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Practical design of reservoirs for rainwater use in buildings in Brazil: behavioural analysis and modelling

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ABSTRACT

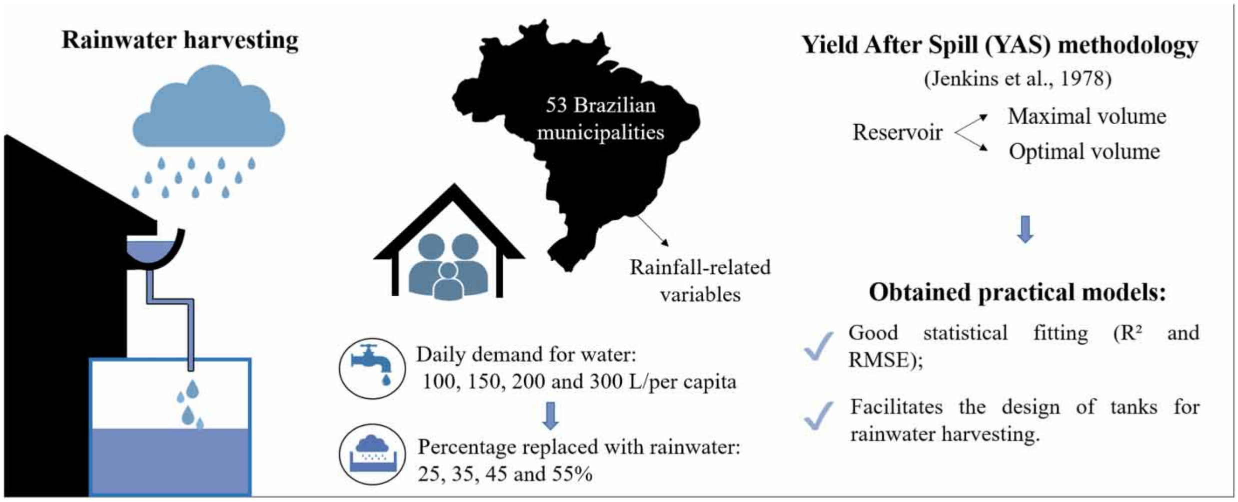
The new version of NBR 15527 (ABNT 2019) determines that any methodology used for the design of rainwater reservoirs must be performed considering the demand for rainwater resources. Thus, the objective of this study was to develop mathematical models for the design of rainwater reservoirs in residential buildings for all Brazilian states. Different use scenarios were simulated, which included drinking water demands of 100, 150, 200, and 300 litres per capita and rainwater replacement for drinking water at rates of 25, 35, 45, and 55%, according to rainfall data from the last decade. The optimal and maximal volumes of each scenario were calculated using the yield after spill (YAS) behavioural method. Based on the values of the volumes obtained, the studied municipalities were grouped, and for each group, the practical models were adjusted and evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE). A good adherence of the models to the observed data was observed, which simplified the estimation of the volume for rainwater reservoirs; practical applications demand that designs use discreet daily rainfall values.

Key words: decentralized sanitation, non-potable water resources, urban hydrology

HIGHLIGHTS

- Rainfall-related variables were used as variables to estimate the reservoir volumes.
- Practical models were obtained for behavioural simulations of the reservoir operations.
- The local climatic conditions influence the feasibility of using rainwater reservoirs.
- The maximal volume of reservoirs tends to increase until reaching a certain maximal water demand, at which point it begins to decrease.

GRAPHICAL ABSTRACT



INTRODUCTION

Global problems related to water scarcity have become increasingly frequent due to factors such as climate change and rapid population and industrial growth, as well as changes in consumption patterns and conflicts of interest related to the use of water resources (Jin *et al.* 2023). According to UNESCO, approximately 3.6 billion people live in regions with the possibility of water shortages for at least one month a year. Estimates indicate that this number could increase to approximately 4.8 billion to 5.7 billion by 2050, which represents more than half of the world's population. In addition, the global demand for water has increased annually by approximately 1%, and this increase is expected to strongly persist over the next two decades (Un-Water 2018).

Lima *et al.* (2020) argue that although Brazil has substantial amounts of available water, problems related to scarcity and misuse of water resources are frequent and increasingly worrying. The authors emphasize the need for public awareness regarding the importance of saving and preserving water, noting the urgency need to develop new products and technologies that can solve or minimize this problem. Similarly, Imteaz & Shadeed (2022) argue that the demands for potable and non-potable water are increasing, while water availability is decreasing, which forces authorities to utilize and encourage the use of alternative sources of water.

Of the available alternative sources of water, i.e., those that are not of surface or underground origin (Qin & Horvath 2020), rainwater (Imteaz & Shadeed 2022) stands out. According to Souto *et al.* (2023), rainwater is a simple and complementary option for water supply that can satisfactorily meet the demands for potable water. Teston *et al.* (2022) reported that even with variations in water availability in Brazil, the use of rainwater in residential buildings has a high potable water-saving potential, ranging from 20 to 65% among the studies reviewed.

Murça *et al.* (2014), Moniruzzaman & Imteaz (2017) and Silva & Maia (2021) point out that the variable cost of rainwater capture and exploitation systems tends to be low and that the main financial considerations of such projects are related to implementation, especially the unit cost of the reservoirs. However, although the initial capital to be invested is high, these systems tend to have a long, useful life, and the implementation costs are recovered approximately 3.5 years after their installation (Lima *et al.* 2020).

Imteaz & Shadeed (2022) argue that systems with larger reservoirs have a higher initial cost. However, undersized reservoirs may be inefficient because they cannot meet the demand for replacing drinking water with rainwater (Souto *et al.* 2023). Thus, Imteaz & Shadeed (2022) state that determining the ideal size of a rainwater reservoir is crucial since the space required for water storage may be limited or costly. In addition, Velasco-Muñoz *et al.* (2019), Rodrigues *et al.* (2020) and Schild *et al.* (2023) state that the successful implementation of a rainwater harvesting system strongly depends on its economic feasibility and technical design, as well as the identification of suitable locations.

The updated version of Brazilian Standard NBR 15527 (ABNT 2019), which defines the requirements for rainwater harvesting from roofs for non-potable uses, does not present or standardize a methodology for designing rainwater reservoirs for non-potable purposes; however, it prescribes that any methodology used must consider the rainwater catchment area, the local rainfall regime and the demand for replacement rainwater. Thus, the use of behavioural models for reservoir design, such as the yield after spill (YAS) model proposed by Jenkins *et al.* (1978), which uses a numerical approach to time integration of the system (Mitchell 2007; Ward *et al.* 2010), provide an interesting perspective.

Given the above, there is a clear, growing, urgent need for studies on alternative water sources, in which the correct design of the system is emphasized so that it is efficient and economically viable. Thus, the objective of this study was to adjust empirical mathematical models that can assist in the practical design of rainwater reservoirs in Brazilian residential buildings and discuss the behaviour associated with the volumes obtained for each selected region. For this, different hydrological variables related to rainfall were chosen considering the different water demands of different scenarios, and the YAS behavioural method was applied.

METHODS

Brazil is located in South America and is the fifth-largest country in the world in area, with a territorial extension of 8,510,417 km² and an estimated population of 213,317,639 inhabitants, according to the Brazilian Institute of Geography and Statistics (IBGE 2023). In all, there are 5,570 municipalities, considering the State District of Fernando de Noronha, which are distributed in 27 federative units, defined as 26 states and one Federal District.

According to the Köppen-Geiger climate classification, there are three types of climates: type A (tropical), type B (dry) and type C (temperate), which are divided into 12 subtypes: Af, Am, Aw, As, Bsh, BWh, Cfa, Cfb, Cwa, Cwb, Csa and Csb (Dubreuil *et al*. 2018). According to the Brazilian climatological norms (1991–2020) published by the National Institute of Meteorology (INMET), the total annual rainfall ranges from 419 to 3,308.3 mm, the average annual temperature ranges from 13.5 to 28.3 °C, and the annual relative humidity ranges from 55.8 to 87.9% (INMET 2020).

Data acquisition and processing

The rainfall data used were obtained from web platforms of INMET and the National Agency of Water and Basic Sanitation (ANA). Stations were chosen that recorded uninterrupted daily observations for at least 5 years, covering the period between 2010 and 2019. In total, time series were selected from 53 different municipalities, two municipalities in each Brazilian state and the Federal District. Spreadsheet software was used to estimate statistical variables related to rainfall monitored by the rainfall stations studied. The average daily rainfall (P_D) was calculated by the quotient of the sum of the accumulated rainfall in the years of observation by the total number of days in the analyzed period. The mean monthly rainfall (P_M) and the mean annual rainfall (P_A) were obtained by calculating the ratio between the accumulated rainfall for the months and years corresponding to the study period.

According to Köppen (1936), dry months are those in which the rainfall is lower than 60 mm, and rainy months are those in which it is higher. Then, for each of the dry months, $P_{d,\mathrm{se}}$ was obtained as the ratio between the accumulated monthly rainfall and the total number of days of the month. The same reasoning was applied to the rainy season.

