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Assisting global rainwater harvesting practitioners: a decision support tool for tank sizing method selection under uncertainty

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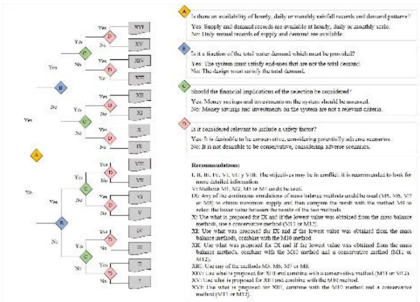
For the first time, a Decision Support Tool has been produced that assists global rainwater harvesting practitioners in selecting an appropriate tank sizing method


Is there an availability of hourly, daily or monthly rainfall records and demand patterns?
Yes: Supply and demand records are available at hourly, daily or monthly scale.
No: Only annual records of supply and demand are available.
Is it a fraction of the total water demand which must be provided?
Yes: The system must satisfy end-uses that are not the total demand.
No: The design must satisfy the total demand.
Should the financial implications of the selection be considered?
No: Money savings and investments on the system are not a relevant criteria.
Is it considered relevant to include a safety factor?
Yes: It is desirable to be conservative, considering potentially adverse scenarios.
No: It is not desirable to be conservative, considering adverse scenarios.
Recommendations:
X: Use what is proposed for IX and if the lowest value was obtained from the mass balance methods, use a conservative method (M11 or M12).
XI: Use what was proposed for IX and if the lowest value was obtained from the mass balance methods, combine with the M10 method.
XII: Use what was proposed for IX and if the lowest value was obtained from the mass balance methods, combine with the M10 method and a conservative method (M11 or M12).
XIII: Use any of the methods M5, M6, M7 or M8.
XV: Use what is proposed for XIII and combine with the M10 method.

Abstract

Rainwater harvesting (RWH) tank sizing can be an onerous task due to the range of available methods. This paper presents a simple, yet robust, end-user and design criteria-focused decision support tool, based on a comparison of 12 well established methods across four types (simplified, mass balance continuous simulation, cost-function and statistical). Each method was applied to two example households located in Bucaramanga, Colombia and considered uncertainty through integrated representation of demand variability, climate change, overflow and financial scenarios. Quantitative and qualitative criteria were used to assess the performance of each method. Based on the summation of these criteria, a diversified approach constituting mass balance simulation, cost-function and probabilistic methods was most suited to RWH tank sizing for houses in Bucaramanga. Global RWH practitioners now have a decision support tool to assist in selecting the best tank sizing approach for their context.

Keywords: Rainwater harvesting, Storage tank, Tank sizing, Decision Support Tool

Water Impact Statement

Rainwater harvesting (RWH) tank sizing methods differ in complexity and data requirements, making selection for a particular context difficult. Over or undersized tanks have financial and performance implications. We present a decision support tool that simplifies method selection to assist global practitioners in designing best-fit RWH systems.

1. Introduction

Rapid population growth, urbanization and climate change in the world have led to an increase in water demand for potable and non-potable uses [1, 2]. This increase creates pressure on centralized supply systems and has catalyzed interest in alternative approaches to ensure water provision. Rainwater harvesting systems (RWH) are alternative water sources or decentralized management options [1, 3]. RWH consists of collecting, storing and treating rainwater from rooftops and terraces [1] and has emerged as a financially feasible alternative, especially for non-potable uses, such as flushing toilets, washing clothes, cleaning and watering gardens [1, 2, 4], leading to a reduction in water consumption from centralized supply systems. Santos and Taveira-Pinto [5] indicate that RWH systems are important to reduce urban water consumption and increase their efficient use.

RWH system configuration depends on several parameters such as climatic conditions, design objectives, catchment area, rainfall patterns, rainwater tank capacity, capture efficiencies and size of first-flow diverters [2, 6, 7]. A critical point in designing domestic RWH systems is the size of the storage tank. According to Campisano, et al. [1], it is necessary to reconcile objectives that are often in conflict (i.e. maximize water savings, maximize rainwater tank emptying to control drainage, minimize costs). Therefore, analysing the sizing of rainwater tanks is essential to optimize their operation and increase benefits and effectiveness [5].

In the last twenty years, different methods have been suggested for sizing RWH tanks [1], whose approaches vary in complexity, precision and context, which has generated criteria disparity. Sizing methodologies can be grouped into four categories: i) Simplified methods, ii) Methods of continuous simulation of mass balance, iii) Cost-function methods, and iv) Statistical methods (probabilistic) with parametric and nonparametric approaches.

The simplified methods are a set of basic procedures, which allow a preliminary sizing of a storage tank. These methods are recommended for small-scale systems with uniform water demand [8], and are used when financial considerations are not a priority [9]. These simplified methods are commonly found in handbooks, standards or technical specifications [8, 10-14].

Sizing methods based on continuous simulations of mass balance track the system inputs and outputs, allowing to define the water volume to be stored according to supply and demand flows. For Campisano, et al. [1], these models depend basically on: a) a behavioural model to represent rainwater demand pattern, b) a rainwater inflow model to represent water provision, and c) a calculation module to simulate tank mass balance. The continuous simulation models assess system's performance by calculating efficiency, which is defined as the ratio between the amount of rainwater used and the non-potable water demand [15]. This type of procedure incorporates the possibility of simulating under different time intervals, which is an advantage, since it allows monitoring different variables and integrating seasonality inputs and outputs. Two fundamental methods have been identified: Yield After Spillage (YAS) and Yield Before Spillage (YBS) [16]. Furthermore, additional balance equations have been proposed, such as the Rippl method and the method suggested by Ghisi and Marcel [17].

The models found in the literature are diverse, some use the YAS balance algorithm [18-22], the YBS algorithm [23-30], intermediate models between YAS and YBS [7, 19, 31, 32], and other authors use different mass balance equations [5, 33-43].

Rainwater tank sizing can also be addressed considering aspects of costs and financial feasibility. López-Patiño, et al. [9] proposed a method based on return maximization of potable water savings by sizing from water balance equations. Likewise, Liaw and Tsai [44] developed a model based on a cost optimization function for pre-stablished values of reliability, catchment area and tank volume. Chiu, et al. [45] generated a model for the city of Taipei, in which they studied system's optimization through the financial feasibility of potable water savings and energy. Other authors have calculated size optimization by the minimization of functions, for instance: Campisano and Modica [46] minimized the Present Value of system costs using regressions that included a dimensionless parameter and the simulation under the YAS equation; Pelak and Porporato [47] minimized total costs by using a model that describes rainfall as a *Poisson* parametric process and incorporates fixed and distributed costs, and Okoye, et al. [48] proposed a model based on linear programming to minimize the Net Present Value of the total construction costs of rainwater tanks and water purchases.

On the other hand, methods for sizing rainwater tanks supported on probabilistic, stochastic and regressive procedures have been increasingly used. These methods incorporate climate change variables, considering extreme events of rainfall and drought [49]. In these methods the probability of rainfall occurrence is analysed, and becomes the input variable to continuous simulation models of mass balances. There are several studies that consider this probabilistic approach in rainwater tank sizing [6, 50-55]. Other authors have applied correlation models, such as Hanson and Vogel [56], who used a multivariate ordinary least squares (OLS) regression to generalize the storage-reliability-yield (SRY) relations. Andrade, et al. [57] studied the relevance of hydrological variables in water savings efficiency, through a multivariate statistical study that included a canonical correlation analysis.

Although there are different methods for sizing rainwater storage tanks, there is no consensus on the most effective method required in a particular context of water availability and demand. Santos and Taveira-Pinto [5] in Portugal, contribute to the analysis of sizing rainwater storage tanks by using six methods that included simplified procedures and continuous simulation models of mass balances. In this paper, 12 methods from the four categories (i.e. simplified, continuous simulation models of mass balances, cost-function and probabilistic) were assessed using quantitative and qualitative criteria in order to develop a tank sizing method selection decision support tool (DST) based on end-user and design criteria. To develop the DST, two residential houses with low (sector A) and high (sector B) water consumption from a developing country context (Colombia) were used as a case study.

2. Materials and methods

To develop the Decision Support Tool, example houses and established methods required identification, in order to compare sizing technique results.

2.1 Study cases

The sizing methods for the rainwater storage tank were applied to two houses located in Bucaramanga (Colombia). The houses are defined by low (130 litres per capita per day -lpcd) and high (203 lpcd) water consumption, named A and B, respectively. Table 1 presents the general information of the two houses.

Table 1. Characteristics and design parameters for house types A and B.

Characteristic/ Design parameter	Units	A	B
Socioeconomic stratum [1]	-	1	6
Number of floors	-	2	2 + Attic
Inhabitants per household (U)	(inhabitants/ household)	5	4
Total built area	(m^2)	48	216
Roof area (A)	(m^2)	30.5	101
Roof material	-	Asbestos-cement	Spanish clay
Runoff coefficient (C)	-	0.9	0.9
Filter efficiency (Ƞ)	-	0.9	0.9
Maximum number of storage days (N)	(days)	25	25
Initial storage volume	(L)	0	0

Average annual rainfall (P)	(mm/year)	974	1053
Rainfall data resolution	-	Daily	Daily
Analysis period	(years)	25	15
Mean temperature	(°C)	25	25
Potable water consumption	(lpcd)	130 ±61	203 ±84
Percentage of water consumption for non-potable uses	(percentage of potable water consumption)	Watering plants: 2.6% House cleaning: 4.8% Laundry: 12%	External tap: 3.4% Internal tap: 5.5% Laundry: 27%
Average non-potable water demand (C_{AE})	(lpcd)	9212	26617

Notes: [1]Stratum 1 and 6 represent the households with the lowest and highest income, respectively.

