

# Large-scale household rainwater harvesting: supply-demand analysis of the One Million Cisterns Program

*Aproveitamento de água de chuva domiciliar em larga escala: análise oferta-demanda no Programa Um Milhão de Cisternas*

*Uso a gran escala del agua de lluvia en los hogares: análisis de oferta-demanda en el Programa 1 Millón de Cisternas*

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## Abstract

The assessment of the supply-demand relationship in domestic rainwater harvesting systems has been much discussed. In particular, large-scale implementation programs would benefit from the availability of demand-supply indicators for the standard systems they implement. Such indicators should be simple, and, thus, of straightforward implementation, yet sufficiently informative to express the supply-demand relationship beyond the water balance. Hence, the aim of this work is to propose new indicators suitable for large-scale programs. Four indicators are evaluated: reliability, efficiency, resilience and surplus. The 1 Million Cisterns Program (P1MC) in Paraíba is taken as a case for the application and evaluation of the indicators. The standard P1MC systems were numerically simulated, taking precipitation series for the 194 municipalities where the cisterns were implemented in Paraíba. The results show that reliability and efficiency, for these systems, have equivalent values, making it possible, without loss of information, to use only reliability.

**Keywords:** Cisterns; Indicators; Semi-arid.

## Resumo

A avaliação da relação oferta-demanda em sistemas domiciliares de aproveitamento de água de chuva tem sido muito discutida. Em particular, programas de implantação em larga escala se beneficiariam da disponibilidade de indicadores de atendimento à demanda pelos sistemas padrão por eles implantados. Tais indicadores devem ser simples, para viabilizar sua implantação, mas suficientemente informativos para expressar a relação oferta-demanda além de um mero balanço hídrico. É este o objetivo deste trabalho: a proposição de novos indicadores, apropriados a tais programas de larga escala. São propostos e avaliados quatro indicadores: confiabilidade, eficiência, resiliência e superávit. O Programa 1 Milhão de Cisternas (P1MC) na Paraíba é tomado como caso para aplicação e avaliação dos indicadores. Os sistemas padrão implantados pelo P1MC foram numericamente simulados, tomando séries de precipitação para os 194 municípios onde as cisternas foram implantadas no Estado. Os resultados mostram que a confiabilidade e a eficiência, para esses sistemas, têm valores equivalentes, sendo possível, sem perda de informação, usar apenas a confiabilidade.

**Palavras-Chave:** Cisternas; Indicadores; Semiárido.

## Resumen

Se ha debatido mucho la evaluación de la relación oferta-demanda en los sistemas domésticos de captación de agua de lluvia. En particular, los programas de implementación a gran escala se beneficiarían de la disponibilidad de indicadores de respuesta a la demanda para los sistemas estándar que implementan. Dichos indicadores deben ser simples para permitir su implementación, pero suficientemente informativos para expresar la relación entre oferta y demanda más allá de un simple balance hídrico. Éste es el objetivo de este trabajo: la propuesta de nuevos indicadores, adecuados a programas de tan gran escala. En este trabajo se proponen y evalúan cuatro indicadores: confiabilidad, eficiencia, resiliencia y excedente. Se toma como caso de aplicación y evaluación de los indicadores el Programa 1 Millón de Cisternas (P1MC) en Paraíba. Los sistemas estándar implementados por P1MC fueron simulados numéricamente, tomando series de precipitación para los 194 municipios donde P1MC implementó cisternas en el Estado. Los resultados muestran que la confiabilidad y la eficiencia, para estos sistemas, tienen valores equivalentes, permitiendo, sin pérdida de información, utilizar solo la confiabilidad.

**Palabras clave:** Cisternas; Indicadores; Semiárido.

## 1 Introduction

The use of rainwater for household consumption has been continuously expanded in Brazil and around the world, both in urban and rural areas (Gleason-Espíndola *et al.*, 2020). It is common to establish a standardized design of these technological systems to encourage and facilitate their implementation and operationalization (e.g., ASA, 2023; Gleason-Espíndola *et al.*, 2020). This standardization has the negative side effect of the eventual inadequacy of the systems to a set of different local circumstances, such as the local rainfall regimes, the expected family demand and the existing house infrastructure, e.g., rooftop catchment area (Cohim, 2013; Silva *et al.*, 2024).

The evaluation of such domestic rainwater harvesting systems (SDAAC for ‘Sistemas Domiciliares de Aproveitamento de Água de Chuva’ in Portuguese) has improved, with several indicators proposed in the literature to estimate their performance (Bitterman *et al.*, 2016; Wang *et al.*, 2024). However, many of these indicators are complex or inadequate for large-scale programs, especially in regions with specific climatic characteristics and demands, such as the Brazilian semi-arid region. In the case of the One Million Cisterns Program (P1MC), for example, the standardization of cistern capacity, *i.e.*, 16 m<sup>3</sup>, does not adequately consider the available catchment area and the water demand of residents, which makes it difficult to adapt these systems to local realities (Cohim, 2013). In addition, the climate in the Brazilian semi-arid region exhibits a high spatial variability, and a strong intra-annual seasonality and high inter-annual variability concerning the distribution and magnitude of precipitation, which reinforces the need for simple but sufficiently informative indicators to express the supply-demand relationship beyond a mere water balance.