Finally, the mean daily rainfall was calculated for the first ($P_{d,1°}$), second ($P_{d,2°}$), third ($P_{d,3°}$) and fourth ($P_{d,4°}$) quarters, as was the coefficient of sampling variation of daily rainfall (CV). The average daily rainfall in each quarter was the quotient between the total rainfall in each quarter and the number of corresponding days in each quarter. The first quarter comprises the months of January, February, and March, the second, April, May, and June, etc.

The Köppen climate classification (Alvares *et al*. 2013; Martins *et al*. 2018; Medeiros *et al*. 2020), the percentage of months classified as drought and the statistical variables related to the historical series of rainfall for each municipality can be viewed in Table 1.

Sizing of reservoirs for rainwater harvesting

The design of rainwater harvesting systems considered scenarios of distinct water needs. Thus, the average Brazilian standard was used to establish that there would be three residents per household (Tokarnia 2020; Sottero 2022; Fleith 2023); that the daily demands for drinking water would be equal to 100, 150, 200, and 300 litres per capita (FUNASA 2019; Pereira *et al*. 2021); and that the rainwater catchment area would be 100 m² (Rodrigues *et al*. 2020).

The percentages for replacing drinking water with rainwater were defined as 25, 35, 45, and 55%. These values were based on potable water savings potential, which accounted for rainwater use and the average water demand for less noble purposes in residential buildings, as presented in previous studies (Ghisi & Ferreira 2007; Campisano *et al*. 2017a; Cureau & Ghisi 2019; Castro *et al*. 2021).

The considered runoff coefficient (C) of the buildings cover was 0.80 (Garofalo *et al*. 2016; Gado & El-Agha 2020; Ibrahim & Ways 2023) and, to improve the water quality of the rainwater system, it is recommended to discard the first rainfall volumes (i.e., 'first-flush' discharge) (ABNT 2007; Zanella 2015; Campisano *et al*. 2017b, Carvalho *et al*. 2018; Charlebois 2021). Thus, as proposed by Sampaio & Alves (2017) and Pinto *et al*. (2022), we adopted the discharge of 1 mm of rainfall after 3 consecutive days without rain. According to the Brazilian Standard NBR 15527 (ABNT 2019), the reservoir must be closed; therefore, evaporation was not considered.

For each of the 16 idealized scenarios, the simulation for the design of the rainwater storage reservoirs was performed by applying a behavioural model, as described by Jenkins *et al*. (1978), and the operation of the reservoir was simulated for a continuous water balance using the YAS algorithm, that is related to the rainwater supply needed to meet the demand. These simulations were made using rainfall time series, being the input the daily rainfall data of the considered years. Thus, the maximal and optimal volumes of the reservoirs were obtained for each of the municipalities.

To calculate the volume of rainfall collected (Sampaio & Alves 2017), Equation (1) was used; Equations (2) and (3), which reference the YAS algorithm, were used to calculate the water needed to meet the rainfall demand and the calculation of the

Table 1 | Köppen climate classification, percentage of months classified as drought and statistical variables related to rainfall in the studied municipalities

Municipalities	CK	%	P_D (mm)	P_M (mm)	P_A (mm)	$P_{d,se}$ (mm)	$P_{d,ch}$ (mm)	$P_{d,1°}$ (mm)	$P_{d,2°}$ (mm)	$P_{d,3°}$ (mm)	$P_{d,4°}$ (mm)	CV (%)
Rio Branco – AC	Am	25.0	5.8	175.4	2,104.4	1.0	7.4	10.7	3.6	2.0	6.7	231.6
Tarauacá – AC	Af	13.3	6.3	190.8	2,289.8	1.3	7.0	10.0	4.9	2.8	7.5	205.8
Jacuípe – AL	Am	43.3	4.1	124.9	1,498.8	1.0	6.5	3.9	7.1	4.5	1.0	243.2
Palmeira dos Índios – AL	As	51.7	2.2	66.1	792.7	0.7	3.8	0.9	3.7	3.0	1.1	269.6
Calçoene – AP	Am	16.7	9.9	302.1	3,625.7	0.6	11.8	17.2	14.7	3.4	4.7	142.8
Macapá – AP	Am	25.0	8.6	263.0	3,156.1	0.6	11.3	14.1	13.2	3.5	3.9	126.6
Lábrea – AM	Am	18.3	6.4	194.9	2,338.2	1.1	7.6	9.9	5.2	2.3	8.3	218.2
Manaus – AM	Af	25.0	5.9	178.5	2,142.0	1.3	7.4	10.2	6.6	2.2	4.6	181.6
Salvador – BA	Af	21.7	4.2	128.1	1,536.5	1.0	5.1	3.1	8.0	3.7	2.1	247.4
Vitória da Conquista – BA	Cfa	73.3	1.8	54.3	650.9	0.9	4.2	2.2	1.1	0.8	3.0	364.3
Fortaleza – CE	As	46.7	5.0	153.2	1,838.8	0.5	9.1	10.5	7.8	1.2	0.8	270.6
Sobral – CE	As	63.3	2.3	69.0	827.8	0.3	5.7	5.8	2.8	0.1	0.4	313.4
Brasília – DF	Aw	45.0	3.9	119.6	1,435.4	0.4	6.8	6.8	1.9	0.4	6.6	257.5
Muniz Freire – ES	Cfa	48.3	3.2	96.9	1,162.2	0.8	5.4	4.0	2.2	0.8	5.8	323.8
Vitória – ES	Am	40.0	3.4	102.1	1,224.9	1.0	4.9	3.1	2.6	2.0	5.7	335.4
Formosa – GO	Aw	48.3	3.4	103.2	1,238.4	0.4	6.2	6.5	1.3	0.2	5.6	273.5
Jataí – GO	Aw	38.3	4.4	135.2	1,622.6	0.5	6.9	8.7	2.4	0.6	6.2	263.4
Chapadinha – MA	Aw	50.0	3.7	112.8	1,353.7	0.5	6.9	7.9	5.7	0.4	0.9	285.7
São Luís – MA	Aw	40.0	5.4	164.1	1,968.7	0.5	8.7	9.0	10.1	1.1	1.4	258.7
Comodoro – MT	Am	30.0	6.2	188.4	2,261.1	0.6	8.6	10.7	3.7	1.2	9.3	212.4
Sinop – MT	Am	38.3	4.7	141.7	1,699.8	0.4	7.3	9.1	1.8	0.9	7.0	264.9
Campo Grande – MS	Am	26.7	3.9	119.4	1,433.1	0.8	5.1	6.2	2.7	1.7	5.2	252.8
Ponta Porã – MS	Cfa	23.3	5.2	158.4	1,900.6	0.9	6.5	7.3	4.4	2.5	6.7	248.9
Patos de Minas – MG	Cwb	38.3	4.3	129.4	1,553.2	0.5	6.6	7.3	1.7	0.8	7.2	262.5
Lavras – MG	Cwb	41.7	3.7	111.1	1,332.6	0.9	5.5	6.3	1.6	1.4	5.3	250.4
Curitiba – PR	Cfb	20.0	4.4	132.8	1,594.0	1.0	5.2	6.4	3.5	2.5	5.0	236.9
Maringá – PR	Cfa	18.3	5.52	167.96	2,015.54	0.87	6.57	7.79	3.67	3.48	7.15	245.36
João Pessoa – PB	As	43.3	4.9	149.5	1,793.9	1.2	7.8	3.4	9.2	5.9	1.1	282.0
São Gonçalo – PB	As	66.7	2.15	65.4	784.84	0.41	5.66	5.67	2.24	0.36	0.40	429.11
Belém – PA	Am	6.7	9.9	302.3	3,627.5	1.4	10.5	17.4	11.4	4.1	7.0	152.0
Conceição do Araguaia – PA	Aw	45.0	4.4	135.0	1,620.2	0.5	7.7	9.0	2.6	0.5	5.8	260.9
Petrolina – PE	BSh	88.3	0.81	24.69	296.24	0.35	4.38	1.83	0.72	0.1	0.61	598.49
Surubim – PE	As	75.0	1.33	40.61	487.34	0.69	3.28	0.95	2.42	1.45	0.52	356.34
Floriano – PI	Aw	51.7	2.64	80.43	965.2	0.48	4.96	5.94	1.5	0.24	2.95	345.79
Piripiri-PI	As	56.7	3.39	103.13	1,237.58	0.58	7.11	8.01	4.33	0.39	0.92	294.09
Apodi –RN	As	78.3	1.34	40.85	490.24	0.41	4.77	2.71	2.26	0.17	0.26	520.66
Natal – RN	As	33.3	4.26	129.79	1,557.52	0.80	6.01	4.76	7.60	3.82	0.92	265.38
Porto Alegre – RS	Cfa	10.0	4.50	136.82	1,641.86	1.06	4.87	4.28	4.49	4.43	4.78	250.88
Santa Maria – RS	Cfa	8.3	5.22	158.92	1,907.06	1.10	5.60	5.16	4.38	4.35	6.99	263.58
Itaperuna – RJ	Aw	43.3	2.81	85.38	1,024.60	0.81	4.36	4.19	1.53	0.99	4.53	309.40

