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## SIZING METHOD FOR STORMWATER HARVESTING TANKS USING DAILY RESOLUTION RAINFALL AND WATER DEMAND DATA SETS

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### Abstract

This work presents a simplified method for rainwater harvesting (RWH) tank sizing using long day-resolution rainfall time series. This method considers heterogeneous contributing catchments and water demand flow rates. For the tank sizing, we proposed to take into account the probability to supply the water demand, as well as the most needed probable time step and their respective variabilities. The method was applied to a specific case study (Pontificia Universidad Javeriana, RHW project), with 73 years of daily-resolution rainfall information (between 1936-2010). For the analysis we used different time periods from data-set and the results were: (i) for the whole data-set 76 years: 395 m<sup>3</sup> (28 days, probability: 78%); (ii) for the last ten years: 494 m<sup>3</sup> (35 days, probability: 89%); (iii) for the last five years: 346 m<sup>3</sup> (25 days, probability: 84%); (iv) for the last year: 155-198 m<sup>3</sup> (11-14 days, probability: 89-90%). These results seem to be influenced by an evolution of rainfall depth in different selected periods, which will be studied in further researches.

Key words: rainwater harvesting system (RWH); time series; rainwater tank sizing; urban water management; water demand.

### MÉTODO DE DIMENSIONAMIENTO PARA TANQUES DE CAPTACIÓN DE AGUA LLUVIA UTILIZANDO SERIES DE RESOLUCIÓN DIARIA DE LLUVIA Y DE DEMANDA DE AGUA

### Resumen

Este trabajo presenta un método simplificado para el dimensionamiento de tanques de aprovechamiento de aguas lluvias (AAL). Este método considera cuencas tributarias heterogéneas y caudales de demanda de agua. Se propone tener en cuenta la probabilidad para suministrar la demanda de agua, así como el paso de tiempo necesario de recolección más probable y sus respectivas variabilidades. El método se aplicó a un estudio específico de caso (Pontificia Universidad Javeriana, proyecto AAL), con 73 años de información de precipitación a resolución diaria (entre 1936-2010). Para el análisis se utilizaron diferentes períodos de tiempo, los volúmenes del tanque con el tiempo de recolección fueron los siguientes: (i) para el conjunto entero de datos 76 años: 395 m<sup>3</sup> (28 días, probabilidad: 78%); (ii) para los últimos diez años: 494 m<sup>3</sup> (35 días, probabilidad: 89%); (iii) para los últimos cinco años: 346 m<sup>3</sup> (25 días, probabilidad: 84%); (iv) para el último año: 155 a 198 m<sup>3</sup> (11 a 14 días,

probabilidad: 89-90%). Estos resultados parecen estar influenciados por una evolución de la altura de lluvia en los diferentes períodos seleccionados, lo cual será estudiado en investigaciones posteriores.

**Palabras clave:** sistemas de aprovechamiento de aguas lluvias; series de tiempo; dimensionamiento de tanques para aprovechamiento de aguas lluvias; gestión de agua urbana; demanda de agua.

