European Journal of Sustainable Development (2025), **14**, 3, 77-90 ISSN: 2239-5938
Doi: 10.14207/ejsd.2025.v14n3p77

The use of Rainwater Harvesting in a Multifamily Building

By Lucas Carvalho Delowski[1], Igor Catão Martins Vaz[2], Enedir Ghisi[3], Liseane Padilha Thives[4]

ABSTRACT:
Water is an indispensable resource for life on Earth, and the means to obtain potable water are becoming increasingly expensive and challenging due to climate change and pollution of natural freshwater sources. Therefore, encouraging the rational use of water and implementing water-saving methods are fundamental to promoting sustainable development. Among the measures adopted to save potable water, rainwater harvesting for non-potable use in residential buildings stands out as a simple and efficient alternative. Thus, this study aims to assess the potential for potable water savings and the economic feasibility of implementing rainwater harvesting in a multifamily building in Florianópolis, southern Brazil. The Netuno computer programme was used to estimate the potential for potable water savings and perform the economic feasibility analysis. Netuno's input data include daily rainfall, rainwater harvesting area, average daily water demand and rainwater demand. Once the ideal tank capacities were determined through the simulations, the potable water savings amounted to 11.78%. The costs involved in implementing the rainwater harvesting system were R$15,293.19, with a payback period of seven months and an internal rate of return of 14.92% per month, making it an economically viable investment.

Keywords: Feasibility assessment; Water Savings; Computer simulation; Buildings; Sustainability.

1. Introduction

Water is a natural resource of immeasurable importance to humanity and is now facing a pressing issue of availability for human consumption. With population growth, especially in large urban centres, the demand for potable water is rising (Martine & Camargo, 1983). According to Shiklomanov (1998), 75% of the planet's surface is covered with water, totalling 1.386 million km³. However, only 2.5% is freshwater, with more than half (68.9%) in the form of glaciers and 29.9% stored in underground aquifers. Consequently, only 0.3% of all the freshwater sources on Earth, including rivers, lakes, and natural reservoirs, are suitable for treatment and consumption, and this context underscores the urgency for research on rainwater harvesting for non-potable use in residential buildings.

Of all the surface water resources generated in South America, 50% are located within Brazilian territory, accounting for 11% of the total worldwide. However, the distribution of water throughout the year and across Brazil is irregular, which makes water management in the country a complex task. The Brazilian Amazon alone is responsible for 71% of the surface water resources nationally, while other basins account for a maximum of 7% each (Tucci et al., 2001). Santa Catarina, one of the southern states in

| [1,2,3,4] Federal University of Santa Catarina, Department of Civil Engineering, Research Group on Management of Sustainable Environments, Laboratory of Energy Efficiency in Buildings, Florianópolis-SC, Brazil.

Brazil, is served by four different water basins, which account for 2.7% of the national surface water resources.

Despite the water availability in Santa Catarina being considered high by the United Nations Environment Programme (UNEP, 2002), preserving water resources must be a priority. According to Ghisi's (2006) projection, Brazil's freshwater reserves will decrease considerably during the century, considering the population growth rate. From 2075 onwards, the southern region is expected to have water availability below 5,000 m^3 per inhabitant per year, which is considered a low level according to the UNEP.

Among the alternatives to help meet the water demand, rainwater harvesting is a viable option for non-potable purposes (Almazroui et al., 2017; Foo et al., 2017; Martins Vaz & Ghisi, 2023). Such a system is considered a low-effort approach that requires a roof harvesting system and simple treatment schemes. Rainwater may be used for different purposes after these procedures. In residential buildings, for example, rainwater can be used for flushing toilets, washing floors and sidewalks, and irrigating plants and gardens, among other uses (Apostolidis & Hutton, 2006).

In addition to providing savings on potable water, the harvesting, storage, and subsequent use of rainwater can reduce problems related to heavy rainfall in densely populated areas. Accelerated and often unplanned urban development reduces permeable areas, leading to decreased rainwater infiltration into the soil and increased runoff. In regions with inadequate urban infrastructure for managing rainwater, heavy precipitation can lead to flooding (Dornelles, 2012). Thus, rainwater harvesting reduces runoff over impervious areas such as sidewalks and asphalt pavements, decreasing the risk of flooding.

Studies analysing the potential for potable water savings by using rainwater have been conducted by various authors (Ghisi, 2006; Ghisi et al., 2006; Hofman-Caris et al., 2019; Yannopoulos et al., 2019). Additionally, comparisons between methods for sizing rainwater tanks have been made, as exemplified in Amorim & Pereira (2008) and Rupp et al. (2011). Thus, this work aims to evaluate the potential for potable water savings by using rainwater for non-potable uses in a multifamily building in Florianópolis, Brazil.