(*Continued.*)

Table 1 | Continued

Municipalities	CK	%	P_D (mm)	P_M (mm)	P_A (mm)	$P_{d,se}$ (mm)	$P_{d,ch}$ (mm)	$P_{d,1°}$ (mm)	$P_{d,2°}$ (mm)	$P_{d,3°}$ (mm)	$P_{d,4°}$ (mm)	CV (%)
Rio de Janeiro – RJ	Am	41.7	3.22	97.99	1,175.88	1.10	4.74	6.26	2.56	1.20	2.92	327.33
Alta Floresta d'Oeste – RO	Am	33.3	5.46	166.30	1,995.64	0.88	7.76	9.55	3.45	1.14	7.77	223.85
Cabixi – RO	Am	36.7	4.70	143.18	1,718.20	0.49	7.17	9.67	2.33	0.56	6.34	241.18
Boa Vista – RR	Am	55.0	3.3	100.6	1,207.4	0.6	6.6	0.6	6.1	5.7	0.8	299.7
Rorainópolis – RR	Af	13.3	6.3	191.1	2,292.7	1.2	7.1	5.1	10.10	5.7	4.2	208.2
Florianópolis – SC	Cfa	6.7	5.0	151.7	1,819.9	1.3	5.3	6.8	4.1	4.0	5.2	235.9
Lages – SC	Cfb	8.3	5.1	155.1	1,861.2	0.9	5.5	5.7	4.3	5.1	5.4	235.7
Itabaianinha – SE	As	48.3	2.9	88.1	1,057.2	0.9	4.7	2.1	5.3	3.1	1.2	278.8
Propriá – SE	As	56.7	2.1	63.1	756.6	0.9	3.7	1.3	3.2	2.7	1.1	282.5
Franca – SP	Cwb	31.7	4.6	141.4	1,696.3	0.6	6.6	8.4	2.1	1.1	7.1	246.2
São Paulo – SP	Cfb	28.3	4.4	134.9	1,618.6	0.8	5.9	8.1	2.6	1.9	5.2	264.5
Araguaína – TO	Aw	38.3	4.2	128.6	1,543.4	0.6	6.5	9.1	2.7	0.6	4.6	258.5
Palmas – TO	Aw	40.0	4.3	129.8	1,558.1	0.2	7.0	7.9	2.7	0.5	6.0	253.8

CK: Köppen climate classification, according to Alvares *et al.* (2013); Af: Humid tropical climate with no dry season; Am: Tropical monsoon climate; As: Humid tropical climate with dry summers; Aw: Humid tropical climate with dry winters; BSh: Dry semiarid climate of low latitude and altitude; Cfa: Humid subtropical climate without dry season and hot summer; Cfb: Humid subtropical climate with temperate summers; Cwa: Humid subtropical climate with dry winters and hot summers; Cwb: Humid subtropical climate with dry winters and mild summers; %: percentage of months with drought periods; P_D: Average Daily Rainfall; P_M: Mean Monthly Rainfall; P_A: Mean Annual Rainfall; $P_{d,se}$: Average Daily Rainfall of the Dry Period; $P_{d,ch}$: Average Daily Rainfall of the Rainy Period; $P_{d,1°}$: Average Daily Rainfall for the first quarter; $P_{d,2°}$: Average Daily Rainfall for the second trimester; $P_{d,3°}$: Average Daily Rainfall for the third trimester; $P_{d,4°}$: Average Daily Rainfall for the fourth quarter and CV: Coefficient of Variation of Daily Rainfall

volume of water in the reservoir, respectively.

$$Q_t = (P_t \times C \times A) - \mathrm{DT}_t \quad (1)$$

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases} \quad (2)$$

$$V_t = \min\begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \quad (3)$$

where Q_t is the volume of rainwater collected in the time interval t (m³); P_t is the rainfall at time t (m); C is the coefficient of direct surface runoff (dimensionless); A is the rainwater harvesting surface area (m²); DT_t is the first-flush water discharge at time t (m³), being its value is equal to zero if any rainfall has occurred on the three previous days; Y_t is the water to supply the demand in time t (m³); D_t is the demand at time t (m³); V_t is the useful volume in the reservoir at time t (m³); and S is the maximal capacity of the reservoir (m³).

To analyze the technical feasibility, the coefficients of water-saving efficiency and full reliability were calculated, which are presented in Equations (4) and (5), respectively (Jenkins *et al.* 1978).

$$E_{\mathrm{eco}} = \frac{\Sigma Y_t}{\Sigma D_t} \quad (4)$$

$$C_{\mathrm{onf}} = \left(\frac{N_D}{N}\right) \times 100\% \quad (5)$$

where E_{eco} is the water-saving coefficient (dimensionless); C_{onf} is the full reliability (%); N is the number of days in the series (days); and N_D is the number of days in which demand was fully supplied (days).

Thus, using the equations above and an electronic spreadsheet, the maximum and optimum volume, as well as the water-saving coefficient and reliability of the rainwater reservoirs were obtained. By definition, the maximum volume ($V_{\max}$) is the volume at which water-saving efficiency is maximized and it was calculated by an iterative numerical method. The optimum volume (V_{opt}) is defined as a threshold volume in which, from its value, there is no proportional gain in water-saving efficiency (Pinto *et al.* 2022).

From the maximum volume calculation, it was possible to determine the stopping criterion for sizing the rainwater reservoir optimum volume, using Equations (6) and (7) to meet the criterion presented in Equation (8).

$$V_{\mathrm{rel}_t} = \frac{V_t}{V_{\max}} \tag{6}$$

$$E_R = \frac{E_{\mathrm{eco}_t} - E_{\mathrm{eco}_{t-1}}}{V_{\mathrm{rel}_t} - V_{\mathrm{rel}_{t-1}}} \tag{7}$$

$$\frac{E_{\mathrm{eco}_t} - E_{\mathrm{eco}_{t-1}}}{V_{\mathrm{rel}_t} - V_{\mathrm{rel}_{t-1}}} \leq \tan 45^\circ, V_{\mathrm{opt}} = V_{t-1} \tag{8}$$

where V_{rel_t} is the relative volume at time t (dimensionless); $V_{\max}$ is the maximal reservoir volume (m³); $V_{\mathrm{rel}_{t-1}}$ is the relative volume at time t–1 (dimensionless); E_{eco_t} is the coefficient of economic efficiency at time t (dimensionless); and $E_{\mathrm{eco}_{t-1}}$ is the coefficient of economic efficiency at time t–1 (dimensionless), and E_R is the efficiency ratio (dimensionless).

With the calculation of V_{rel_t} (Equation (6)), the volume leading to the optimal size determination was performed with values ranging from 0 to 1, i.e., the same scale for the water-saving efficiency. From Equation (8), there is a point in which an increase in volume does not lead to an efficiency rise at the same proportion. E_R is the tangent of the angle defined by t and t–1 points and so, when its tangent reaches a value below 1, the stopping criterion and the optimal volume were found.

Grouping of municipalities and formation of subgroups

The maximal and optimal volumes, the water-saving coefficient (E_{eco}), the full reliability (C_{onf}) and the statistical variables related to the historical series of rainfall for each municipality were used as variables in the hierarchical clustering analysis (HCA) to group the cases studied (municipalities). These variables were standardized as Z scores to minimize any interference that their magnitudes might cause in the analysis (Singh *et al.* 2004; Vicini *et al.* 2018). The HCA was performed using Euclidean distance (Hair *et al.* 2009).

The Ward's method (Ward 1963) was used in the agglomerative linkage process, and the analysis was performed using the trial version of the Excel package XLStat® (Addinsoft 2022). The divisions used to form the groups allowed the greatest possible internal similarity. Then, according to the groupings, determined by statistical criteria, the data were refined and subgrouped based on the visual similarity of the distribution of points for the calculated volume values, due to the demand for non-potable water resources. The subgrouping was visually conducted because the only adopted criterion in this step was the definition of data with similar behaviour.

The locations of the municipalities in each subgroup for the maximal and optimal volume are shown in Figure 1(a) and 1(b), respectively.

The subgroups formed by HCA could still be segregated into regions of reservoir volume trend due to increasing demand for rainwater. This separation of volume behaviour regions was carried out visually, by the definition of data with similar trends: only ascending, only descending or peaking behaviours. For this purpose, the maximal points of volume obtained in relation to a given demand were considered, as well as the existence of subgroups with only ascending or only descending behaviour.

For the subgroups with peaking behaviour, regions of ascending and descending trends were separated to perform the models fitting. The peaking inflection point, which separated these regions, was also defined by visual analysis; being this value a point of maximal demand common to all municipalities in the subgroup. In addition, each of these different behaviour regions for peaking trends should have, at least, two pairs of values. After these steps, empirical mathematical models for the practical design of rainwater reservoirs were fitted for each subgroup.