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## INTRODUCTION

Nowadays it exists an increasing attention on the rainwater harvesting (RWH) as an alternative source of water (Hatt, Deletic, & Fletcher, 2006) for non-potable uses (Appan, 2000; Coombes, Argue, & Kuczera, 2000; Coombes & Mitchell, 2006; EPA, 2004; Fewkes, 1999; Ghisi, Tavares, & Rocha, 2009; Handia, Tembo, & Mwiindwa, 2003; Hatt et al., 2006; Herrmann & Schmida, 2000; X.-Y. Li & Gong, 2002; Marinovski, Ghisi, & Gómez, 2004; Wong, 2007) which is additionally recognized as one of the specific adaptation strategies that the water sector should implement to deal with climate changes (Aladenola & Adeboye, 2009; Boelee et al., 2012; Mukheibir, 2007; Muller, 2007; Mwenge Kahinda, Taigbenu, & Boroto, 2010; Pandey, Gupta, & Anderson, 2003; Rozos, Makropoulos, & Butler, 2010). This technique have been successfully implemented as alternative water source in some countries such as China (F. Li, Cook, Geballe, & Burch Jr, 2000), South Korea (Song, Han, & Kim, n.d.), Malaysia (Lariyah, Mohd Nor, Mohamed Roseli, Zulkefli, & Amirah Hanim, 2011), Australia (Duan, Attwater, & Min, 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, McCarthy, Deletic, & Fletcher, 2008): "How much stormwater can be harvested? How reliable is this supply source? (Farreny, Gabarrell, & Rieradevall, 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 (Campisano & Modica, 2012; Imteaz, Rahman, & Ahsan, 2012; Imteaz, Shanableh, Rahman, & Ahsan, 2011; Seo, Choi, & Park, 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 & Jayasuriya, 2010; Walsh, Pomeroy, & Burian, 2014). Other studies focus on the effect that produces the use of rainwater tanks on the sewer system design (Vaes & Berlamont, 2001). More recently, (Youn, Chung, Kang, & Sung, 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 (Sanchez & Caicedo, 2003) and non-potable uses (Ballén, Galarza, & Ortiz, 2006; Lara Borrero et al., 2007; Palacio Castañeda, 2010; Ramírez, 2009; Torres, Méndez-Fajardo, et al., 2011). (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 & Garzón, 2005; Mora, Alvarado, & Torres, 2011; Navarro & Saldarriaga, 2008; Torres et al., 2012; Vélez et al., 2004). 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.

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## MATERIALS

The study case is the Pontificia Universidad Javeriana Bogotá (PUJB) RWH project. The PUJB campus includes 18.4 ha and almost 200000 m<sup>2</sup> 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 Bogotá's center (Torres, Estupiñán Perdomo, & Zapata García, 2011).

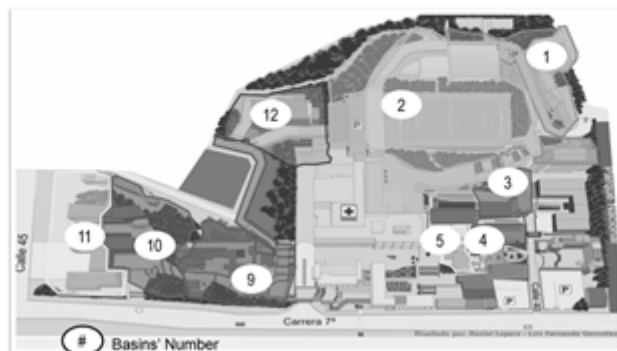
The RWH project in the PUJB was born within the framework of the PUJB Environmental Management Plan. A first project was proposed with the objective of assess economic and technical feasibilities of RWH as an alternative for irrigation and washing hard areas and buildings' facades. This project was leaded 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, Lara-Borrero, Torres, Estupiñán, & Méndez-Fajardo, 2011). Taking into account these results, Torres et al. (2011) 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: multiCRIteriaDEcision 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, Torres, Moura, & Lara-Borrero, 2015). 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., 2011) using SUDS (Sustainable Urban Drainage

Systems) as basins, bioretention gardens, permeable paving and constructed wetlands (CIRIA, 2000) for collection and treatment of the rainwater (Galarza-Molina et al., 2015).

**Figure 1.** PUJ Campus. Basins defined for the scenario number five.

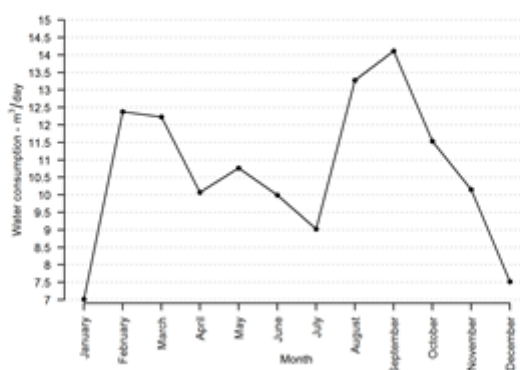
Source: figure given by PRD



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 2.2 ha and with a weighted runoff coefficient of 0.51.

