Water Supply

 Water Supply Vol 22 No 1, 14 doi: 10.2166/ws.2021.291

Socioeconomic potential for rainwater harvesting systems in southern Brazilian municipalities

L. C. Tavares [a,*], J. M. Bravo [a], R. Tassi [b], I. R. Almeida [a] and D. Wartchow[a]

[a] Hydraulic Research Institute (IPH), Federal University of Rio Grande do Sul (UFRGS), Campus do Vale, Av. Bento Gonçalves, 9500, Agronomia, Porto Alegre, RS 91501-970, Brazil

[b] Environmental and Sanitary Engineering Department, Technology Center, Federal University of Santa Maria (UFSM), Cidade Universitária, Av. Roraima, 1000, Camobi, Santa Maria, RS 97105-900, Brazil

*Corresponding author. E-mail: ligiactavares@outlook.com

LCT, 0000-0003-3435-0896; JMB, 0000-0001-5585-1257; RT, 0000-0002-8315-5686; IRA, 0000-0001-6916-3295

ABSTRACT

The implementation of rainwater harvesting (RWH) systems depends on technical and socioeconomic assessments. However, most studies do not consider socioeconomic aspects, which could lead to different degrees of RWH implementation and technology selection due to economic constraints and local regulations. We evaluated the socioeconomic potential for RWH as an alternative for the water supply of 24 southern Brazilian municipalities with less than 50,000 inhabitants. A total of 10,080 RWH configurations were assessed and a reliability analysis was carried out to define the RWH system configurations potentially implementable (RWH+) in each municipality. RWH economic benefits were estimated from a social point of view, based on the reduction of the monthly water payment. Overall, RWH+ supplying higher demands with higher economics savings were feasible, as expected. However, several municipalities that showed RWH+ supplying 100% of the domestic water demands obtained lower economic savings, due to low water tariff and water consumption. Still, a set of municipalities presented RWH+ for rainwater demand replacing 50% to 60% of the residential demand, for which the high water tariffs were reflected in higher economic savings. The advantages of using the RWH systems stand out even more when the investments at Federal and Local levels are considered.

Key words: rainwater harvesting, reliability, socioeconomic, suitability, water supply

HIGHLIGHTS

- Socioeconomic potential for rainwater harvesting in 24 Brazilian municipalities.
- 10,080 system configurations were assessed for demand, rooftop area, tank capacity.
- System configuration was implementable if it reached at least 80% reliability.
- Economic savings of water payment were influenced by water tariff and consumption.
- The advantages of using rainwater stand out when the investments are considered.

1. INTRODUCTION

Rainwater harvesting (RWH) is a best management practice that offers several benefits, including reducing public water supply system demand and acting as a potential solution to minimize the effects of increasing runoff in urban areas (Kim Han & Lee 2012; Gwenzi & Nyamadzawo 2014; Pelak & Porporato 2016; Campisano *et al.* 2017; Amos *et al.* 2018; Bashar Karim & Imteaz 2018; Pala *et al.* 2021). In addition, RWH is an important source of drinking water in some circumstances, such as droughts and water scarcity (WHO 2011) or household emergency water demand for the prevention of COVID-19 (Kanno *et al.* 2021).

The implementation of RWH systems depends on an assessment of technical and socioeconomic criteria. The technical standard includes analysis of the potential use and performance of the system. This assessment generally considers the following variables: tank storage volume and water use demand, given a catchment (roof) area and rainfall time-series (Hashim *et al.* 2013; Sanches Fernandes *et al.* 2015; Lopes *et al.* 2017; Brandão & Marcon 2018; Guo & Guo 2018; Amos *et al.* 2020; Pala *et al.* 2021).

In Brazil, several studies have considered the technical evaluation of rainwater harvesting for specific buildings, normally placed in urban centres (Sampaio & Alves 2017; Geraldi & Ghisi 2018), including households (Ghisi & de Oliveira 2007; Ghisi *et al*. 2012; Marinoski *et al*. 2018), industrial companies (Azambuja Teixeira *et al.* 2016; Andrade *et al*. 2017) and educational institutions (Salla *et al.* 2013; Marques *et al*. 2014; Amorim *et al.* 2017; da Silva *et al.* 2019; Thomé *et al*. 2019).

However, most of these studies do not consider socioeconomic aspects, which could lead to different degrees of RWH implementation and technology selection due to economic constraints and local regulations (Lee *et al.* 2016; Campisano *et al.* 2017; Adham *et al.* 2018). Socioeconomic criteria should incorporate issues such as distance from settlements, family size, education level and water price, which can improve RWH effectiveness (Pavolová *et al.* 2019) while at the same time allowing for the planning of future structures. Furthermore, other factors such as funding and government subsidies (Fernandes *et al.* 2020; Shiguang & Yu 2021) can make RWH economically viable. Nevertheless, the establishment of good socioeconomic indicators associated with RWH system performance is much more difficult for socioeconomic conditions than for technical conditions (Adham *et al.* 2018).

Although Brazil is considered a water-rich country, there are inequalities related to the availability of water resources and access to sanitation, including the drinking water supply (ANA 2015). In light of this, the government has implemented public policies to encourage the use of alternative sources of water, including reclaimed water and rainwater. The major public policy is the Política Nacional de Saneamento Básico (National Policy on Basic Sanitation) that establishes the concept of the Basic Sanitation Plan (BRASIL 2007), which are references for financing improvements in the sector and for the appropriate use of public investments.

Basic sanitation plans are mainly composed of three phases: diagnosis, prognosis, and strategic planning. The diagnosis must show the current situation of municipal basic sanitation. Future scenarios regarding municipal basic sanitation are studied in the prognosis, which allows identification of areas where improvements must occur, according to population growth projections. Finally, projects are developed to implement these improvements in the strategic planning phase.

During the development of several Municipal Basic Sanitation Plans (PMSB) in the State of Rio Grande do Sul, the southernmost state in Brazil, it was possible to observe deficiencies in access to drinking water (Tavares *et al.* 2018). Based on these findings, for this paper we evaluated the socioeconomic potential for rainwater harvesting as an alternative scenario for water supply in the strategic planning of the municipal basic sanitation plans for 24 municipalities with populations below 50,000 inhabitants. The analyses accomplished enable support of technical decision-making for the application of RWH systems, the elaboration of municipal policies as well as the offer of financial incentives to promote the adoption of RWH.

2. METHODOLOGY

An analysis of the socioeconomic profile, climatology and water consumption of the 24 southern Brazilian municipalities was developed to assess the socioeconomic potential for RWH. Initially, the potential for RWH was evaluated with a daily water balance model, and the reliability analysis was performed for a set of 10,080 scenarios which combined different rooftop areas, rainwater demands and storage tank volumes. Socioeconomic benefits arising from the RWH usage were estimated from a social point of view based on the reduction of the monthly water payment.

2.1. Municipalities' climate and water socioeconomics

The study area consists of 24 municipalities located in the State of Rio Grande do Sul (Figure 1), with areas ranging from 67.9 km^2 (Lajeado do Bugre) to 1,757.6 km^2 (Herval), and populations ranging from 1,923 (Porto Vera Cruz) to 36,506 (Marau). These municipalities are included in phase 1 (one) of the Decentralized Execution Agreement, a partnership established between the Federal University of Rio Grande do Sul (UFRGS) and the National Health Foundation (FUNASA) of Brazil, for the elaboration of the Municipal Basic Sanitation Plan (PMSB). The PMSBs are instruments for planning and management, which assist municipalities in working toward the universalization of access to basic sanitation services. According to Brazilian standards, all these municipalities are classified by the Federal Government as small, with populations of less than 50 thousand inhabitants.

According to Köppen's classical classification (Moreno 1961), the State of Rio Grande do Sul is in the south temperate zone, and the climate is predominantly Cfa (humid subtropical), although Cfb (oceanic climate) occurs in the higher-altitude areas near the coast. The average temperatures range from 15 °C to 19 °C; however, during hot humid summers, the highs frequently surpass 40 °C in some regions, and lows usually fall below 9 °C, reaching as low as −10 °C. The average annual rainfall is approximately 1,450 mm, well distributed throughout the year, although convective rainfall events (greater