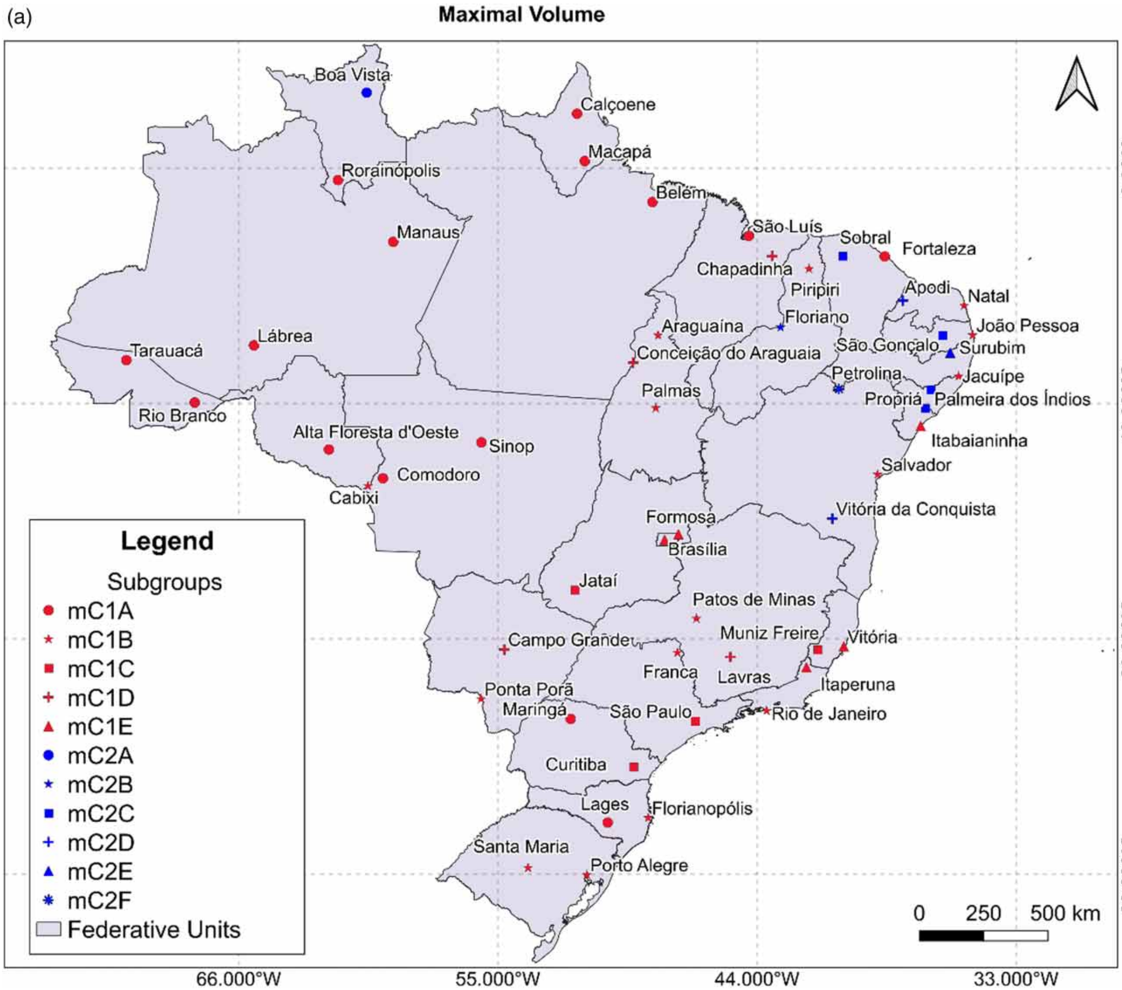


Figure 1 | (a) Municipalities of each subgroup formed for the maximal volume. (b) Municipalities of each subgroup formed for the optimal volume. (*continued*.).

Models fitting process and adequacy evaluation

Once the volumes were calculated for the reservoirs, several empirical equations were fitted according to the variables related to rainfall (Table 1) for each of the subgroups. For the subgroups, the mean value among the municipalities for the statistical variables related to rainfall was considered to fit the parameters. The model parameters were fitted to the maximal and optimal volume conditions by using the Solver tool of the Excel® software by the Generalized Reduced Gradient (GRG) nonlinear method. The adequacy of the fit was assessed using the coefficient of determination (R^2), root mean square error (RMSE) and bias (B), which were obtained according to Equation (9).

$$B = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i) \quad (9)$$

where is $\hat{y}_i$ the value estimated by the fitted models (m³); y_i is the observed value (m³); and n is the total number of data pairs.

RESULTS AND DISCUSSION

Maximal volume

Figure 2 shows the behaviour of the average maximal volume as a function of the average daily demand for each subgroup. An analysis of the values obtained for the maximal volume showed that most subgroups, except for C1A and C2F, exhibited two distinct, well-characterized behaviours, in which there was an inflection from an ascending to a descending trend.

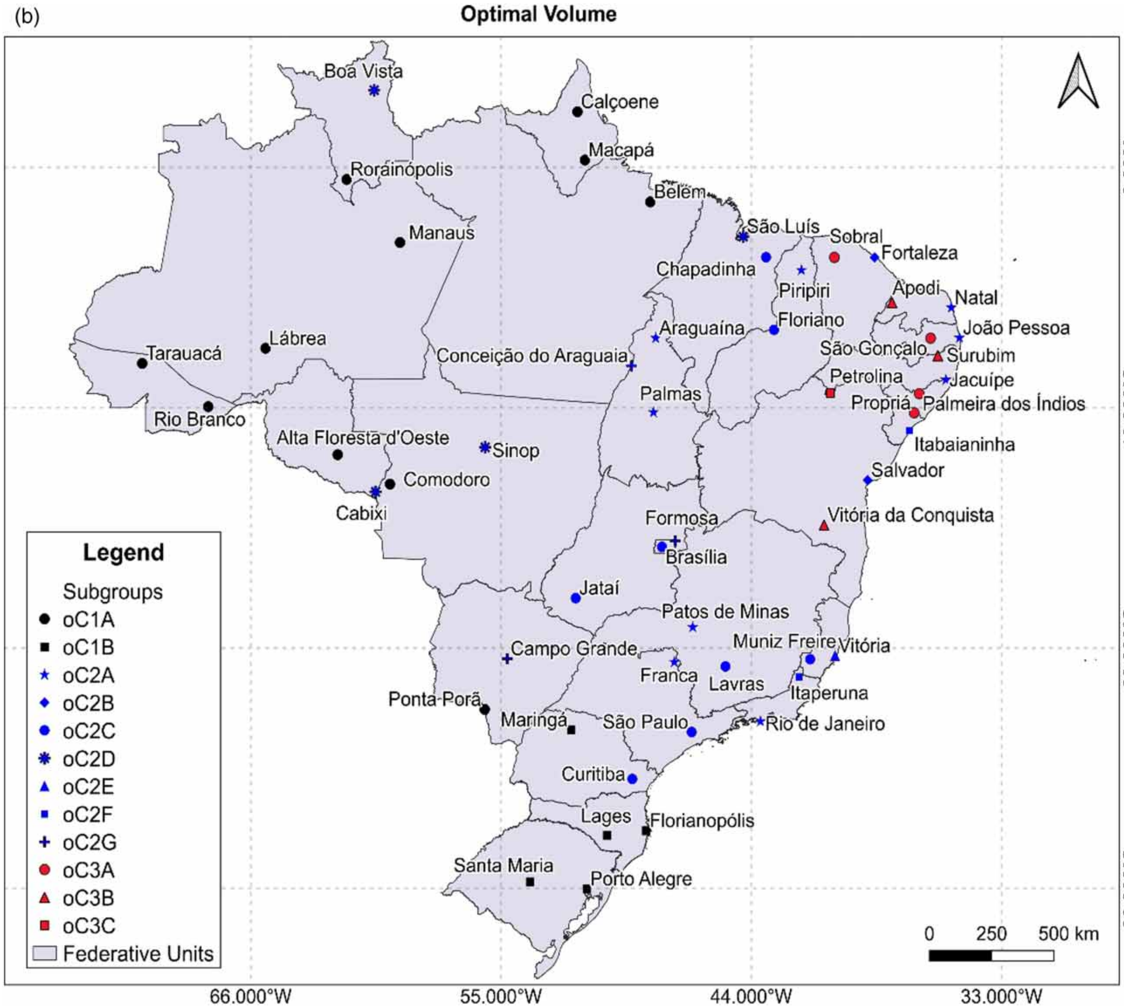


Figure 1 | Continued.

This pattern indicates that, at first, the greater the demand is for rainwater in residential buildings, the greater the average maximal volume of water required in the reservoirs and, consequently, the greater their storage capacity should be. However, at a certain moment, as indicated by the inflection point in the graphs, the average maximal volume required for the reservoirs begins to decrease. At first sight, this behaviour may be considered contradictory, however, considering the water balance, from a given demand, the reservoir's water withdrawal rate becomes so intense compared to the runoff generation, that the rainfall volume, required to be accumulated inside the reservoirs, begins to decline, which consequently reduces the maximum volume required by the reservoirs.