2. Methodology

The methodology of this study was established to estimate the potential for potable water savings by using a rainwater harvesting system in a multifamily building. First, one provides the characterisation of the object of study, including available data on the water demand, harvesting area and daily rainfall. Data for estimating the potable and non-potable water demands were obtained via questionnaires administered to the building's residents. Secondly, input data were used in a water balance model performed with the Netuno computer programme, version 4, which was chosen to estimate the potential for potable water savings. Third, an optimal system was chosen based on the simulations. At last, an economic analysis was conducted to assess the feasibility of the system. A flowchart illustrating the research processes is presented in Figure 1.

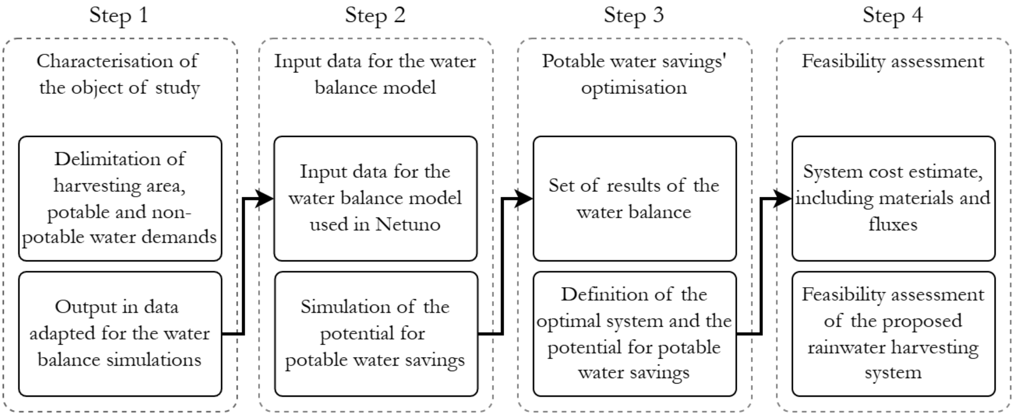

Figure 1: *Flowchart of the methodology*

2.1 Object of study

The object of study is a multifamily building in Florianópolis, Santa Catarina, Brazil. The building contains several blocks in a low-rise neighbourhood, of which four specific blocks were chosen to assess the theoretical rainwater harvesting system. The set of blocks chosen for analysis in this study was supplied by a common water tank, thus facilitating the systems required for rainwater harvesting. Figure 2 shows the location of the building.

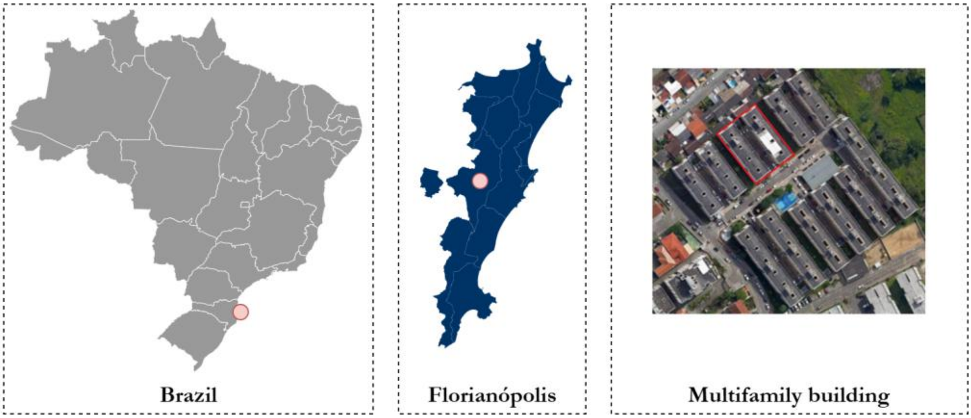

Figure 2: *Location of the multifamily building.*

A questionnaire was distributed among residents to collect data on the frequency and duration of water appliance use, thereby determining potable and non-potable water demands. The questionnaire was divided according to the days of the week due to the difference in water appliance usage and residents' time spent in the building, particularly between weekdays and weekends. The water consumption in each flat was determined by obtaining the frequency of use of each water appliance through questionnaire responses and measuring the water flow rate.

To determine the flow rate of each water appliance, one employed a container of known capacity and measured the time required to fill it. To ensure the test was standardised and accurate, the faucets were opened at 360°, taking one second to make a complete turn. The test was repeated three times for each water appliance, and the average was taken as the final flow rate. The appliances in which the flow rates were measured were the shower, sink, kitchen basin, and utility area sink. The flow rate, calculated based on volume and time, is described in Equation 1. After measuring the water appliances and gathering responses from residents through the questionnaires, it was possible to estimate the potable and non-potable water demands through Equation 2.

$$\boldsymbol{Q = \frac{V}{t}} \qquad \text{Equation 1}$$

$$\boldsymbol{C = Q \cdot t \cdot f} \qquad \text{Equation 2}$$

Where: C is the total daily consumption for each appliance, including potable and non-potable water uses (litres/day); Q is the flow rate of each appliance (litres/second); V is the volume of the container (litres); t is the measured duration of use of each appliance (seconds); f is the frequency with which the appliance is used (times/day).

