Potential for drinking water savings through rainwater use: a case study in Brazil

Potencial de economia de água potável utilizando água da chuva: estudo de caso no Brasil

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Abstract

This article assesses the potential for drinking water savings through a rainwater harvesting system for non-potable purposes in a flat. The appliances' water flows were measured; users made daily notes of water consumption, time of use of each appliance, and the number of times this occurred; and daily readings of the water meter were made over fifteen days. Based on these data, the water end-uses and the average daily consumption were calculated. The measurements showed that the percentage of water for activities that do not require drinking water (toilet flushing, cleaning and washing machine) was 36.5% of the total consumption. Through the *Netuno* computer programme, the ideal capacities of rainwater tanks were determined for variable and average water consumption. It was found that a 10,000-litre tank provides drinking water savings of 34.8%, fully meeting the demand over 95% of the days. The study showed that, even with a considerable variation in consumption, the ideal capacity of the lower tank and the water savings achieved do not vary significantly when using variable or the average water consumption.

Keywords: Drinking water savings. Rainwater harvesting. Rainwater storage. Non-potable water demand.

Resumo

Este artigo avalia o potencial de economia de água potável por meio de um sistema de captação de água da chuva para fins não potáveis em um apartamento. As vazões de água dos aparelhos foram medidas; os usuários fizeram anotações diárias de uso da água, do tempo de uso de cada aparelho, e do número de vezes que isso ocorreu; e leituras diárias do medidor de água foram feitas ao longo de quinze dias. Com base nesses dados, foram calculados os usos finais de água e o consumo diário médio. As medições realizadas mostraram que o percentual de água para atividades que não necessitam de água potável (descarga, limpeza e máquina de lavar) foi de 36,5% do consumo total. Por meio do programa computacional Netuno, foram determinadas as capacidades ideais dos reservatórios de água da chuva para consumo variável e médio de água. Verificou-se que um tanque de 10.000 litros proporciona economia de água potável de 34,8%, atendendo integralmente à demanda de 95% dos dias. O estudo mostrou que, mesmo com uma variação considerável no consumo, a capacidade ideal do reservatório inferior e a economia de água alcançada não variam significativamente quando se utiliza dados variáveis ou o consumo médio de água.

Palavras-chave: *Economia de água potável. Captação de água da chuva. Reservação de água de chuva. Demanda de água não potável.*

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Introduction

Studies on the current and future availability of water resources are increasingly being needed as these resources are becoming scarcer due to population growth, high water consumption, increased levels of environmental pollution and climate change. According to the 2020 United Nations World Water Development Report (UN-Water (United Nations Water); UNESCO (United Nations Educational, Scientific and Cultural Organization) (UNITED…, 2020), "[…] global water use has increased by a factor of six in the last 100 years and continues to grow steadily at a rate of about 1% per year as a result of increasing population, economic development and changing consumption patterns […]". Another significant concern is the imbalance between water supply and demand caused by irregular water distribution worldwide. According to Ghisi (2005), 69% of the water available in Brazil is located in the North region, which comprises 45% of the territorial area, but is home to only 8% of the population, while the Southeast region, occupied by 43% of the Brazilian population, has only 6% of the available water.

Given this scenario, several studies are being developed in search of alternatives capable of mitigating the consequences of environmental pollution and climate changes and as opportunities and potential responses to optimise water consumption in homes. Alternative water sources can provide many economic and environmental benefits, i.e. they can decrease drinking water consumption and help with supply problems. Among the strategies that are being applied to reduce the consumption of drinking water is the installation of systems that allow the harvesting of rainwater for non-potable uses. Evidently, the implementation of such systems should always consider the local climatic conditions, the different technology uses, the water end-uses, and the level of acceptance of the measures adopted to reduce the consumption of drinking water.

Studies have already shown that much of the water needed for household use does not require drinking water, such as flushing toilets, cleaning houses, garden irrigation, among others. From this perspective, this study aims to evaluate the potential for drinking water savings obtained by using a rainwater harvesting system for non-potable purposes, based on data collected in a flat located in Belo Horizonte, Minas Gerais, southeastern Brazil.

Literature review

Several studies that have already been carried out show that rainwater harvesting can provide several benefits in addition to reducing drinking water consumption. Lade *et al.* (2013) show that the use of rainwater harvesting systems can transform risks, such as floods and polluted water, into local water resources. According to Aladenola and Adeboye (2009), another benefit is that the effective use of rainwater can reduce pressure on public water supply systems that, in most cases, are not efficient due to inadequate logistics and infrastructure.

Regarding regulations on use of rainwater in Brazil, Pacheco *et al.* (2017) evaluated the Brazilian state and municipal scenario. The authors pointed out that the assessment of the extent to which Brazil is implementing rainwater harvesting as an alternative to municipal water supply systems is hampered by the wide variety of legislation and regulations in force in various parts of the country. At the state level, Minas Gerais does not have a law about the use of rainwater for non-potable uses. In Belo Horizonte, the new master plan, in force since 2020, requires the implementation of rainwater tanks in urban lots, but only to help to avoid floods. That is to decrease the discharge of rainwater in the public drainage network and to improve the functioning of the micro and macro drainage system. It is said, however, that such tanks could be used as a reservoir for the use of rainwater. Likewise, Law no. 10840, of August 28, 2015 (CÂMARA…, 2015) requires that buildings adopt the reuse of greywater to encourage the rational use of water and, consequently, encourage the multiple uses of water. However, this law only applies to buildings where consumption is greater than 20,000 litres/day. Belo Horizonte also has legislation that encourages sustainable practices in buildings, such as the use of rainwater, granting bonuses, such as increasing the maximum allowed built area or applying discounts on the Urban Property and Territorial Tax, the so-called Green Tax ("IPTU Verde" in Portuguese).

However, even though the use of rainwater offers positive results, some factors still make its implementation difficult. Ward *et al.* (2013) identified that the general receptivity to the rainwater harvesting system is high, but factors related to cost and maintenance represent threats to such receptivity.

Marinoski *et al.* (2013) performed analyses on the acceptance of alternative water sources in low-class homes in the metropolitan region of Florianópolis. They concluded that the percentage of acceptance of treated rainwater for potable water end-uses, such as showering and washing dishes, ranged from 27% to 59%. For non-potable end-uses, washing machines and toilet flushing, the acceptance ranged from 84% to 95%.

Correlation analysis showed that the lower the level of education of the residents, the greater the acceptance of the use of rainwater for potable end-uses.

Several studies have been developed to verify the water end-uses and evaluate the potential for savings obtained in various typologies to minimise drinking water consumption in buildings by using rainwater. Ghisi, Montibeller and Schmidt (2006) found potential for drinking water savings ranging from 34% to 92%, depending on the water demand, in 62 cities in Santa Catarina, Brazil, with an average potential of 69%.

Barreto (2008) conducted a study in houses located in the west of the city of São Paulo to know the consumption patterns of users in buildings and their water end-uses. It was possible to quantify the potential savings generated using rainwater. The analysis of water end-uses showed that 33.8% of the daily consumption in households was used to wash clothes, and 5.5% to flush toilets. Together, these uses correspond to 39.3% of the total daily consumption. As such activities do not require drinking water, rainwater could be used instead.

Lima *et al.* (2011), when evaluating the drinking water savings potential for the residential sector in 40 cities in the Amazon, found that it varies between 21% and 100%, depending on the demand for drinking water, with an average potential of 76%.