With regard to subgroup C1A, the means of the variables related to rainfall on a daily, monthly and annual scale (P_D, P_M and P_A), calculated from the values presented in Table 1, were 6.50, 195.66 and 2,347.81 mm, respectively; these values were the highest among the subgroups. In addition, the average CV of daily rainfall was 211.89%, and the average percentage of months classified as drought was 23.88%, which were the lowest values in the C1 group. These results are in line with the geographical location of the municipalities in this subgroup, of which 60% are located in the North region of the country, characterized by high rainfall (Santos *et al.* 2015a, 2015b; Silva *et al.* 2019).

The use of average values provides a general understanding of precipitation patterns in a specific region, allowing for the assessment of water resources availability for rainwater collection. Thus, designers can estimate the potential water to be collected and stored in reservoirs. Additionally, the use of average values helps to understand rainfall variability in different regions, as indicated by the values of the standard deviation (CV). This variability is crucial for determining the appropriate

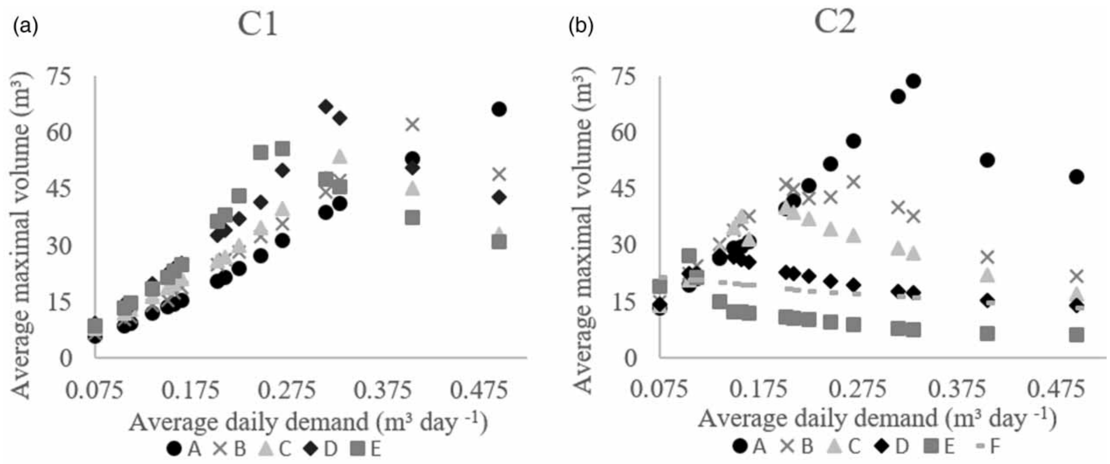


Figure 2 | Behaviour of the average maximal volume of each subgroup (m³) as a function of the average daily demand (m³ day^{-1}).

reservoir size to meet demand throughout the year. In this sense, based on these considerations, the use of the average has a practical nature, which coincides with the primary objective of defining empirical equations: to facilitate the sizing process (Pinto *et al.* 2022).

Hoseini & Hosseini (2020) determined the ideal volume of rainwater reservoirs in Iran, aiming to reduce system implementation costs and achieve greater efficiency. The authors stressed the importance of average annual rainfall and runoff coefficient for calculating the collected rainfall amount of and, ultimately, determining the reservoir volume. The implementation costs of a rainwater harvesting system can vary according to rainfall conditions. Financial feasibility studies conducted in different locations have shown that the initial investment and operational costs of rainwater harvesting systems can vary significantly, depending on local prices and rainfall patterns. Geraldi & Ghisi (2019) proposed three indicators to describe the rainfall used in the sizing of rainwater reservoirs: average annual precipitation, seasonality index, and average number of dry days per year.

Additionally, Istchuk & Ghisi (2023) evaluated the influence of these indicators and other design variables on the financial viability of RWH systems in eight Brazilian cities. The authors concluded that locations with lower rainfall seasonality indices and shorter dry periods are likely to have greater financial viability for rainwater harvesting systems and that the financial benefit of these systems can be influenced by local water tariff schemes, as some cities have structures that favour savings while others do not.

Pinto *et al.* (2022) evaluated the influence of temporal and spatial variability of rainfall on the design of reservoirs for rainwater harvesting in Brazil, considering a household with a daily rainwater demand of 240 L day^{-1}. Using a multivariate analysis, the authors found that the lower the CV of the P_D, the lower the variability, and, consequently, the lower the uncertainty by definition associated with the system; as well as a higher P_D, P_M or P_A are presumably associated with a more predictable weather, i.e. a lower CV, resulting on a greater supply of the building system's demand. Thus, for this study, due to the high supply, the inflection point of the C1A curve occurs at the greater demand point, as demonstrated by the upwards behaviour of the average maximal values as a function of the average daily demand for this subgroup (Figure 2(a)).

For the subgroups of group C1 that presented two distinct behaviours, the change in trend of the maximal volume of subgroups B, C, D and E decreased from the average daily demands of 0.405; 0.330; 0.315; and 0.270 m³ day^{-1}, respectively (Figure 2(a)). Similarly, these behaviours can be explained by the influence of rainfall on the supply needed to meet the average daily demand of each subgroup.

The C1B subgroup, for which the change in maximal volumes occurred in line with the greater demand of the C1 group, had a mean P_D of 4.41 mm and CV of 261.39%, the second lowest value among the subgroups. In addition, the mean P_M and P_A were 134.11 and 1,609.25 mm, respectively, with a mean percentage of months classified as drought of 31.55%, a relatively low value compared to those in Table 1. The C1E subgroup, in turn, had the lowest rainfall, the highest mean CV of daily rainfall (290.92%) and the highest mean percentage of months classified as dry (44.98%) among the subgroups. Consequently, due to the uncertainties related to the rainwater supply demanded by the building, the inflection point of the reference curve was the lowest average daily demand value of the C1 group.

For group C2 (Figure 2(b)), the change in maximal volume behaviour for subgroups A, B, C, D and E decreased from the average daily demand of 0.330, 0.210, 0.203, 0.135, and 0.105 m³ day^{-1}, respectively. As shown in Figure 1(b), subgroups C2A and C2E correspond to the municipalities of Boa Vista and Surubim, respectively. According to the values presented in Table 1, Boa Vista had the highest mean rainfall (P_D, P_M and P_A) and the lowest mean CV of the C2 group, with 55.0% of the months classified as drought. In addition to having P_D, P_M and P_A and the second highest mean CV among the subgroups, the municipality of Surubim (C2E) was in drought in 75.0% of months, one of the highest values among all the municipalities, which was 36.6% higher than that of Boa Vista.

In this sense, the difference in behaviour of the average maximal volume curves of the subgroups (Figure 2(b)) is in accordance with the uncertainties related to the rainwater demand: since the average CV of the P_D of the municipality of Boa Vista was approximately 16% lower than that of the municipality of Surubim, the C2A subgroup presented an inflection point in line with the highest average daily demand value of the group; furthermore, C2E had the lowest average daily demand, a result of the magnitude and temporal distribution of rainfall in the their respective regions.

On the other hand, the C2F subgroup, the municipality of Petrolina (Figure 1(a)), exhibited a distinct behaviour, which can be explained by the lower rainfall indices, the higher CV of daily rainfall of the C2 group and the higher percentage of months classified as drought (88.3%) among the 53 municipalities analyzed. Given this unfavourable scenario, the low supply leads to a downwards behaviour of the maximal average volumes of the reservoirs with the increase in demand.

Pinto *et al.* (2022), when studying the influence of spatial and temporal variability of rainfall on the design of rainwater reservoirs in Brazil, found that, from a hydrological perspective, the use of a rainwater harvesting system in the municipality of Petrolina is not advantageous due to the low demand supply. Taferre *et al.* (2016), in turn, evaluated the feasibility of using rainwater harvesting systems in a semiarid region of the African continent and found that one of the main factors that lead to the infeasibility of the systems is incorrect design, which occurs when the rainfall regime of the region is not considered. Mehrabadi *et al.* (2013) analyzed the installation of rainwater harvesting systems for non-potable purposes under three different climatic conditions and found that for the arid climate, the system was not efficient, as demand could be met in only 23% of the period considered.

In addition, a comparison between groups C1 and C2 showed that, except for subgroup C2A, group C2 presented values of average daily demand and average maximal volume lower than those obtained for group C1. This is because, except for Boa Vista, all municipalities in group C2 are located in the Northeast region of the country (Figure 1(a)), with 60% of these municipalities having a climate classified as 'As' (Table 1). This region is characterized by low rainfall (Brito *et al.* 2018; Siqueira *et al.* 2021), which elucidates the behaviour of the maximal average volumes obtained when the supply of rainwater is too low to meet the demand for it.