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

**Figure 2.** PUJ Monthly water uses in m<sup>3</sup>/day for floor cleaning, sanitary discharge and landscape irrigation in PUJB. Source: The authors



## METHODOLOGY

A script based on Rational Method was developed in R (R Development Core Team, 2012) considering daily rainfall, contributing catchment and water uses. We chose this method because of the size of the catchment (less than 80 ha) and its simplicity. The input data were

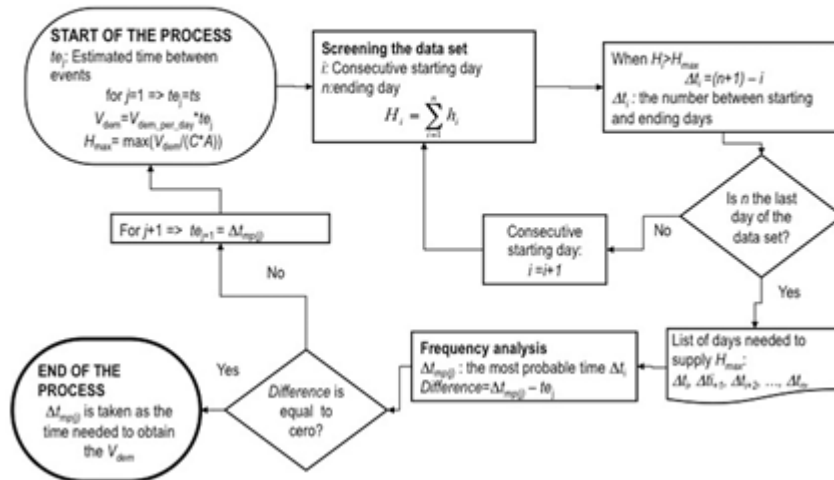
the 73 years of inter-monthly precipitation information between 1936 and 2010 (without years 1969 and 1988 with no data) (Figure 3) and the water uses (demand). The rainfall data-set was collected from a daily rain gauge near the university campus (San Luis - type: Pluviograph station; latitude:  $4^{\circ}38'$ ; longitude:  $74^{\circ}02'$ ; 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  $22026\text{m}^2$ , composed by a sport centre, a parking structure, a sport field and green zones and roads, with a weighted runoff coefficient of 0.51.