This study used the questionnaires to characterise consumption, between potable and non-potable outputs, and water bills to quantify the final volume. This approach is known to be limited, which is why rainwater demand ranges were considered, as shown in section 2.3. Through the questionnaires administered to the residents and Equations 1 and 2, it was possible to estimate the daily potable and non-potable share. The monthly bills from the water utility were reviewed to obtain the average water consumption per person during the period analysed, considering the number of blocks, flats, and residents served. Thus, the daily water consumption and the percentage of water consumption that rainwater may supply were obtained. The appliances that may be supplied with rainwater instead of potable water were the toilet, washing machine, and utility area sink.

2.2 Water balance model

The water balance model was used to assess how much of the non-potable demand could be supplied with rainwater. Ghisi & Cordova's (2014) model within the Netuno programme was used to calculate the water balance through a deterministic algorithm, obtaining the potential for potable water savings. In other words, the rainfall, water consumption, potable and non-potable demands, and physical characteristics of the model are determined to understand the water flows in the building. Equations 3 to 7 show the water balance model used by the Netuno programme (Ghisi & Cordova, 2014). The equations were adapted from the description by Freitas & Ghisi (2020).

$$\mathrm{V}_{flows}^{i} = R_i \cdot \mathrm{A} \cdot K_{runoff} \qquad \text{Equation 3}$$

$$\mathrm{V}_{begin}^{i} = \min \begin{cases} V_{cap} \\ V_{end}^{i-1} + V_{flows}^{i} \end{cases} \qquad \text{Equation 4}$$

$$R_c^i = \min\begin{cases} R_{demand}^i \\ V_{begin}^i \end{cases}$$ Equation 5

$$V_{end}^i = \min\begin{cases} V_{begin}^i - R_c^i \\ V_{cap} - R_c^i \end{cases}$$ Equation 6

$$W_{save} = 100 \cdot \frac{\sum_{i=1}^{n} R_c^i}{\sum_{i=1}^{n} P_{demand}^i}$$ Equation 7

Where V_{flows}^i is the rainwater volume intercepted by the harvesting surface on day i (litres/day); R_i is the rainfall volume on the day i (mm); A is the harvesting area (m²) ; K_{runoff} is the coefficient of available rainwater in the harvesting surface after losses (non-dimensional); V_{begin}^i is the volume of rainwater in the tanks at the beginning of the day i (litres); V_{cap} is the maximum capacity of water in the tank (litres); $V_{\mathrm{inf}\_end}^{i-1}$ is the volume available at the end of the previous day (litres); R_c^i is the rainwater consumed on day i (litres); R_{demand}^i is the rainwater demand of the day i (litres); V_{end}^i is the volume of rainwater available at the end of the day i (litres); W_{save} is the potential for potable water savings obtained through the use of rainwater (%); P_{demand}^i is the total (potable and non-potable) water demand on the day i (litres); i is the specific day assessed; n is the number of days simulated (days).

One final detail is essential to note. As the object of study is a multifamily building, two rainwater tanks are necessary, with one below ground (lower) and the other on the building's top floor (upper). Rainwater is transported between the tanks by pumping stations and therefore requires electricity. More details about this model are described in the following sections and the Netuno manual (Ghisi & Cordova, 2014). The upper rainwater tank was sized through Netuno's method, which considers the tank size equal to the average daily rainwater demand, i.e. the average amount of rainwater required daily by the residents. The lower rainwater tank was sized through a technical threshold described in section 2.4.

2.3 Input data for the water balance simulation

The input data necessary to simulate the potential for potable water savings include the following:

- Roof characteristics: harvesting area and runoff coefficient;
- Rainfall data: daily rainfall data for Florianópolis;
- Water use pattern: Total (potable and non-potable) daily water consumption and percentage of the water consumption that may be supplied by rainwater (non-potable demand).

Starting with the roof characteristics, the runoff coefficient is based on the type of material that constitutes the rainwater harvesting surface. The coefficient adjusts the amount of rainwater available by diminishing losses related to evaporation and absorption of the roof materials. Thus, since the roof of the building is made of fibre cement, a coefficient of 0.80 was considered based on the literature. Additionally, the building's roof area was determined by separately analyzing the structural plans of one of the blocks and then multiplying the result by four to obtain the total roof area, as the blocks are identical.