Sources: House A [58]; House B [59]

Rainfall records were taken from the meteorological network of stations from the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM), selecting the stations closest to each study site (500 meters for A and 2000 meters for B). The information has a daily temporal resolution with 25 years of records for A and 15 years for B. The rainfall regime in both cases was bimodal, with two rainy and two dry periods during the year (Figure 1). The driest months are December, January and February, and to a lesser extent, June, July and August, while the rainiest months extend from March to May and September to November [60].

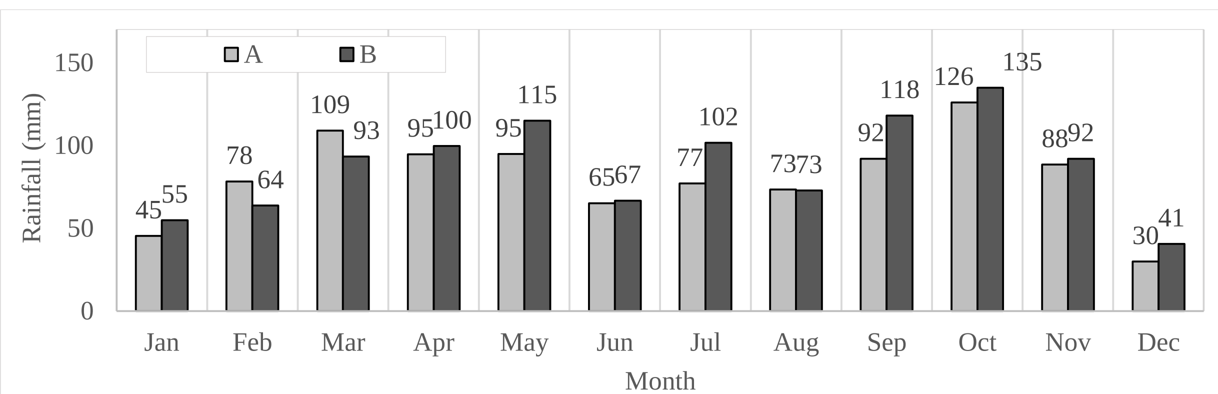


Figure 1. Average rainfall patterns for the periods considered in house locations A and B.

Regarding end-uses, people expressed their willingness to use rainwater for irrigation, house cleaning and laundry in the case of A [58], and laundry (washing machine and sink), external tap and internal tap in the case of B [59]. In this study, toilet flushing was not considered as rainwater use, because the formerly designed systems used treated greywater for this purpose. In the existing design, a 500-liters storage tank was proposed for A [58], and a 2000-liters for B [59].

To apply the different sizing methods, demand patterns were considered on a daily scale (Figure 2). These patterns were proposed based on consumption percentages obtained from national regulations [61] and from previous studies [58, 59, 62]. To obtain a weekly water consumption pattern for each house, a percentage of the total demand was estimated for each use and assigned, taking into account the frequency of the associated uses during the week.

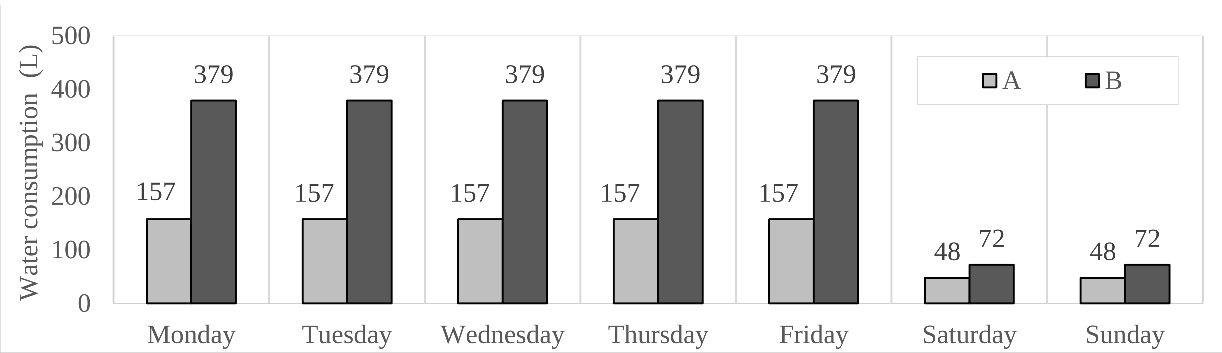


Figure 2. Weekly water consumption patterns for house types A and B.

2.2 Application of methods for sizing rainwater storage tanks

Twelve methods of sizing rainwater storage tanks were applied, according to four proposed categories i) Simplified methods, ii) Methods of continuous simulation of mass balance, iii) Methods with cost functions, and iv) Statistical (probabilistic) methods. The supplementary information provided with this paper expands the explanation of the different methodologies applied according to category. Similarly, criteria used for the calculations is included in the supplementary information.

2.2.1 Simplified methods

In this category, four methods suggested by institutions were applied: a) Portuguese Association for Quality and Efficiency in Building Services (ANQIP) [8], b) German Institute for Standardization (DNI) [11], c) Environmental Agency (EA) [10] and d) International Water and Sanitation Centre (IRC) [13]. These methods are defined by relationships between easily measured variables that were collected for each case study, and substituted in the corresponding equations. These variables were:

mean multi-annual rainfall, catchment area, inhabitants per household, annual per capita demand and a runoff coefficient.

2.2.2 Continuous simulation of mass balance methods

In this category, five methods were tested: YAS [16], YBS [16], theta (θ) [16], Neptune [17], and Rippl [39, 40]. In these methods, changes in water storage in a previously fixed tank volume were selected through mass balance equations [44]. Except for the Rippl method, for all continuous simulations, system performance was assessed through efficiency for different tank sizes. All the models addressed correspond to continuous simulations performed on a daily scale, differing in the mass balance equation that describes the behaviour of the amount of water stored.

2.2.3 Cost functions methods

One method that includes information on system costs was applied. The method is based on maximizing the return on investment on an annual scale from savings obtained by stop using potable water from the conventional system [9]. A ratio of unamortized investment costs was built according to tank size, which was contrasted against a curve associated to financial savings due to not using public mains water. Two functions were prepared to implement the method. The function of amortized costs was formulated considering the investment costs required for building a system for a defined tank size (Figure 3). To describe this function, a regression model that fits the investment-volume behaviour was used. The function of potable water savings costs was generated using the continuous simulation models YAS, YBS, θ and Neptune. The efficiencies found by the continuous simulations were multiplied by the annual demand, according to the proposed uses, to obtain the amount of water supplied by the RWH system per year. Subsequently, using the unit price of drinking water set by the utility, financial savings due to not using mains water from the utility were estimated.

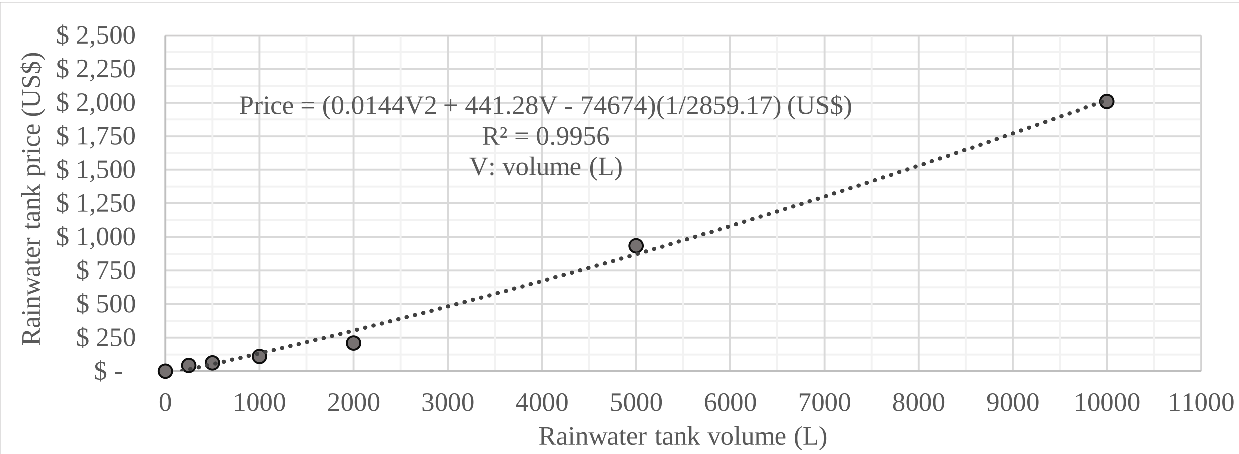


Figure 3. Adjustment curve which represents the cost of the tank according to its volume.

2.2.4 Statistical methods

This category comprised two methods: a) Nonparametric stochastic rainfall [6]; and b) Probabilistic model [53]. Both methods used the continuous mass balance equations YAS, YBS, θ and Neptune, since they allow assessing the performance for different tank sizes, but the methods provide a rainfall input provided by statistical methods.

The non-parametric stochastic rainfall generator method described an algorithm for the generation of a stochastic rainfall based on nonparametric techniques. This method uses probabilities to describe rainfall occurrence. However, these are derived directly from local observations, which allowed generating a portable model that works for any historical precipitation period. The tool "Estimation of Storage and Reliability" (in its acronyms SARET) [6] was used (See Supplementary Material).