Athayde Júnior, Dias and Gadelha (2008), in a study of houses with different economic patterns in the city of João Pessoa, northeastern Brazil, concluded that the use of rainwater is viable only in high-standard homes due to the water tariff scenario at the time of the study, resulting in high payback periods.

When studying the economic feasibility of installing a rainwater harvesting system in a multi-storey residential building in Florianópolis, southern Brazil, Maykot and Ghisi (2020) concluded that, among several scenarios, the most economically viable system, with lower payback and higher internal rate of return, is to provide rainwater only for toilet flushing.

Sousa *et al.* (2020) researched alternatives to reduce drinking water consumption, including rainwater harvesting, reuse of greywater and water-saving appliances, and their combined uses, in houses in Caruaru, Pernambuco. The authors concluded that the long payback of most of the proposed alternatives, except for the use of water-saving appliances alone, highlights the need for public policies that offer financial incentives to the population, preventing socio-economic conditions from being the main obstacle to the adoption of practices for the conservation of water resources.

Internationally, Abdulla and Al-Shareef (2009) found that the estimated potential for saving drinking water in homes in twelve provinces in Jordan ranges from 0.27% to 19.7%. Eroksuz and Rahman (2010) investigated the potential for water savings through rainwater harvesting systems in three Australian cities and concluded that a larger tank capacity was more appropriate to maximise drinking water savings. They also concluded that water savings in the driest years would be 37% to 42%, showing that great water savings can be achieved even in dry years.

Domènech and Saurí (2010) studied the use of rainwater harvesting in single and multi-family buildings in the metropolitan region of Barcelona. They considered users' practices and perceptions, drinking water savings and costs. The results showed that the demand for toilet flushing in a single-family home can be met using a relatively small tank despite the low precipitation and the high precipitation variability. A 17,000 litre-tank can fully meet the toilet flushing demand, but an 11,000 litre-tank would be enough to meet 97.9% of the demand. The authors found that the average drinking water savings in residential buildings was 18%.

Belmeziti, Coutard and Gouvello (2014) estimated that the potential for drinking water savings could reach up to 11% in the Paris metropolitan area using rainwater and that residential buildings account for up to 2/3 of such a potential.

Abdulla (2020) investigated the potential for water savings and optimal tank sizing and performed a cost-benefit analysis in different rainfall zones in Jordan. The author concluded that implementing a rainwater harvesting system is not economically viable at a low water price, but this should not prevent the adoption of the system since it can generate long-term benefits, such as reducing the impact on local water resources and reducing surface and groundwater withdrawals.

Farreny *et al.* (2011) analysed some types of roofs to maximise the availability and quality of rainwater in Spain and found that sloping smooth roofs can collect up to 50% more rainwater than flat rough roofs. Herrmann and Schmida (2000) found that the drinking water savings for a house in Germany could range from 30% to 60%, depending on consumption habits and roof area.

Mehrabadi, Saghafian and Fashi (2013) studied the use and performance of rainwater harvesting systems for the daily supply of non-potable water in three different climates. According to the results, in a humid climate, with larger roof areas, it is possible to supply at least 75% of the demand for non-drinking water for a maximum of 70% of the days. For small roofs, supply also meets 75% of the demand, but for a maximum period of 45% of the days. The same demand is met, at most, in 40% of the days in buildings with larger roofs for the Mediterranean climate. The demand is met in only 23% of the days in the arid climate.

As for the adoption of other strategies combined with rainwater harvesting, Muthukumaran, Baskaran and Sexton (2011) showed that the use of alternative water sources associated with water-saving appliances could generate drinking water savings of up to 77%. It was also found that the use of rainwater alone can save up to 40% of drinking water in homes in Australia.

In another study that also analysed the potential for drinking water savings, but using greywater and rainwater alone or combined in a multi-family building, Ghisi and Ferreira (2006) concluded that using only rainwater, the potential for water savings ranges from 14.7% to 17.7%. With rainwater and greywater combined, the drinking water savings ranged from 36.7% to 42.0%.

To explore the impacts of rainfall variation on the efficiency and reliability of rainwater harvesting systems, the study by Zhang *et al.* (2018) in three cities in China indicated that these impacts depend not only on trends and extents of rainfall variation but also on tank sizes and water demand scenarios. This result shows the importance of incorporating rainfall variations in the design and evaluation of rainwater harvesting systems. Santos *et al.* (2020) conducted a study in residential buildings in Portugal to analyse the impacts of climate change on rainwater harvesting systems. Daily simulations were performed using future rainfall data. The results showed that there would be no significant changes in the performance of the rainwater harvesting systems in the future in the areas studied.

In a municipal-scale analysis for single-family and multi-family residential, public and commercial sectors in Joinville, southern Brazil, Cureau and Ghisi (2019) concluded that when the demand for non-drinking water is low, the reuse of greywater is the most viable strategy to be implemented. However, rainwater is the best alternative to save drinking water when the demand is high and there is a large catchment area. It was found that up to 47.2% of the water could be saved by harvesting rainwater.

Regarding aspects related to user behaviour, Hameed, Javed and Nawaz (2021) concluded that factors such as people’s understanding of the potential benefits of the system and the use of incentive and penalty mechanisms may affect people’s willingness to adopt rainwater harvesting systems in the future.

Therefore, the studies presented in this section show that there is a great interest in research on the use of rainwater as a strategy to reduce the consumption of drinking water by the general population, bringing benefits to urban supply and drainage systems and for environmental preservation.

Method

To calculate the potential to reduce drinking water consumption through rainwater use, daily water consumption was measured over 15 days through a questionnaire carried out by the residents of the flat that was the object of study. Daily notes about water consumption, time of use of each appliance and the number of times this occurred throughout the day were made. The appliances’ water flows were estimated, and daily readings of the water meter were taken. It was also necessary to obtain rainfall data for the city, roof area of the flat and define the water end-uses, so that it would be possible to estimate the drinking water consumption that could be replaced with non-potable water. The collected data were used in the *Netuno* computer programme (GHISI; CORDOVA, 2014a) to find the ideal capacity of the rainwater tank and thus obtain the drinking water savings potential.

Residential building

The case study considered to evaluate the potential for reducing drinking water consumption was a flat located in the city of Belo Horizonte, Minas Gerais, southeastern Brazil. The built area of the flat is approximately 245 m², distributed over three floors, where three people live. Currently, there is not any rainwater harvesting system in the building.

The methodology was based on the daily reading of the water meter installed at the supply pipes of the building, separated for each apartment. In addition, daily notes were made by the residents indicating the use of water, the time of use of each appliance and the number of times the appliances were used over a period of fifteen days, from July 16th to July 30th, 2021.

The flat has three bathrooms, two balconies, kitchen and service area. Currently, two residents work from home. At least twice a week a general cleaning is carried out throughout the flat. It is also important to highlight that the study was carried out in the winter period, which was characterised by being an extremely cold and dry winter.