It is important to emphasize that the use of historical data for sizing stormwater reservoirs is a common and justifiable practice for several reasons. Historical data provide a solid and reliable basis for understanding precipitation patterns over time, offering a comprehensive view of the availability of stormwater in a given region. Several authors, with different specific objectives, have used historical data in stormwater reservoir sizing, as exemplified in the bibliometric and systematic literature review on rainfall data types used in stormwater reservoir sizing by Fioramonte *et al.* (2022). According to the authors, worldwide, the most used data are historical series of over 30 years, derived from meteorological stations. In addition, they emphasize that other types of data and different sizes of historical series can also be used. However, it is important to recognize the inherent limitations in the representativeness of historical data, especially in a climate uncertainty scenario. This is because climate change has the potential to alter rainfall patterns, directly impacting the sizing and efficiency of not only stormwater reservoirs.

Ballarin *et al.* (2023) made climate projections for the entire Brazilian territory using, among others, rainfall data for the historical period (1980–2013) and future (2015–2100), considering the SSP2-4.5 and SSP5-8.5 scenarios. According to the simulated results, rainfall will undergo significant changes (>10%) in most of the Brazilian territory in both scenarios, with similar spatial patterns of change throughout the country. A projected average rainfall decrease was observed in the Amazon, Caatinga biomes, and part of the Cerrado. Meanwhile, in the Pampa and Atlantic Forest biomes, a slight increase is expected, showing that the expected behaviour of possible changes in climate patterns is not expected to follow a single trend.

Alamdari *et al.* (2018) investigated the effects of climate change on rainwater harvesting systems in different locations in the United States, using historical and future data. The authors observed that, due to climate change, some systems designed for current conditions may be less effective in the future. In this regard, incorporating climate projections in the sizing stages of rainwater harvesting reservoirs can contribute to establishing appropriate management and adaptation measures necessary for developing systems resilient to the challenges posed by climate uncertainties scenarios (Preeti *et al.* 2022). However, Santos *et al.* (2020) comment, that there are no indications regarding the use of historical data or future projections for sizing rainwater harvesting systems. The decision-making process should be left to the designer, provided recent rainfall data are used.

In the context of this discussion, it is important to recognize that the application of deterministic methods for sizing rainwater harvesting reservoirs carries certain limitations inherent to this approach type. While it provides valuable information, deterministic analysis may not fully capture the variability of rainfall patterns and, consequently, rainwater demand (Cheng *et al.* 2021). Considering this, stochastic methods may emerge as an alternative that, in addition to incorporating uncertainties inherent in this context, can offer a more realistic understanding of climatic elements, considering the occurrence of extreme events, for example (Lopes *et al.* 2017; Guo & Guo, 2018). In summary, the combination of deterministic and stochastic approaches can be considered a strategy that contributes to a more comprehensive and integrated understanding of the system, enhancing the potential of rainwater harvesting reservoir sizing procedure.

Considering this perspective, it is recommended that future research incorporate climate change scenarios to assess the potential impact of these on the rainwater reservoir design. However, although the limitations of the exclusive use of historical data are recognized, it continues to be a valuable tool when combined with other sources of information and considered with caution, since there are different uncertainties associated with the occurrence of historical rainfall as well as those based on climate change scenarios.

The best models obtained for estimating the volumes of rainwater reservoirs, as a function of the maximal volumes and the joint analysis of R^2 and RMSE, are shown in Table 2.

According to the results shown in Table 2, the R^2 values obtained for the behaviour of the first region were closer to 1, indicating greater suitability of the models fitted to the data of this region in relation to the fittings made for the second region. The C2E subgroup stands out, as it presented satisfactory values for the statistical indicators of adjustment, since the RMSE was equal to 0.00005 m³, the bias was almost zero and the R^2 was equal to 1; that is, the fitted model was able to explain all the variation present in the observed data. The limit of highest occurrence of the first behaviour region was the demand of 0.320 m³ day^{-1}, referring to three subgroups (33.3%) among the nine that present two behaviour regions.

Optimal volume

Figure 3 shows the behaviour of the average optimal volume as a function of the average daily demand of each subgroup of groups C1, C2 and C3.

For the C1A subgroup, higher values of the average optimal volume were obtained as a function of the average daily demand, whose upwards behaviour can be seen in Figure 3. In this subgroup, 81.8% of the locations belong to the North region of the country and the other 18.1% to the Centre-West region. The mean P_D, P_M and P_A of the subgroup were 6.91, 210.11 and 2,521.25 mm, respectively, with a mean CV of 195.63 and 20.90% of months classified as drought, a relatively low value compared to the other subgroups (Table 1, Figure 3(a)). The maximal E_{eco} among the municipalities ranged from 77.02 to 88.88%; these values were expected due to the high rainfall in the region. These characteristics are favourable for providing the high supply of rainwater demanded by the building, which leads to higher average maximal volumes and, consequently, higher values of average optimal volumes; to obtain such volumes, these characteristics must first exist. The same upwards behaviour of maximal values can be observed for the C1A subgroup (Figure 2(a)), for which most municipalities are in the same region.

When compared to the C1A subgroup, the C1B subgroup provided lower values of average optimal volume as a function of the average daily demand. In this subgroup are the municipalities of Maringá, Florianópolis, Lages, Porto Alegre and Santa Maria, all located in the southern region of the country. Even so, the maximal E echoes of the municipalities varied between 81.08 and 86.74%, values that were obtained due to the low mean CV of the subgroup (246.28%) and which were the second lowest among the C1, C2 and C3 groups.

The C2 group, in general, obtained higher mean optimal volume values as a function of the mean daily demand considering the three groups, especially due to the C2E subgroup, represented by Vitória (Figure 1(b)), for which the highest optimal

Table 2 | Best practical models for estimating the volume of the rainwater reservoir, considering the YAS algorithm and the maximal volume of the reservoir

Subgroup	1st Region	R^2	RMSE (m³)	Bias (m³)	1st Region Limit	2nd Region	R^2	RMSE (m³)	Bias (m³)
C1A	$V = 4.225 \cdot CV \cdot e^{4.206 \cdot D_d}$	0.711	10.517	0.138	–	–	–	–	–
C1B	$V = 0.011 \cdot P_{d,ch} \cdot A \cdot e^{5.986 \cdot D_d}$	0.745	7.878	0.408	0.400	$V = 99.746 \cdot \left(\frac{D_d}{P_{d,se} \cdot A}\right)^{0.070}$	0.677	3.464	0.083
C1C	$V = 0.011 \cdot P_{d,ch} \cdot A \cdot e^{5.986 \cdot D_d}$	0.881	5.348	−2.300	0.320	$V = 50.066 \cdot \left(\frac{D_d}{P_{d,3^\circ} \cdot A}\right)^{0.023}$	0.013	10.233	0.007
C1D	$V = 0.012 \cdot P_{d,ch} \cdot A \cdot e^{6.999 \cdot D_d}$	0.935	4.184	−0.164	0.320	$V = 101.176 \cdot \left(\frac{D_d}{P_{d,3^\circ} \cdot A}\right)^{0.126}$	0.310	15.315	0.406
C1E	$V = 0.015 \cdot P_D \cdot A \cdot e^{9.700 \cdot D_d}$	0.814	6.542	−0.074	0.260	$V = 100.204 \cdot \left(\frac{D_d}{P_{d,1^\circ} \cdot A}\right)^{0.073}$	0.116	7.690	16.391
C2A	$V = 0.036 \cdot P_D \cdot A \cdot e^{5.791 \cdot D_d}$	0.981	2.233	0.167	0.320	$V = 99.755 \cdot \left(\frac{D_d}{P_A \cdot A}\right)^{0.043}$	0.878	11.540	−0.077
C2B	$V = 2.970 \cdot CV \cdot e^{7.647 \cdot D_d}$	0.964	1.773	0.079	0.205	$V = 49.600 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.037}$	0.843	8.768	−0.083
C2C	$V = 0.056 \cdot P_D \cdot A \cdot e^{6.012 \cdot D_d}$	0.622	6.519	0.188	0.215	$V = 50.578 \cdot \left(\frac{D_d}{P_{d,3^\circ} \cdot A}\right)^{0.070}$	0.216	5.344	5.976
C2D	$V = 0.035 \cdot P_{d,1^\circ} \cdot A \cdot e^{8.581 \cdot D_d}$	0.816	2.762	−0.041	0.140	$V = 49.352 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.125}$	0.973	3.663	−1.402
C2E	$V = 2.188 \cdot CV \cdot e^{11.881 \cdot D_d}$	1.000	0.00005	-3.38×10^{-5}	0.110	$V = 49.211 \cdot \left(\frac{D_d}{P_{d,2^\circ} \cdot A}\right)^{0.209}$	0.791	3.979	0.774
C2F	$V = 0.006 \cdot P_M \cdot A \cdot e^{0.864 \cdot D_d}$	0.973	3.984	−0.400	–	–	–	–	–

The grouping of municipalities as shown in Figure 1(a). V: Maximal Volume; D_d: Average Daily Demand; A: Catchment Area; P_D: Average Daily Rainfall; P_M: Mean Monthly Rainfall; P_A: Mean Annual Rainfall; $P_{d,se}$: Average Daily Rainfall of the Dry Period; $P_{d,ch}$: Average Daily Rainfall of the Rainy Period; $P_{d,1^\circ}$: Average Daily Rainfall for the first quarter; $P_{d,2^\circ}$: Average Daily Rainfall for the second trimester; $P_{d,3^\circ}$: Average Daily Rainfall for the third trimester; $P_{d,4^\circ}$: Average Daily Rainfall for the fourth quarter, CV: Coefficient of Variation of Daily Rainfall.