Numerical simulation is widely used to assess the performance of these systems, and it is an effective tool for predicting deficits and identifying possibilities for overcoming them at local, municipal, or microregional scales (Zortea *et al.*, 2003; Palla *et al.*, 2012; Yu *et al.*, 2023; Pacheco and Alves, 2023). Related studies focusing on the evaluation of P1MC and other rainwater harvesting systems, both in urban and rural areas, reinforce the importance of specific indicators that consider the differences between these local circumstances (Nóbrega *et al.*, 2007; Rocha *et al.*, 2022; Silva *et al.*, 2024).

The assessment of the supply-demand relationship must take into account the local rainfall regime, including its intra-annual seasonality and inter-annual variability (Yu *et al.*, 2023; Silva *et al.*, 2023). It must also use assessment indicators that best express the behavior of the systems in supplying water to users' demands (Silva *et al.*, 2024). These indicators must be easy to calculate and understand to facilitate the (re)design and (re)development of SDAAC initiatives, as well as in a later phase of improvement and expansion.

Recent studies still use only reliability, *i.e.*, percentage of time when demand was met or percentage of demand met, to assess the performance of these systems, such as those by Yu *et al.* (2023) in Kenya, Chen *et al.* (2024) in China, and Silva *et al.* (2023) in Brazil. Other studies corroborate the diversified approach, showing that, although the use of indicators such as reliability is already common, the introduction of measures such as efficiency, resilience, and surplus, improves the analysis of systems with storage limitations as pointed out by Hashimoto *et al.* (1982). For example, Silva *et al.* (2024) simulated the performance of SDAACs throughout Brazil using indicators of idle volume

and cistern overflow. Despite this, such indicators still cannot describe the performance of the systems in a multifaceted manner, as desired.

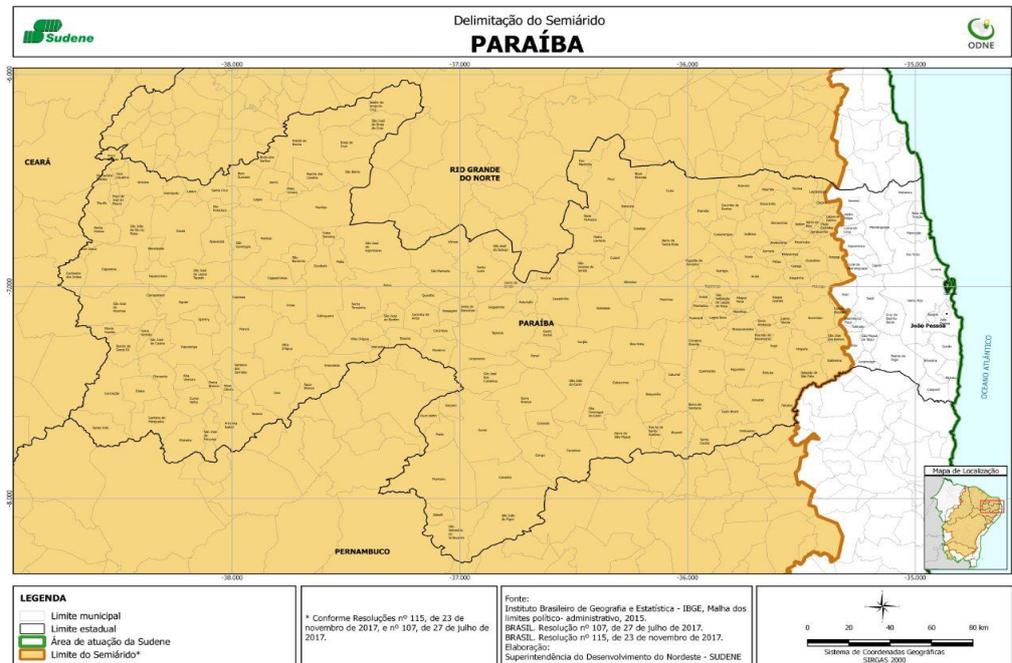
This article proposes four indicators for evaluating SDAACs based on the classic indicators proposed by Hashimoto *et al.* (1982) for large-scale water resource systems, such as dams. One of the challenges in using these indicators is the size of the system since SDAACs contain relatively small storage capacity, which is very sensitive to periods of drought and not adequately captured by classic indicators. Therefore, this work proposes new indicators that can be used in initiatives such as the P1MC, considering the typology of the systems and the local climate specificities.