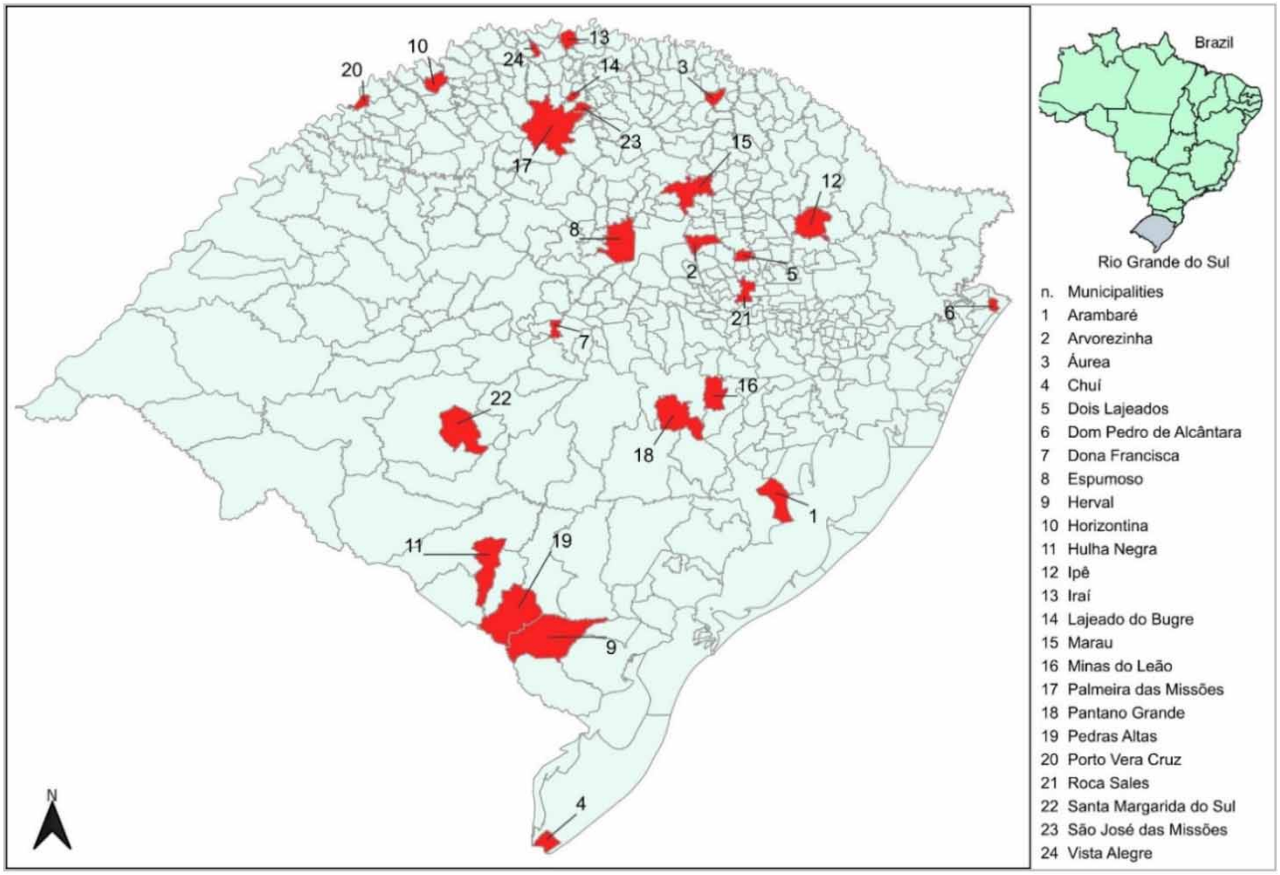

Figure 1 | State of Rio Grande do Sul and its municipalities. The studied municipalities are red-highlighted and numbered.

intensity) are more common during spring and summer, and frontal rainfall events are predominant during winter (INMET 2019). Occasional droughts can occur, especially during summer, and water shortages are frequent during these periods.

As can be seen in Figure 1, the studied municipalities are distributed throughout the state. Iraí (number 13 in Figure 1) is located the farthest to the north, whereas Chuí is southernmost in the state, bordering Uruguay along with Herval and Pedras Altas. Porto Vera Cruz is located to the west, bordering Argentina, while Dom Pedro de Alcantara is located to the east near the Atlantic coast. In addition to spatial differences, the studied municipalities are also quite different in their social, economic and demographic aspects. The municipality of Arambaré, for example, has a tourism-based economy, while Arvorezinha has an economy based on agricultural production of yerba mate (*Ilex paraguariensis*), and the economy of its neighbour Espumoso is marked by soy production.

The Rio Grande do Sul is an important state for the Brazilian economy, having the fifth largest gross domestic product (GDP) per capita (US$ 10,416.19) among the states. Moreover, its Human Development Index in 2010 (HDI-2010) is 0.746, above the national average of 0.699 (IBGE 2012). Table 1 shows the socioeconomic profiles of the studied municipalities, highlighting the average monthly wage of formal workers (AWW) and GDP, in addition to the municipal HDI. Four of the studied municipalities (Dois Lajeados, Espumoso, Horizontina and Marau) have HDI above the state average, and eight have per capita GDP above the state and national average. The AWWs range from US$ 443.15 to US$ 910.92. Six studied municipalities show an AWW higher than US$ 600, 12 have an AWW between US$ 500 and US$ 600, and six other studied municipalities show AWWs lower than US$ 500.

By assessing the three variables presented in Table 1, it is possible to observe that there is no direct relationship between these values in the municipalities, except for Horizontina, which has high values of the three variables. This situation can be explained by the strong presence of informal workers in these small municipalities in the state. For instance, the Chuí socioeconomic profile indicates that this municipality has a trade-based economy, which should have a positive impact on workers' wages, but the municipality has the lowest average monthly wage.

Table 1 | Socioeconomic profile of the studied municipalities

Municipalities	GDP per capita (2018) US$	HDI-2010	Average monthly wage of formal workers (2018) US$
1. Arambaré	8,675.15	0.691	541.63
2. Arvorezinha	6,153.97	0.694	492.39
3. Áurea	7,801.75	0.707	517.01
4. Chuí	14,745.62	0.706	443.15
5. Dois Lajeados	7,334.72	0.757	590.86
6. Dom Pedro de Alcântara	5,545.47	0.691	541.63
7. Dona Francisca	6,294.56	0.697	541.63
8. Espumoso	12,821.92	0.765	615.48
9. Herval	5,062.91	0.687	492.39
10. Horizontina	21,782.14	0.783	910.92
11. Hulha Negra	7,748.29	0.643	517.01
12. Ipê	7,707.03	0.728	541.63
13. Iraí	5,970.89	0.691	467.77
14. Lajeado do Bugre	4,931.79	0.613	517.01
15. Marau	12,187.72	0.774	590.86
16. Minas do Leão	5,669.70	0.681	566.25
17. Palmeira das Missões	11,255.99	0.737	615.48
18. Pantano Grande	9,639.26	0.661	541.63
19. Pedras Altas	14,162.12	0.640	615.48
20. Porto Vera Cruz	5,753.75	0.690	689.34
21. Roca Sales	10,563.43	0.729	492.39
22. Santa Margarida do Sul	23,014.14	0.663	566.25
23. São José das Missões	6,020.29	0.651	615.48
24. Vista Alegre	7,817.54	0.739	492.39

The analysis of the percentages of the municipalities' populations without access to a water supply service (Figure 2) shows that this value can represent more than 50% of the municipal total, as observed in Áurea, Dom Pedro de Alcantara, Santa Margarida do Sul and Vista Alegre. In some municipalities, all inhabitants have access to the water supply service, such as in Dois Lajeados and Lajeado do Bugre.

The average per capita urban water demand was estimated based on the total urban water demand and urban population of each municipality, based on the data available from several water companies in SNIS (2020). The daily domestic water demand (Table 2) ($L{\cdot}day^{-1}$) was estimated from the average daily per capita urban water demand ($L{\cdot}hab^{-1}{\cdot}day^{-1}$) provided by the water supply company from each municipality multiplied by the average number of inhabitants in the residences. Table 2 shows that the average per capita water demand is typically between 100 and 200 $L{\cdot}hab^{-1}{\cdot}day^{-1}$, except in the municipalities of Arambaré, Horizontina, Hulha Negra and Iraí, where this value is greater than 200 $L{\cdot}hab^{-1}{\cdot}day^{-1}$. The values found are in accordance with the reference values used for the design of drinking water distribution systems, following the recommendations of the Brazilian Technical Standards Association.

2.2. Assessing the potential for RWH

To evaluate the potential for RWH in the studied municipalities, a water-balance model for long-term simulation was implemented and applied to the data set for each municipality. A total of 10,080 RWH configurations were assessed through a combination of several rainwater demands, rooftop areas and tank storage capacities. Based on the model results, a reliability analysis was performed to define the RWH system configurations potentially implementable in each municipality.