For the method based on a probabilistic model, probabilistic relationships between tank capacity and supply deficit rates described by Su, et al. [53] were applied. For this, two steps were followed: i) a simulation model of mass balance, using water balance equations YAS, YBS, θ and Neptune; ii) a probabilistic model, adopting the concept of exceedance probability or return period to study the critical events in which the deficit rates are exceeded. For this, the probability distributions were integrated to generate a graph that describes the deficits based on the tank size for a certain return period. The probabilistic behaviour of the random variables was described by using the normal distribution, as proposed by Su, et al. [53].

2.3. Comparison of the results obtained with the sizing methods studied

A comparative analysis was carried out to identify methods with the greatest application potential for sizing rainwater storage tanks. Comparison was based on qualitative and quantitative criteria. To identify qualitative criteria for comparison of the methods, an extensive literature review was carried out. However, a limited number of studies comparing qualitative aspects of sizing methods were identified (i.e. [5, 22, 42, 63]). Consequently, qualitative criteria for comparison resulted from discussions among the group of authors. Six qualitative criteria were selected: conceptual robustness, associated to the theoretical development of the methods; synergy, linked to the potential of methods to join and improve results; predictive ability, based on the inclusion of future challenges and threats; variability in multiple simulations; information level required; and easiness of application. Quantitative comparison was based on the tank volumes obtained using the different sizing methods for all the efficiencies with 5% increments (see Tables 2 and 3). Qualitative comparison also included the results obtained for volumes with 65% of the maximum efficiency, since it is considered, this efficiency avoids tank oversizing. A proposal of the method that best fits the conditions of the study context is suggested, based on the quantitative and qualitative comparison between the methods.

2.4. Proposal of a decision support tool to assist in the selection of sizing methods

A decision support tool to assist in the selection of the tank sizing methodology was proposed. It was developed based on the improved understanding of the methods, as a result of their application in the two case studies. Selection criteria to initiate the DST were design objectives, information requirements and the practitioner's knowledge. The DST comprises a flow diagram where the input data are the design objectives and the available information of the context and the output is a recommended tank sizing method.

3. Results and Discussion

3.1 Application of the methods for sizing the storage tank

Volumes obtained from the application of each method to A and B are presented in Table 2 and 3, respectively. A relation between tank capacity and efficiency (i.e. if required by the method) for the methods is presented.

Simplified methods have the advantage of allowing quick and simple sizing using basic, annual and easily accessible information. However, these procedures are limited to small-scale projects where demand is approximately uniform over time (i.e. multifamily housing, offices, commercial and industrial buildings of small or medium size). These methods have disadvantages. For instance, they do not consider patterns of rainfall and demand at a resolution better than annual (i.e. monthly, daily, hourly). Tables 2 and 3 show that ANQIP [8], DNI [11] and EA [10] methods resulted in larger volumes compared to continuous simulations of mass balance methods, providing values close to those with efficiencies of 50% and 70% for A and B respectively, while the IRC method [13] yielded lower values. The first three methods generated similar tank sizes due to an empirical coefficient (Z_i, see Supplementary Material), which depend on the method, even though their values are similar across methods. This coefficient is a percentage applied to the volumes collected and demanded annually. In ANQIP [8], Z_i is associated to retention days; in IRC [13], Z_i is linked to climatic zone and design objective. For the two remaining methods [10, 11], Z_i is empirical. On the other hand, unlike the first three methods, the fourth does not choose the minimum value between supply and demand, which could lead to tank oversizing, in situations of significant rainfall and low demand.

The continuous simulation of mass balance methods are detailed procedures that allow monitoring the tank status during a certain period. These methods have ability to include temporal variability to any time interval, as long as rainfall records and demand patterns are available for a desired temporal resolution. These methods, with the exception of Rippl, analyse system behaviour through efficiency for different tank capacities, allowing users to decide on the desired performance. Data from Tables 2 and 3 show that not always an increase in tank volume results in a remarkable increase in efficiency. The behaviour resembles an asymptotic growth limited by maximum efficiency (i.e. defined as the ratio between the volume of rain stored in such a large tank – all the rain is harvested - and the general demand) (Figures 4 and 5). If required, maximum efficiency can be understood as the average of the input ratios (AR/D) [64], computed for each year, where A is the roof area, D annual demand, and R annual rainfall. The maximum efficiency can also be defined as the ratio between the volume of rain stored in such a large tank – all the rain is harvested - and the general demand.

From Tables 2 and 3, it is observed that YAS is more conservative, YBS less conservative, while $\theta = 0.5$ and Neptune provide intermediate values. YBS and $\theta = 0.5$ do not need a tank for small efficiencies, which could be inadequate. The Rippl method only provides a single result, corresponding to the water surplus required to be stored during rainy season to counteract drought. For this reason, Rippl could lead to tank oversizing. The result of Rippl for A was greater than volumes corresponding to the maximum efficiency volumes obtained with the continuous simulation of mass balance methods. Opposite results were obtained in B. Understanding this behaviour facilitates selecting the method when looking to supply the total demand. This is due to the supply-demand relationship measured by the average of the annual input ratios (AR/D) of the system or the maximum efficiency, which is lower for A (0.5804) than for B (0.899). In other words, if AR/D is close to cero, this means that the proposed system allows capturing a small volume of rainfall with respect to what is demanded, Rippl will probably result in greater oversizing compared to the other continuous simulation of mass balance methods. In the opposite situation, when AR/D is close to one, this means the proposed system allows capturing a significant volume of rainfall with respect to what is demanded. Thus, the continuous simulation of mass balance methods will probably result in greater oversizing compared to the Rippl.

Table 2. Results from the methods studied for sizing the storage tank - A.

<table>
<tr><th rowspan="2">Group</th><th rowspan="2" colspan="2">Method</th><th colspan="13">Efficiency (%)</th><th>Max.</th></tr>
<tr><th>0%</th><th>5%</th><th>10%</th><th>15%</th><th>20%</th><th>25%</th><th>30%</th><th>35%</th><th>40%</th><th>45%</th><th>50%</th><th>55%</th><th>57%</th><th>58.04%</th></tr>
<tr><td rowspan="4">Simplified</td><td colspan="2">ANQIP (M1)</td><td colspan="14">1114</td></tr>
<tr><td colspan="2">DNI (M2)</td><td colspan="14">1444</td></tr>
<tr><td colspan="2">EA (M3)</td><td colspan="14">1203</td></tr>
<tr><td colspan="2">IRC (M4)</td><td colspan="14">527</td></tr>
<tr><td rowspan="5">Continuous simulation of mass balance</td><td colspan="2">YAS (M5)</td><td>0</td><td>27</td><td>61</td><td>102</td><td>153</td><td>214</td><td>294</td><td>404</td><td>563</td><td>818</td><td>1274</td><td>2442</td><td>4041</td><td>10890</td></tr>
<tr><td colspan="2">YBS (M6)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>36</td><td>107</td><td>208</td><td>356</td><td>599</td><td>1047</td><td>2202</td><td>3808</td><td>10711</td></tr>
<tr><td colspan="2">θ = 0.5 (M7)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>56</td><td>111</td><td>177</td><td>276</td><td>425</td><td>668</td><td>1118</td><td>2273</td><td>3872</td><td>10728</td></tr>
<tr><td colspan="2">Neptune (M8)</td><td>0</td><td>18</td><td>41</td><td>72</td><td>110</td><td>158</td><td>229</td><td>328</td><td>477</td><td>721</td><td>1171</td><td>2326</td><td>3911</td><td>10748</td></tr>
<tr><td colspan="2">Rippl (M9)</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td><td>19326</td></tr>
<tr><td rowspan="4">Cost-function</td><td rowspan="4">Economic sizing method (M10)</td><td>YAS</td><td colspan="7">630</td><td colspan="7">Associated with an annual profitability of 17.52 (US$) and an efficiency of 41.6%</td></tr>
<tr><td>YBS</td><td colspan="7">440</td><td colspan="7">Associated with an annual profitability of 20.11 (US$) and an efficiency of 42.1%</td></tr>
<tr><td>θ = 0.5</td><td colspan="7">510</td><td colspan="7">Associated with an annual profitability of 19.27 (US$) and an efficiency of 42.1%</td></tr>
<tr><td>Neptune</td><td colspan="7">560</td><td colspan="7">Associated with an annual profitability of 18.62 (US$) and an efficiency of 42.0%</td></tr>
<tr><td rowspan="16">Statistical</td><td rowspan="4">Nonparametric method (M11)</td><td>YAS</td><td>0</td><td>28</td><td>63</td><td>109</td><td>162</td><td>229</td><td>321</td><td>440</td><td>692</td><td>979</td><td>1600</td><td>5866</td><td>7974</td><td>11018</td></tr>
<tr><td>YBS</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>52</td><td>126</td><td>261</td><td>439</td><td>695</td><td>1506</td><td>4781</td><td>6978</td><td>7917</td></tr>
<tr><td>θ = 0.5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>67</td><td>130</td><td>203</td><td>322</td><td>466</td><td>793</td><td>1412</td><td>4557</td><td>7712</td><td>9545</td></tr>
<tr><td>Neptune</td><td>0</td><td>19</td><td>44</td><td>77</td><td>116</td><td>176</td><td>253</td><td>368</td><td>541</td><td>851</td><td>1569</td><td>4287</td><td>5644</td><td>7901</td></tr>
<tr><td rowspan="12">Probabilistic method (M12)</td><td>YAS Tr = 2 Years</td><td>0</td><td>30</td><td>65</td><td>105</td><td>155</td><td>215</td><td>295</td><td>405</td><td>565</td><td>820</td><td>1275</td><td>2445</td><td>4045</td><td>10920</td></tr>
<tr><td>YAS Tr = 5 Years</td><td>0</td><td>35</td><td>70</td><td>120</td><td>175</td><td>250</td><td>350</td><td>500</td><td>755</td><td>1270</td><td>3590</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>YAS Tr = 10 Years</td><td>0</td><td>35</td><td>75</td><td>125</td><td>190</td><td>270</td><td>385</td><td>570</td><td>950</td><td>1915</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>YBS Tr = 2 Years</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>40</td><td>110</td><td>210</td><td>360</td><td>600</td><td>1050</td><td>2205</td><td>3810</td><td>10715</td></tr>
<tr><td>YBS Tr = 5 Years</td><td>0</td><td>0</td><td>0</td><td>0</td><td>5</td><td>70</td><td>160</td><td>300</td><td>535</td><td>1045</td><td>3370</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>YBS Tr = 10 Years</td><td>0</td><td>0</td><td>0</td><td>0</td><td>20</td><td>95</td><td>200</td><td>365</td><td>725</td><td>1710</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>θ = 0.5 Tr = 2 Years</td><td>0</td><td>0</td><td>0</td><td>0</td><td>60</td><td>115</td><td>180</td><td>280</td><td>430</td><td>670</td><td>1120</td><td>2275</td><td>3875</td><td>10735</td></tr>
<tr><td>θ = 0.5 Tr = 5 Years</td><td>0</td><td>0</td><td>0</td><td>20</td><td>85</td><td>145</td><td>230</td><td>365</td><td>605</td><td>1120</td><td>3435</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>θ = 0.5 Tr = 10 Years</td><td>0</td><td>0</td><td>0</td><td>30</td><td>95</td><td>165</td><td>260</td><td>430</td><td>795</td><td>1790</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Neptune Tr = 2 Years</td><td>0</td><td>20</td><td>45</td><td>75</td><td>115</td><td>160</td><td>230</td><td>330</td><td>480</td><td>725</td><td>1175</td><td>2330</td><td>3915</td><td>10755</td></tr>
<tr><td>Neptune Tr = 5 Years</td><td>0</td><td>25</td><td>50</td><td>85</td><td>130</td><td>195</td><td>280</td><td>420</td><td>655</td><td>1170</td><td>3435</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Neptune Tr = 10 Years</td><td>0</td><td>25</td><td>55</td><td>95</td><td>145</td><td>215</td><td>315</td><td>485</td><td>845</td><td>1825</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td></tr>
</table>