## 2 Study area

As a case study for the proposed indicators, the SDAACs implemented in the semi-arid region of the Paraíba State by the 1 Million Cisterns Program - P1MC (ASA, 2023) were evaluated. The P1MC is the largest program for implementing these systems on a large scale in Brazil, and one of the largest in the world (Gleason-Espíndola *et al.*, 2020).

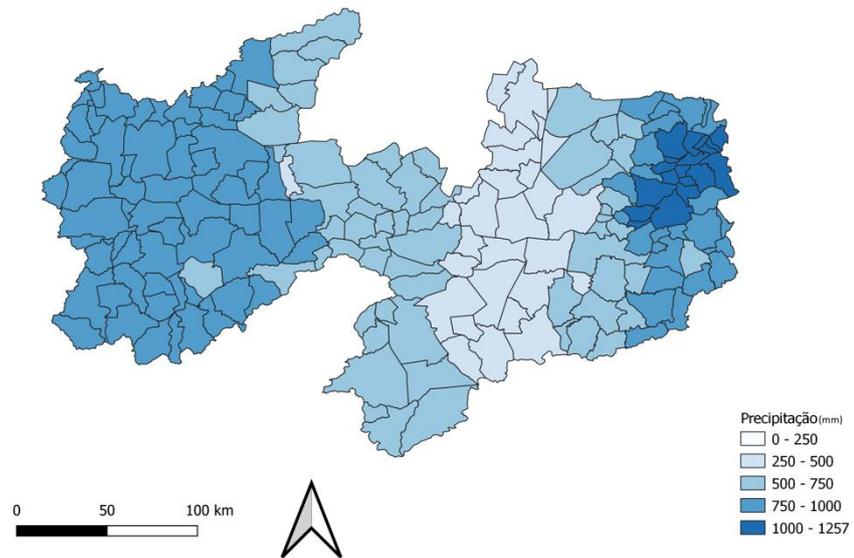
The Paraíba semi-arid region - SAPB (Figure 1) includes 194 municipalities, approximately 91% of the territory of Paraíba, corresponding to an area of 51,334.637 km<sup>2</sup> and delimited by Resolution No. 115 of November 23, 2017 of SUDENE (BRASIL, 2017). The municipalities have an average annual rainfall ranging from approximately 400 to 1,260 mm (Figure 2). Paraíba has six homogeneous rainfall regions, distributed as shown in Figure 3 (Braga and Silva, 1990). Since the coastal region is not part of the Paraíba semi-arid region, it was not taken into account in this work.

**Figure 1:** Semi-arid region of Paraíba.



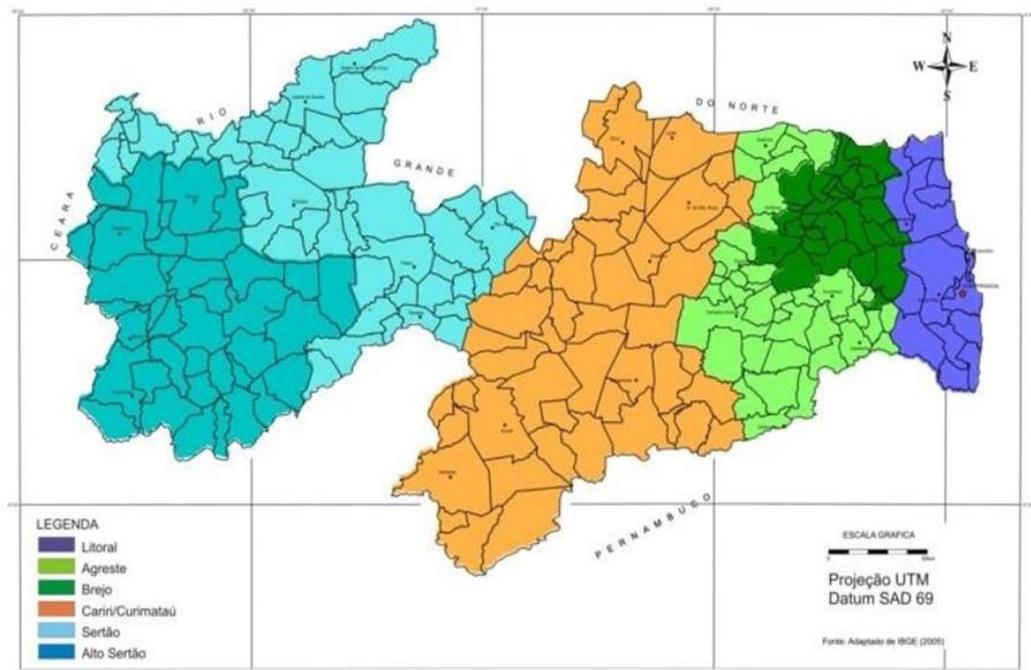
Source: SUDENE (2023).