Data collection

Roof area

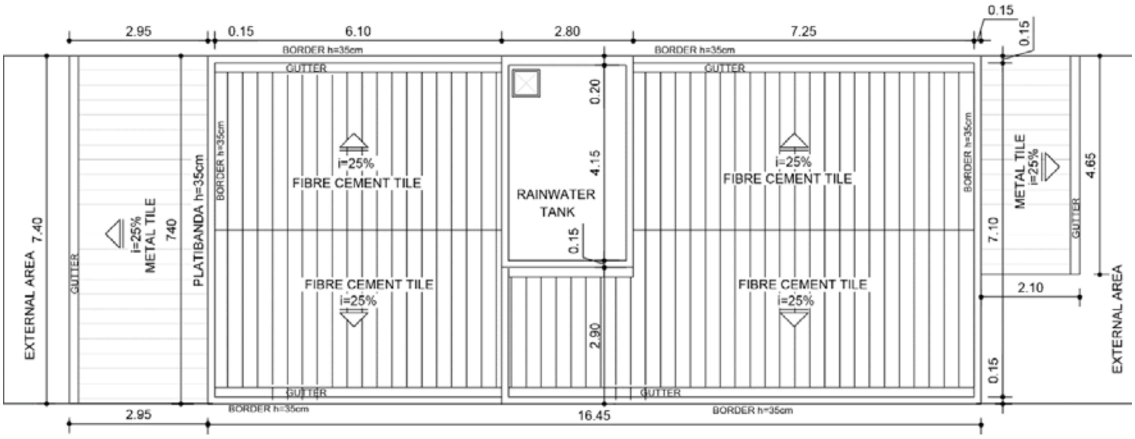
The rainwater catchment area was obtained from the building design. The survey of the roof areas was necessary to estimate the ideal capacity of the rainwater tank. The roof of the entire building and the roofs of the balconies were considered. Such roofs are made of fibre-cement tile and metal tile, respectively, as shown in Figure 1. The fibre-cement tile roof area is equal to 103.44m² (76.62% of the total roof area considered) and the metal tile is equal to 31.56m² (23.7% of the total area), resulting in a roof area of 135 m².

Rainfall data

The rainfall data used in this study were provided by the Meteorological Database of the National Institute of Meteorology (INMET) (INSTITUTO…, 2021). They were collected from the Pampulha A51 Station, located on the Pampulha campus of the Federal University of Minas Gerais (UFMG) and include information on daily rainfall from 10/09/2006 to 21/07/2021, i.e. approximately fifteen years.

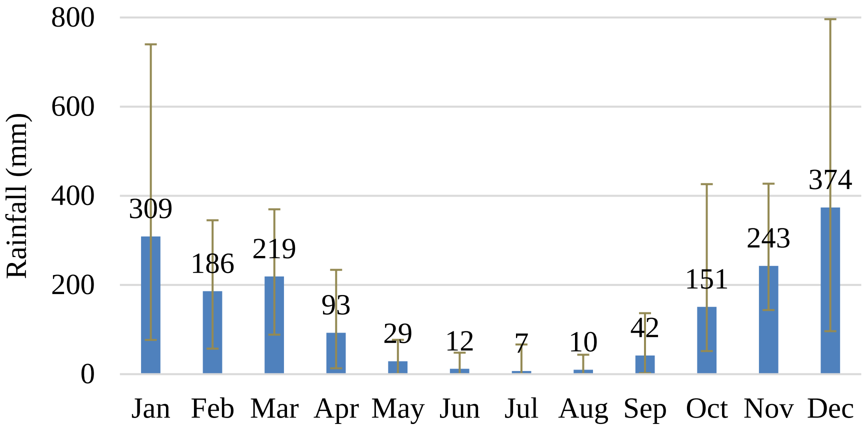
Figure 2 shows the average, maximum and minimum monthly rainfall from 2007 to 2020. The data indicate that rainfall in the region is not well distributed throughout the year. From May to August, the average rainfall was low, with periods of no rain in some years, while in January and December, rainfall was very high, reaching a maximum of 740 mm and 796 mm, respectively.

Figure 1 **- Roof areas in the building**



Note: measurements in meters.

Figure 2 **-Average, minimum and maximum monthly rainfall from January 2007 to December 2020 in Belo Horizonte**



Water end-uses

The water flows of taps and showers were obtained by measuring the time required for the water to fill a container of a known capacity. This process was performed three times for each appliance, and an average was taken. For the taps, they were fully opened during the three measurements. For the showers, a measurement was made according to the usage pattern of each user, that is, each user opened the shower once, totalling three measurements, and then the average was calculated.

The amount of water used for cleaning the flat was measured in buckets since this is the most common cleaning method used by the residents. Therefore, the amount of water used to fill the bucket was measured to standardise water consumption for cleaning.

For the toilets, all equipped with flushing valves, a flow rate of 0,76 litres/second was adopted as recommended by the manufacturer. To calculate the volume of water used for toilet flushing, the time from activation until the end of water release was measured.

For the washing machine, it was adopted the amount of water recommended by the manufacturer for each complete washing cycle (extra-low, low, medium, high). Daily notes about the consumption were made through questionnaires placed in toilets, kitchen, and laundry to collect the general information about water consumption in the flat. This helped identify the time of consumption and the number of times all appliances were used.

Daily data were collected on the time of use of taps, flushing the toilet and showers. For time measurements, users were instructed to count the seconds in activities requiring less time of use, such as flushing and washing hands. For more time-consuming activities, such as showering, time was measured using stopwatches. For cleaning, the number of buckets were counted and when the amount used was less than a full bucket of water, the users were instructed to use a measurement container to identify the amount used. The selected water level (extra-low, low, medium, high) and the frequency were recorded for the washing machine. A complete washing machine cycle considers two stages, one for prewash and one for washing. However, it was possible to perform only one stage. Thus, the times in which the cycles were interrupted were also recorded. A questionnaire was created for each room depending on the use of water in that room, and a sample of them can be seen in Table 1.

The total daily water consumption in each appliance was estimated based on the time of use and frequency data recorded in the questionnaires and also on the estimated water flow rates.

The calculation of the average daily water consumption *per capita* for the appliances whose water flow rate was known was performed using Equation 1.

$$Cap = t \times Q \tag*{Eq. 1}$$

Where:

Cap is the daily water consumption *per capita* for taps, showers and toilets (litres/day);

t is the daily time of use of taps, showers and toilets (seconds/day); and

Q is the flow rate of taps, showers and toilets (litres/second).

Table 1 - **Sample of the questionnaires applied in the flat**

Questionnaire 1: Bathroom					
Appliance: Shower		Appliance: Tap		Activity: Toilet flushing	
Date (day/month)	Time of use (minutes)	Date (day/month)	Time of use (seconds)	Date (day/month)	Time of use (seconds)
Questionnaire 2: Kitchen					
Activity: Cooking		Activity: Wash dishes		Activity: Drinking	
Date (day/month)	Time of use (minutes)	Date (day/month)	Time of use (minutes)	Date (day/month)	Time of use (minutes)
Questionnaire 3: Laundry					
Appliance: Washing machine		Appliance: Tap		Activity: cleaning	
Date (day/month)	Water level (low/medium/high)	Date (day/month)	Time of use (minutes)	Date (day/month)	Buckets (quantity)

For general cleaning, Equation 2 was used.

$$Clg = n \times v \qquad \text{Eq. 2}$$

Where:

Clg is the daily water consumption *per capita* for general cleaning (litres/day);

n is the number of buckets used to perform cleaning (number of times/day); and

v is the capacity of the bucket used (litres).