Notes: NA: Not applicable since the method does not allow linking volume and efficiency (i.e. M9) or because the method has particularities that prevent this (i.e. M12). In all cases, volumes are in litres.

Table 3. Results from the methods studied for sizing the storage tank - B.

Group	Method		Efficiency (%) 0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	87%	Max. 89.9%
Simplified	ANQIP (M1)		3988																			
	DNI (M2)		5169																			
	EA (M3)		4307																			
	IRC (M4)		1888																			
Continuous simulation of mass balance	YAS (M5)		0	54	117	191	277	374	488	625	787	995	1270	1652	2200	2962	4241	6384	11932	32377	48347	64232
	YBS (M6)		0	0	0	0	0	0	53	173	319	509	759	1126	1657	2409	3691	5786	11359	31704	47674	63725
	θ = 0.5 (M7)		0	0	0	0	0	119	231	341	482	669	920	1288	1814	2565	3838	5945	11518	31856	47826	63761
	Neptune (M8)		0	35	75	127	188	259	343	455	605	792	1047	1415	1934	2697	3964	6082	11662	31962	47932	63861
	Rippl (M9)		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	14801
Cost-function	Economic sizing method (M10)	YAS	1710	Associated with an annual profitability of 52.01 (US$) and an efficiency of 55.6%																		
		YBS	1285	Associated with an annual profitability of 58.97 (US$) and an efficiency of 56.7%																		
		θ = 0.5	1435	Associated with an annual profitability of 56.87 (US$) and an efficiency of 56.6%																		
		Neptune	1565	Associated with an annual profitability of 55.23 (US$) and an efficiency of 56.6%																		
Statistical	Nonparametric method (M11)	YAS	0	57	126	205	303	406	520	686	892	1130	1381	1779	2358	3269	4620	6885	16383	33823	45954	54770
		YBS	0	0	0	0	0	0	122	215	371	626	826	1374	1831	2819	4124	6215	12145	29491	46446	46152
		θ = 0.5	0	0	0	0	0	156	265	403	561	773	1019	1478	2055	3271	4082	7117	17297	34466	41986	39616
		Neptune	0	37	80	136	200	281	379	518	676	893	1243	1587	2083	3007	4604	8287	15145	48480	60609	50480
	Probabilistic method (M12)	YAS Tr = 2 Years	0	55	120	195	280	375	490	630	790	1000	1275	1655	2205	2965	4245	6385	11935	32380	48350	64235
		YAS Tr = 5 Years	0	65	140	230	325	440	575	750	975	1285	1715	2355	3325	5040	8185	21210	NA	NA	NA	NA
		YAS Tr = 10 Years	0	75	155	250	355	480	635	840	1120	1505	2085	2950	4535	7065	18140	NA	NA	NA	NA	NA
		YBS Tr = 2 Years	0	0	0	0	0	0	55	175	320	510	760	1130	1660	2410	3695	5790	11360	31705	47675	63730
		YBS Tr = 5 Years	0	0	0	0	0	40	165	320	515	795	1210	1825	2785	4485	7580	20865	NA	NA	NA	NA
		YBS Tr = 10 Years	0	0	0	0	0	95	235	415	660	1020	1575	2435	4005	6490	17815	NA	NA	NA	NA	NA
		θ = 0.5 Tr = 2 Years	0	0	0	0	0	120	235	345	485	670	925	1290	1815	2570	3840	5950	11520	31860	47830	63765
		θ = 0.5 Tr = 5 Years	0	0	0	0	85	210	320	470	670	940	1355	1970	2920	4635	7740	20895	NA	NA	NA	NA
		θ = 0.5 Tr = 10 Years	0	0	0	0	130	250	380	560	800	1160	1715	2570	4145	6630	17925	NA	NA	NA	NA	NA
		Neptune Tr = 2 Years	0	40	80	130	190	260	345	460	610	795	1050	1420	1935	2700	3965	6085	11665	31965	47935	63865
		Neptune Tr = 5 Years	0	50	100	165	235	325	435	585	790	1065	1480	2090	3050	4765	7895	20980	NA	NA	NA	NA
		Neptune Tr = 10 Years	0	55	115	185	265	360	495	680	920	1290	1835	2700	4270	6765	18030	NA	NA	NA	NA	NA

Notes: NA: Not applicable since the method does not allow linking volume and efficiency (i.e. M9) or because the method has particularities that prevent this (i.e. M12). In all cases, volumes are in litres.

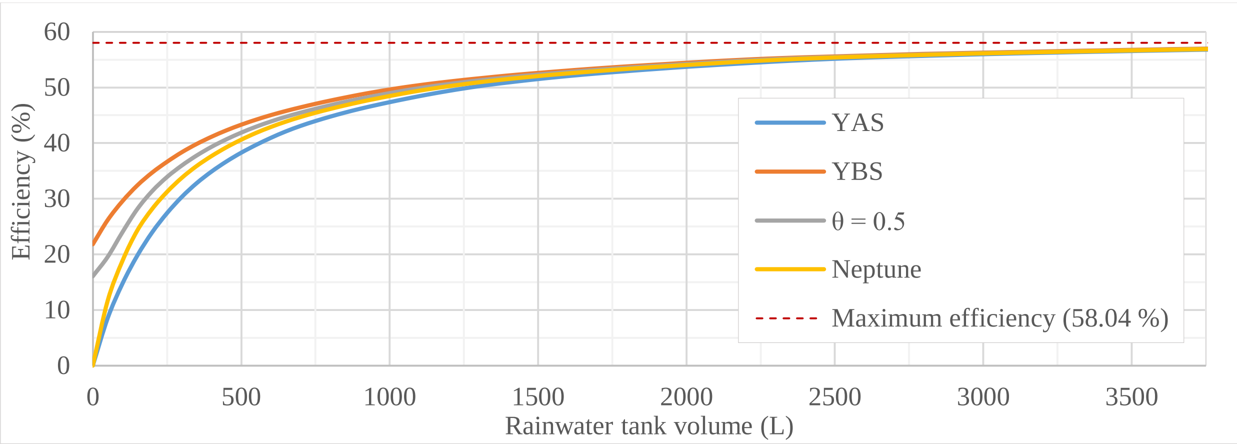


Figure 4. Efficiency in terms of volume for A.

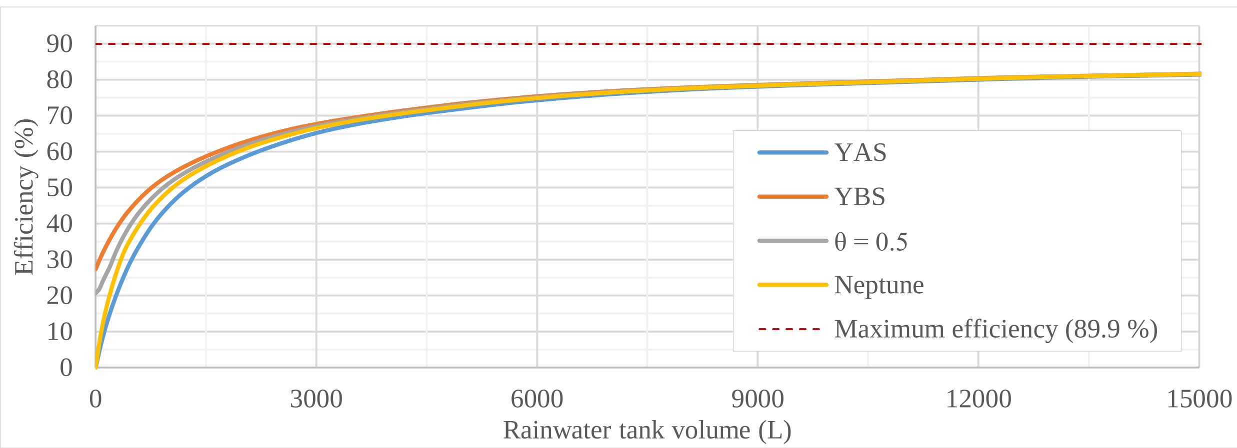


Figure 5. Efficiency in terms of volume for B.