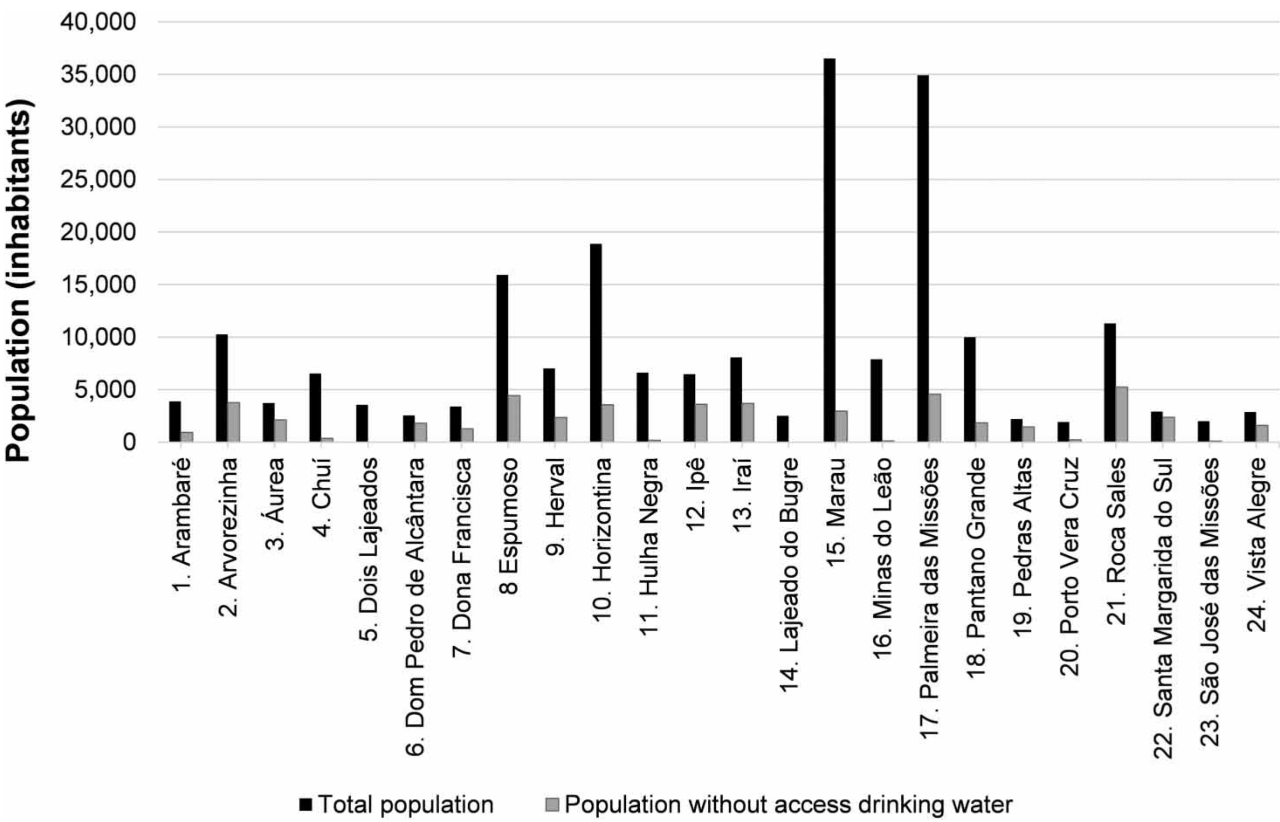

Figure 2 | Total population and population without access to water supply services in each studied municipality.

2.2.1. Water balance model

A daily time-step water-balance model (Liaw & Tsai 2004; Palla *et al.* 2011; Mun & Han 2012; de Gois *et al.* 2015) was used (Equations (1) and (2)):

$$Q_t = P_t \times A \times \eta \tag{1}$$

$$\begin{aligned} &S_t = S_{t-1} + Q_t - D_t, \text{ when } 0 \leq S_t \leq V, \text{ then } O_t = 0 \text{ and } FV_t = 0; \\ &O_t = S_{t-1} + Q_t - D_t - V, \text{ when } S_{t-1} + Q_t - D_t > V, \text{ then } S_t = V \text{ and } FV_t = 0; \\ &FV_t = \text{abs}\,(S_{t-1} + Q_t - D_t) \text{ when } S_{t-1} + Q_t - D_t < 0, \text{ then } S_t = 0 \text{ and } O_t = 0; \\ &S_0 = V \text{ (initial condition)} \end{aligned} \tag{2}$$

where Q_t is the runoff volume produced by the rooftop area at time t (L), P_t is the precipitation depth at time t (mm), A represents the rooftop area (m^2), η is a coefficient, which takes into account the losses due to the rainwater filter device for solids removal and initial flow deviation, in addition to the runoff coefficient itself, S_t is the water volume in the rainwater tank at time t (L), S_{t-1} is the water volume stored in the rainwater tank at time $t-1$ (L), D_t is the rainwater demand at time t (L), V is the maximum capacity of the storage tank (L), FV_t is the missing volume to meet the rainwater demand at time t, and O_t is the overflow at time t.

The runoff volume (Q) is the inflow to the RWH storage tank, while outflows are the daily rainwater demand (D) and the overflow (O) when the tank is full. The input data required are daily time series of precipitation and rainwater demands, the rooftop area and the storage tank capacity (as presented below). The simulation outputs are daily time series of (a) stored water volume in the rainwater tank, (b) overflows and (c) missing volume to meet the rainwater demand.

Table 2 | Average daily domestic water demand in the studied municipalities

Municipality	Average daily per capita urban water demand (L·hab^{-1}·day^{-1})	Average number of inhabitants per house	Daily domestic water demand (L·day^{-1})
1. Arambaré	283.31	3	849.92
2. Arvorezinha	131.75	4	527.00
3. Áurea	134.97	3	404.90
4. Chuí	163.86	4	655.44
5. Dois Lajeados	199.38	4	797.54
6. Dom Pedro de Alcântara	180.00	3	540.00
7. Dona Francisca	157.06	4	628.23
8. Espumoso	173.75	4	695.00
9. Herval	137.00	3	411.00
10. Horizontina	240.00	3	719.99
11. Hulha Negra	235.09	4	940.35
12. Ipê	140.75	4	563.00
13. Iraí	240.06	3	720.19
14. Lajeado do Bugre	179.85	3	539.54
15. Marau	164.27	3	492.81
16. Minas do Leão	166.75	4	667.00
17. Palmeira das Missões	162.00	4	648.00
18. Pantano Grande	168.75	4	675.00
19. Pedras Altas	141.13	3	423.38
20. Porto Vera Cruz	170.53	3	511.60
21. Roca Sales	156.87	4	627.47
22. Santa Margarida do Sul	146.71	4	586.83
23. São José das Missões	176.76	2	353.52
24. Vista Alegre	117.50	4	470.00

2.2.2. Time series of daily precipitation in the studied municipalities

For long-term modelling, a long-term time series of daily precipitation was first established for each municipality using a spatial interpolation procedure, because only seven municipalities (Arambaré, Dona Francisca, Herval, Iraí, Palmeira das Missões, Pantano Grande and Pedras Altas) had rain gauges.

To do this, time series of daily precipitation for a 60-year period (01/01/1958–31/12/2017) were used in the interpolation processes, using data from 233 rain gauge stations covering the State of Rio Grande do Sul (Figure 3). This database was freely obtained from the National Water Agency (ANA) network. The time series for each municipality was defined by the deterministic method (inverse-square distance) (Burrough & McDonnell 1998). This methodology preserves the observed precipitation data at the location where it was recorded (municipalities with rain gauges) and uses the weighted average of the distances from the rain gauge stations to estimate the precipitation in municipalities without rain gauges. Furthermore, this methodology also allows missing data to be filled in. Based on this methodology, 24 continuous time series of daily precipitation with 21,915 days were obtained.

The average annual precipitation obtained over the 60-year period is presented in Figure 3 for each municipality and ranges from 1,272.2 mm (Chuí) to 1,949.9 mm (Áurea), highlighting the differences in the potential for rainwater that can be harvested at locations within the same state. In addition to the difference of more than 650 mm between these two municipalities that are spatially located at opposite ends of the state, it is noticed that the rainfall volumes decrease from the northwest to southeast of the state (Basso *et al.* 2016).

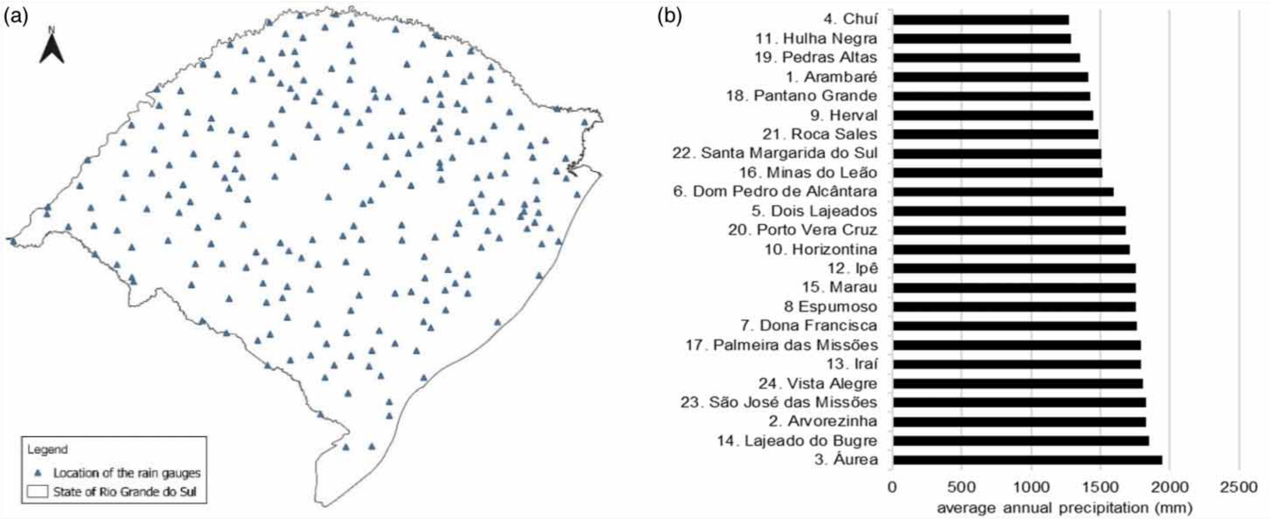

Figure 3 | Precipitation data for the State of Rio Grande do Sul: (a) location of the rain gauges, (b) average annual precipitation in the studied municipalities (mm·year^{-1}) for the period from 01/01/1958 to 31/12/2017.