**Figure 3.** Evolution of total rain depth per year for 73 years from San Luis station. Source: The authors.

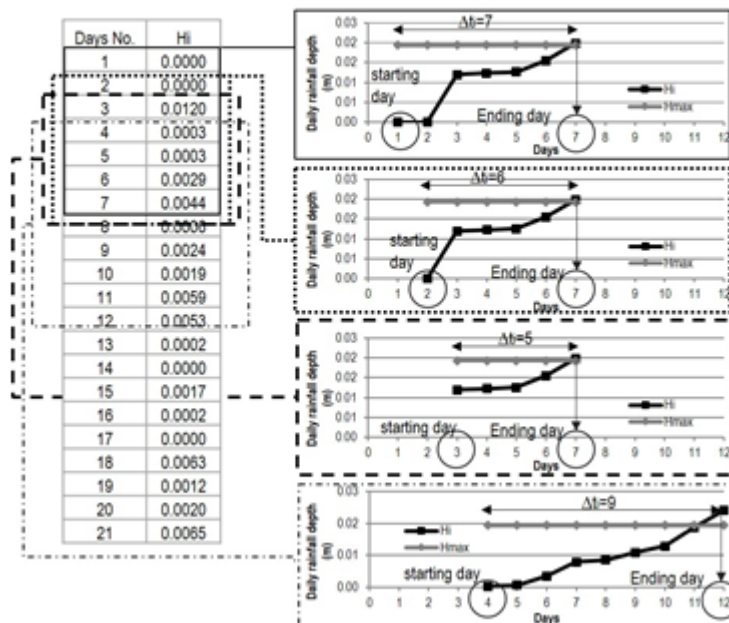


Figure 4 shows the process proposed for estimating the time needed to obtain the demand volume. This process is divided in five steps. The first one is the determination of the maximum value of storage  $H_{max}$  needed to supply the water demand.  $H_{max}$  is calculated using the amount of water needed per month, the contributing catchment characteristics (area and runoff coefficient) and the estimated time between events ( $te_j$ ). In order to begin the iterative procedure explained below, we used a time seed ( $ts$ ) (the script is executed for  $ts$  from 1 day to 100 days) for the first  $te_j$ . The second step is the screening the data-set from the first ( $i=1$ ) to the last day ( $i=n$ ) for consecutive starting days  $i$ . Then the cumulative daily depth height ( $H_i$ ) is computed until  $H_i$  is greater than  $H_{max}$ . The third step is undertaken when  $H_i > H_{max}$ , the number days between starting and ending days (time in days needed to supply  $H_{max}$ ) is recorded as  $\Delta t_i$ , and the procedure is undertaken again with the next consecutive starting day ( $i+1$ ) (see Figure 5). The result of this step is a list of days needed to supply  $H_{max}$ :  $\Delta t_i, \Delta t_{i+1}, \Delta t_{i+2}, \dots, \Delta t_n$ , where  $i$  denotes the starting day. By using a frequency analysis (fourth step), the most probable time  $\Delta t_i$  to obtain the demand volume is calculated ( $\Delta tmp(j)$ ), and is compared with  $te_j$ . If they are equal (fifth step),  $\Delta tmp(j)$  is taken as the time needed to obtain the demand volume; otherwise the process will begin again with  $\Delta tmp(j)$  as  $te_{j+1}$  until there is no difference between  $te_{j+k}$  and  $\Delta tmp(j+k)$ .

**Figure 4.** Procedure proposed to estimate the time needed to obtain de demand volume Source: The authors.



**Figure 5.** Procedure Rainfall data-set, the cumulative daily rainfall depth (\$H\_i\$) is computed until \$H\_i\$ is greater than \$H\_{max}\$, for which the corresponding time is called "ending day". Source: The authors.



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 (Q1) and the third quartiles (Q3) to define the confidence intervals bound.

$$\text{Upper\_bound} = Q_3 + 1.5 * (Q_3 - Q_1) \quad (1)$$

$$\text{Lower\_bound} = Q_1 - 1.5 * (Q_3 - Q_1) \quad (2)$$

To support the selection of  $\Delta tmp$  (the most probable time to obtain the demand volume) two variability indexes (Vli) are calculated using equation 3 and 4: the relation between the minimum  $\Delta tmp_i$  and maximum  $\Delta tmp_i$ ; and the relation between the minimum ( $\min P(\Delta tmp_i)$ ) and maximum ( $\max P(\Delta tmp_i)$ ) probability which each  $\Delta tmp$  would have.

$$Vli_{\Delta tmp} = \min(\Delta tmp_i) / \max(\Delta tmp_i) \quad (3)$$

$$Vli_{Probability} = \min(P(\Delta tmp_i)) / \max(P(\Delta tmp_i)) \quad (4)$$

$\Delta tmp$  is chosen taking into account three criteria: higher values of  $Vli_{\Delta tmp}$  and  $Vli_{Probability}$  (difference between upper and lower bounds), lower values of  $\Delta tmp$  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  $\Delta tmp$ .

