable time– and $VI_{iProbability}$ –using the probability–) were calculated.

4.1 All the data-set

For the first execution, (upper part of Figure 5), with all the rainfall data-set (solid line type), Δt_{mp} (the most probable time Δt_i) varies between 1 day and 641 days. Significant differences between the probabilities' intervals of 73%-86% and 97%-99% can be observed, for the Δt_{mp} confidence bounds.

4.2 The last ten years of the rainfall data-set

For the last ten years of the rainfall data-set (dashed line type) Δt_{mp} varies between 1 day and 125 days. Significant differences between the probability's interval of 83% and 94% can be observed for the confidence bounds of Δt_{mp}.

4.3 The last five years of the rainfall data-set

In the case of the execution of the last five years of the rainfall data-set (dotted line type), Δt_{mp} varies between 1 day and 144 days. Highest differences between the confidence bounds of Δt_{mp} were found in the probability's interval of 85% and 95%.

4.4 The last year of the rainfall data-set

Finally, for the execution with the last year of the rainfall data-set (dot-lined type), Δt_{mp} varies between 1 day and 53 days. In this case significant differences for median values and confidence bounds of Δt_{mp} were found in the probability's interval of 93% and 99%.

4.5 Variability indexes

Figure 5 shows $VI_{i\Delta tmp}$ for each probability and the most probable times (Δt_{mp}) needed to obtain the demand volume in days. Taking into account the first criterion (high values of VI) it was chosen a high value of $VI_{\Delta tmp}$= 85% (lower part of Figure 5). The results for each execution are shown in Table 1: the tank volume is calculated with the maximum demand value (14.11 m^3/day, Figure 2) and the corresponding Δt_{mp} value.

The Figure 6 shows the Δt_{mp} versus $VI_{Probability}$. First it was chosen a high value of $VI_{Probability}$= 95%. The results for each execution are shown in Table 2, the tank volume is calculated with the maximum demand value (14.11 m^3/day, Figure 2) and Δt_{mp} values.