Daily rainfall data were obtained directly from the Environmental Resources and Hydrometeorology Information Centre (CIRAM) database (EPAGRI, 2023), which includes historical rainfall for Florianópolis. The measurement period started on 08/01/1996 and extends to the present day at the station owned by the Foundation for Support of Sustainable Rural Development of the State of Santa Catarina (FUNDAGRO). However, one limited the timespan between 08/01/1998 and 31/12/2022, which is longer than the minimum of fifteen years, as stated by Geraldi & Ghisi (2018), for Netuno's simulations. After obtaining the rainfall data, missing information was treated as zero precipitation and appropriately organised in Netuno's input data format.

Table 1 summarises the scenarios simulated. In addition to the rainwater demand, four scenarios were included with variations of -10%, -5%, +5%, and +10%. Therefore, a range of possible variations in the rainwater demanded were included. Scenario numbering follows the description presented in Table 1. All other parameters were kept constant according to the characteristics of the study object.

Table 1: Input data used in the Netuno simulations.

Variable input data	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Rainwater demand (%)	19	24	29	34	39
Fixed input data	For all scenarios				
Initial runoff (mm)	2				
Harvesting area (m²)	742				
Water demand (L/capita/day)	127.55				
Number of residents	125				
Surface runoff coefficient	0.8				
Volume of the lower tank	Varied and optimised according to Netuno's threshold				
Volume of the upper tank	Average daily water demand calculated via Netuno				

2.4 Rainwater tank sizes

To enable Netuno to determine the ideal capacity of the lower tank, three parameters must be defined based on the physical constraints of the simulation: the maximum simulation volume, the interval between the tank sizes assessed by the programme (in litres), and the threshold for optimal tank selection. The first presents a maximum tank size, which may be limited due to cost, structural or market limitations. The second defines the number of tank sizes simulated. Values of 25,000 litres for the maximum simulated capacity and 500 litres for the interval of the simulated capacities were considered in this study.

The threshold for optimal tank selection defines a limit value for the ratio between the increase in the potential for potable water savings and the increase in the tank size. When the simulation results in a lower tank which does not increase the potable water savings potential above the threshold, the capacity is selected as the optimal choice. In this study, the threshold of 1%/m³ was selected, which means that whenever an increase of 1m³ provides less than 1% of potential for potable water savings, the optimal solution has been reached. However, one reiterates that other constraints, such as the environmental and cost consequences of the tank capacity, should also be considered in the optimisation.

The upper tank capacity was considered equal to the average daily rainwater demand. However, this capacity does not match commercially available tank sizes and thus requires adjustment. An upper tank size of 7,500 litres was selected for the study, which corresponds to the available tank size in Florianópolis' stores and surpasses the average daily rainwater demand.

2.5 Feasibility assessment

Based on the construction and maintenance costs of the system, as well as the water savings, an economic analysis can be conducted using Netuno. The analysis estimates the net present value (NPV), the payback period, and the internal rate of return (IRR), providing information on the feasibility of the system. Other variables required for the cash flow analysis include the analysis period (in years), the estimated monthly inflation rate, the adjustment period for maintenance costs and water and energy tariffs, the minimum attractive rate (on a monthly basis), and the month in which the harvesting system is installed.

Since the exact quantity of pipes, fittings, and filters needed for the system's installation is unknown, a percentage of the cost of tanks, pumps and labour was applied to represent the cost of these materials. As Ferreira (2005) demonstrated, pipes and fittings account for a small portion of the final project cost, and for systems of a similar nature to the one presented in this study, a factor of 15% of the total estimated cost can be applied. This percentage represents, in addition to the nominal costs of pipes, fittings and filters, the cost associated with installation processes in the building. Therefore, a price survey was conducted in three stores in Florianópolis to determine the actual costs of the tanks and pumps. The cost considered for each item was the lowest price obtained from the surveyed stores. The most current reports available in the National System of Construction Costs and Indexes (SINAPI) were used to estimate the labour cost required for the installation.

To establish the net present value, payback period, and internal rate of return, the determined period of analysis for the economic study was 20 years, considered to be equal to the system's lifespan. Such a period of analysis was chosen as it is commonly used in other works of a similar nature (Freitas & Ghisi, 2020; Martins Vaz et al., 2020). As for the economic variables: the National Index of Price to the Ample Consumer (IPCA) was used to determine the inflation rate based on the average values between October 2022 and September 2023; the adjustment period for electricity, water, and sewage tariffs used was 12 months; and the rate values applied by the utility companies CELESC (electricity) and CASAN (water), respectively, were based on the tariffs of September 2023. Equations 8 and 9 show how the NPV and IRR were calculated.

$$\text{NPV} = \sum_{i=0}^{20} \frac{CF_i}{(1+MAR)^i} \qquad \text{Equation 8}$$

$$IRR \xrightarrow{yields} NPV = 0 = \sum_{i=0}^{20} \frac{CF_i}{(1+IRR)^i} \quad \text{Equation 9}$$

Where NPV is the Net Present Value in Brazilian currency (R$); CF_i is the cash flow of the year i, which considers all costs and savings in the year adjusted by inflation and utility adjustment on the tariffs (R$); MAR is the minimum attractive rate (%); IRR is the internal return rate, which yields a balanced (equal to zero) cash flow considering discounted figures (%).