Since the estimates of consumption and water end-uses are made based on the occupants' responses by estimating time, these are subject to possible errors. Daily readings of the water meters installed next to the flat's supply pipes were made to verify the accuracy of the data obtained. To accept the results indicated by the occupants, a margin of error of 10% was admitted.

The water end-uses were calculated based on the equations presented above and the data obtained in the questionnaires. To differentiate the use of the tap in the kitchen, the notes in the questionnaires were separated between the following: washing dishes, cooking and drinking.

Potential for drinking water savings

Rainwater demand

The rainwater demand, i.e. the percentage of water used for non-potable uses that could be replaced with rainwater, was obtained from the water end-uses analysis explained in the previous section. The rainwater demand is necessary to estimate the potential for drinking water savings. This study considered that the water used for toilet flushing, general cleaning, and washing machine could be replaced with rainwater.

Optimal capacity of the rainwater tank

To simulate the implementation of a rainwater harvesting system, the *Netuno* programme, version 4, was used (GHISI; CORDOVA, 2014a). The programme can estimate the drinking water savings potential for different tank capacities.

The input data required for the programme are daily rainfall data, the definition of the first flush, roof area, total water demand *per capita*, number of residents, rainwater demand, surface runoff coefficient and capacity of the upper rainwater tank.

The first flush is defined to simulate the discharge of the first rain necessary to prevent dust, leaves and debris accumulated on the roofs from being taken to the rainwater tank (GHISI; CORDOVA, 2014b).

The total water demand represents the amount of water needed to meet the user's needs, and it can be considered in the simulations as a constant figure or variable if the flat presents variable water consumption. This study considered two scenarios:

(a) variable water consumption: the simulations were run using the measured water consumption of each day since some activities that presented high consumption were not performed every day; and

(b) average water consumption: the simulations were run using the average consumption obtained during the fifteen days.

The surface runoff coefficient represents the percentage of the total volume of precipitation collected by the rainwater system after the first flush and the losses through absorption and evaporation of rainwater upon reaching the roof surface. This coefficient depends mainly on the surface's type of material. Rocha (2009) shows runoff coefficients for the standard materials in buildings, thus a runoff coefficient of 0.8 was used, equivalent to the fibre-cement tile coefficient, considering that it represents 76.62% of the total roof area and that the programme considers only one coefficient. For this research, no other losses were considered in the system besides the losses through absorption and evaporation and the first flush of each precipitation, as a way to eliminate impurities and undesirable debris in rainwater.

For the upper tank, it was defined that the capacity would be equal to the average daily rainwater demand. It was also determined that when the capacity of the upper tank decreases to 10%, rainwater is pumped from the lower tank.

To define the ideal capacity of the lower rainwater tank, simulations were run for capacities from zero to 50,000 litres at intervals of 1,000 litres. This procedure was conducted in a way that for each tank capacity the programme would calculate a new potential for potable water savings. To choose an optimal capacity for the lower rainwater tank, the difference between potable water savings potential for each tank capacity was defined as 2%/m³.

Another input data in the programme is the rainwater demand, i.e. the percentage of daily drinking water to be replaced by rainwater. Such a demand was defined according to the water consumption results found in the flat. In this research, it was considered that the water used for toilet flushing, general cleaning and washing machine could be replaced by rainwater.

Results and discussion

Data obtained

The data obtained through the questionnaires made it possible to estimate the daily water consumption in the flat and the volume of water needed to supply the rainwater demand (toilet flushing, general cleaning and washing machine). The water flow rates of each appliance and the capacities used are shown in Table 2, which also shows the average, minimum and maximum time of use of each appliance.

In Figure 3, it is possible to observe the daily water consumption, both estimated and measured. This analysis showed that the daily consumption had significant variations, but the estimated and the measured were within the ±10% margin of error in all fifteen days.

Table 2 - **Water flow rates of appliances and capacities**

Room	End-use	Water flow or capacity	Maximum time of use	Minimum time of use	Average time of use
Bathroom 1	Toilet flushing Tap Shower	0.76 l/s 0.05 l/s 2.7 l/min	9s 2min6s 14min	2s 9s 5min	6s 36s 7min42s
Bathroom 2	Toilet flushing Tap	0.76 l/s 0.06 l/s	20s 5min03s	4s 16s	9s 49s
Bathroom 3	Toilet flushing Tap Shower	0.76 l/s 0.05 l/s 4.8 l/min	40s 4min 26min58s	6s 36s 4min58s	18s 1min44s 15min32s
Kitchen	Cooking Washing dishes Drinking	4.5 l/min 4.5 l/min 4.5 l/min	3min03s 20min10s 2min37s	27s 5min56s 40s	1min25s 12min48s 1min20s
Laundry	Tap Washing machine Bucket	0.07 l/s 70 l/cycle 8 l	1min40s 2.5 cycles 21 buckets	36s 1 cycle 1.46 litres (measured)	1min07s 1.5 cycles 7 buckets

Figure 3 - **Daily water consumption measured and estimated over a 15-day period in winter, July 16-30, 2021**

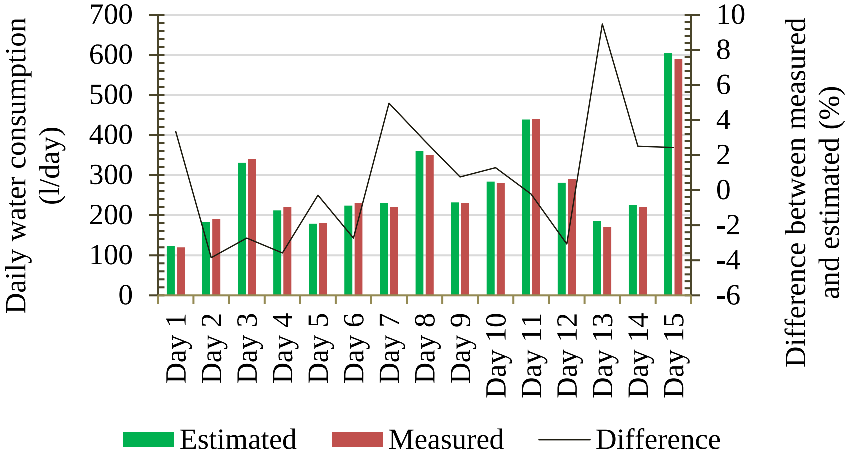


Table 3 **- Water consumption on a daily basis over the 15-day period**

Room	**End-use**	**Flow**	**Daily consumption (litres)**				
			Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Bathroom 1	Toilet flushing	0.76 l/s	5.32	3.8	6.08	6.84	3.04
	Tap	0.05 l/s	2.07	2.92	2.92	2.20	1.98
	Shower	2.7 l/min	13.5	14.08	14.08	17.23	0.00
Bathroom 2	Toilet flushing	0.76 l/s	3.04	12.16	15.20	5.32	10.64
	Tap	0.06 l/s	3.12	2.40	1.04	2.34	1.75
Bathroom 3	Toilet flushing	0.76 l/s	30.40	19.76	14.44	18.24	20.52
	Tap	0.05 l/s	7.56	9.25	9.30	11.98	3.52
	Shower	4.8 l/min	23.84	59.12	76.32	74.08	83.36
Kitchen	Cooking	4.5 l/min	5.47	6.00	13.72	8.50	7.60
	Washing dishes	4.5 l/min	26.70	42.60	29.02	59.40	34.57
	Drinking	4.5 l/min	3.00	6.00	3.00	6.00	10.00
Laundry	Tap	4.6 l/min	0.00	4.60	4.60	0.00	2.50
	Washing machine	70 l/cycle	0.00	0.00	105.00	0.00	0.00
	General cleaning	8.00 l	0.00	0.00	36.00	0.00	0.00
Total estimated			124.02	182.69	330.72	212.13	179.48
Total measured			120.00	190.00	340.00	220.00	180.00
Difference (%)			3.35	-3.85	-2.73	-3.58	-0.29