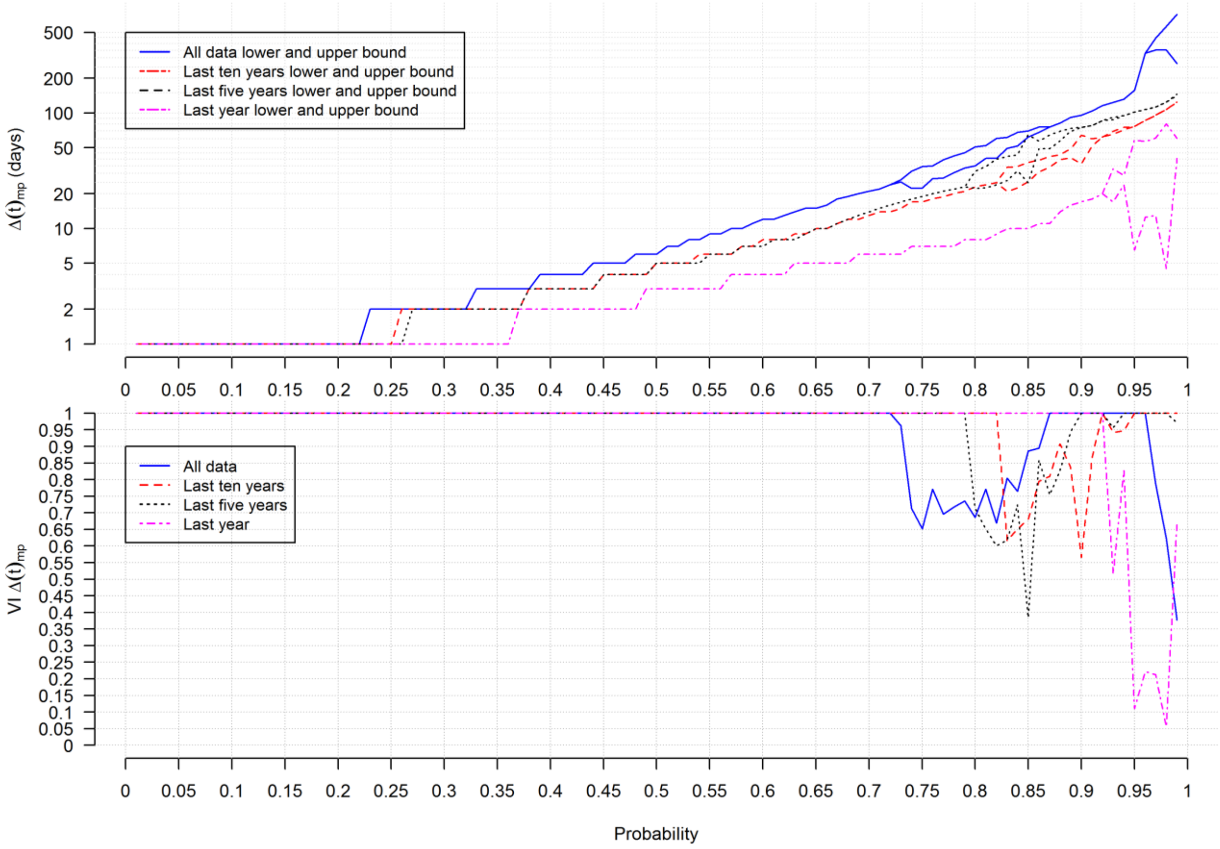

Figure 5. Variability index ($VI\Delta t_{mp}$) for each probability. The upper part of Figure shows the most probable time (Δt_{mp}) needed to obtain the demand volume in days, extracted from the four executions. (—) All data lower and upper bound, (— —) Last ten years lower and upper bound, (--) Last five years lower and upper bound and (-·-) Last year lower and upper bound.

In accordance with the second criteria (lower values of Δt_{mp} to avoid oversized tank and high retention times) it was chosen Δt_{mp} between 20 and 30 days (282 and 423 m^3). For this time step the minimum $VI\Delta t_{mp}$ is 0.735 (from the all data execution, see Figure 5) and $VI_{Probability}$ is 0.93 (from last five years execution, see Figure 6). The corresponding probabilities range between 69% and 93% for $VI\Delta t_{mp}$ (Figure 5) and between 69% and 98% for $VI_{Probability}$ (considering all the executions, see Figure 6). If we chose another time step Δt_{mp} lower than 30 days, for example between 15 and 20 days (212 and 282 m^3), the minimum $VI\Delta t_{mp}$ is 1 (from the all data execution, see figure 5) and $VI_{Probability}$ is 0.985 (from the last five years execution, see Figure 6) with a probability between 64% and 94.5% for $VI\Delta t_{mp}$ (Figure 5) and between 65% and 90% for $VI_{Probability}$ (considering all the executions, see Figure 6).

On the other hand, in accordance with the third criteria (higher values of probability of Δt_{mp}) if we chose probability values upper than 60%, it can be obtained Δt_{mp} values higher than 12 days (169 m^3) (see figure 5 and 6). It seems important to study in detail the Δt_{mp} intervals 14 to 16 (198 and 226 m^3) days and 18 to 20 days (254 and 282 m^3) (Figure 6): in these intervals $VI_{Probability}$ values for all the executions are the highest, with a minimum value of 0.985. The time step probability for the intervals 14 to 16 days and 18 to 20 days are between 63% and 89% and between 67% and 92%, respectively. Hence, it can be chosen any Δt_{mp} within these intervals – 14-16 or 18-20 days – (e.g. for Δt_{mp}= 20 days with VI = 1 and a probability between 70% and 90%, with a tank capacity of 282 m^3)

Table 1. Tank volumes of each execution for a $VI_{\Delta tmp}$= 85%

Execution	Probability (%)	Δt_{mp} (days)	Tank volume (m^3)
All the data	73	25–27	353 – 381
	85	60–70	847 – 988
	97.5	350–425	4939 – 5997
Last ten years	82.5	23–28	324 – 395
	87.5	35–43	494 – 607
	88.3	40–48	677 – 734
	91	52–60	734 – 847
Last five years	79.5	22.5–25	318 – 353
	86	49–57	691 – 804
	88.5	60–70	847 – 988
Last year	95.2	19–24	268 – 339