2.2.3. RWH configurations

Based on the most frequent patterns of building areas found in these municipalities, the modelling was accomplished by considering six different rooftop areas, which were adopted to cover the range of diversity in residences in the evaluated municipalities: 75 m^2, 100 m^2, 125 m^2, 150 m^2, 175 m^2 and 200 m^2. In addition, following the predominant housing pattern in these cities, it was assumed that the population resides in single-family buildings.

Ten different daily rainwater demand levels were defined as percentages of the daily domestic water demand in each municipality, following the reference values presented in Table 2. It was assumed that the demands to be met with the RWH system could range from 10% of the daily domestic water demand up to 100%, increasing by 10% in every simulation for a total of ten possible daily rainwater demands to be supplied. According to Brazilian domestic water consumption data, non-potable uses normally make up from 10% to 20% of the total daily use, representing the first two demand levels to be evaluated, while the subsequent levels of water demand represent additional demands that could be fulfilled by rainwater.

During modelling, the reliability was evaluated for seven volumes of available commercial tanks (0.5 m^3, 0.75 m^3, 1 m^3, 1.5 m^3, 2 m^3, 3 m^3 and 5 m^3) by combining the demands and the rooftop areas. Briefly, ten daily rainwater demands, six rooftop areas and seven storage tank capacities were evaluated for each of the 24 municipalities, resulting in a total of 10,080 RWH configurations.

2.2.4. Reliability analysis

In this study, the potential contribution of RWH systems was obtained through a reliability analysis and derived through Equation (3). In this sense, reliability represents the percentage of the total water demand supplied by the RWH system.

$$R(V,\ D_t,\ A,\ M) = \left(1 - \frac{\sum FV_t}{\sum D_t}\right) \times 100 \tag{3}$$

where $R(V, D_t, A, M)$ is the reliability (%) of the RWH system with a maximum capacity of the storage tank equal to V, rainwater demand D_t, rooftop area A, at the municipality M.

In each municipality, for a pre-defined rainwater demand and rooftop area, a reliability curve was derived based on the reliability values obtained for several storage tank capacities. As six different rooftop areas and ten different rainwater demands were analysed, 60 reliability curves were derived for each municipality. A reliability value of at least 80% was considered to classify a RWH as suitable to be implemented. Thus, combinations of rooftop area, rainwater demand and storage tank capacity that reached reliabilities higher than 80% were classified as potentially implementable rainwater configuration (RWH+).

Among the configurations classified as RWH+ in each municipality, a suitable demand was defined as the maximum domestic water demand supplied with at least 80% reliability. The value of the suitable demand was used in assessing the economic benefits of the RWH system. To clarify the methodology within the scope of municipal management, the 60 reliability curves found for the Palmeira das Missões municipality were chosen for analysis. For this set, the suitable demand and the RWH configurations that better meet the domestic water demands are presented.

2.3. Socioeconomic assessment

The socioeconomic benefits of an RWH system were studied to better understand the need for improvements in the water supply system (WSS) of the studied municipalities and, thus, to understand how RWH systems best fit in the social contexts of these locations. This assessment was based on the analysis of reliability and the number of people without access to the WSS, in addition to the list of investments planned for the sector in the current Multiannual Plan (MAP) of each municipality, the diagnosis presented by the Urban Supply Atlas of the National Water Agency of Brazil (ANA 2015) and the water tariff (Table 3).

The number of people without access to the WSS (Figure 2 and Table 3) is based on the total number of households in the municipality, the number of households connected to the WSS, and the average number of inhabitants per house, for the year 2017.

The MAP concerns the investments that should be made by city halls to improve the WSS of the municipalities, which constitute medium-term planning and must be carried out by law. In the MAP, priorities were identified for four years (2016–2020) and for major investments. The Urban Supply Atlas of the National Water Agency (ANA 2015) presents an assessment of water supply and demand in Brazilian municipalities. This document states that if the water supply is

Table 3 | Diagnosis of the current situation of the WSS and water tariff in the studied municipalities

Municipalities	Population without access to the WSS (%)	Water price (US$/m^3)	Need for expansion of the WSS? If Yes, shows investment value (ANA)	There is investment in WSS in the MAP?
1. Arambaré	24%	2.13	No	No
2. Arvorezinha	37%	1.94	No	Yes (R-U)[a]
3. Áurea	57%	2.03	No	Yes (R-U)
4. Chuí	6%	1.86	No	No
5. Dois Lajeados	0%	0.67	Yes. US$ 588,446.24	Yes (R-U)
6. Dom Pedro de Alcântara	70%	0.61	Yes. US$ 267,110.75	Yes (R-U)
7. Dona Francisca	38%	1.74	No	Yes (R-U)
8. Espumoso	28%	1.55	Yes. US$ 1,166,798.00	Yes (U)
9. Herval	34%	2.03	No	No
10. Horizontina	19%	1.69	No	Without MAP
11. Hulha Negra	3%	0.05	Yes. US$ 280,292.08	Yes (R-U)
12. Ipê	56%	1.94	Yes. US$ 580,579.85	Yes (R)
13. Iraí	46%	1.82	No	Without MAP
14. Lajeado do Bugre	0%	0.73	No	Yes (R-U)
15. Marau	8%	1.73	No	Yes (U)
16. Minas do Leão	2%	1.81	No	No
17. Palmeira das Missões	13%	1.77	Yes. US$ 2,996,706.85	No
18. Pantano Grande	18%	1.76	No	Yes (R-U)
19. Pedras Altas	66%	2.03	Yes. US$ 273,038.43	No
20. Porto Vera Cruz	11%	0.71	Yes. US$ 554,708.64	Yes (R-U)
21. Roca Sales	46%	1.77	Yes. US$ 2,301,908.96	Yes (R-U)
22. Santa Margarida do Sul	81%	1.99	Yes. US$ 271,099.83	Yes (R-U)
23. São José das Missões	5%	0.13	No	Yes (R-U)
24. Vista Alegre	55%	1.99	Yes. US$ 790,709.26	No

[a]Investments in the MAP are for rural and urban areas (R-U) or only rural (R) area.

considered satisfactory by 2025, there would be no need for investment in system expansion; otherwise, a value necessary to carry out the expansion of the system is stipulated. These two Brazilian governmental documents present various data for each municipality related to the planned expansion and investment allocation in water supply systems.

In 75% of the municipalities, the water supply service is provided by the state, whereas in the remaining 25% the service is provided by the municipalities themselves. Although most municipalities are served by the state, there are different tariff values for each location. Table 3 presents information on water tariff values obtained from the municipal governments.

As can be observed in Table 3, some municipalities do not expect to invest in the expansion of the WSS, although they have some percentage of the population without access to water. This divergence may occur because the investment study by ANA (2015) considered only the urban areas of these municipalities, while the number of inhabitants without access to the WSS also includes the rural ones.

On the other hand, there are municipalities where investments are foreseen, although 100% of the current population has access to water. This occurs because the investment forecast made by ANA and presented in Table 1 considers the projection of the population growth for the year 2025, and the necessary expansion in this sector to meet this population growth.

Anyway, Table 3 suggests that most municipalities that foresee investments in the water supply sector for the current multi-year period require improvements. It also shows that three municipalities (Chuí, Vista Alegre and Palmeira das Missões) that need to expand the existing WSS are not investing in this. Evaluating these documents together, we can see that 17 municipalities require some means of improvement in the water supply system. Therefore, the use of alternative sources of water such as rainwater would be a way of relieving the pressure for investments in this sector.

The municipalities also have laws encouraging the implementation of RWH systems, where the initial investment to construct the RWH system is supported by municipal resources. By considering these aspects, the benefits related to the implementation of RWH systems at the individual residences were estimated for the RWH+ configuration (with reliability equal to or higher than 80%) with the suitable demand (maximum domestic water demand supplied).

In this sense, the RWH+ system benefits were estimated from a social point of view, based on the reduction of the monthly water payment, given that an amount of the water demand (the suitable demand) would be supplied by the RWH+ system and no longer by the regular distribution system. For an example of this case, we consider a residence that pays US$ 10.00 per month for a demand of 1 m^3 for the regular water supply service, which charges a water tariff of 10.00 US$/$m^3$. In this case, if an 80% reliability RWH system (RWH+) is installed to supply 50% of the domestic water demand (suitable demand), the monthly benefits due to the RWH system total US$ 4.00 (10 US$/$m^3 \times$ (1 $m^3 \times$ 50%) $\times$ 80%). In other words, the residence would spend only US$ 6.00 per month for the regular water supply service.

3. RESULTS AND DISCUSSION

3.1. Potential for rainwater harvesting systems

The reliability curves obtained from the results of the water-balance model for long-term simulation for the Palmeira das Missões municipality are presented in Figure 4. The results for other municipalities are presented in the Supplementary Material. Each graph of Figure 4 presents results for a rooftop area and shows ten reliability curves, each related to a different daily rainwater demand ranging from 10% to 100% of the domestic water demand.

The municipality of Palmeira das Missões has a suitable demand equal to 80% of the domestic water demand, with 121 of the 420 RWH configurations assessed classified as RWH+ with 80% or more reliability (Table 4).