Cost-based sizing adopts all characteristics from continuous simulation of mass balance methods (YAS, YBS, $\theta = 0.5$ and Neptune). This alternative requires easily accessible data, except for the amortized cost function of the system, which demand a detailed study. The behaviour of financial savings from drinking water as a function of tank capacity (Figures 6 and 7) is similar to that shown by efficiency curves (Figures 4 and 5). Figures 6 and 7 show the method allows assessing several options. However, in this case the most profitable situation corresponds to a single volume associated with a point behind the asymptotic growth, a volume corresponding to efficiency between 60% and 85% of the maximum efficiency approximately. This percentage tends to be 85% for cases of low maximum efficiency and similar to 60% for cases of higher maximum efficiency. For instance, B has a maximum efficiency closer to 100% (or an AR/D close to one). Thus, the volume obtained through this method is linked to efficiency close to 60% of the maximum efficiency. For the proposed conditions, cost-based sizing showed that the investment is profitable, with yields close to 17.49 (US$) for A and 55.96 (US$) for B.

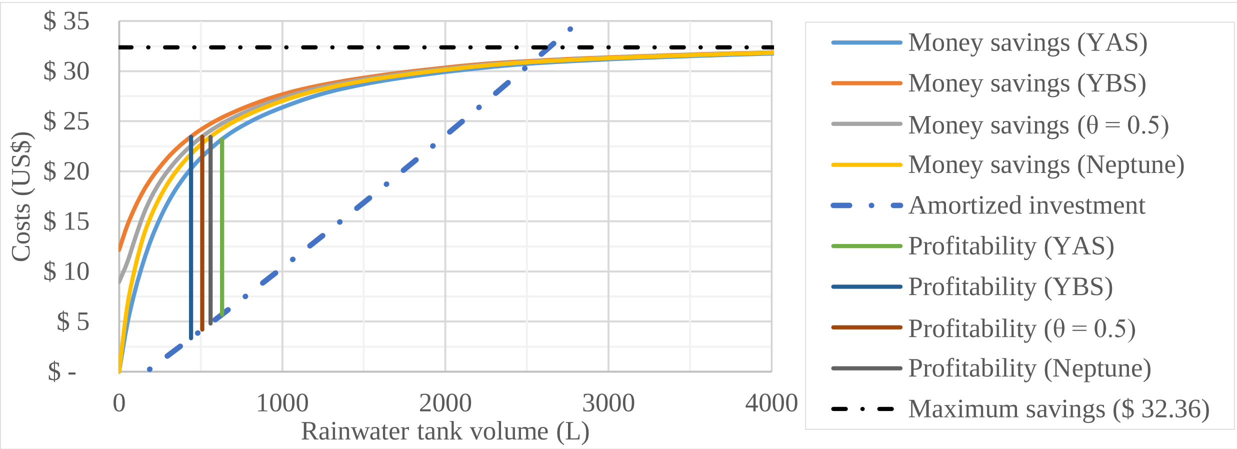


Figure 6. Investment and money savings on an annual scale according to tank size for A.

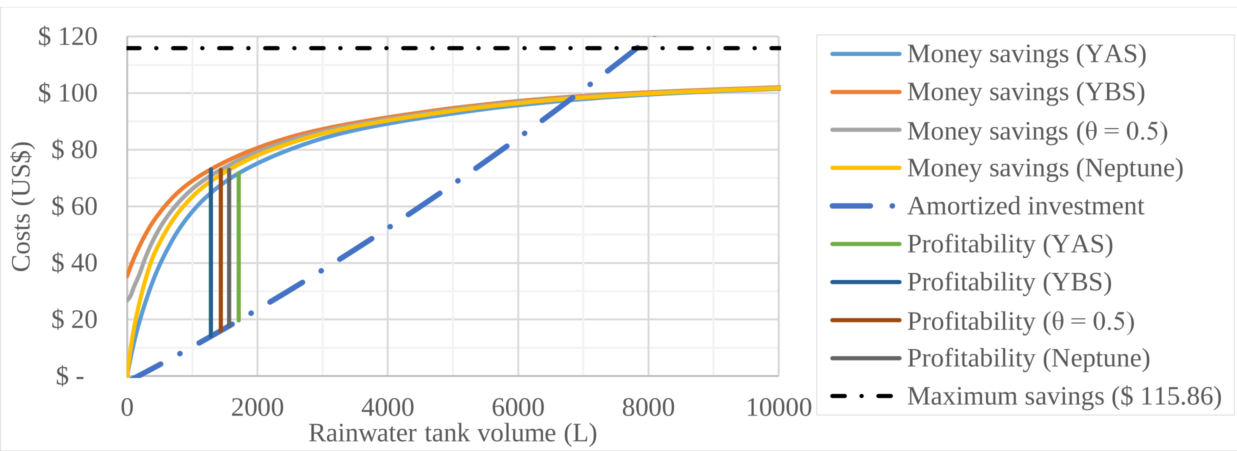


Figure 7. Investment and money savings on an annual scale according to tank size for B.

Regarding statistical methods, the nonparametric method generates stochastic rainfall samples from an algorithm based on random values. This rainfall samples can be input data to any other continuous water balance simulation. Volumes in Tables 2 and 3 indicate that for most efficiencies, results are more conservative compared to the values calculated using the methods of continuous simulations of mass balance. However, this behaviour may not apply for efficiencies near the maximum. The results of this method can vary because the algorithm is based on random numbers; that is, each new simulation generates new rainfall samples that provide different volumes for the same efficiency. Figure 8 shows how the variability in the results tends to decrease for larger efficiencies. Despite the variability, the method has the advantage that it does not require the adoption of a probability density function that fits the data. The probabilistic method is also more conservative than the continuous simulations of mass balance methods. However, for high return periods it is difficult to reach higher efficiencies, this is because for more adverse conditions, the method decreases the maximum efficiency (see Tables 2 and 3 and Figure 9).

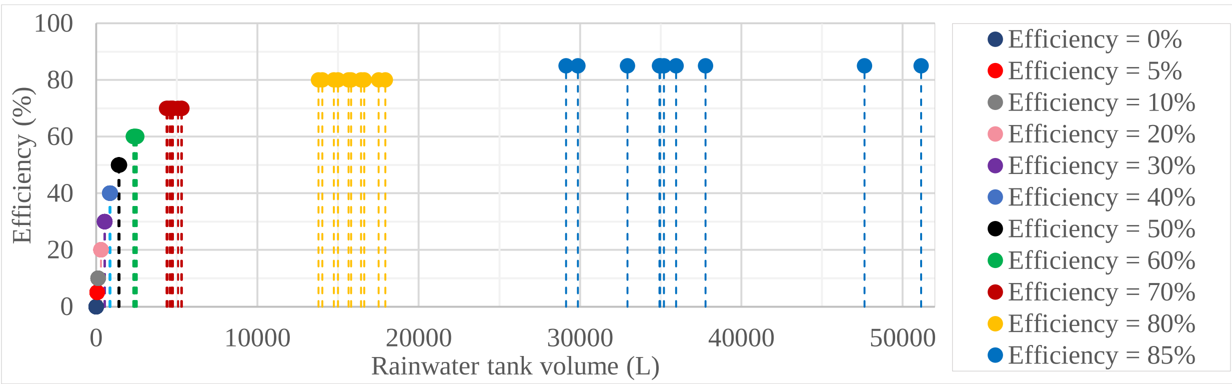


Figure 8. Nonparametric method variability behaviour for ten simulations and different efficiencies (each colour), example for B using YAS balance equations.

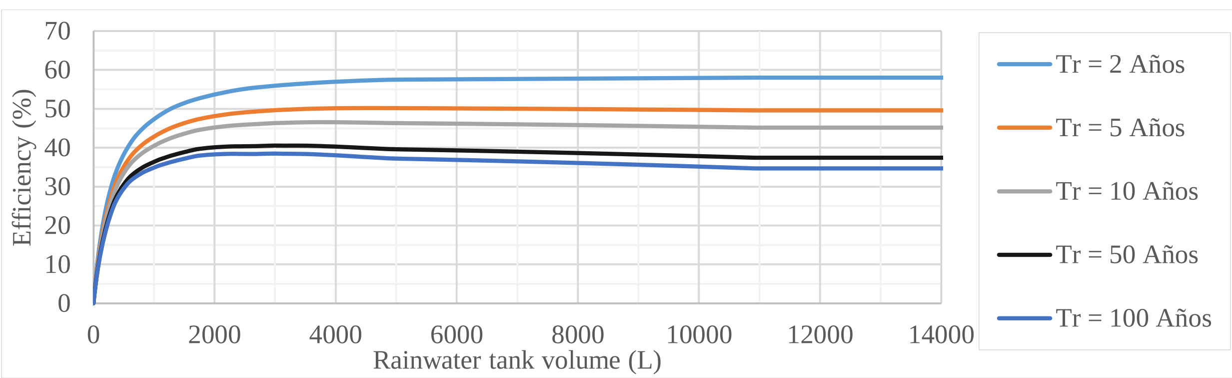


Figure 9. Decay of maximum efficiency for incremental return periods (Tr), YAS simulation for A.