The minimum attractive rate considered was 0.5% per month, as it is the base interest rate for savings deposits, according to the Central Bank of Brazil. Although conservative, the minimum attractive rate was adopted to minimise possible interferences in the net present value analysis. If the IRR exceeds the MAR, the consequent NPV is positive, corresponding to a feasible alternative. Finally, the system was considered as installed in September.

It is important to emphasise that the values considered may change according to the country's macroeconomic scenarios, including interest rates and inflation increases and decreases. Also relevant is the tariff context, from which many sustainable solutions have obtained discounts as a tax incentive for adopting the technology. In this way, differences in tariff adjustments, MAR, implementation costs and inflation have a direct impact on the economic viability results. They should be better explored in future studies, including the evaluation of different scenarios. It is also important to emphasise that differences between the financial reality in Brazil and other countries can impact the replicability of this study in other locations and should be taken into account.

3. Results and discussion

3.1 Rainfall data and water use in the building

Rainfall data, recorded daily over 27 years, yielded an average daily precipitation of 5 mm, with an average annual rainfall of 1,696 mm. The roof area of one block was 185.5 m²; therefore, the total area for analysing the four blocks together was 742 m². With both variables and a harvesting surface of fibre cement, one obtained the amount of rainwater input in the water balance, which was automatically calculated through Netuno.

In sequence, one compiled the applied questionnaires to obtain the water consumption pattern in the building. However, even with the instructions that the questionnaire should be filled out daily and as accurately as possible, the average water consumption recorded per resident differed from the average obtained according to the utility bills. Such an error can occur due to residents' inaccuracies in recording the usage time of appliances, the low response rate to the questionnaires, or comparisons made with previous months' bills instead of considering the period corresponding to the responses. Therefore, the questionnaires were only used to estimate the percentage of the total water demand to be supplied by rainwater. Table 2 shows the results of the questionnaires, including the frequency and average usage time of the water appliances.

Table 2: Frequency and average usage time of water appliances per resident.

Usage	Usage frequency (times/day)	Average usage time (min)
Showering	1.44	10.46
Flushing	4.16	0.06
Washing hands and face	5.97	0.33
Brushing teeth or shaving	2.49	0.36
Washing dishes	1.74	5.72
Cooking	2.01	0.57
Sink	0.52	0.20
Washing machine	0.37	-
Others	0.07	1.20

The measurement of the flow rates of the appliances was carried out in one flat. Three measurements were taken for each water appliance at different times. Table 3 presents the water flows, along with the container capacities used for the measurements. Such an assessment presents a limitation, as other flats may diverge in the water appliances used; however, one believes such uncertainty is minimal compared to other uncertainties.

Based on the water flow rates, usage times, and frequencies, one can determine the average water consumption per appliance and inhabitant. Table 4 shows the per capita average water consumption for all appliances in one day for the set of blocks analysed. To determine the rainwater demand, the percentage of water consumption for each appliance was calculated. Rainwater may replace potable water in the toilet, washing machine, and laundry sink, totalling 59.2 L/inhabitant/day, which represents 28.6% of the total water consumption.

Table 3: Measured water flow rates on each of the water appliances.

Appliance	Container capacity (L)	Time to fill the container (s)				Flow rate (L/s)
		T1	T2	T3	Average	
Shower	5.2	55.20	52.38	56.10	54.56	0.10
Basin tap	0.5	3.80	3.86	3.81	3.82	0.13
Sink tap	0.5	8.20	8.67	8.65	8.51	0.06
Laundry tap	0.5	6.65	7.03	7.21	6.96	0.07

Table 4: Estimated average daily potable water consumption per inhabitant.

Usage	Average consumption (L/inhabitant.day)	Consumption share (%)
Showering	86.33	41.67
Toilet flushing	25.48	12.30
Washing hands/face	15.28	7.38
Brushing teeth/shaving	7.02	3.39
Washing dishes	35.12	16.95
Cooking	4.04	1.95
Laundry tap	0.44	0.21
Washing machine	33.24	16.05
Others	0.20	0.10
Total	207.15	100.00

Observation: The grey lines indicate the appliances that may be supplied with rainwater.

Through the records kept by the building's administration, it was possible to obtain the monthly water consumption in the building from January 2018 to July 2023. The average consumption of the set of blocks during the period analysed was 478.33 m³, and, considering the building has an average of 125 residents, it was possible to determine the average daily water consumption per capita. Thus, the average water consumption was 127.55 litres per person per day, which is significantly lower than the estimate in Table 4. The value of 127.55 is much closer to the national average from the National Sanitation Information System (SNIS) and was the value considered in the Netuno simulation.