The analysis in Figure 4 and Table 4 suggests that it is not possible to obtain a satisfactory potential to attend to rainwater demands of greater than 80% of the domestic water demand. The RWH configuration with rainwater demands equal to 80% of the domestic water demand and the largest rooftop area (200 m^2) and storage tank volume (5 m^3) had a reliability of 82% (yellow line in Figure 4(f)). Thus, if the goal were to supply more than 80% of the domestic water demand with rainwater, it would be necessary to increase the rooftop area and/or the storage tank volume, which would become technically unfeasible for a residence scale in these municipalities.

To meet 70% of the domestic water demand, rooftop areas of 150 m^2 and greater start presenting RWH+ when associated with a 5 m^3 storage tank. However, to meet 50% of domestic water demand, which represents all non-potable water use in the residence, the following parameters would suffice: (i) a 3 m^3 storage tank and a minimum rooftop area of 125 m^2, and (ii) a 5 m^3 storage tank and a minimum rooftop area of 100 m^2.

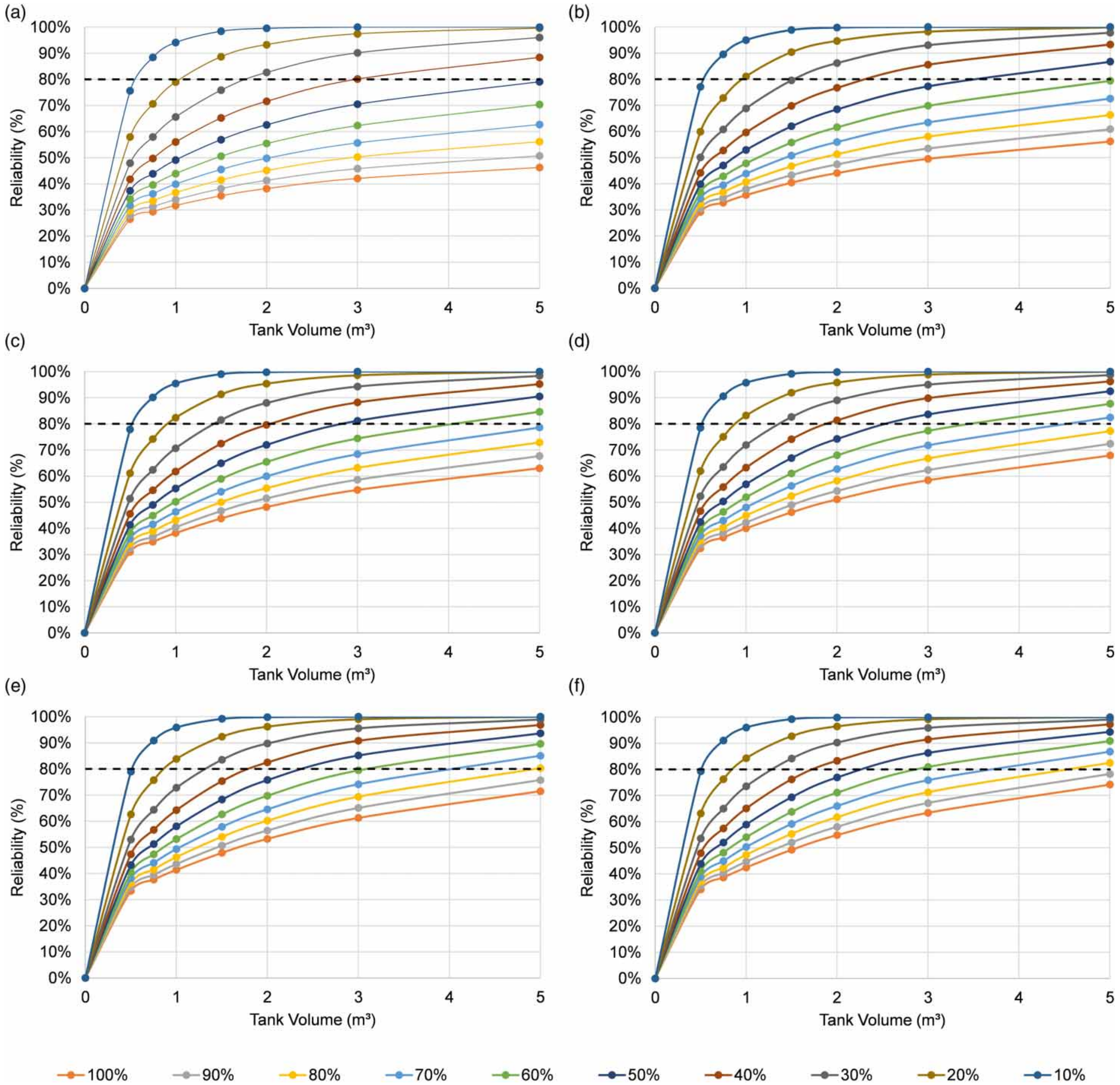

Figure 4 | Reliability curves for the municipality of Palmeira das Missões for different rainwater demands (from 10% to 100% of the domestic water demand). Rooftop areas of: (a) 75 m^2, (b) 100 m^2, (c) 125 m^2, (d) 150 m^2, (e) 175 m^2, (f) 200 m^2.

Analysing the results according to the catchment area, the smallest rooftop (75 m^2) could satisfactorily meet 40% of the domestic water demand with a rainwater source by using a 3 m^3 storage tank at minimum and 10% of the demands with a 0.75 m^3 storage tank. Likewise, an RWH system with a 100 m^2 rooftop and 1 m^3 storage tank would satisfy the demands for external non-potable domestic water uses and for toilet flushing, which represent 20% of the domestic water demand. When combined with a 5 m^3 storage tank this same rooftop area meets 50% of the domestic water demand. An RWH system with a 125 m^2 rooftop and a 5 m^3 storage tank would be enough to meet 60% of the domestic water demand and another with a 150 m^2 rooftop would meet 70% of the domestic water demand with the same storage capacity.

Assessing the minimum and maximum rainwater demand that could be met in this municipality by the analysed RWH+ configurations, the minimum storage capacity needed was 0.75 m^3 to meet 10% of the demands with any rooftop area. RWH systems with a rooftop area equal to 175 m^2 or 200 m^2 and a 5 m^3 storage tank could supply 80% of the domestic water demand as a maximum rainwater demand (suitable demand).

Table 4 | RWH configurations potentially implementable (RWH+) in the Palmeiras das Missões municipality

Rooftop area (m²)	Tank storage (m³)	Domestic water demand									
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
75	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	No	Yes
	1.5	No	No	No	No	No	No	No	No	Yes	Yes
	2	No	No	No	No	No	No	No	Yes	Yes	Yes
	3	No	No	No	No	No	No	Yes	Yes	Yes	Yes
	5	No	No	No	No	No	No	Yes	Yes	Yes	Yes
100	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	Yes	Yes
	1.5	No	No	No	No	No	No	No	No	Yes	Yes
	2	No	No	No	No	No	No	No	Yes	Yes	Yes
	3	No	No	No	No	No	No	Yes	Yes	Yes	Yes
	5	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
125	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	Yes	Yes
	1.5	No	No	No	No	No	No	No	Yes	Yes	Yes
	2	No	No	No	No	No	No	No	Yes	Yes	Yes
	3	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	5	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
150	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	Yes	Yes
	1.5	No	No	No	No	No	No	No	Yes	Yes	Yes
	2	No	No	No	No	No	No	Yes	Yes	Yes	Yes
	3	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	5	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
175	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	Yes	Yes
	1.5	No	No	No	No	No	No	No	Yes	Yes	Yes
	2	No	No	No	No	No	No	Yes	Yes	Yes	Yes
	3	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	5	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
200	0.5	No	No	No	No	No	No	No	No	No	No
	0.75	No	No	No	No	No	No	No	No	No	Yes
	1	No	No	No	No	No	No	No	No	Yes	Yes
	1.5	No	No	No	No	No	No	No	Yes	Yes	Yes
	2	No	No	No	No	No	No	Yes	Yes	Yes	Yes
	3	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
	5	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The same analyses related to RWH+ configurations potentially to be implemented for Palmeira das Missões were carried out in other municipalities and are shown in the Supplementary Material.

When all results are analysed together, out of 420 RWH configurations assessed in each of the 24 municipalities, there were 247 RWH+ configurations (potentially implementable) in at least one municipality (Table 5). Thus, there were 173 RWH configurations where the reliability was less than 80% in all the studied municipalities. As the combination of small rooftop areas and high rainwater demand was assessed, the number of municipalities with RWH+ was reduced. Additionally, no municipality showed a RWH+ configuration with a rooftop area equal to 75 m^2 and a rainwater demand equal to 100% of the domestic water demand.

To meet all the demands of the residence (rainwater demand equal to 100% of domestic water demand) the minimum necessary configurations were (i) a 3 m^3 storage tank associated with a minimum 150 m^2 rooftop area (serving only two studied municipalities satisfactorily) and (ii) a 5 m^3 storage tank combined with an area equal to or bigger than 100 m^2 (serving nine municipalities satisfactorily when the rooftop area is 200 m^2).