## RESULTS AND DISCUSSION

With the script described above, the rainfall data-set, the water uses (demand) and time seed (ts) from 1 to 100 days, the results were extracted from four executions:

- With all the rainfall data-set
- With the last ten years of the rainfall data-set
- With the last five years of the rainfall data-set
- With the last year of the rainfall data-set

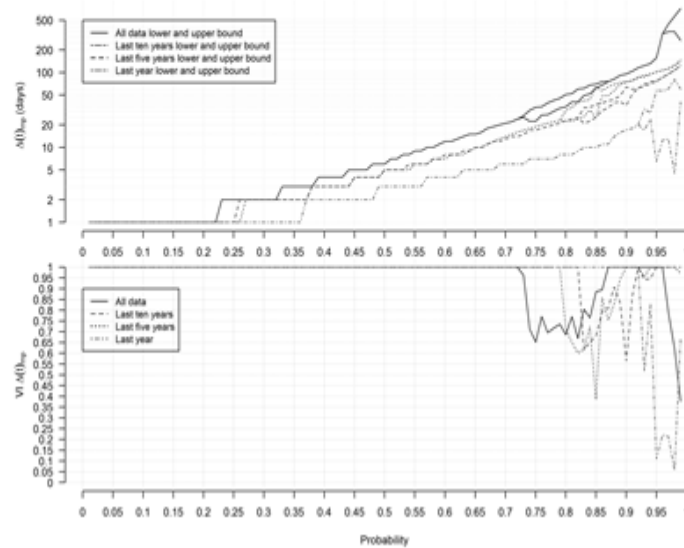
Taking into account the methodology for the selection of the  $\Delta tmp$ , the variability indexes ( $Vli_{\Delta tmp}$  and  $Vli_{Probability}$ ) were calculated. Figure 5 shows  $Vli_{\Delta tmp}$  for each probability and the most probable times ( $\Delta tmp$ ) needed to obtain the demand volume in days.

For the first execution, (upper part of Figure 6), with all the rainfall data-set (solid line type),  $\Delta tmp$  varies between 1 day and 641 days. Significant differences between the probabilities' intervals of 73% – 86% and 97% – 99% can be observed, for the  $\Delta tmp$  confidence bounds. For the last ten years of the rainfall data-set (dashed line type)  $\Delta tmp$  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  $\Delta tmp$ . In the case of the execution of the last five years of the rainfall data-set (dotted line type),  $\Delta tmp$  varies between 1 day and 144 days. Highest differences between the confidence bounds of  $\Delta tmp$  were found in the probability's interval of 80% and 89%. Finally, for the execution with the last year of the rainfall data-set (dot-lined type),  $\Delta tmp$  varies between 1 day and 53 days. In this case significant differences for median values and confidence bounds of  $\Delta tmp$  were found in the probability's interval of 93% and 99%.



On the other hand, taking into account the first criterion (high values of VI) it was chosen a high value of  $VI_{\Delta t_{mp}} = 85\%$  (lower part of Figure 6). The results for each execution are shown in Table 1: the tank volume is calculated with the maximum demand value ( $14.11 \text{ m}^3/\text{day}$ , Figure 2) and the corresponding  $\Delta t_{mp}$  value.

**Figure 6.** Variability index ( $VI_{\Delta t_{mp}}$ ) for each probability. The upper part of Figure shows the most probable time ( $\Delta t_{mp}$ ) 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. Source: The authors.



**Table 1.** Tank volumes of each execution for a  $VI_{\Delta t_{mp}} = 85\%$ . Source: The authors.

Execution	Probability (%)	$\Delta t_{mp}$ (days)	Tank volume ( $\text{m}^3$ )
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

The Figure 7 shows the  $\Delta t_{mp}$  versus  $VI_{\text{Probability}}$ . First it was chosen a high value of  $VI_{\text{Probability}} = 95\%$ . The results for each execution are shown in Table 2, the tank volume is calculated with the maximum demand value ( $14.11 \text{ m}^3/\text{day}$ , Figure 2) and  $\Delta t_{mp}$  values.