Room	**End-use**	**Flow**	**Daily consumption (litres)**				
			Day 6	**Day 7**	**Day 8**	**Day 9**	**Day 10**
Bathroom 1	Toilet flushing	0.76 l/s	5.32	4.56	5.25	3.04	3.80
	Tap	0.05 l/s	6.30	0.54	0.63	0.58	0.00
	Shower	2.7 l/min	14.80	37.80	15.12	16.15	16.87
Bathroom 2	Toilet flushing	0.76 l/s	12.92	7.60	9.12	3.80	3.80
	Tap	0.06 l/s	18.20	1.49	3.31	1.04	1.17
Bathroom 3	Toilet flushing	0.76 l/s	5.32	10.50	13.68	6.84	6.84
	Tap	0.05 l/s	4.60	7.14	2.20	2.67	6.76
	Shower	4.8 l/min	70.00	64.24	105.60	72.24	30.08
Kitchen	Cooking	4.5 l/min	10.00	8.00	3.50	2.00	3.00
	Washing dishes	4.5 l/min	63.00	59.55	65.00	49.87	58.52
	Drinking	4.5 l/min	11.80	6.00	3.50	3.50	5.75
Laundry	Tap	4.6 l/min	0.00	0.00	0.00	0.00	0.00
	Washing machine	70 l/cycle	0.00	0.00	0.00	70.00	105.00
	General cleaning	8.00 l	1.46	23.50	133.00	0.00	42.00
Total estimated			223.72	230.92	359.91	231.73	283.59
Total measured			230.00	220.00	350.00	230.00	280.00
Difference (%)			-2.73	4.96	2.83	0.75	1.28

Room	**End-use**	**Flow**	**Daily consumption (litres)**				
			Day 11	**Day 12**	**Day 13**	**Day 14**	**Day 15**
Bathroom 1	Toilet flushing	0.76 l/s	5.32	3.80	3.80	5.32	1.52
	Tap	0.05 l/s	0.45	0.45	1.62	0.00	0.54
	Shower	2.7 l/min	35.32	21.6	0.00	18.22	35.37
Bathroom 2	Toilet flushing	0.76 l/s	3.80	4.56	4.56	6.84	7.60
	Tap	0.06 l/s	1.56	2.73	0.97	1.49	1.56
Bathroom 3	Toilet flushing	0.76 l/s	11.40	4.56	10.64	14.44	16.72
	Tap	0.05 l/s	3.76	2.20	2.58	1.83	2.35
	Shower	4.8 l/min	119.84	63.76	69.20	77.28	129.44
Kitchen	Cooking	4.5 l/min	13.45	2.50	6.50	3.20	2.50
	Washing dishes	4.5 l/min	88.12	57.75	79.75	90.75	59.25
	Drinking	4.5 l/min	9.00	5.20	6.50	6.15	4.50
Laundry	Tap	4.6 l/min	0.00	7.00	0.00	0.00	0.00
	Washing machine	70 l/cycle	140.00	105.00	0.00	0.00	175.00
	General cleaning	8.00 l	7.00	0.00	0.00	0.00	168.00
Total estimated			439.02	281.11	186.12	225.52	604.35
Total measured			440.00	290.00	170.00	220.00	590.00
Difference (%)			-0.22	-3.07	9.48	2.51	2.43

The average daily water consumption estimated from July 16th to July 30th was 273 litres, i.e., only 0.6% greater than the average measured consumption. The average daily water consumption *per capita* found was 91 litres *per capita*/day, a figure lower than the average daily water consumption *per capita* in the city of Belo Horizonte – which is equal to 200 litres *per capita*/day, according to the Minas Gerais Sanitation Company (Copasa) (COMPANHIA..., 2021) – and also lower than the amount of water considered sufficient to meet the basic needs of a person, according to the UN – 110 litres *per capita*/day. The consumption obtained was also lower than those found by Willis, Stewart and Emmonds (2020) in 38 houses in Australia, i.e., 153.2 litres *per capita*/day, and the one found by Hammes, Ghisi and Thives (2020) in a house in Blumenau, 141 litres *per capita*/day.

The data recorded in the questionnaires made it possible to estimate the daily water end-uses. It was also possible to understand the user's consumption patterns and the distribution of water by activity during the analysis. These data can be seen in Table 3 and Figure 4. When the end-uses were analysed, it was observed that showers respond for the highest share in the water consumption, with a total consumption of 1,388.5 litres during the fifteen days, representing 33.9% of the total consumption, as shown in Figure 5. The second highest consumption was for washing dishes, reaching a total of 863.8 litres, representing 21.1% of the total. Similar results were found by Marinoski, Rupp and Ghisi (2018) in a study in homes in southeastern Brazil, indicating 30% in showers and 23% in the kitchen tap. The study by Marinoski *et al.* (2013) in lower-class households in Florianópolis also found similar results, i.e. 32.7% in showers and 18.0% for washing dishes.

Figure 4 - **Estimated daily water end-uses**

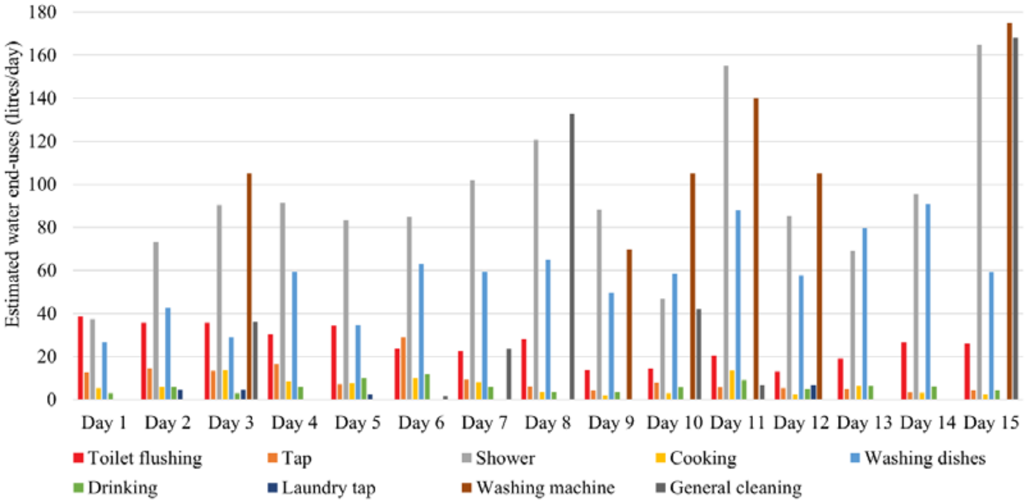
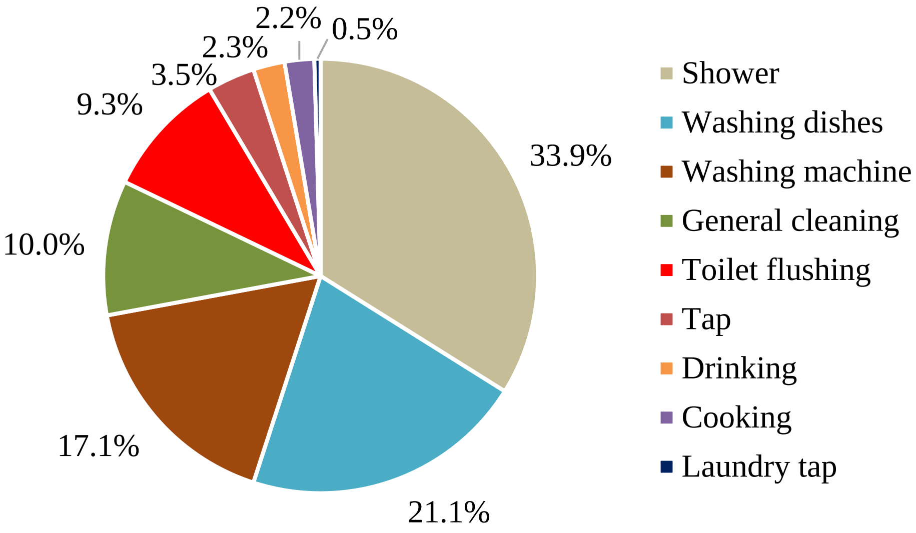