3.2 Analysis of tanks sizing

The comparison of the results obtained from the different sizing alternatives demonstrates the quantitative and qualitative differences between the methods. Quantitatively, tank volume varies between the methods according to the suggested efficiency, which presents the asymptotic behaviour described (Figures 4 and 5). To facilitate the analysis and avoid tank oversizing without obtaining greater benefits, it is suggested to design for a volume associated with an efficiency of approximately 65% of maximum efficiency (Figure 10) (i.e. point prior to asymptotic growth), as long as the maximum efficiency is less than 100%. Figure 10 shows that although some methods (i.e. M1, M2, M3, M4, M10 and M9) do not allow designing for different efficiencies, two of these (i.e. M4 and M10) provide results near to the point behind the asymptotic growth (65% efficiency) raised, while others (i.e. M1, M2, M3 and M9) tend to oversize the system.

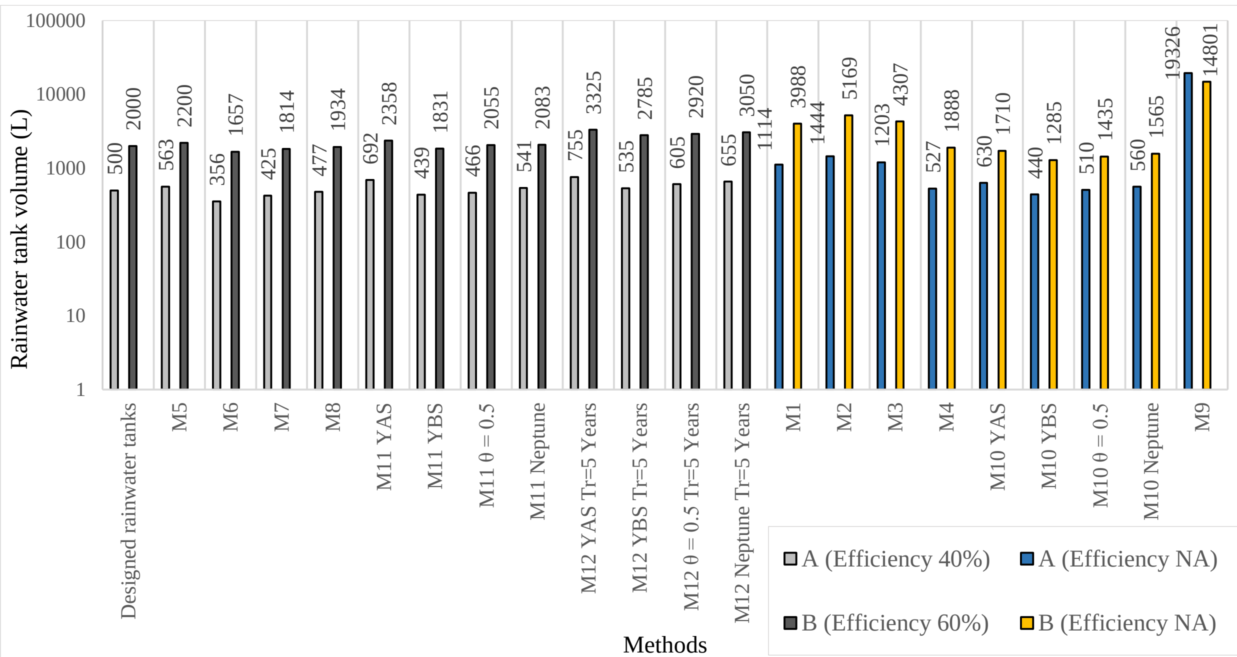


Figure 10. Volumes calculated by different methods for a predefined efficiency level, including methods that are not based on efficiencies.

Note: NA: Not applicable.

Regarding the designed tanks in the analysed study cases (500-L for A and 2000-L for B), the volumes were similar to those associated with 65% of maximum efficiency (Figure 10). This rules out that the selection of commercial volumes has led to unnecessary system oversizing. Considering that different methods provide different volumes for different efficiencies, problems could arise when choosing commercially available tank volumes, as these could be above or below the ideal volume. The methods analysed allow the choice of the upper or lower commercial limit of the tank volume based on the analysis of the behaviours regarding saving-investment and volume-efficiency.

Analysing the measures of dispersion from the methods in Figure 10 (Table 4), it is evident that if only the methods that design for 65% of the maximum efficiency are considered, the coefficient of variation of A is similar to that of B. However, the volume ranges are greater in B because the requirements are higher compared to those in A. This behaviour shows that the greater the demand of the system, a more detailed analysis is required because the choice of method is not limited to small ranges (i.e. 399 litres for A) but considers higher ranges (i.e. 1668 litres for B or even higher) that could unnecessarily affect the volume and costs of the system. On the other hand, considering all the methods (i.e. those that include efficiencies and those that do not), Table 10 shows that the coefficient of variation and the range are greater in A than in B, this is because for A, Rippl oversizes the system unnecessarily, which does not happen in B. Therefore, when quantifying the volume, it is important to discriminate the methods that allow choosing any efficiency and those that do not, due to the order of magnitude in the ranges of the results.

Table 4. Dispersion measures for the results in Figure 10.

Method	Arithmetic mean (L)	Range (L)	Mean absolute deviation (L)	Standard deviation (L)	Coefficient of variation (%)
Methods for A (Efficiency: 40%)	542	399	93	118	22
Methods for B (Efficiency: 60%)	2334	1668	461	551	24
All methods for A	1536	18970	1694	4086	266
All methods for B	3055	13516	1554	2877	94

Qualitatively, it is evident that the conceptual differences represent advantages for some methods compared to others. Table 5 shows that, if possible, the design using simplified methods should be avoided. Thus, provided that the tools and information required are available, the statistical methods and the cost method, which also include mass balances should be the preferred alternatives for tank sizing.

Table 5. Qualitative comparison of the storage tank sizing methods.

Method	Conceptual robustness	Potential for incorporation into other methods	Capacity to adapt to changes (resilience)	Variability	Information required	Difficulty of application
ANQIP (M1)	++	+	++	++++	++	+
DNI (M2)	+	+	+	++++	++	+
EA (M3)	+	+	+	++++	++	+

IRC (M4)	+	+	++	++++	++	+
YAS (M5)	+++	+++++	+++	++++	+++	+++
YBS (M6)	+++	+++++	+++	++++	+++	+++
θ = 0.5 (M7)	+++	+++++	+++	++++	+++	+++
Neptune (M8)	+++	+++++	+++	++++	+++	+++
Rippl (M9)	+++	++	+++	++++	+++	+++
Cost-function (M10)	++++	+++++	++++	++++	++++	++++
Nonparametric (M11)	++++	+++	++++	++	+++	+++++
Probabilistic (M12)	++++	++++	++++	++++	++++	++++

Notes: The symbols correspond to very high (+++++), high (++++), medium (+++), low (++) and very low (+).

3.3 Development of a Decision Support Tool

As discussed in the Introduction, a literature review identified limited decision support for practitioners in the selection of the most convenient method, considering relevant criteria. Consequently, based on the previous sections, which have presented a comprehensive comparison of different methods of sizing rainwater storage tanks, a decision support tool is proposed for use in different contexts, catering for the end-user and based on design goals, which may vary according to the project characteristics and priorities. The following aspects were identified as key to the selection of the sizing method:

- For small-scale rainwater harvesting, and availability of only annual rainfall records, the most recommended methods are simplified methods, since the lack of information would prevent the use of statistical or continuous simulations of mass balance methods.
- For systems that require a level of performance, the methods that allow the selection considering system performance based on the tank capacity (YAS, YBS, θ and Neptune) are recommended.
- For systems where rainwater availability broadly meets demand, and the total demand must be satisfied, Rippl is the most appropriate method because it calculates volume without oversizing, as the other methods that use mass balances would.
- For systems where it is required to incorporate potable water savings into the analysis when implementing a RWH system, the methods that estimate the tank volume and offer the best profitability are recommended.
- For systems where water provision relies heavily on RWH, safety factors and future projected capacities must be considered. Therefore, probabilistic methods are recommended, since they incorporate the probability of exceeding the deficit for a range of

capacities and efficiencies. Another alternative is the method based on a nonparametric rainfall generator, which adjusts well to different precipitation patterns, but may have difficulties in the results variability.

When the input information is not a limiting factor, the combination of the mass balance, cost-function and probabilistic methods is proposed. The probabilistic method (M12) and the cost-function method (M10) are compatible with the continuous simulation methods (YAS (M5), YBS (M6), θ (M7) and Neptune (M8)), generating synergies (Table 5). For example: conceptual robustness, by using the three most robust methods; potential for incorporation into other methods (i.e. this combination can easily be incorporated into any method that generates rainfall from climate predictions); resilience, when considering precipitation forecasts and cost analysis. In addition, this approach does not have variability issues since the methods that comprise the proposed combination do not rely on random values to perform their internal processes, therefore, for each new simulation (under the same conditions), the same results are obtained. This combination considers key aspects of the design and study context, which represents a high application potential in places where the required information is easily accessible.