3.2 Netuno analysis and optimal system

Figure 3 shows the potential for potable water savings obtained for the systems proposed.

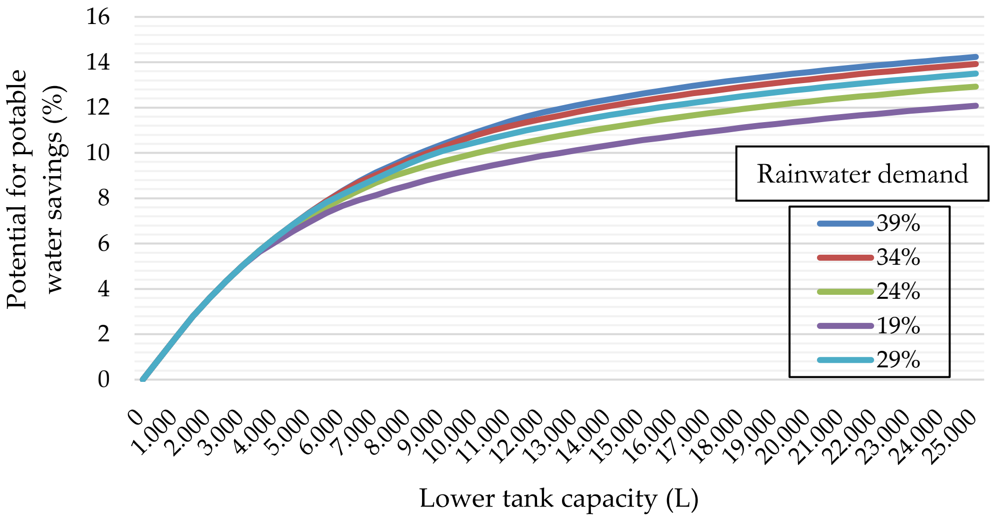

Figure 3: *Potential for potable water savings for the five scenarios.*

Considering Figure 3, it can be seen that, for all the scenarios modelled, the curve relating to the potential for potable water savings is less steep for volumes above 10,000 litres in the lower tank. This means that even if the volume of the lower tank increases, the difference in the potential for potable water savings becomes less and less noticeable. For example, for a rainwater demand of 39%, the ideal volume of 12,000 litres provides 11.78% savings in drinking water. If a lower reservoir volume of 15,000 litres were selected, the percentage increase in potable water savings would only be 0.83%.

The simulations carried out by Netuno showed that the potential for potable water savings for the five scenarios analysed using the previously defined criteria was 11.13%, 10.93%, 11.24%, 11.34% and 11.78%, respectively. For these results, the ideal reservoir volumes were 12,000 litres, 17,000 litres, 14,500 litres, 11,500 litres and 12,000 litres, respectively. Table 5 consolidates all the results from the various scenarios analysed.

Table 5: Simulation results for all five scenarios.

Results	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Ideal lower tank capacity (L)	12,000	17,000	14,500	11,500	12,000
Potential for potable water savings (%)	11.13	10.93	11.24	11.34	11.78
Daily rainwater consumption (L/day)	1774.63	1743.43	1791.74	1808.58	1877.76
Daily potable water consumption (L/day)	14,169.12	14,200.32	14,152.01	14,135.17	14,065.99

Table 5 shows that the highest potential for potable water savings (11.78%) occurred in scenario five, where the percentage of substitution of drinking water for rainwater adopted was 10% higher than the one stipulated in the questionnaires. In this scenario, the ideal volume of the lower tank was set at 12,000 litres. Scenario five was chosen as the basis for the economic analysis, as it had the greatest potential for potable water savings and the second-lowest ideal volume of the lower reservoir, along with scenario one. Finally, for the selected scenario, Netuno indicates that the ideal capacity for the upper tank is equal to the average daily rainwater consumption, which was calculated based on the rainwater demand. The upper tank indicated in scenario five has a volume of 6,218 litres, which was increased to 7,500 litres due to availability in the local market.

3.3 Feasibility of the optimal systems

The prices obtained for the selected tanks were R$6,549.00 for the 12,000L lower tank and R$3,975.51 for the 7,500L upper tank. As previously stated, the estimated costs for pipes and fittings were budgeted at 15% of the tank costs, resulting in R$982.35 for the pipes and fittings connecting to the lower tank and R$596.33 for the pipes and fittings connecting to the upper tank. To estimate the required labour cost, the hourly rate for a plumber was R$28.02, based on the September 2023 costs and compositions table from SINAPI for the state of Santa Catarina. Considering an 8-hour workday, it was estimated that 10 days would be required to install the tanks, yielding a labour cost of R$2,241.60.