**Figure 2:** Average annual precipitation for SAPB municipalities.



Source: Authors (2024), from CHIRPS data (Funk *et al.*, 2015).

**Figure 3:** Homogeneous rainfall regions of Paraíba.



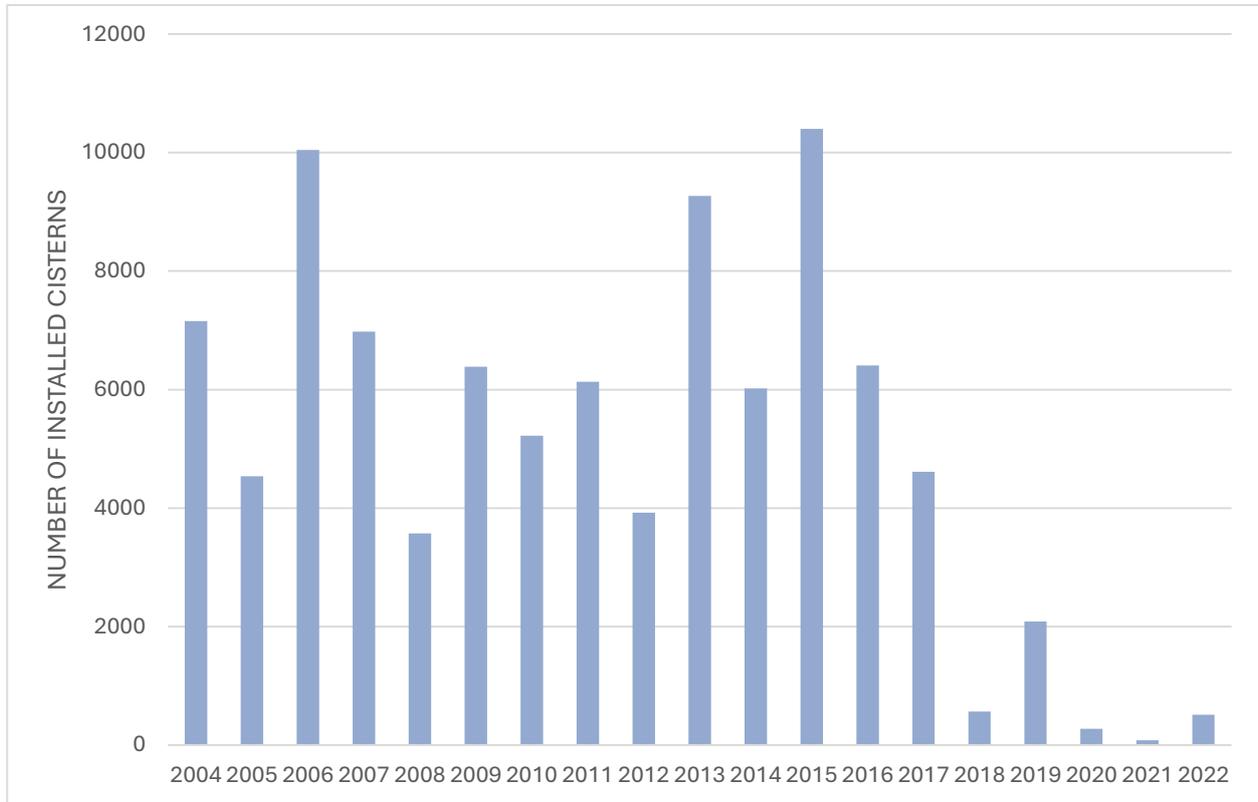
Source: Braga and Silva (1990).

The P1MC adopted rainwater tanks, hereafter called cisterns with a standardized capacity of 16 m<sup>3</sup> for all rooftop supplied SDAACs. This capacity was established considering an average annual precipitation of 400 mm, catchment area (roof) of 40 m<sup>2</sup>, and a water demand of 15 L per capita. Following these parameters, a family of five would have enough water stored in the cistern for a period of eight months without precipitation (ASA, 2015). These cisterns are cylindrical, semi-buried, and made of concrete plates and covered with slab.

The P1MC implemented 94,180 SDAACs in SAPB between 2004 and 2022 (MIC, 2023). Similar to what occurred in other states, the largest number of cisterns was implemented

in SAPB between 2004 and 2014 (approximately 74%), with the highest numbers in 2006 (10,046) and 2015 (10,349), as shown in Figure 4.