As well as the inclusion of climate change, introduced in the proposed tool through the statistical methods, an improvement in terms of resilience, would be the consideration of stormwater attenuation, as has been suggested in studies in the field [7, 12, 51, 54, 65-68].

There are also RWH tank sizing approaches which use pluviograph rainfall data with 6 minute time steps, together with daily temperature records, and probabilistic behavioural water demand models to account for variability in rainfall inputs and climate dependent household water demand throughout each day [69]. According to studies in Australia [69], this dimensioning approach overcomes under-sizing of RWH tanks (8 – 19%) that are incurred when using the assumption of a daily time step for rainfall inputs and daily average water demand. However, this approach demands both climatic and consumption information that may not be available for system planning in many contexts, which may limit its application. In some of their works, these authors used pluviograph (6 minute) rainfall inputs and household water consumptions monitored at 6 minute intervals using smartmeter data obtained from real households [70].

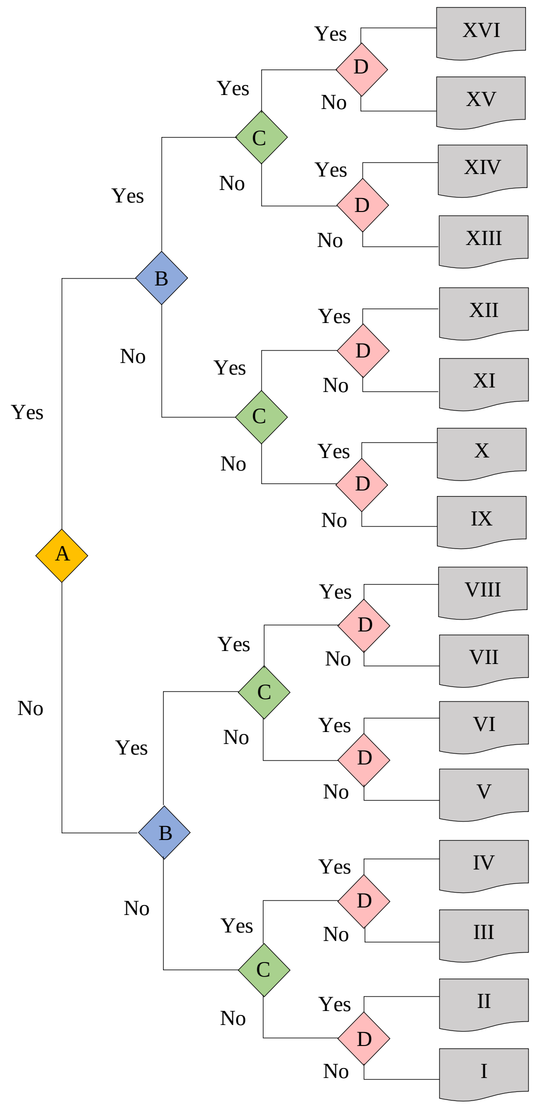
On the other hand, the economic benefits associated to RWH have been captured in this research taking into account sizing methods which depend on maximizing the return on investment on an annual scale from savings obtained by stop using potable water from the conventional system [9]. This analysis is limited since it has been recognized that RWH have economic benefits beyond not using public mains water [58]. An improved economic analysis of RWH should go beyond the direct costs and benefits for the homeowner and include broader study of the costs and benefits that the implementation of these systems represents for the society as a whole [71]. For instance, the economic benefits to the community are derived from mains water savings, construction and depreciation savings resulting from a reduced requirement for stormwater infrastructure and interest earned on community savings due to the deferral of new water supply dams [72].

As a decision support tool, a four-stage flow chart (Figure 11), which includes the 12 methods studied, was prepared. Each stage is a question that the practitioner must answer to achieve the selection of the method. The first stage (A) filters the possible methods based on the information available for the design. The subsequent stages (B, C and D) consider the design objectives. As an example of application, two hypothetical scenarios were considered:

Scenario 1 - A practitioner aims to design a RWH system to obtain a financial benefit by stopping extracting water from the mains system to supply at least a fraction of the total non-potable consumption of a household. In addition, the practitioner has detailed input data. Thus, the route followed in the flow chart is: A-Yes, B-Yes, C-Yes and D-No. This leads to option XV, which suggests using any of the mass balance methods, combined with the cost function method.

Scenario 2 - A practitioner seeks to design a RWH system with the single objective of achieving 100% reduction in the water required for flushing toilets, but only has annual rainfall information. The route followed in the flow chart is: A-No, B-No, C-No and D-No, which leads to option I, which suggests that with the methods considered, it is not possible to generate the tank size for the purpose desired without having more detailed information. This would suggest to the practitioner that they obtain a greater resolution of rainfall data – perhaps from the nearest rain gauge possible, or that installation of a rain gauge and delayed implementation of RWH might be the most sensible way to proceed.

In this way, the tool would facilitate the selection of the sizing method among the twelve methods considered. However, in the literature there are a number of methods not included in the tool that could be incorporated under future research. Similarly, there are sizing criteria that were not incorporated. For example, in the latter aspect, the criteria related to stormwater attenuation, reduction of pressure on sewerage systems, or facing specific climate variability and change scenarios were not included [7, 12, 55, 73, 74]. Future research could represent an improvement in terms of resilience in the DST, if consideration of stormwater attenuation was included to complement the inclusion of climate change, which is already included in the tool through the statistical methods.



A Is there an availability of hourly, daily or monthly rainfall records and demand patterns?

Yes: Supply and demand records are available at hourly, daily or monthly scale.
No: Only annual records of supply and demand are available.

B Is it a fraction of the total water demand which must be provided?

Yes: The system must satisfy end-uses that are not the total demand.
No: The design must satisfy the total demand.

C Should the financial implications of the selection be considered?

Yes: Money savings and investments on the system should be assessed.
No: Money savings and investments on the system are not a relevant criteria.

D Is it considered relevant to include a safety factor?

Yes: It is desirable to be conservative, considering potentially adverse scenarios.
No: It is not desirable to be conservative, considering adverse scenarios.

Recommendations:

- I, II, III, IV, VI, VII y VIII: The objectives may be in conflict, it is recommended to look for more detailed information.
- V: Methods M1, M2, M3 or M4 could be used.
- IX: Any of the continuous simulations of mass balance methods could be used (M5, M6, M7 or M8) to obtain maximum supply and then compare the result with the method M9 to select the lower value between the results of the two methods.
- X: Use what is proposed for IX and if the lowest value was obtained from the mass balance methods, use a conservative method (M11 or M12).
- XI: Use what was proposed for IX and if the lowest value was obtained from the mass balance methods, combine with the M10 method.
- XII: Use what was proposed for IX and if the lowest value was obtained from the mass balance methods, combine with the M10 method and a conservative method (M11 or M12).
- XIII: Use any of the methods M5, M6, M7 or M8.
- XIV: Use what is proposed for XIII and combine with a conservative method (M11 or M12).
- XV: Use what is proposed for XIII and combine with the M10 method.
- XVI: Use what is proposed for XIII, combine with the M10 method and a conservative method (M11 or M12).

Figure 11. Synthesis of recommendations for the selection of a rainwater harvesting system storage tank sizing method – a Decision Support Tool.

4. Conclusions

Twelve methods for storage tank sizing from four categories (i.e. simplified methods, methods of continuous simulation of mass balance, cost-function method and statistical methods) were applied in low (130 lpcd) and high (203 lpcd) water consumption individual households. Seven methods yielded results depending on tank efficiency. Tank sizes for these methods showed important quantitative differences. In both case studies, the tank sizes in descending order were for the YAS, Neptune, θ and YBS methods. The five methods that provided a single tank size had the following volumes for low and high consumption households respectively: Rippl: 19326 L and 14801 L, DIN: 1444 L and 5169 L, ANQIP: 1114 L and 3988 L, EA: 1203 L and 4307 L and IRC: 527 L and 1888 L.

When the results of the twelve methods were compared (i.e. using for the seven methods that require it, optimal efficiencies of 40% and 60%, for the households with low and high consumption respectively), it was evidenced that the methods that provide a single capacity value tend to overestimate the tank size. The other seven methods yielded values close to the tanks originally designed and around the commercial sizes available. The installation of commercial tanks affects the precision generated by the application of the methods.

The qualitative comparison based on the six variables described complements the qualitative criteria, improving the selection process and is an approach that to the authors' knowledge had not been explicitly addressed in the existing literature on tank sizing methods. The qualitative analysis showed that there are underlying conceptual differences in the approach of the methods. In addition, the methods that are potentially more resilient and adaptable in comparison to other methods are promising alternatives for thoughtful and rigorous sizing strategies.

The application of the methods for tank sizing showed that the decision on the most appropriate method is sensitive to criteria such as: contextual information, simulation tool availability, the design objective/s and the maximum efficiency required for the system. Generally, simplified methods should be avoided and for the cases presented a diversified approach combining continuous simulation of mass balance methods, cost-function and statistical methods was most appropriate when considering key contextual and design aspects. This led to the development of a decision support tool to assist international rainwater harvesting practitioners with tank sizing method selection, which should ensure that future system designs better incorporate uncertainty and resilience.