Table 5 | Number of municipalities with an RWH configuration meeting the requirements to potentially be implemented

Rooftop area (m²)	Tank storage (m³)	Domestic water demand									
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
75	0.5	0	0	0	0	0	0	0	0	1	12
	0.75	0	0	0	0	0	0	0	1	7	23
	1	0	0	0	0	0	0	0	2	11	23
	1.5	0	0	0	0	0	1	2	10	22	23
	2	0	0	0	0	1	2	8	15	23	24
	3	0	0	0	2	2	7	12	22	23	24
	5	0	1	2	2	7	11	21	23	24	24
100	0.5	0	0	0	0	0	0	0	0	2	13
	0.75	0	0	0	0	0	0	0	2	7	23
	1	0	0	0	0	0	0	1	3	16	23
	1.5	0	0	0	0	0	2	4	11	23	23
	2	0	0	0	1	2	3	10	20	23	24
	3	0	0	2	2	3	10	20	23	23	24
	5	2	2	3	8	11	20	22	23	24	24
125	0.5	0	0	0	0	0	0	0	0	2	14
	0.75	0	0	0	0	0	0	0	2	7	23
	1	0	0	0	0	0	0	2	5	17	23
	1.5	0	0	0	0	1	2	7	17	23	23
	2	0	0	0	2	2	7	11	22	23	24
	3	0	2	2	3	9	14	22	23	24	24
	5	2	3	8	11	17	22	23	23	24	24
150	0.5	0	0	0	0	0	0	0	0	2	15
	0.75	0	0	0	0	0	0	0	2	9	23
	1	0	0	0	0	0	0	2	7	18	23
	1.5	0	0	0	0	2	2	7	17	23	24
	2	0	0	1	2	2	8	16	23	23	24
	3	2	2	2	7	10	18	22	23	24	24
	5	3	8	10	15	21	23	23	24	24	24
175	0.5	0	0	0	0	0	0	0	0	3	16
	0.75	0	0	0	0	0	0	0	2	10	23
	1	0	0	0	0	0	0	2	7	19	23
	1.5	0	0	0	0	2	3	9	19	23	24
	2	0	0	1	2	3	10	17	23	23	24
	3	2	2	4	8	11	20	23	23	24	24
	5	8	10	13	20	22	23	23	24	24	24
200	0.5	0	0	0	0	0	0	0	0	3	16
	0.75	0	0	0	0	0	0	0	3	11	23
	1	0	0	0	0	0	1	2	7	19	23
	1.5	0	0	0	1	2	3	10	19	23	24
	2	0	1	2	2	4	10	18	23	23	24
	3	2	2	6	10	14	22	23	23	24	24
	5	9	10	15	21	22	23	23	24	24	24

Regarding the non-potable uses of rainwater, which represent up to 20% of the domestic water demand, more than 20 of the 24 studied municipalities have several RWH configurations that can potentially be implemented with any rooftop area and a 1.5 m^3 or higher capacity storage tank.

3.2. Socioeconomic evaluation

As previously discussed, the success of a rainwater harvesting system does not depend only on technical aspects but also on how well it fits into the social context and on the economic benefit it provides. Figure 5 shows the suitable demand (maximum domestic water demand supplied with at least 80% reliability) and the maximum economic savings that would be achieved by using a reliable RWH+ system considering all evaluated scenarios.

Figure 5 shows that even if the potential to supply all domestic water demands by rainwater is higher in a particular municipality this may not be reflected in the monthly amount of money saved because of lower water tariffs. By comparing the municipalities of Ipê and São José das Missões, it is possible to note that although in both cases 100% of the domestic water demand could be supplied by rainwater, the economic impact that the RWH system can generate in Ipê

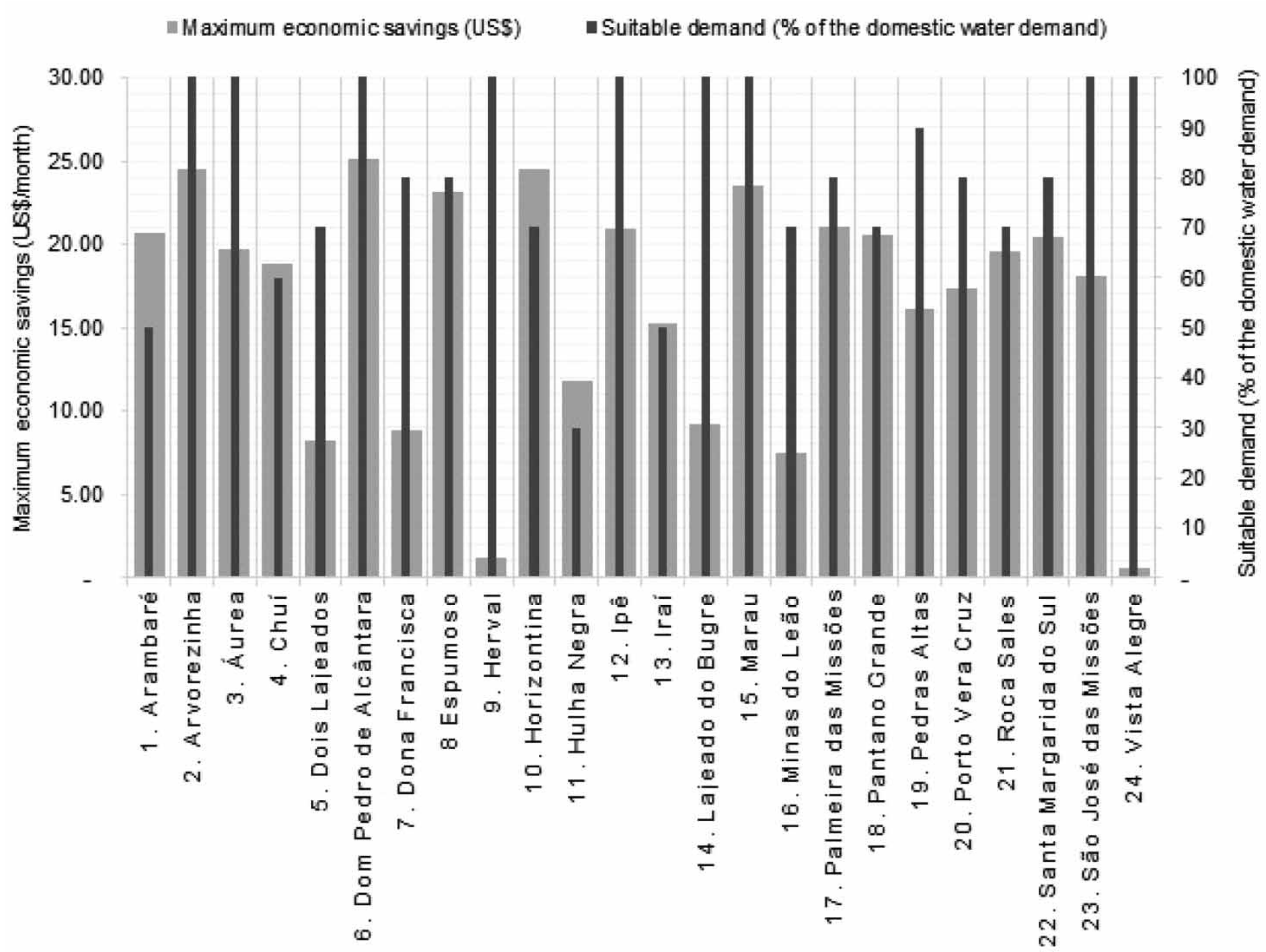

Figure 5 | Water savings in US$/month and suitable demand in each municipality.

(26.22 US$/month by residence) is much higher than in São José das Missões (1.09 US$/month by residence). This fact is explained by the water tariff and the residential water consumption in each municipality. The water tariff is US$ 1.94/m^3 in Ipê and the domestic water consumption per residence is approximately 0.56 m^3/day, while in São José das Missões the water tariff is US$ 0.13/m^3 and the residential water consumption is 0.35 m^3/day.

Although São José das Missões has strong potential for RWH, the monthly costs related to water supply are very low, which may not make the RWH attractive. Another factor that may be a disadvantage for RWH implementation in São José das Missões is the fact that only 5% of the population (110 inhabitants) does not have access to water supply services (Table 3), one of the lowest values among the municipalities in the study area. In addition, the municipal government predicts in its current MAP an investment for WSS maintenance and expansion. However, it is assumed that when using the RWH system as a source of a complementary WSS the volume of water that will no longer be exploited by the WSS may supply the population without access, and the investment provided for in MAP may be directed to other public services such as health and education.

Among the municipalities that have the capacity to meet all water demands by rainwater with economic impact higher than 20 US$/month by residence, the municipalities of Ipê and Vista Alegre show the most alarming situations related to the need for a source complementary to the WSS. In Ipê the planned investments are directed only to rural areas while there is a clear need for investments totalling US$ 580,579.85 in the urban area. Still, in this municipality, 56% of the population does not have access to this service. In Vista Alegre the situation is even more complicated because 55% of its population does not have access to the regular water supply service and there is a need to expand the system with an investment of US

$790,709.26 according to ANA (2015). However, even in this context, the current MAP of Vista Alegre does not include investments for the basic sanitation sector or for improvements in the WSS.

In addition to Vista Alegre, the municipalities of Arambaré, Chuí, Herval, Minas do Leão and Palmeira das Missões do not show any investments in the water supply, consistent with the data from ANA (2015). Given this situation, the installation of an RWH system in these municipalities would be the most viable alternative for residences that need to increase water availability since the available rainwater has the potential to meet at least half of the domestic water demands. Additionally, the economic impact that the RWH system can generate represents savings of 17.59–22.44 US$/month per residence.