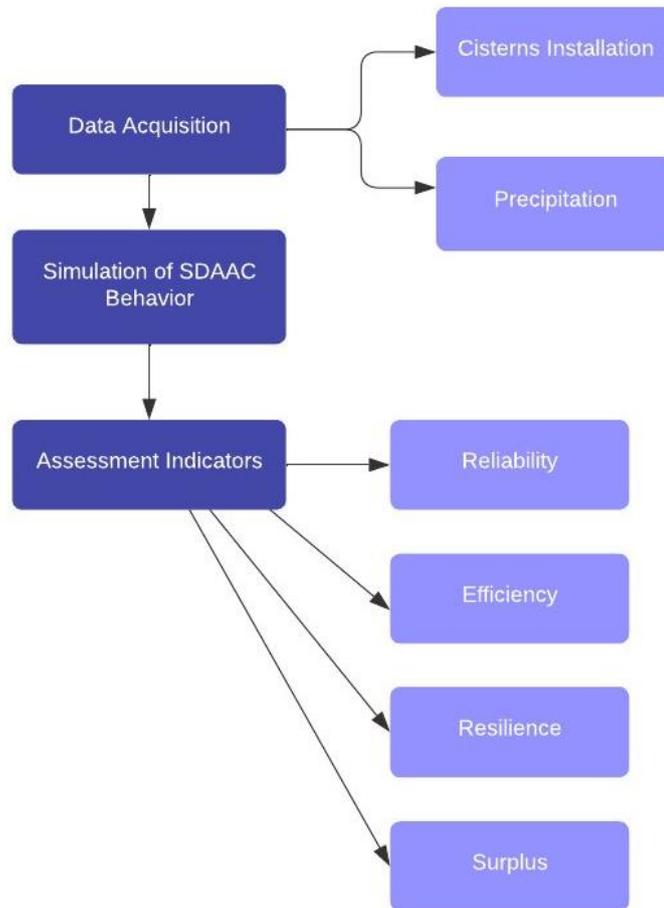
**Figure 4:** Installation of cisterns in the State of Paraíba by P1MC.



Source: MIC (2023).

### 3 Methodology

The work was initially developed with the collection of data to run the SDAAC simulations. After data acquisition, the performance of the SDAAC was assessed through four indicators, considering the rainfall data of each municipality. The summary of the methodological process can be seen in Figure 5.

**Figure 5:** Work methodology.

### 3.1 Data acquisition

Two main data sets were used to analyze the behavior of the SDAAC and assess the supply-demand relationship: information on the installation of the cisterns (Section 3.1.1) and rainfall data (Section 3.1.2). This database allowed a detailed numerical simulation of the water collected and their deficits, *i.e.*, when demand is not met, which are useful for subsequent analyses, such as the simulation of the water balance of the systems (Section 3.2) and the assessment of the performance of the cisterns based on specific indicators (Section 3.3).

#### 3.1.1 Cisterns installation data

The Ministry of Citizenship publishes data on the implementation of SDAACs through the Secretariat for Assessment, Information Management and Single Registry (SAGICAD). The data are accessed through the VISDATA portal: the number of cisterns implemented monthly on a national, state and municipal scale. However, the portal does not inform what type of cistern is being used, *e.g.*, school cistern or household cistern, but only that it is a system used for human consumption. For the purposes of this study, it was assumed that all cisterns are household cisterns, as this does not interfere with the objectives.

The Cisterns Program database was also used; its data was fed by the Ministry of Development and Social Assistance, Family and Fight against Hunger. Through this portal, it is possible to obtain data on the type of SDAAC implemented and the municipality in

which it was built. However, this platform does not contain information on the year in which the cisterns were built.

### 3.1.2 Rainfall data

A 30-year historical daily precipitation series (1993–2022) was used to represent precipitation variability in the current climate. Data were extracted from the Climate product Hazards Group InfraRed Precipitation with Station Data (CHIRPS) daily database and interpolated to local scale and time using Google Earth Engine (GEE). CHIRPS is a global set, combining data from in situ stations with satellite products, which generates precipitation time series outputs (Funk *et al.*, 2015). CHIRPS temporal scale is daily and has a spatial resolution of 0.05°. For this study, the representation of both the magnitude of events and the daily distribution and seasonality is very important, and therefore CHIRPS was chosen. Several studies have focused on this product, having validated it for the Brazilian semi-arid region (e.g., Santos *et al.*, 2019; Costa *et al.*, 2019). Brito *et al.* (2022) evaluated the performance of CHIRPS for a basin in the semi-arid region of Paraíba, concluding that it can satisfactorily represent local precipitation characteristics.

Using the GEE functions `ee.filterBounds` to determine the spatial cutout and the `ee.filterDate` function to determine the time interval, it was possible to delimit the region and the period of interest. For the region, the Semi-arid delimitation provided by SUDENE (2017) in shapefile format was used, filtering the municipalities belonging only to the state of Paraíba.

### 3.2 Simulation of SDAAC behavior

The methodological approach adopted in this study to assess the supply-demand relationship in the SDAAC was numerical simulations. The sequential water balance of the system was simulated, considering the precipitation series, system characteristics, and required demand. Thus, it is possible to simulate the volumes stored in the cisterns on each day of the time series and also to quantify the supply-demand relationship indicators. In the simulations, the following system characteristics were assumed, which correspond to the standard of the P1MC beneficiary users (ASA, 2015): cistern capacity ( $C_c$ ) of 16 m<sup>3</sup>, demand ( $D$ ) of 0.075 m<sup>3</sup>/day (around 0.015 m<sup>3</sup>/person/day for a family of five people), and roof catchment area of 40 m<sup>2</sup>.