Conflicts of Interest

There are no conflicts of interest to declare

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References

1. A. Campisano, D. Butler, S. Ward, M. J. Burns, E. Friedler, K. DeBusk, L. N. Fisher-Jeffes, E. Ghisi, A. Rahman, H. Furumai and M. Han, *Water Res.*, 2017, **115**, 195-209.
2. S. Sendanayake, N. P. Miguntanna and M. T. R. Jayasinghe, *Asian J. Wat. Environ. Pollut.*, 2014, **11**, 87-93.
3. X. Yan, S. Ward, D. Butler and B. Daly, *J. Clean. Prod.*, 2018, **172**, 2167-2173.
4. L. Handia, J. M. Tembo and C. Mwiindwa, *Phys. Chem. Earth*, 2003, **28**, 893-896.
5. C. Santos and F. Taveira-Pinto, *Resour. Conserv. Recycl.*, 2013, **71**, 1-6.
6. M. Basinger, F. Montalto and U. Lall, *J. Hydrol.*, 2010, **392**, 105-118.
7. P. Melville-Shreeve, S. Ward and D. Butler, *Water*, 2016, **8**.
8. A.-A. n. p. a. q. n. i. predials, Portugal, 2015, vol. ETA 0701
9. G. López-Patiño, F. J. Martínez-Solano, V. S. Fuertes-Miquel and P. A. López-Jiménez, *Tecnologia Ciencias Agua*, 2011, **2**, 51-64.
10. E. Agency, *Harvesting rainwater for domestic uses: an information guide. Bristol: Environment Agency*, Environmental Agency, Almondsbury, Bristol 2010.
11. DNI, *Rainwater harvesting systems- Part 1: Planning, installation, operation and maintenance*, Deutsches Institut für Normung, 2002.
12. R. Kellagher, *Stormwater management using rainwater harvesting*, HR Wallingford, UK, 2012.
13. T. Thomas and D. Martinson, *Roofwater Harvesting: A Handbook for Practitioners.*, Technical Paper Series, Delft, The Netherlands, 2007.
14. UNEP, *Rainwater Catch it While You Can: A Handbook on Rainwater Harvesting in the Caribbean*, ONU, USA, 2009.
15. A. Fewkes, *Struct. Surv.*, 2012, **30**, 174-194.
16. A. Fewkes, *Urban Water*, 2000, **1**, 323-333.
17. E. Ghisi and M. Marcel, *Neptuno 4 - Manual de usuario*, Universidad Federal de Santa Catarina – UFSC, Florianópolis, Brazil, 2014.
18. A. Campisano and C. Modica, 2014.
19. A. Fewkes, *Build. Environ.*, 1999, **34**, 765-772.
20. C. H. Liaw and Y. C. Chiang, *Water*, 2014, **6**, 3913-3933.
21. L. Liuzzo, V. Notaro and G. Freni, *Water*, 2016, **8**.

22. S. Ward, F. A. Memon and D. Butler, in *Water Sci. Technol.*, IWA Publishing, 2010, vol. 61, pp. 85-96.
23. E. Hajani and A. Rahman, *Water*, 2014, **6**, 945-960.
24. M. A. Imteaz, A. Ahsan, J. Naser and A. Rahman, *Resour. Conserv. Recycl.*, 2011, **56**, 80-86.
25. M. A. Imteaz, A. Rahman and A. Ahsan, *Resour. Conserv. Recycl.*, 2012, **66**, 1-7.
26. M. A. Imteaz, A. Shanableh, A. Rahman and A. Ahsan, *Resour. Conserv. Recycl.*, 2011, **55**, 1022-1029.
27. M. R. Karim, M. Z. I. Bashar and M. A. Imteaz, *Resour. Conserv. Recycl.*, 2015, **104**, 61-67.
28. A. Khastagir and N. Jayasuriya, *J. Hydrol.*, 2010, **381**, 181-188.
29. A. Rahman, J. Keane and M. A. Imteaz, *Resour. Conserv. Recycl.*, 2012, **61**, 16-21.
30. E. L. Villarreal and A. Dixon, *Build. Environ.*, 2005, **40**, 1174-1184.
31. A. Fewkes and D. Butler, Rainwater Catchment Systems Conference-“Rainwater Catchment: An Answer to the Water Scarcity of the Next Millennium.” Petrolina, Brazil, 1999.
32. V. G. Mitchell, *Hydrological Processes: An International Journal*, 2007, **21**, 2850-2861.
33. E. Ghisi, *Water Resour. Manage.*, 2010, **24**, 2381-2403.
34. E. Ghisi, D. L. Bressan and M. Martini, *Build. Environ.*, 2007, **42**, 1654-1666.
35. E. Ghisi and P. N. Schondermark, *Water Resour. Manage.*, 2013, **27**, 2555-2576.
36. E. Ghisi, D. d. F. Tavares and V. L. Rocha, *Resour. Conserv. Recycl.*, 2009, **54**, 79-85.
37. K. Jung, T. Lee, B. G. Choi and S. Hong, *Water Resour. Manage.*, 2014, **29**, 961-972.
38. A. C. Lopes, R. F. Rupp and E. Ghisi, *Water Sci. Technol. Water Supply*, 2016, **16**, 533-541.
39. C. Matos, C. Santos, S. Pereira, I. Bentes and M. Imteaz, *Int. J. Sustain. Environ.*, 2013, **2**, 109-118.
40. L. F. Sanches Fernandes, D. P. S. Terêncio and F. A. L. Pacheco, *Sci. Total Environ.*, 2015, **529**, 91-100.
41. A. S. Silva and E. Ghisi, *J. Environ. Manage.*, 2016, **180**, 82-93.
42. A. Soni, R. Aggarwal and N. Khullar, *Journal of Research*, 2008, **45**, 196-199.
43. E. L. Souza and E. Ghisi, *Water*, 2012, **4**, 607-628.
44. C. H. Liaw and Y. L. Tsai, *J. Am. Water Resour. Assoc.*, 2004, **40**, 901-912.
45. Y. R. Chiu, Y. L. Tsai and Y. C. Chiang, *Water*, 2015, **7**, 6285-6300.
46. A. Campisano and C. Modica, *Resour. Conserv. Recycl.*, 2012, **63**, 9-16.
47. N. Pelak and A. Porporato, *J. Hydrol.*, 2016, **541**, 1340-1347.
48. C. O. Okoye, O. Solyali and B. Akintuğ, *Resour. Conserv. Recycl.*, 2015, **104**, 131-140.
49. IPCC, *Adaptation needs and options*, Intergovernmental Panel on Climate Change, New York, 2014.
50. Y. Guo and B. W. Baetz, *J. Hydrol. Eng.*, 2007, **12**, 197-205.
51. D. Lash, S. Ward, T. Kershaw, D. Butler and M. Eames, *Journal of Water and Climate Change*, 2014, **5**, 526-539.
52. A. Raimondi and G. Becciu, 2014.
53. M. D. Su, C. H. Lin, L. F. Chang, J. L. Kang and M. C. Lin, *Resour. Conserv. Recycl.*, 2009, **53**, 393-399.
54. C. H. Wang and J. M. Blackmore, *Water Resour. Manage.*, 2012, **26**, 4381-4396.

55. S. G. Youn, E. S. Chung, W. G. Kang and J. H. Sung, *Resour. Conserv. Recycl.*, 2012, **65**, 136-144.
56. L. S. Hanson and R. M. Vogel, *Environ.Res.Lett.*, 2014, **9**.
57. L. R. Andrade, A. G. Maia and P. S. Lucio, *J. Hydrol.*, 2017, **545**, 163-171.
58. I. Domínguez, S. Ward, J. G. Mendoza, C. I. Rincón and E. R. Oviedo-Ocaña, *Water*, 2017, **9**.
59. E. R. Oviedo-Ocaña, I. Dominguez, S. Ward, M. L. Rivera-Sanchez and J. M. Zaraza-Peña, *Environ. Sci. Pollut. Res.*, 2018, **25**, 19200-19216.
60. IDEAM, *Boletín agroclimático nacional*, Instituto de Hidrología, Meteorología y Estudios Ambientales, Colombia, 2017.
61. J. Ángel, J. Rozo, L. Hernández and D. Valderrama, *Rev Regul-CRA*, 2001, **7**, 15-42.
62. E. Ghisi and D. F. Ferreira, *Build. Environ.*, 2007, **42**, 2512-2522.
63. P. A. Londra, A. T. Theocharis, E. Baltas and V. A. Tsihrintzis, *Water Resour. Manage.*, 2015, **29**, 4357-4377.
64. A. Fewkes and P. Warm, *Build Serv Eng Res Technol*, 2000, **21**, 257-265.
65. M. Almazroui, M. N. Islam, K. S. Balkhair, Z. Şen and A. Masood, *Atmos. Res.*, 2017, **189**, 11-23.
66. M. Y. Han and J. S. Mun, *Water Sci. Technol.*, 2011, **63**, 2796-2801.
67. M. M. Haque, A. Rahman and B. Samali, *J. Clean. Prod.*, 2016, **137**, 60-69.
68. J. Mwenge Kahinda, A. E. Taigbenu and R. J. Boroto, *Phys. Chem. Earth*, 2010, **35**, 742-751.
69. P. J. Coombes and M. E. Barry, in *Water Sci. Technol.*, eds. A. Deletic and T. Fletcher, 2007, vol. 55, pp. 125-133.
70. S. A. Lucas, P. J. Coombes and A. K. Sharma, *Water Sci. Technol. Water Supply*, 2010, **10**, 69-80.
71. E. Friedler and M. Hadari, *Desalination*, 2006, **190**, 221-234.
72. P. J. Coombes, G. Kuczera, J. D. Kalma and J. R. Argue, *Urban Water*, 2002, **4**, 307-320.
73. H. Kim, M. Han and J. Y. Lee, *Sci. Total Environ.*, 2012, **424**, 213-218.
74. A. Palla, I. Gnecco and P. La Barbera, *J. Environ. Manage.*, 2017, **191**, 297-305.