Figure 5 - **Estimated average water end-uses**



Other uses that draw attention are water consumption in the washing machine and general cleaning. The total water consumption for such activities was 700 litres and 411 litres, respectively, so even considering that they are not performed every day, they represent the flat's third and fourth highest consumption. Water consumption for the toilet flushing represented the fifth-highest consumption, 9.3% of the total.

These results made it possible to define the percentage of rainwater demand by adding the percentages of toilet flushing, general cleaning, and washing machine. Thus, the demand for rainwater was 36.5%, i.e. 99.6 litres/day. Ghisi, Montibeller and Schmidt (2006), when evaluating the potential for drinking water savings in homes in 195 municipalities in southeastern Brazil, found similar results, presenting an average equal to 41% (ranging from 12% to 79%). With that percentage defined, the input data was entered into the programme, as shown in Table 4.

Rainwater tank

The ideal capacity of the lower tank and its corresponding drinking water savings potential was obtained using the *Netuno* computer programme with the input data described previously. In this study, as previously reported, two simulations were performed, one using variable water consumption and the other using the average water consumption.

Figure 6 shows the drinking water savings potential as a function of the lower tank capacity. The ideal capacity indicated by the programme is marked as a red line. Such a capacity was defined considering the difference between drinking water savings potential for each tank capacity. For a given capacity, the curve begins to form a level in which the savings increase less than the 2%/m³ defined previously due to the increase in the tank capacity.

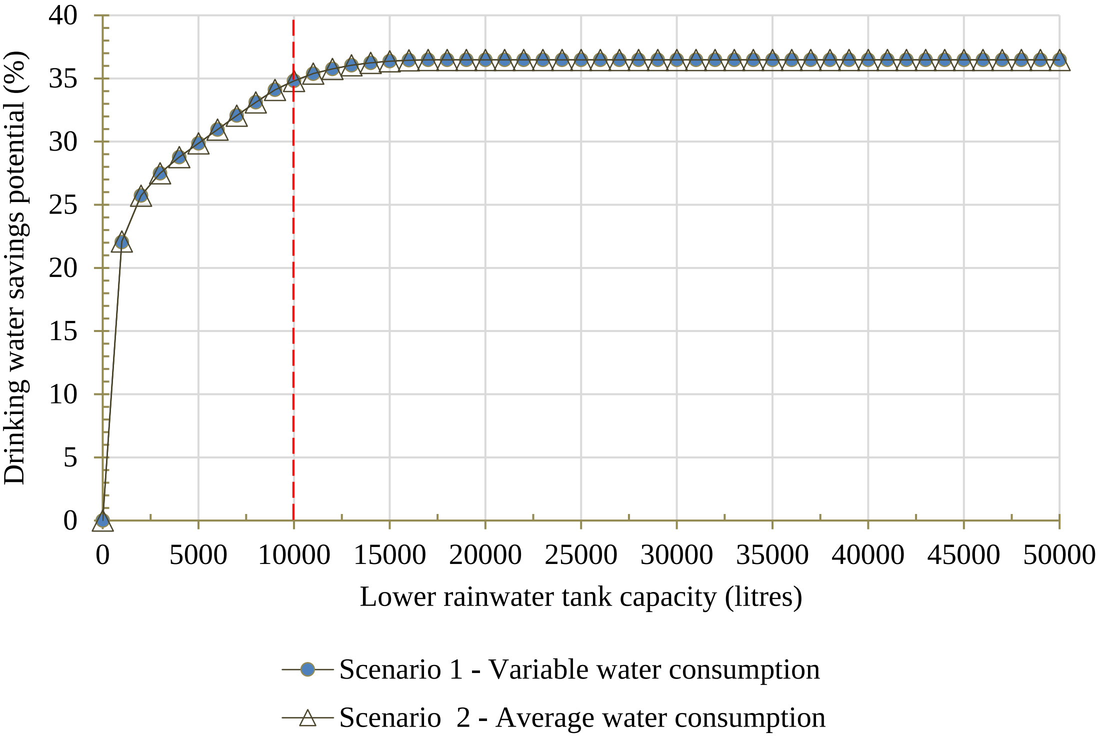
The ideal capacity indicated by the programme for the first case, where water demand was variable, was 10,000 litres, resulting in drinking water savings potential equivalent to 34.8% and average rainwater consumption of 94.8 litres/day. For the second case, where the demand was 91 litres *per capita*, the capacity was 10,000 litres, with the same savings of 34.8% and average rainwater consumption of 95 litres/day. Marinoski, Rupp and Ghisi (2018) found similar drinking water savings for the same tank size, i.e. 33% of the monthly water consumption.

It is noted that the drinking water savings potential stops to increase at 15,000 litres for both scenarios. The curve becomes increasingly constant when the potential for savings is 36.4%. From this capacity on, the increase in the savings potential becomes small, being less than 0.4%.

Table 4 - **Input data used in the *Netuno* programme**

Input	Data
Rainfall data	Belo Horizonte, Pampulha A51 - 2006 to 2021
First flush	2 mm
Rainwater catchment area	135 m²
Total daily water demand	Variable (15 days) and fixed
Number of residents	3
Rainwater demand (% of daily drinking water demand)	36.5%
Surface runoff coefficient	0.8
Upper rainwater tank capacity (litres)	Volume equal to the average daily rainwater demand
Water volume in the upper tank below which rainwater is pumped	10%
Simulation for different lower tank capacities	Yes
Maximum capacity of the lower tank (litres)	50,000
Interval between lower tank capacities (litres)	1,000
Indicate optimal capacity for the lower tank	Yes
Difference between potable water savings potential for each tank capacity	2%/m³

Figure 6 - **Potential for drinking water savings as a function of the capacity of the lower rainwater tank for variable and average water consumption**



The rainwater is first stored in the lower tank and then pumped to the upper tank, where it will be available for consumption. In this study, the capacity of the upper tank was defined according to the rainwater demand, so this capacity was also different for both cases. The capacity of the upper tank indicated by the programme was 99.4 litres for the first scenario and 99.6 litres for the second scenario, that is, a difference of only 0.2 litres. The results of daily rainwater consumption according to the size of the lower tank are shown in Figure 7.