The daily storage of the cistern is calculated based on the sequential water balance of the reservoir (Equation 1).

$$Varm_t = Varm_{t-1} + Vent_t - Cons_t \quad (1)$$

Where:

$Varm_t$  = the volume stored at the end of day t (m<sup>3</sup>);

$Varm_{t-1}$  = the volume stored at the end of day t-1 (m<sup>3</sup>);

$Vent_t$  = the volume captured on day t (m<sup>3</sup>);

$Cons_t$  = the volume consumed on day t (m<sup>3</sup>).

For the first day of storage, that is, when  $t=1$ , it is considered  $Varm_{t-1} = 0$ . When the stored volume is greater than the cistern capacity, the difference must be considered as an overflow volume (Equation 5) and the volume stored at the end of that day is assumed to be the cistern capacity.

The volume captured on day t is calculated by Equation 2.

$$Vent_t = At * P * C \quad (2)$$

Where:

At = the roof catchment area (m<sup>2</sup>);

P = daily precipitation (m);

C = the system efficiency coefficient, to consider losses in the collection and drainage system to the cistern (dimensionless, between 0 and 1, 0.75 adopted here).

Consumption is defined by the portion of demand met (D), expressed by Equation 3.

$$Cons = (Vent_t + Varm_{t-1}, D) \quad (3)$$

When consumption is lower than demand, a water deficit occurs, *i.e.*, the cistern, on that day, did not have sufficient storage to meet demand. This value should be considered as follows (Equation 4).

$$Def = D - Cons \quad (4)$$

When  $Varm_t > Cc$  (cistern capacity), the cistern overflow (Ext) must be considered, which will be calculated by Equation 5.

$$Ext = Varm_t - Cc \quad (5)$$

### 3.3 Assessment indicators

In order to evaluate the performance of the cisterns in meeting user demands, four indicators were used. These indicators can potentially reveal particularities of the behavior of the systems in relation to the characteristics of local rainfall regimes. Three of the indicators, *i.e.*, reliability, efficiency and resilience, were based on Hashimoto *et al.* (1982) and Fewkes (1999). The fourth indicator, surplus, is a contribution of this work, not being present among the classic indicators proposed by those authors.

#### 3.3.1 Confiabilidade

Reliability (Conf) refers to the satisfactory state of the system, in other words, whether the system can meet the demand for which it was built. The indicator expresses the probability of the system meeting the needs of users, that is, of not having service failures. However, it does not measure the magnitude of the failure. Reliability (Equation 6) is calculated as the percentage of days in which the volume stored at the end of the day was greater than zero after the withdrawal of the day's demand, over the entire simulated period T (Hashimoto *et al.*, 1982).

$$Conf = \frac{\sum_{t=1}^T Varm_t > 0}{T} * 100 \quad (6)$$

#### 3.3.2 Efficiency

Efficiency (E) reveals the magnitude of the failure to meet user demand. The indicator seeks to measure what portion of user demand was met on days when there were failures (Fewkes, 1999). Efficiency can also be considered as the complement of vulnerability as defined by Hashimoto *et al.* (1982). Efficiency can be formulated (Equation 7), as a percentage, by the ratio between the volume consumed and the volume demanded on the day, over the entire simulated period T (Hashimoto *et al.* 1982; Fewkes, 1999).

$$E = \frac{\sum_{t=1}^T \text{Const}_t}{\sum_{t=1}^T D} * 100 \quad (7)$$

### 3.3.3 Resilience

Resilience describes the system's ability to recover and return to a satisfactory state, *i.e.*, how long the system takes to meet demand again after a failure (Hashimoto *et al.*, 1982). Therefore, this time count (in days) starts from the day of the first failure (when the stored volume at the beginning of the day is zero) and goes until the first day when demand was fully met. For example, in one of the simulations, the cistern starts receiving rainwater on 01/05/1993 and starts to fail on 01/12/1993, recovering on 01/18/1993. In this situation, the system took 7 days to recover, and, consequently, the resilience of this event is computed as seven days. If this failure-recovery situation is repeated in several other periods during the simulation, the SDAAC resilience is considered here as the average of all these values identified in the simulation.

### 3.3.4 Surplus

The surplus represents the amount of water collected by the roof that is not used due to the limited storage capacity of the cistern. It can be used as a guideline for expanding the storage capacity of current systems, or for designing new systems with increased capacity. It is expressed by the annual average of overflows (Ext, Equation 5) during the entire simulated series.