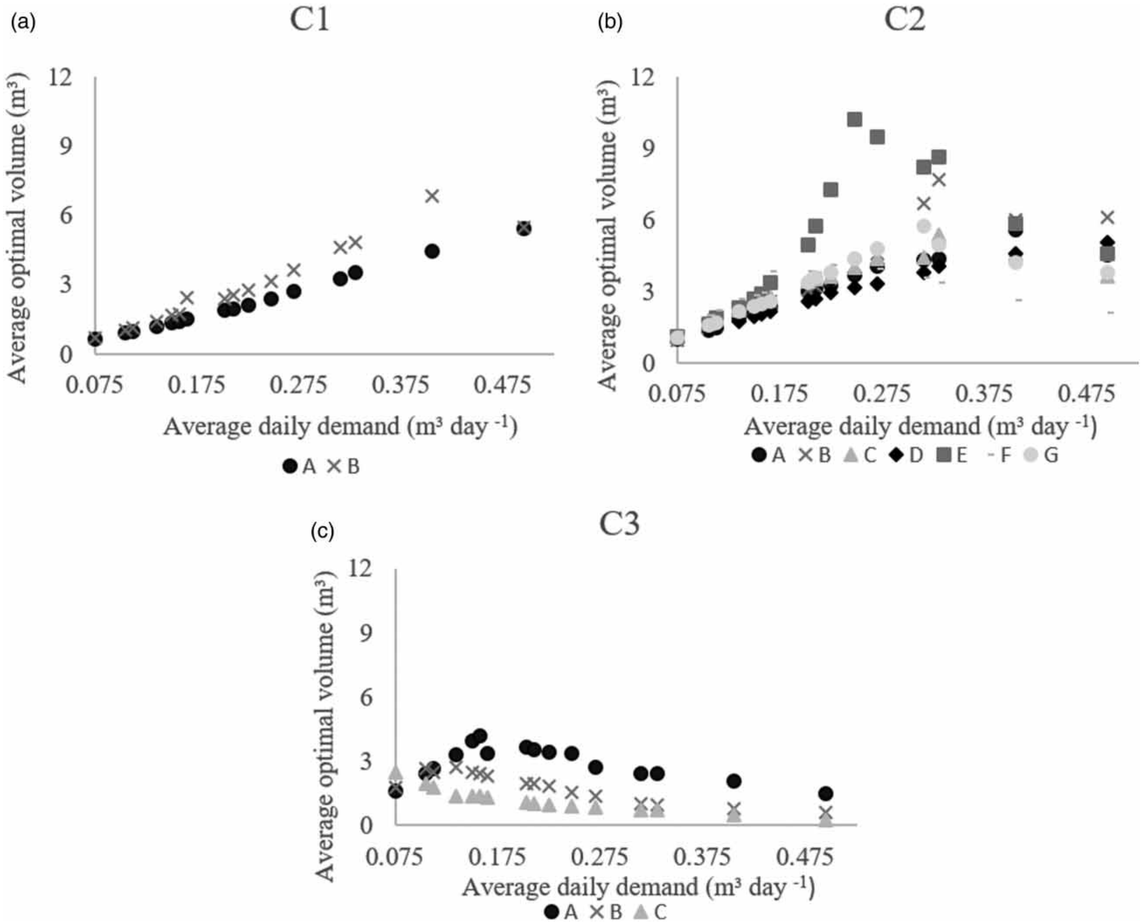


Figure 3 | Behaviour of the average optimal volume of each subgroup (m³) as a function of the average daily demand (m³ day^{-1}).

volume value of the group (10.22 m³ for average daily demand of 0.248 m³ day^{-1}. This municipality presented a percentage of months classified as drought of 40.0% and a mean CV of 335.40%, the highest in the C2 group, while its maximal Echo was 82.17%. These values initially indicate that there is a high rainfall supply to meet demand due to a high level of rainfall, which can be visualized by the upwards behaviour of optimal volumes (Figure 3(b)). However, despite having favourable rainfall, the high CV value indicates that the rainfall is more concentrated at certain periods throughout the year, which explains the divergent behaviour of this subgroup and leads to a large upwards slope of the observed values of the reservoir volume to the point of inflection. Their observed descending values are similar to those of the other subgroups of the same group. Pinto *et al.* (2022) analyzed the effect of temporal and spatial variability of rainfall on the design of rainwater reservoirs for 63 locations in Brazil, considering a fixed demand of 240 L day^{-1}, and observed that the municipality of Vitória exhibited a behaviour similar to that of other municipalities analyzed, and higher volumes were obtained for this municipality than for the others.

For group C3, the lowest mean optimal volume values were obtained among the three groups analyzed. The municipalities belonging to this group have climates classified as As, Cfa and Bsh (Table 1) and are located in the Northeast region of Brazil (Figure 1(b)), which is characterized by low rainfall (Brito *et al.* 2018; Siqueira *et al.* 2021). The C3A and C3B subgroups showed a similar pattern of behaviour, with the highest values related to demands lower than 0.165 m³ day^{-1}, followed by a progressive decrease in average optimal volumes with increasing average daily demand. The C3C subgroup, in turn, exhibited a single decreasing behaviour (Figure 3(c)). These results agree with the average rainfall indices of each subgroup, which influence supply and, consequently, the behaviour of volumes with increased demand.

All the municipalities in the C3 group had the lowest mean P_D, P_M and P_A and the highest mean CV among the three groups. In addition, the E_{eco} ranged from 41.08 to 50.19%, relatively low values compared to those of the other subgroups. The C3C subgroup stands out, represented by the municipality of Petrolina (Figure 1(b)), whose average daily, monthly and annual rainfall were 0.81, 24.69 and 296.24 mm, respectively, with an average CV of 598.49%. In this sense, the local climatic conditions can be considered a limiting factor to the use of rainwater for non-potable uses.

Santos & Farias (2017) analyzed the potential of rainwater harvesting in a semiarid region of northeastern Brazil. The results showed that the total water savings could reach at least 25%. However, although this percentage is low, the authors report that the installation of rainwater harvesting systems could reduce the pressure on the public supply system.

Table 3 presents the best practical models for estimating the rainwater reservoir considering the optimal volume. Behaviour models of the second region showed lower quality of fit compared to those of the first region, since the Bias values were predominantly negative and the R^2 values were lower than 0.5 for more than 50% of the subgroups. Furthermore, behaviour models of the first region had higher R^2 values, indicating a better quality of fit.

The behaviour of the first region was predominantly limited by the demand of 0.320 m³ day^{-1} among the subgroups (33.3%), followed by those of 0.260 m³ day^{-1} (22.2%) and 0.400 m³ day^{-1} (22.2%), for which there were two occurrences each. In general, the differences in the R^2 values between the two regions regarding model behaviour may be related to the number of data pairs observed. In most of the first behaviour regions of each subgroup, the amount of data was greater than their respective second behaviour regions and, in many cases, the second region had only two pairs of data.

Of the 23 subgroups formed, considering the maximal volume and the optimal volume, 19 (82.6%) presented Two regions of behaviour. Of these 19 subgroups, 6 (31.6%) had a demand limit of 0.320 m³ day^{-1}; 3 (15.7%), 0.400 m³ day^{-1}; and 3 (15.7%), 0.260 m³ day^{-1}. These values indicate the feasibility of using rainwater for non-potable purposes, since in these cases, there would be greater replacement, lower consumption of treated water and smaller reservoir volume, all of which imply a lower cost of system implementation (Faria *et al.* 2021).