It should be noted that in the case of implementing the system, the upper tank capacity should be 100 litres for both scenarios.

Figures 8 and 9 show the percentage of days when the rainwater demand is completely met, partially met, and not met throughout the year. It is observed that using a 10,000-litre tank, the percentage of days in which the amount of rainwater available meets completely the rainwater demand is 95.44% for the first scenario and 95.02% for the second scenario. The percentage of days in which it does not meet the demand is 4.30% and 4.28%, respectively, showing that, even if there is no good rainfall distribution throughout the year, the amount of rainwater available meets the rainwater demand for most of the year. Hammes, Ghisi and Thives (2020) found similar results for a house located in Blumenau, i.e. in 95% of days the amount of rainwater available meets the non-potable water demand, and in approximately 3% of days it does not meet the demand, but using a 2,000-litre tank. This can be explained through the good distribution of rainfall throughout the year in Blumenau and the house has a larger roof area, differently from what happens in this study.

The monthly results for scenarios 1 and 2 are shown in Tables 5 and 6. It is noted that the rainwater demand was completely met in almost every month, reaching 36.5% of savings every day, except from June to September, which can be explained by the reduction in the rainfall at this time of year. Tables 5 and 6 also show data on the overflow volume. It can be observed that a large amount of water is lost, even using a 10,000-litre tank. In November, which presented the highest result, 1,220 litres of rainwater were spilled out.

Through the Netuno computer programme, it was also possible to estimate the monthly drinking water and rainwater consumption according to the chosen tanks, and then it was possible to analyse the savings generated in the two scenarios. The results show that there are, in fact, significant water savings with the use of the rainwater harvesting system, producing drinking water savings of 34,618 litres *per capita*/year in the first scenario and 34,682 litres *per capita*/year in the second scenario.

The analyses showed that, even with a considerable variation in water consumption, the ideal capacity of the lower tank and the drinking water savings do not present significant variation when using either the variable or the average daily water consumption.

Figure 7 - **Daily volume of rainwater consumed as a function of the capacity of the lower rainwater tank for variable and average water consumption**

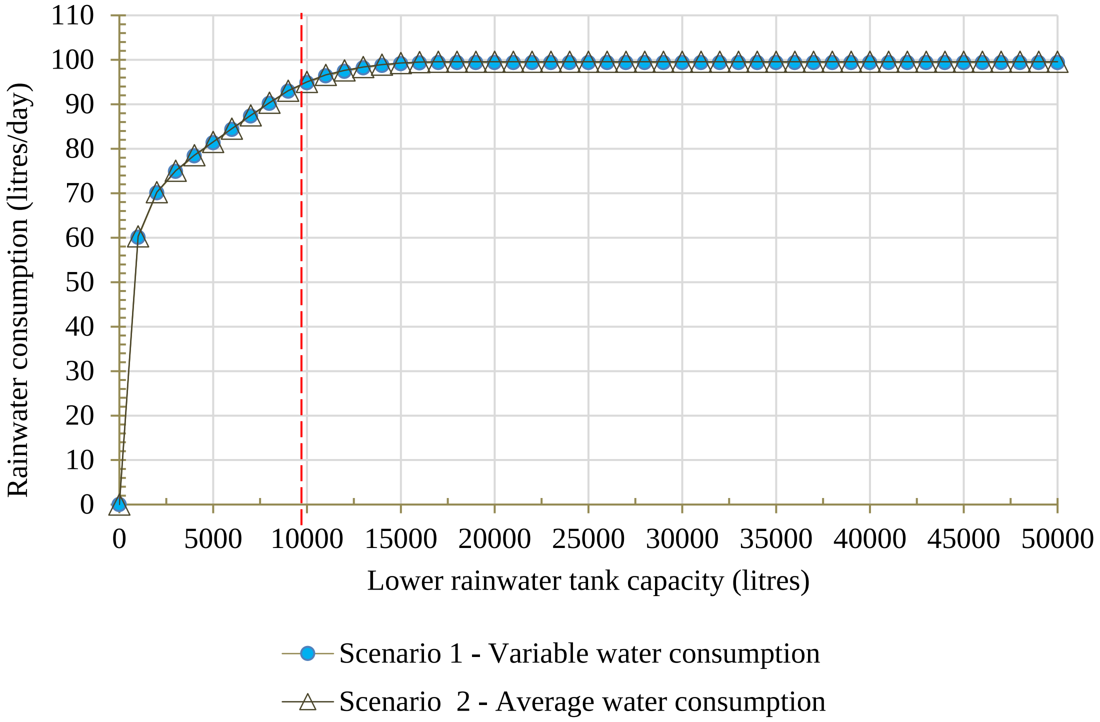


Figure 8 - **Percentage of days when the rainwater demand is completely met, partially met, and not met - variable water consumption**

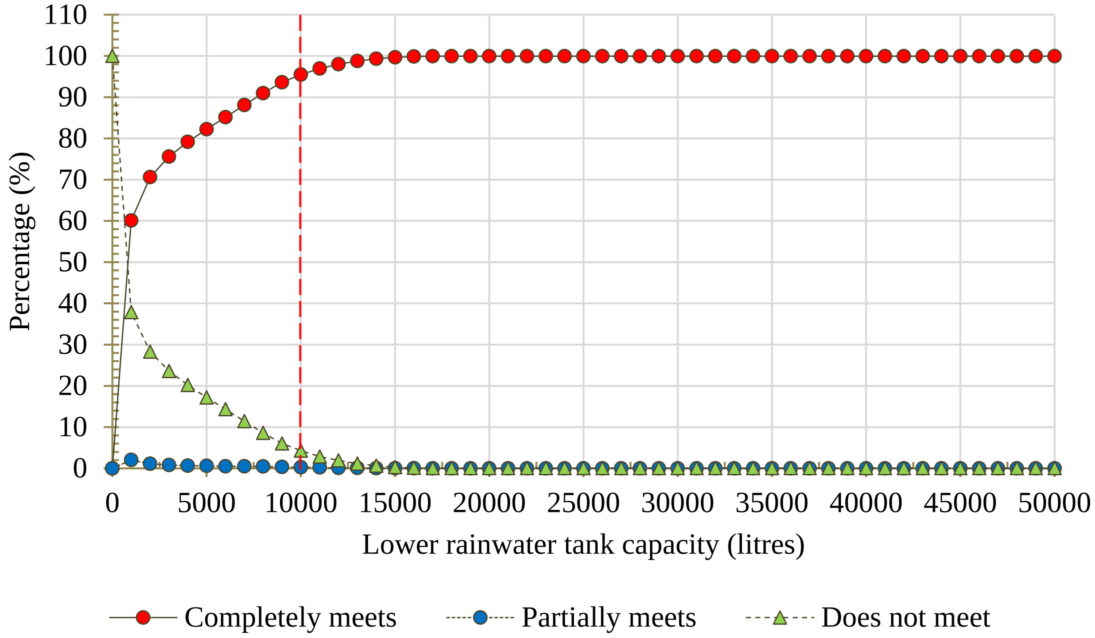


Figure 9 - **Percentage of days when the rainwater demand is completely met, partially met, and not met - average water consumption (91 litres per capita/day)**