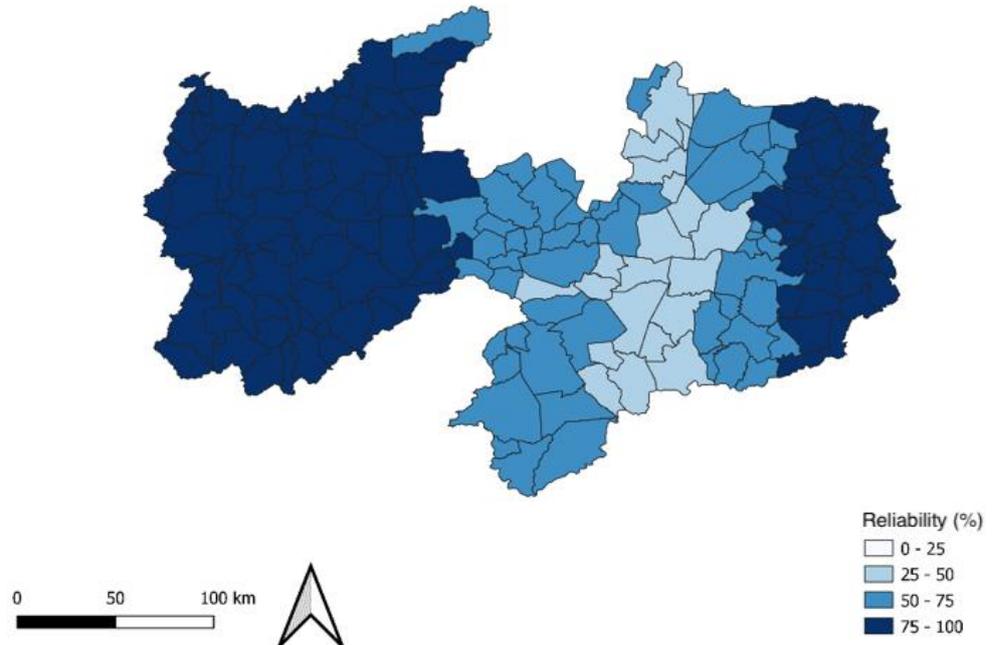
## 4 Results and discussion

This section presents the main results and discussion the indicators used to assess the performance of SDAAC in meeting users' water demands. The analysis includes reliability, efficiency, resilience and surplus indicators, which allow us to assess how the systems respond to local climate variability and supply needs over time. Each indicator is discussed for the municipalities of the semi-arid region of Paraíba, considering the specificities of precipitation and cistern capacity, with the aim of identifying and discussing the limitations and opportunities for improvement of these systems.

#### 4.1 Reliability

Reliability was assessed for each municipality, obtaining the average annual values presented in Figure 6. One might expect that reliability would be directly proportional to the average annual precipitation (Figure 2), but seasonality and temporal variability are also determinants of it (e.g., Silva *et al.*, 2023; Chen *et al.*, 2024). Only 28 of the 194 municipalities achieved a reliability above 90%, with the lowest value being 29.31% and the highest being 99.24%. All municipalities that exceed the ninety percent value have an average annual precipitation higher than 800 mm.

**Figure 6:** Average reliability of cisterns for SAPB municipalities.

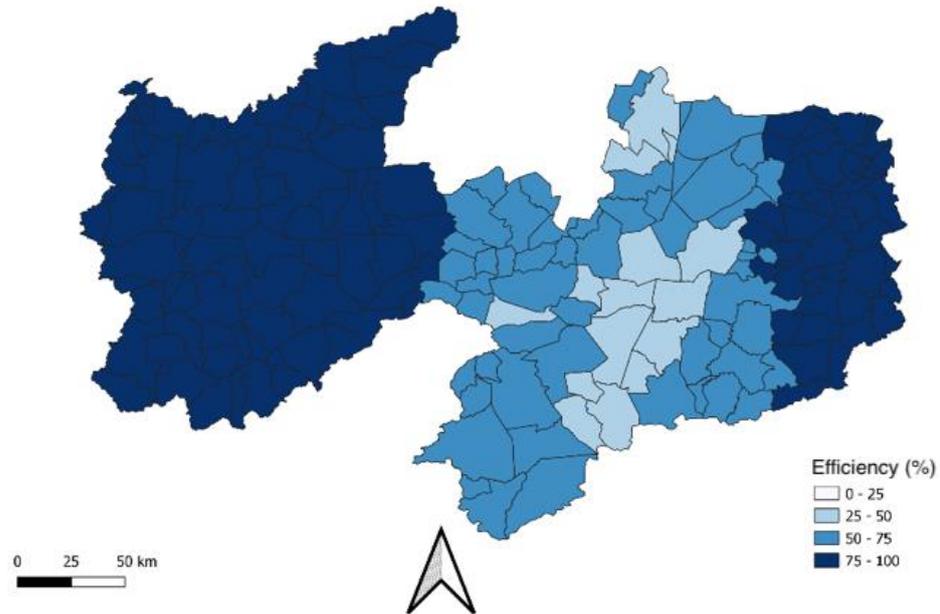


Source: Authors (2024).