Table 3 | Best practical models for estimating the volume of the rainwater reservoir, considering the YAS algorithm and the optimal reservoir volume

Subgroup	1st Region	R^2	RMSE (m³)	Bias (m³)	1st Region Limit	2nd Region	R^2	RMSE (m³)	Bias (m³)
C1A	$V = 0.420 \cdot CV \cdot e^{3.962 \cdot D_d}$	0.842	0.571	0.011	–	–	–	–	
C1B	$V = 0.276 \cdot CV \cdot e^{6.072 \cdot D_d}$	0.837	0.536	0.012	0.400	$V = 100.017 \cdot \left(\frac{D_d}{P_{d,3^\circ} \cdot A}\right)^{0.407}$	0.065	1.568	0.001
C2A	$V = 0.394 \cdot CV \cdot e^{4.522 \cdot D_d}$	0.835	0.461	0.008	0.400	$V = 99.772 \cdot \left(\frac{D_d}{P_{d,1^\circ} \cdot A}\right)^{0.417}$	0.151	1.231	− 0.036
C2B	$V = 0.001 \cdot P_{d,2^\circ} \cdot A \cdot e^{6.825 \cdot D_d}$	0.974	0.237	0.003	0.320	$V = 10.002 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.056}$	0.018	1.109	0.0005
C2C	$V = 0.469 \cdot CV \cdot e^{4.174 \cdot D_d}$	0.716	0.607	0.006	0.320	$V = 9.958 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.109}$	0.275	1.131	− 0.015
C2D	$V = 0.521 \cdot CV \cdot e^{2.827 \cdot D_d}$	0.799	0.563	0.030	–	–	–	–	–
C2E	$V = 0.103 \cdot CV \cdot e^{13.556 \cdot D_d}$	0.994	0.218	− 0.032	0.260	$V = 9.967 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.030}$	0.959	1.237	0.704
C2F	$V = 0.426 \cdot CV \cdot e^{5.320 \cdot D_d}$	0.783	0.456	0.001	0.260	$V = 9.929 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.163}$	0.767	0.805	− 0.026
C2G	$V = 0.371 \cdot CV \cdot e^{5.808 \cdot D_d}$	0.802	0.640	0.010	0.320	$V = 9.841 \cdot \left(\frac{D_d}{P_{d,se} \cdot A}\right)^{0.172}$	0.354	1.347	− 0.057
C3A	$V = 0.218 \cdot CV \cdot e^{11.180 \cdot D_d}$	0.311	0.959	− 0.107	0.155	$V = 9.842 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.163}$	0.423	1.123	− 0.056
C3B	$V = 0.002 \cdot P_{d,ch} \cdot A \cdot e^{13.413 \cdot D_d}$	0.199	0.561	− 0.077	0.110	$V = 9.677 \cdot \left(\frac{D_d}{P_{d,ch} \cdot A}\right)^{0.237}$	0.677	1.042	− 0.096
C3C	$V = 0.193 \cdot CV \cdot e^{0.0001 \cdot D_d}$	0.791	0.547	− 0.60	–	–	–	–	–

Legend: Grouping of municipalities as shown in Figure 1(b). V: Maximal Volume; D_d: Average Daily Demand; A: Catchment Area; P_D: Average Daily Rainfall; P_M: Mean Monthly Rainfall; P_A: Mean Annual Rainfall; $P_{d,se}$: Average Daily Rainfall of the Dry Period; $P_{d,ch}$: Average Daily Rainfall of the Rainy Period; $P_{d,1^\circ}$:Average Daily Rainfall for the first quarter; $P_{d,2^\circ}$:Average Daily Rainfall for the second trimester; $P_{d,3^\circ}$: Average Daily Rainfall for the third trimester; $P_{d,4^\circ}$: Average Daily Rainfall for the fourth quarter, CV: Coefficient of Variation of Daily Rainfall.

The maximal and minimum volumes obtained for the rainwater reservoir for non-potable use, considering the different simulated demands, can be seen in Table 4.

The statistical variables related to rainfall most appropriate for the fit of models for maximal volume (Table 4) were, for the behaviour of the first region, CV and the $P_{d,ch}$ and P_D, with three occurrences each, and for the second region, $P_{d,3°}$, with three occurrences. In general, considering the two regions, $P_{d,ch}$ was the most appropriate, with a total of five occurrences. The C1B and C2F subgroups provided, respectively, the highest and lowest values for the maximal volume, 94.575 and 21.471 m³, while the C1A and C2B subgroups presented, in that order, the lowest and highest values for the minimum volume, 1.394 and 14.678 m³, respectively.

In turn, Table 4 shows that for the behaviour of the first region, the statistical variable related to rainfall that most helped in the fitting of the models to the optimal volumes was CV, with 10 occurrences for 12 subgroups. For the second region, the predominant variable was $P_{d,ch}$. However, although the variable CV helped most in fitting the models for the first region of behaviour, such was not the case for the second region. Regarding the maximal volume, the highest value was obtained for the C2E subgroup, 10.217 m³, while the lowest was obtained for the C1A subgroup, 4.584 m³. For the minimum volume, the highest and lowest values, 1.285 and 0.268 m³, were obtained for the C2F and C1A subgroups, respectively.

Thus, in a general context, the statistical variables that best suited the fit of the maximal and optimal reservoir volume models were CV and $P_{d,ch}$. Notably, the calculation of the volume of the reservoirs was based on daily rainfall data, and its operation was simulated from a continuous water balance, which, in turn, is related to the rainwater supply needed to meet the demand. Therefore, as the CV is related to the rainfall that occurs on a daily basis and the $P_{d,ch}$ is relevant for meeting the demand, the predominance of both variables in the characterization of the reservoir volumes can be explained.

Finally, Mashford & Maheepala (2015) and Ali & Sang (2023) emphasize that the efficiency of rainwater harvesting systems and their use are mainly affected by the input data, structure and parameters of the model used in the calculations for reservoir sizing. Thus, Fewkes & Butler (2000), Imteaz & Shadeed (2022), Cauteruccio & Lanza (2023) and Raimondi *et al.* (2023) point to the efficiency and popularity of using behavioural models based on the daily water balance, such as YAS and Yield Before Spill (YBS), in relation to other methods such as the critical period, which identifies and uses sequences of flows when demand exceeds supply to determine the storage, and Moran's method (1959), which uses a system of simultaneous equations based upon queuing theory to relate reservoir capacity, demand, and supply. However, it should be noted that the YAS algorithm tends to underestimate the performance of the harvesting systems, whereas the

Table 4 | Statistical variable relative to the rainfall that was most suitable for fitting the practical models and the highest and lowest volumes for each of the subgroups defined for analysis of the maximal and optimal volume of the reservoirs

Maximal volume					**Optimal volume**				
Subgroup	**V.1R**	**V.2R**	**V_{max} (m³)**	**V_{min} (m³)**	**Subgroup**	**V.1R**	**V.2R**	**V_{max} (m³)**	**V_{min} (m³)**
C1A	CV	–	87.954	1.394	C1A	CV	–	7.643	0.268
C1B	$P_{d,ch}$	$P_{d,se}$	94.575	2.530	C1B	CV	$P_{d,3°}$	8.768	0.585
C1C	$P_{d,ch}$	$P_{d,3°}$	62.834	3.832	C2A	CV	$P_{d,1°}$	9.724	0.675
C1D	$P_{d,ch}$	$P_{d,3°}$	83.638	5.316	C2B	$P_{d,2°}$	$P_{d,ch}$	9.066	0.900
C1E	P_D	$P_{d,1°}$	81.362	4.106	C2C	CV	$P_{d,ch}$	7.072	0.734
C2A	P_D	P_A	73.654	13.104	C2D	CV	–	5.695	0.788
C2B	CV	$P_{d,ch}$	46.924	14.786	C2E	CV	$P_{d,ch}$	10.217	1.078
C2C	P_D	$P_{d,3°}$	47.440	7.547	C2F	CV	$P_{d,ch}$	4.584	1.285
C2D	$P_{d,1°}$	$P_{d,ch}$	27.786	9.883	C2G	CV	$P_{d,se}$	6.791	0.900
C2E	CV	$P_{d,2°}$	27.145	6.059	C3A	CV	$P_{d,ch}$	5.672	0.848
C2F	P_M	–	21.471	13.161	C3B	$P_{d,ch}$	$P_{d,ch}$	3.915	0.280
–	–	–	–	–	C3C	CV	–	2.457	0.256

V.1R: Variable relative to rainfall for the 1st region; V.2R: Variable relative to rainfall for the 2nd region; V_{max}: maximal volume; V_{min}: minimum volume; P_D: Average Daily Rainfall; P_M: Mean Monthly Rainfall; P_A: Mean Annual Rainfall; $P_{d,se}$: Average Daily Rainfall of the Dry Period; $P_{d,ch}$: Average Daily Rainfall of the Rainy Period; $P_{d,1°}$: Average Daily Rainfall for the first quarter; $P_{d,2°}$: Average Daily Rainfall for the second trimester; $P_{d,3°}$: Average Daily Rainfall for the third trimester; CV: Coefficient of Variation of Daily Rainfall

YBS algorithm usually overestimates it. Thus, the use of the YAS model is more suitable for design purposes, resulting in a more conservative estimate of the water demand supplied.

CONCLUSIONS

1. It was possible to model equations that describe the behaviour of the volume of the reservoir as a function of the demand for rainwater for non-potable use by using statistical variables related to rainfall, which simplifies the estimation of reservoir volumes without the need for discrete use of the daily rainfall values for the design.
2. In most of the subgroups analyzed, at first, the increased demand for rainwater in residential buildings leads to higher average maximal volumes, while at a certain point, these volumes begin to decrease due to higher water withdrawal rate.
3. In addition, for municipalities with climatic conditions favourable for providing rainwater able to meet demand, the maximal volumes and, consequently, the optimal volumes of the reservoirs tend to be higher.
4. The statistical variables that best suited the fit of the maximal and optimal volume models were, in general, CV and $P_{d,ch}$, since they are related to rainfall on a daily scale and the ability of rainfall to meet the demand for water, respectively.
5. In a practical way, the fitted models are easy to apply thus, they will facilitate the sizing procedures of rainwater harvesting reservoirs by the engineers, having the precision related to behavioural models, however, with the use of only one equation and without the need to perform the water balance of the reservoir.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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