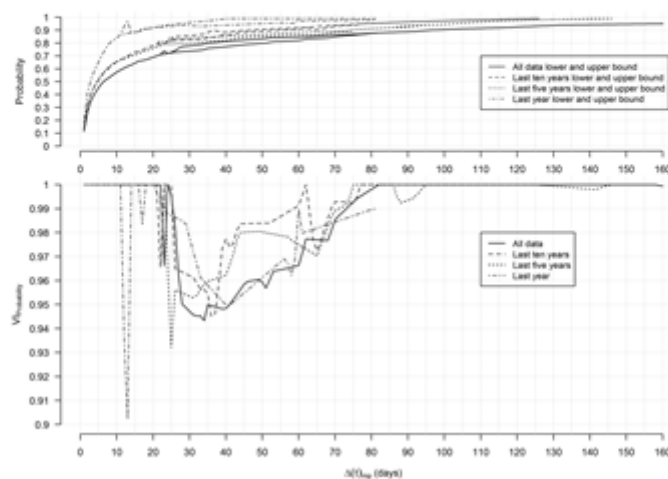
Table 2. Tank volumes of each execution for a  $VI_{Probability} = 95\%$ . Source: The authors.

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

In accordance with the second criteria (lower values of  $\Delta t_{mp}$  to avoid oversized tank and high retention times) it was chosen  $\Delta t_{mp}$  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 6) and  $VI_{Probability}$  is 0.93 (from last five years execution, see Figure 7). The corresponding probabilities range between 69% and 93% for  $VI_{\Delta t_{mp}}$  (Figure 6) and between 69% and 98% for  $VI_{Probability}$  (considering all the executions, see Figure 7). If we chose another time step  $\Delta t_{mp}$  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 6) and  $VI_{Probability}$  is 0.985 (from the last five years execution, see Figure 7) with a probability between 64% and 94.5% for  $VI_{\Delta t_{mp}}$  (Figure 6) and between 65% and 90% for  $VI_{Probability}$  (considering all the executions, see Figure 7).

On the other hand, in accordance with the third criteria (higher values of probability of  $\Delta t_{mp}$ ) if we chose probability values upper than 60%, it can be obtained  $\Delta t_{mp}$  values higher than 12 days (169  $m^3$ ) (see figure 5 and 6). It seems important to study in detail the  $\Delta t_{mp}$  intervals 14 to 16 (198 and 226  $m^3$ ) days and 18 to 20 days (254 and 282  $m^3$ ) (Figure 7): 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  $\Delta t_{mp}$  within these intervals – 14-16 or 18-20 days – (e.g. for  $\Delta t_{mp} = 20$  days with  $VI = 1$  and a probability between 70% and 90%, with a tank capacity of 282  $m^3$ ).

**Figure 7.** Zoom of the  $\Delta t_{mp}$  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  $\Delta t_{mp}$ . (—) All data, (— —) Last ten years, (— — —) Last five years and (— · —) Last year. Source: The authors



## 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) we found that the results differ depending on the selected period and the variability indexes: (i) whole data series - 76 years: 395 to 593 m<sup>3</sup> (**VIPprobability**= 95%: 28 to 42 days, probability range: 73-82 %) and 353 to 5997 m<sup>3</sup> (**VI $\Delta t_{mp}$** = 85%: 25 to 425 days, probability range: 73-97.5%); (ii) last ten years: 508 and 529 m<sup>3</sup> (**VIPprobability**= 95%: 36 and 37.5 days, probability range: 84-89%) and 324 to 847 m<sup>3</sup> (**VI $\Delta t_{mp}$** = 85%: 23 to 60 days, probability range: 82.5% – 91%); (iii) last five years: 346 and 360 m<sup>3</sup> (**VIPprobability**= 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<sup>3</sup> (**VIPprobability**= 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 depth in different selected periods, which will be studied in further researches by considering a possible climate change.

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