Pumps were considered with a power of 1/2 horsepower, which would be sufficient to meet the manometric height of the systems and the required water flow. Therefore, a centrifugal pump from the Schneider brand, model BC-98, was chosen. In the price research, the cost of the selected model in local stores was R$474.20. Following the recommendation of NBR 5626 (ABNT, 2020), two pumps were used for the system, with a total cost of R$948.40. Therefore, the estimated cost for implementing the rainwater harvesting system was R$15,293.19.

With the initial cash flow defined, one used Netuno's feasibility assessment tool with the following input data: an analysis period of 20 years, a minimum attractive rate of 0.5% per month, an inflation rate of 0.42% per month, and adjustments to water, sewage, and electricity tariffs every 12 months. The tariff for electricity was considered 0.59296 R$/kWh, and the tariff for water was considered 19.39 R$/m^3.

For installing the rainwater harvesting system in the scenario analysed, the net present value was R$440,119.52, with an internal rate of return of 14.92% per month and a payback period of seven months. As the net present value was positive, the system is considered viable and was suggested to the building's administration as a way to reduce operational costs.

Using rainwater can be an essential tool for reducing costs in the building, as the annual cost of water supply represents a significant share of the operational costs. In addition, using rainwater may be environmentally adequate, diminishing the chemicals and energy required to treat water in a centralised manner. Overall, this paper presents an attractive perspective from the viewpoint of a residential building in a Brazilian city, where adopting rainwater harvesting may result in a considerable cost reduction throughout the system's lifespan.

3.4 Limitations and future studies

The first limitation that can be observed concerns the questionnaires carried out, per capita water consumption, and the percentage of potable and non-potable uses. The relevance of user behaviour in the research can be highlighted due to its impact on the simulations and, consequently, on economic viability, and the potential for reducing potable water consumption through rainwater harvesting. There is also the possibility of a rebound effect in water consumption with the use of alternative systems, with a consequent increase in per capita demand due to the realisation that, because people are saving water, they can waste it elsewhere. All these aspects could be addressed in future studies, expanding knowledge about the potential use of rainwater harvesting.

In the same context, the research's potential for internationalisation should be highlighted. Although Brazilian data was used, there are no limitations to applying the method to other cities in Brazil or other countries, including rainfall data and water consumption patterns. However, it is important to comment that Florianópolis is a city with a low seasonal index and high average annual rainfall. These factors lead to good results in saving potable water and the consequent economic viability of using rainwater harvesting. These aspects should be considered before extrapolating the results of this research to buildings in different cities, and this study may be used as a comparison.

Cost is also a factor that has been simplified in this research and requires more detail in future studies to validate the economic viability observed. Implementation costs consider local market dynamics, availability of materials and specialised labour. In other words, future studies should evaluate with greater specificity the costs of implementing a system similar to the one presented in this research. To this end, it is advisable to obtain the building's executive plans to be able to position the pipes, gutters, manholes and structures needed to collect, treat and use rainwater.

Finally, this study uses a deterministic approach based on specific values with scenarios to consider the uncertainties attributed to the questionnaires – potable and non-potable water demands. However, other parameters in the simulation can also be varied and associated with uncertainties. Therefore, statistical analyses based on probabilistic models can be considered, with more information on the likelihood of economic viability. One may consider variability in costs, user patterns and rainfall profiles, for example. Future studies should consider all the elements mentioned in this section to increase the robustness of knowledge about the economic viability of rainwater harvesting in different countries.

4. Conclusion

This study evaluated the potential for potable water savings through rainwater harvesting in a multifamily building in Brazil, including the economic feasibility of implementing this system. For different rainwater demands, the potential for potable water savings ranged from 10% to 12% in optimal scenarios, corresponding to an annual reduction of between 582 and 700 m³ of water. The assessment indicated the ideal capacity for the lower tank as 12,000 litres, while the upper tank was designed with a capacity of 7,500 litres. The cost assessment was performed to understand the system's feasibility, which was confirmed by an NPV of over R$400,000.00, an IRR of approximately 15% per month, and a discounted payback period of seven months. Thus, it is confirmed to be a viable solution.

Such a result is similar to the literature, which shows that rainwater harvesting may be a viable solution for residential buildings worldwide, especially in cities with well-distributed rainfall, such as Florianópolis. However, unaccounted costs may hinder the feasibility, and one reiterates that this study has limitations regarding the executive project needed to construct, maintain, and ascertain the system's correct use and consequential benefits. Nevertheless, one can conclude that rainwater harvesting is an important tool for cost optimisation and water efficiency in the building, and such practice needs to be better used in a world with continuous climate change and water scarcity.