In Pedras Altas, the RWH system has the capacity to meet up to 90% of the domestic water demands in a residence and to generate monthly savings of US$ 18.53 per residence. This fact, associated with the 66% of the population without access to the regular water supply service (Table 3), shows the need for investments of US$ 273,038.43 in the sector (ANA 2015). In fact, the current MAP just pointed out the network construction actions without presenting the amount of investment needed. In this case a complementary source of water in the residences is needed, and rainwater harvesting has potential to meet this need.

The RWH systems implemented in the Dona Francisca, Espumoso, Horizontina, Minas do Leão, Palmeira das Missões, Pantano Grande, Santa Margarida do Sul and Roca Sales municipalities have the potential to meet between 70% and 80% of the domestic water demands providing monthly economic savings of at least US$ 18.66 by residence. This situation supports the installation of RWH systems, especially in municipalities that do not intend to invest in the water supply sector, although expansion is required, as in the case of Palmeira das Missões. The RWH is also suitable for municipalities such as Dona Francisca, Pantano Grande, Arvorezinha and Áurea, which do not need to expand the WSS although investments in the sector have been planned to assist the part of the population without access to regular water supplies.

Although Porto Vera Cruz has the capacity to meet up to 80% of its domestic water demands by using rainwater, the monthly economic savings there with the RWH system are comparatively low, less than US$ 7.00 by residence. In addition, in Porto Vera Cruz, about 15% of the investments defined by ANA (2015) are dedicated in MAP for improvements in the water supply sector. This value becomes representative when we consider that only 219 inhabitants do not have access to the service.

The municipality of Arambaré has the highest average monthly expenses related to water supply services. Even in this municipality, which has the potential to supply a maximum of 50% of its domestic water demands by rainwater, the implementation of an RWH system is an alternative that could generate good monthly economic savings, exceeding US$ 21.77 by residence. In addition, there are no financial resources for the water supply sector provided for in the current MAP, nor for the improvement of other sanitation services, although about 24% of the population has no water supply access. Similar observations can be made for the municipality of Chuí, which has the potential to meet a maximum of 60% of domestic demand with the use of rainwater with monthly savings of up to US$ 17.58 per household, which could avoid the need for expansion of the current water supply system.

Iraí also has high expenses for the regular WSS, and even though the municipality has the potential to supply only 50% of residential water demand by rainwater, that gives a monthly saving of US$ 20.65. This municipality does not provide information related to WSS improvement on its current MAP and there is no need to expand the WSS according to ANA (2015), similar to Horizontina. However, in both municipalities, about 3,500 people do not have access to the WSS.

Finally, the municipality of Hulha Negra has a low potential for using rainwater and has low monthly expenses for its water supply service, and these factors make establishing an RWH system unfeasible. However, other factors must be analysed within the municipal socioeconomic reality. The municipality requires expansion of its system with an investment of US$ 280,292.08 by 2025, and according to the current MAP, only a small amount is allocated to solve this situation. The municipality serves 97% of its population, however, it suffers constant periods of drought and water restriction.

4. CONCLUSIONS

A technical and socioeconomic analysis of an RWH system for 24 municipalities located in Southern Brazil was accomplished under several configurations (different rooftop areas, storage tank volumes and rainwater demands) by using long-term daily water balance modelling, reliability indices and the estimate of water savings.

Technical feasibility was assessed for each municipality and a set of potentially implementable RWH configurations (with reliability higher than 80% and named RWH+) was selected between all the studied configurations. Socioeconomic benefits of each RWH+ were analysed from a social point of view. For doing this, the monthly reduction in the amount paid to the regular water distribution system due to the rainwater usage and the investment needed for improving the water supply systems defined at Federal and Local levels were considered.

In general, out of 420 RWH configurations assessed in each of the 24 municipalities, there were 247 RWH+ configurations in at least one municipality. Among these municipalities, 37.5% (nine) presented an RWH+ configuration where 100% of the domestic water demands could be supplied by rainwater, being technically suitable. However, socioeconomic factors of low water tariff, low water consumption and a reduced percentage of the municipality population without access to the WSS could make rainwater use less attractive in this set of municipalities.

In contrast, although a major part of the municipalities (50%) presented an RWH+ configuration that could supply lower domestic water demands with rainwater (from 50% to 60%), being technically less efficient, the higher water tariffs and the need for investments in the WSS from Federal and Local levels turned the RWH+ into an advantageous alternative for the municipalities.

Finally, in three municipalities (12.5%) technical and socioeconomic criteria pointed in the same direction. A low percentage of domestic water demands that could be supplied by a potentially implementable RWH system configuration was associated with lower economic savings, mainly due to lower water tariff in these municipalities, making the implementation infeasible.

These results reflect how important was adding socioeconomic elements to the technical analysis normally used in the evaluations of the RWH system, allowing its long-term effectiveness and feasibility to be increased.

It is important to highlight that the individual initial costs related to the infrastructure that enables the rainwater harvesting to be implemented in residences (storage tank, pipes, gutters, filters, pumps, etc.) were not considered. In the same way, costs related to maintenance and operation over the years were disregarded. As an alternative for further studies an investigation by using the payback period for return on rainwater harvesting system investment is recommended.

Finally, the use of rainwater proved to be feasible as an alternative scenario in small municipalities, mainly for those municipalities that need to expand the water supply system.

ACKNOWLEDGEMENTS

This research effort was supported by the National Health Foundation of Brazil. This work has also been partially supported by the following Brazilian research agencies: CAPES and CNPq.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Adham, A., Sayl, K. N., Abed, R., Abdeladhim, M. A., Wesseling, J. G., Riksen, M., Fleskens, L., Karim, U. & Ritsema, C. J. 2018 A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq. *International Soil and Water Conservation Research* **6** (4), 297–304. https://doi.org/10.1016/j.iswcr.2018.07.003.

Agência Nacional das Águas (ANA) 2015 *Atlas do Abastecimento Urbano de Água – Resultado por Município*. Superintendência de Planejamento de Recursos Hídricos – SPR, Brasília, Brasil. Available at: http://atlas.ana.gov.br/Atlas/forms/Home.aspx (accessed 27 June 2018).

Amorim, M. C. C., Brito, L. T. d. L., Nascimento, G. S. G. d., Silva Neto, J. A. d. & Leite, W. d. M. 2017 Captação e armazenamento de água de Chuva, Petrolina, PE: avaliação de aspectos estruturais e de qualidade da água. *Revistas AIDIS de Ingeniería y Ciencias Ambientales* **10** (1), 18–30 (in Portuguese).

Amos, C. C., Rahman, A., Karim, F. & Gathenya, J. M. 2018 A scoping review of roof harvested rainwater usage in urban agriculture: Australia and Kenya in focus. *Journal of Cleaner Production* **202**, 174–190. https://doi.org/10.1016/j.jclepro.2018.08.108.

Amos, C. C., Ahmed, A. & Rahman, A. 2020 Sustainability in water provision in rural communities: the feasibility of a village scale rainwater harvesting scheme. *Water Resources Management* **34**, 4633–4647. https://doi.org/10.1007/s11269-020-02679-1.

Andrade, M. A. N., Lisboa, M. B. & Lisboa, H. d. M. 2017 Reservatório de ardósia para sistemas de aproveitamento de água de chuva. *Engenharia Sanitária e Ambiental* **22** (3), 563–570. https://doi.org/10.1590/s1413-41522017177829.

Azambuja Teixeira, C., Zattoni, G. T., Nagalli, A., Freira, F. B. & Teixeira, S. H. C. 2016 Technical and economic viability analysis of rain water use in a metal-mechanic industry in the metropolitan region of Curitiba, Parana state, Brazil. *Gestão e Produção* **23** (3), 638–648. http://dx.doi.org/10.1590/0104-530(1655-14 (in Portuguese).

Bashar, M. Z. I., Karim, M. R. & Imteaz, M. A. 2018 Reliability and economic analysis of urban rainwater harvesting: a comparative study within six major cities of Bangladesh. *Resources, Conservation and Recycling* **133**, 146–154. https://doi.org/10.1016/j.resconrec.2018.01.025.

Basso, R. E., Allasia, D. G., Tassi, R. & Pickbrenner, K. 2016 Revisão das isozonas de chuvas intensas do Brasil. *Engenharia Sanitária e Ambiental* **21** (4), 635–641. https://doi.org/10.1590/S1413-41522016133691 (in Portuguese).

Brandão, J. L. B. & Marcon, P. 2018 Análise dos métodos de dimensionamento de reservatórios de águas pluviais sugeridos pela NBR 15527/07 com base na simulação diária. *Engenharia Sanitária e Ambiental* **23** (6), 1031–1041. http://dx.doi.org/10.1590/s1413-41522018129228 (in Portuguese).

Burrough, P. A. & McDonnell, R. A. 1998 *Principles of Geographical Information Systems*. Oxford University Press, Oxford, UK. Available from: https://pdfs.semanticscholar.org/d8e0/b6b225b36cac23608b41a51e13ddb2746cbd.pdf (accessed 2 July 2020).