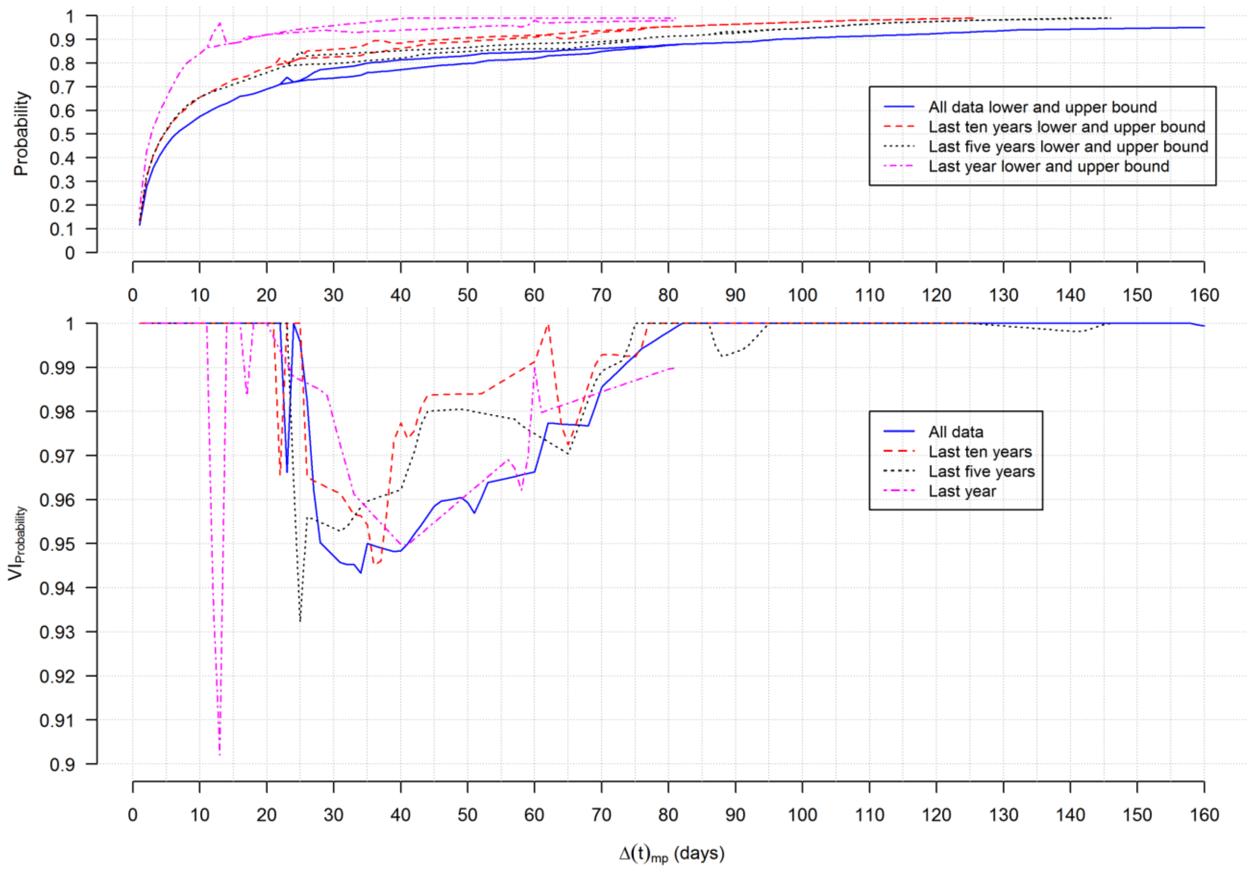

Figure 6. Zoom of the Δt_{mp} interval 1 – 160 days, which shows huge changes of the variability index (min/max). The upper part of the Figure represents the maximum probability of each Δt_{mp}. (—) All data, (— —) Last ten years, (--) Last five years and (-·-) Last year.

Table 2. Tank volumes of each execution for a $VI_{Probability}$= 95%

Execution	Δt_{mp} (days)	Probability (%)	Tank volume (m^3)
All the data	28	73–78	395
	35	76–80	494
	42	79–82	593
Last ten years	36	84–89	508
	37.5	85–89	529
Last five years	25	79–84	346
	26	79–83	360
Last year	12	86–92	169
	14	87–94	198
	40	94–99	564
	41	94–99	579
	42	94–99	593

5 CONCLUSIONS

This paper proposes a simplified method to sizing rainwater tanks using long day-resolution rainfall time series for heterogeneous catchment areas. This is a specific method based on the probability that has the daily rainfall to supply the water demand, as well as the most probable time step needed and their respective variabilities.

After applying this method to a specific case study (PUJ campus rainwater harvesting tank sizing) it was found that the results differ depending on the selected period and the variability indexes: (i) whole data series - 76 years: 395 to 593 m^3 ($VI_{Probability}$= 95%: 28 to 42 days, probability range: 73-82%) and 353 to 5997 m^3 ($VI\Delta t_{mp}$= 85%: 25 to 425 days, probability range: 73-97.5%); (ii) last ten years: 508 and 529 m^3 ($VI_{Probability}$= 95%: 36 and 37.5 days, probability range: 84-89%) and 324 to 847 m^3 ($VI\Delta t_{mp}$= 85%: 23 to 60 days, probability range: 82.5% – 91%); (iii) last five years: 346 and 360 m^3 ($VI_{Probability}$= 95%: 25 and 26 days, probability range: 79-84%) and 318 to 988 ($VI\Delta t_{mp}$= 85%: 22.5 to 70 days, probability range: 79.5-88.5%); (iv) last year: 169 to 593 m^3 ($VI_{Probability}$= 95%:12 to 42 days, probability range: 86-99%) and 268 and 339 ($VI\Delta t_{mp}$= 85%: 19 and 24 days, probability: 95.2%). The above results seem to be influenced by an evolution of rainfall heights in different selected periods, which will be studied in further researches by considering a possible climate change.

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