Acknowledgment: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

References

ABNT - Associação Brasileira de Normas Técnicas (2020). NBR 5626:2020: Sistemas prediais de água fria e água quente – Projeto, execução, operação e manutenção. 56 p. (in Portuguese).

Almazroui, M., Islam, M. N., Balkhair, K. S., Şen, Z., & Masood, A. (2017). Rainwater harvesting possibility under climate change: A basin-scale case study over the western province of Saudi Arabia. Atmospheric Research, 189, 11–23. https://doi.org/10.1016/j.atmosres.2017.01.004

Amorim, S. V. de, & Pereira, D. J. de A. (2008). Estudo comparativo dos métodos de dimensionamento para reservatórios utilizados em aproveitamento de água pluvial. Ambiente Construído, 8(2), 53–66.

Apostolidis, N., & Hutton, N. (2006). Integrated Water Management in brownfield sites—More opportunities than you think. Desalination, 188(1–3), 169–175. https://doi.org/10.1016/j.desal.2005.04.114

Dornelles, F. (2012). APROVEITAMENTO DE ÁGUA DE CHUVA NO MEIO URBANO E SEU EFEITO NA DRENAGEM PLUVIAL. Universidade Federal do Rio Grande do Sul.

EPAGRI. (2023). EPAGRI Rainfall dataset. EPAGRI/CIRAM database.

Ferreira, D. F. (2005). Aproveitamento de águas pluviais e reuso de águas cinzas para fins não potáveis em um condomínio residencial localizado em Florianópolis—SC. Universidade Federal de Santa Catarina.

Foo, S. W., Mah, D. Y. S., & Ayu, B. E. (2017). Modelling rainwater harvesting for commercial buildings. Water Practice and Technology, 12(3), 698–705. https://doi.org/10.2166/wpt.2017.077

Freitas, D. A., & Ghisi, E. (2020). Economic feasibility analysis of rainwater harvesting: A case study in Imbituba, Brazil. Urban Water Journal, 17(10), 905–911. https://doi.org/10.1080/1573062X.2020.1846062

Geraldi, M. S., & Ghisi, E. (2018). Assessment of the length of rainfall time series for rainwater harvesting in buildings. Resources, Conservation and Recycling, 133, 231–241. https://doi.org/10.1016/j.resconrec.2018.02.007

Ghisi, E. (2006). Potential for potable water savings by using rainwater in the residential sector of Brazil. Building and Environment, 41(11), 1544–1550. https://doi.org/10.1016/j.buildenv.2005.03.018

Ghisi, E., & Cordova, M. M. (2014). Netuno 4, programa computacional. LABEEE. http://www.labeee.ufsc.br/.

Ghisi, E., Montibeller, A., & Schmidt, R. W. (2006). Potential for potable water savings by using rainwater: An analysis over 62 cities in southern Brazil. Building and Environment, 41(2), 204–210. https://doi.org/10.1016/j.buildenv.2005.01.014

Hofman-Caris, R., Bertelkamp, C., De Waal, L., Van Den Brand, T., Hofman, J., Van Der Aa, R., & Van Der Hoek, J. P. (2019). Rainwater Harvesting for Drinking Water Production: A Sustainable and Cost-Effective Solution in The Netherlands? Water, 11(3), 511. https://doi.org/10.3390/w11030511

Martine, G., & Camargo, L. (1983). CRESCIMENTO E DISTRIBUIÇÃO DA POPULAÇÃO BRASILEIRA: TENDÊNCIAS RECENTES. CNHR.

Martins Vaz, I. C., & Ghisi, E. (2023). Rainwater Harvesting during the COVID Outbreak: A Case Study in Brazil. ECWS-7 2023, 16. https://doi.org/10.3390/ECWS-7-14172

Martins Vaz, I. C., Ghisi, E., & Thives, L. P. (2020). Life cycle energy assessment and economic feasibility of stormwater harvested from pervious pavements. Water Research, 170, 115322. https://doi.org/10.1016/j.watres.2019.115322

Rupp, R. F., Munarim, U., & Ghisi, E. (2011). Comparação de métodos para dimensionamento de reservatórios de água pluvial. Ambiente Construído, 11(4), 47–64. https://doi.org/10.1590/S1678-86212011000400005

Shiklomanov, I. A. (1998). World water resources: A new appraisal and assessment for the 21st century; 1998. UNESCO.

Tucci, C. E. M., Hespanhol, I., & Cordeiro Netto, O. de M. (2001). Gestão da água no Brasil (2a. ed). UNESCO.

UNEP. (2002). State of the environment and policy retrospective: 1972—2002.

Yannopoulos, S., Giannopoulou, I., & Kaiafa-Saropoulou, M. (2019). Investigating the Current Situation and Prospects for the Development of Rainwater Harvesting as a Tool to Confront Water Scarcity Worldwide. Water, 11(10), 2168. https://doi.org/10.3390/w11102168