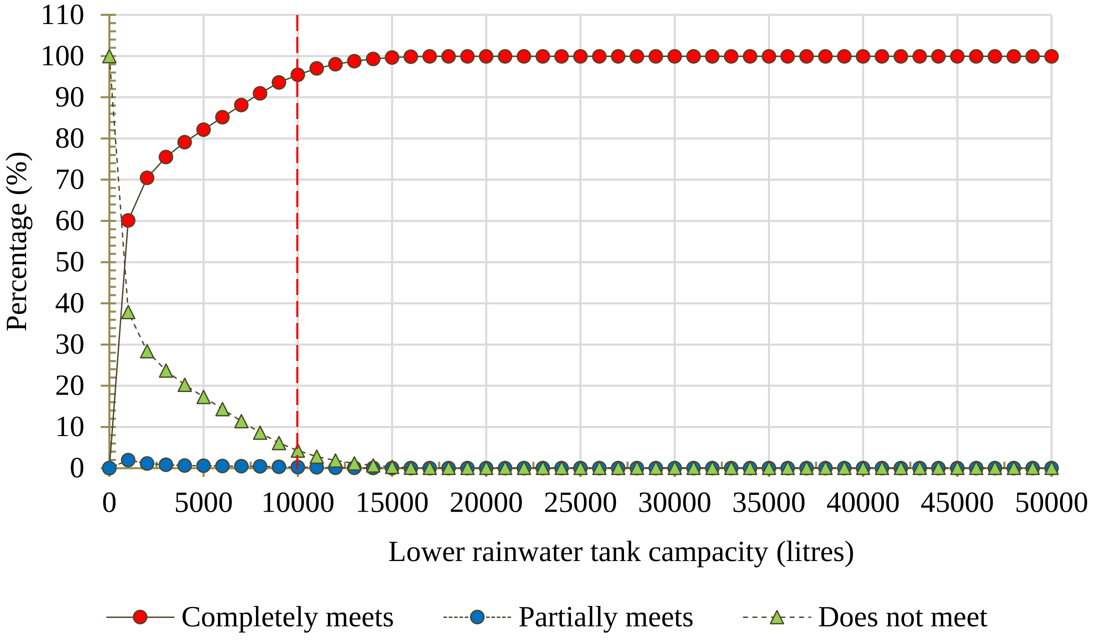


Table 5 - **Monthly results of simulation 1 - variable water consumption**

Month	**Potential for drinking water savings (%)**	**Average daily rainwater consumption (l/*capita*.day)**	**Average daily drinking water consumption (l/*capita*.day)**	**Total rainwater spilled out (l/*capita*.day)**	**Days when the rainwater demand is completely met (%)**	**Average monthly rainfall in Belo Horizonte (mm)**
January	36.50	99.48	173.08	664.43	100.00	309
February	36.50	99.27	172.70	658.11	100.00	186
March	36.50	99.46	173.04	241.18	100.00	219
April	36.50	99.43	172.92	36.73	100.00	93
May	36.50	99.81	173.64	6.30	100.00	29
June	35.98	98.29	174.88	0.00	98.19	12
July	32.86	89.18	182.23	0.00	90.09	7
August	24.67	67.09	204.87	11.55	66.82	10
September	32.51	88.27	183.26	200.16	88.44	42
October	36.50	99.76	173.55	683.81	100.00	151
November	36.50	99.43	172.97	1,220.66	100.00	243
December	36.50	99.28	172.73	915.70	100.00	374
Average	34.82	94.84	177.55	384.56	95.44	140
Total in a year (*per capita*)	**-**	**34,618**	**64,805**	**140,366**	**-**	**-**

Table 6 - **Monthly results of simulation 2 - average water consumption (91 litres *per capita*/day)**

Month	**Potential for drinking water savings (%)**	**Average daily rainwater consumption (l/*capita*.day)**	**Average daily drinking water consumption (l/*capita*.day)**	**Total rainwater spilt (l/*capita*.day)**	**Days when the rainwater demand is completely met (%)**	**Average monthly rainfall in Belo Horizonte (mm)**
January	36.50	99.64	173.36	664.10	100.00	309
February	36.50	99.64	173.36	658.21	100.00	186
March	36.50	99.64	173.36	240.80	100.00	219
April	36.50	99.64	173.36	36.92	100.00	93
May	36.50	99.64	173.36	6.66	100.00	29
June	35.88	97.97	175.03	0.00	98.19	12
July	32.98	90.02	182.98	0.00	89.86	7
August	24.53	66.96	206.04	11.66	66.82	10
September	32.52	88.78	184.22	198.79	88.89	42
October	36.50	99.64	173.36	682.88	100.00	151
November	36.50	99.64	173.36	1220.24	100.00	243
December	36.50	99.64	173.36	916.24	100.00	374
Average	34.82	95.02	177.55	384.37	95.46	140
Total in a year (*per capita*)	**-**	**34,682**	**64,963**	**140,296**	**-**	**-**

Silva and Ghisi (2016) conducted a study where the drinking water demand is the leading independent variable analysed, varying the average daily demand *per capita*, the routine repetition interval and the sampling coefficient of variation for eight cities in Brazil. The results showed no significant difference in the potential for drinking water savings when considering the average drinking water demand compared to the variable drinking water demand, with a variation in uncertainty ranging from 3.1% to 4.8%. However, regarding the ideal size of the lower tank, uncertainty ranged from 3.6% to 9.4% in all cities. The authors concluded that using the average drinking water demand instead of a detailed distribution still creates uncertainties, but it can be ignored given that most of the considerable uncertainties had a low probability of occurrence.

The results showed that the savings of approximately 35% by using rainwater for non-potable uses can be considered significant for a single-family flat, especially in the face of water crises. However, it is also necessary to evaluate the cost-benefit of constructing the tank since the indicated capacity is significant to meet the demand of a flat. It is essential to highlight that using a 5,000-litre tank, which would imply lower costs, also leads to good drinking water savings potential, i.e. 29.8%, and fully meeting the demand over 81.9% of days, figures also considered significant.

Conclusion

This article evaluated the drinking water savings potential through a rainwater harvesting system for non-potable purposes in a single-family flat located in the city of Belo Horizonte, south-eastern Brazil.

By analysing the consumption patterns of users in the flat for fifteen days, computer simulations were carried out considering the use of rainwater for toilet flushing, general cleaning and washing machine, using variable water consumption and average water consumption.

In both scenarios, it was verified that using a 10,000-litre lower tank and an upper tank of capacity equal to the average daily rainwater demand, a drinking water savings potential of 34.8% could be achieved. Comparing the two scenarios, it is noted that, even with a considerable variation in water consumption, the ideal capacity of the lower tank and the drinking water savings do not present significant variation when using either the variable or the average daily water consumption.

The study showed a good potential for drinking water savings using a rainwater harvesting system, fully meeting the demand in approximately 95% of days and saving approximately 34,682 litres *per capita*/year. Though, it is necessary to carry out an economic assessment to verify the financial viability of this system due to the high costs of implementing a 10,000-litre tank. However, even if the system does not prove to be economically viable, the rainwater harvesting system is an important measure to save water resources for the future.

For a lower installation cost, one option would be using a smaller tank, i.e. 5,000-litre, which also leads to a drinking water savings potential of 29.8% and fully meets the demand over 81.9% of days, figures also considered significant.

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