Campisano, A., Butler, D., Ward, S., Burns, M. J., Friedler, E., DeBusk, K., Fisher-Jeffes, L. N., Ghisi, E., Rahman, A., Furumai, H. & Han, M. 2017 Urban rainwater harvesting systems: research, implementation and future perspectives. *Water Research* **115**, 195–209. https://doi.org/10.1016/j.watres.2017.02.056.

da Silva, L. C. C., Filho, D. O., Silva, I. R., Vargas e Pinto, A. C. & Vaz, P. N. 2019 Water sustainability potential in a university building – case study. *Sustainable Cities and Society* **47**, 101489. https://doi.org/10.1016/j.scs.2019.101489.

de Gois, E. H. B., Rios, C. A. S. & Costanzi, R. N. 2015 Evaluation of water conservation and reuse: a case study of a shopping mall in southern Brazil. *Journal of Cleaner Production* **96**, 263–271. https://doi.org/10.1016/j.jclepro.2014.08.097.

Fernandes, S., Bonfante, M. C., de Oliveira, C. T., Maldonado, M. U. & Campos, L. M. S. 2020 Decentralized water supply management model: a case study of public policies for the utilization of rainwater. *Water Resources Management* **34** (9), 2771–2785. https://doi.org/10.1007/s11269-020-02575-8.

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. & de Oliveira, S. M. 2007 Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. *Building and Environment* **42** (4), 1731–1742. https://doi.org/10.1016/j.buildenv.2006.02.001.

Ghisi, E., Cardoso, K. A. & Rupp, R. F. 2012 Short-term versus long-term rainfall time series in the assessment of potable water savings by using rainwater in houses. *Journal of Environmental Management* **100**, 109–119. https://doi.org/10.1016/j.jenvman.2011.12.031.

Guo, R. & Guo, Y. 2018 Stochastic modelling of the hydrologic operation of rainwater harvesting systems. *Journal of Hydrology* **562**, 30–39. https://doi.org/10.1016/j.jhydrol.2018.04.062.

Gwenzi, W. & Nyamadzawo, G. 2014 Hydrological impacts of urbanization and urban roof water harvesting in water-limited catchments: a review. *Environmental Processes* **1**, 573–593.

Hashim, H., Hudzori, A., Yusop, Z. & Ho, W. S. 2013 Simulation based programming for optimization of large-scale rainwater harvesting system: Malaysia case study. *Resources, Conservation and Recycling* **80**, 1–9. https://doi.org/10.1016/j.resconrec.2013.05.001.

Instituto Brasileiro de Geografia e Estatística (IBGE) 2012 *Censo Brasileiro de 2010*. IBGE, Rio de Janeiro, Brazil.

Instituto Nacional de Meteorologia (INMET) 2019 Dados climatológicos. Rio Grande do Sul, 2019. INMET, Brasília, Brazil.

Kanno, G. G., Lagiso, Z. A., Abate, Z. G., Areba, A. S., Gondol, B. N., Temesgen, H., Van Wyk, R. & Aregu, M. B. 2021 Estimation of rainwater harvesting potential for emergency water demand in the era of COVID-19. The case of Dilla town, Southern Ethiopia. *Environmental Challenges* **3**, 100077. https://doi.org/10.1016/j.envc.2021.100077.

Kim, H., Han, M. & Lee, J. Y. 2012 The application of an analytical probabilistic model for estimating the rainfall–runoff reductions achieved using a rainwater harvesting system. *Science of the Total Environment* **424**, 213–218. https://doi.org/10.1016/j.scitotenv.2012.02.021.

Lee, K. E., Mokhtar, M., Hanafiah, M. M., Halim, A. A. & Badusah, J. 2016 Rainwater harvesting as an alternative water resource in Malaysia: potential, policies and development. *Journal of Cleaner Production* **126**, 218–222. https://doi.org/10.1016/j.jclepro.2016.03.060.

Liaw, C. H. & Tsai, Y. L. 2004 Optimum storage volume of rooftop rain water harvesting systems for domestic use. *Journal of the American Water Resources Association* **40** (4), 901–912. https://doi.org/10.1111/j.1752-1688.2004.tb01054.x.

Lopes, V. A. R., Marques, G. F., Dornelles, F. & Medellin-Azuara, J. 2017 Performance of rainwater harvesting systems under scenarios of non-potable water demand and roof area typologies using a stochastic approach. *Journal of Cleaner Production* **148**, 304–313. https://doi.org/10.1016/j.jclepro.2017.01.132.

Marinoski, A. K., Rupp, R. F. & Ghisi, E. 2018 Environmental benefit analysis of strategies for potable water savings in residential buildings. *Journal of Environmental Management* **206**, 28–39. https://doi.org/10.1016/j.jenvman.2017.10.004.

Marques, C. M., Athayde Júnior, G. B. & de Luna, Y. H. D. M. 2014 Proposição de sistema de aproveitamento de água de chuva para uma instituição de ensino na Região Nordeste do Brasil: estudo da viabilidade econômica. *Revista AIDIS de Ingeniería y Ciencias Ambientales: Investigación, desarrollo y práctica* **7** (3), 259–271 (in Portuguese).

Moreno, J. A. 1961 *Clima do Rio Grande do Sul*. Secretaria da Agricultura, Porto Alegre, Brazil.

Mun, J. S. & Han, M. Y. 2012 Design and operational parameters of a rooftop rainwater harvesting system: definition, sensitivity and verification. *Journal of Environmental Management* **93** (1), 147–153. https://doi.org/10.1016/j.jenvman.2011.08.024.

Pala, G. K., Pathivada, A. P., Velugoti, S. J. H., Yerramsetti, C. & Veeranki, S. 2021 Rainwater harvesting – a review on conservation, creation & cost-effectiveness. *Materials Today: Proceedings* **45**, 6567–6571. https://doi.org/10.1016/j.matpr.2020.11.593.

Palla, A., Gnecco, I. & Lanza, L. G. 2011 Non-dimensional design parameters and performance assessment of rainwater harvesting systems. *Journal of Hydrology* **401** (1–2), 65–76. https://doi.org/10.1016/j.jhydrol.2011.02.009.

Pavolová, H., Bakalár, T., Kudelas, D. & Puškárová, P. 2019 Environmental and economic assessment of rainwater application in households. *Journal of Cleaner Production* **209**, 1119–1125. https://doi.org/10.1016/j.jclepro.2018.10.308.

Pelak, N. & Porporato, A. 2016 Sizing a rainwater harvesting cistern by minimizing costs. *Journal of Hydrology* **541** (Part B), 1340–1347. https://doi.org/10.1016/j.jhydrol.2016.08.036.

Presidência da República Federativa do Brasil 2017. Lei n°. 11.445, de 05 de janeiro de 2007. Estabelece diretrizes nacionais para o saneamento básico; altera as Leis nos 6.766, de 19 de dezembro de 1979, 8.036, de 11 de maio de 1990, 8.666, de 21 de junho de 1993, 8.987, de 13 de fevereiro de 1995; revoga a Lei no 6.528, de 11 de maio de 1978; e dá outras providências. Casa Civil, Subchefia para Assuntos Jurídicos, Brasília, Brazil (in Portuguese).

Salla, M. R., Lopes, G. B., Pereira, C. E., Neto, J. d. C. M. & Pinheiro, A. M. 2013 Viabilidade técnica de implantação de sistema de aproveitamento de água pluvial para fins não potáveis em universidade. *Ambiente Construído* **13** (2), 167–181. http://dx.doi.org/10.1590/S1678-86212013000200013 (in Portuguese).

Sampaio, F. E. d. O. V. & Alves, C. d. M. A. 2017 A procedure to analyze the viability of rainwater harvesting systems in urban areas based on pre-defined diagrams. *Brazilian Journal of Water Resources* **22**, e60. http://dx.doi.org/10.1590/2318-0331.0217160012.

Sanches Fernandes, L. F., Terêncio, D. P. S. & Pacheco, F. A. L. 2015 Rainwater harvesting systems for low demanding applications. *Science of the Total Environment* **529**, 91–100. https://doi.org/10.1016/j.scitotenv.2015.05.061.

Shiguang, C. & Yu, Z. 2021 Water saving potential and economic viability assessment of rainwater harvesting system for four different climatic regions in China. *Water Science and Technology: Water Supply* **21** (1), 386–400. https://doi.org/10.2166/ws.2020.307.

Sistema Nacional de Informações sobre o Saneamento (SNIS) 2020 Série Histórica. Ministério do Desenvolvimento Regional, Secretaria Nacional de Saneamento (SNS), Brasília, Brazil. Available at: http://app4.mdr.gov.br/serieHistorica/aguaEsgoto (accessed 19 February 2020).

Tavares, L. C., de Almeida, I. R., de Souza, F. B. & Wartchow, D. 2018 Estudo do atendimento das demandas de água em municípios do Rio Grande do Sul: um estudo de caso do termo de Execução Descentralizada N° 02/2015. In: *29° Congresso Nacional de Saneamento e Meio Ambiente*, 18–20 September, SP, Brazil (in Portuguese).

Thomé, A. C. B., Santos, P. G. & Fisch, A. G. 2019 Using rainwater in cooling towers: design and performance analysis for a petrochemical company. *Journal of Cleaner Production* **224**, 275–283. https://doi.org/10.1016/j.jclepro.2019.03.249.

World Health Organization 2011 *Guidelines for Drinking-Water Quality*, 4th edn. WHO, Geneva, Switzerland. Available from: http://www.who.int (accessed 8 August 2019).

First received 28 April 2021; accepted in revised form 19 August 2021. Available online 1 September 2021