#### 4.2 Efficiency

The average annual efficiency was calculated for the municipalities in the region studied (Figure 7). Similar to reliability, the municipality with the lowest value of the indicator presented 30.72%, while the highest value was 99.35%. Only 32 municipalities presented efficiency above 90% and, for the most part, they are municipalities belonging to the Brejo region of Paraíba.

**Figure 7:** Average efficiency of cisterns for SAPB municipalities



Source: Authors (2024).

When comparatively analyzing the reliability and efficiency indicators, it is observed that even though they have different concepts their values are generally equivalent in homogeneous precipitation regions. This fact occurs due to the low value required to reach the satisfactory state (reaching 100% reliability), as well as to meet the necessary demand (reaching 100% efficiency). As previously mentioned, with only 2.5 mm/day it is possible to meet both reliability and efficiency. Pacheco and Alves (2021) also observed that when analyzing cistern sizing estimation methods for cisterns with a volume of 15 m<sup>3</sup> the efficiency and reliability values were very close.

### 4.3 Resilience

To analyze resilience behavior, municipalities from four of the rainfall-homogeneous regions were chosen (Table 1).

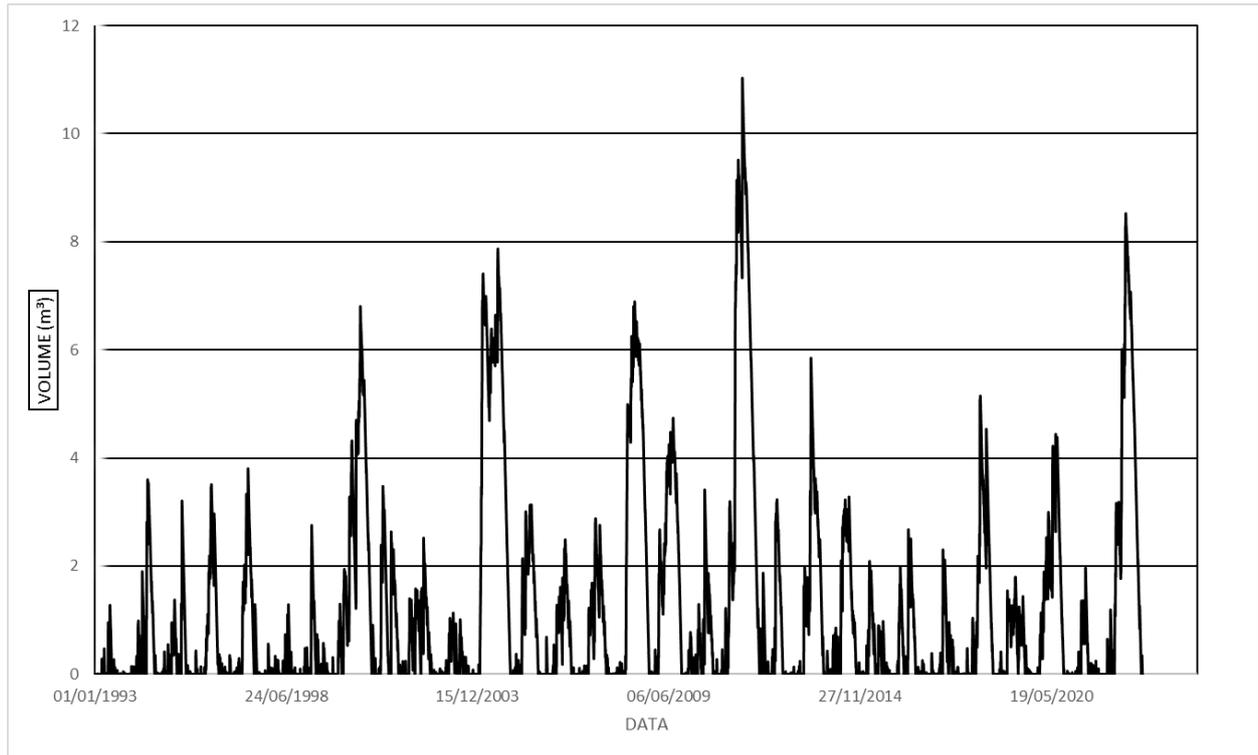
**Table 1:** Average annual resilience of cisterns for some SAPB municipalities.

| Municipality   | Region           | Resilience (days) | Average annual precipitation (mm) |
|----------------|------------------|-------------------|-----------------------------------|
| Campina Grande | Agreste          | 12                | 563,51                            |
| Sumé           | Cariri/Curimataú | 17                | 552,10                            |
| Patos          | Sertão           | 21                | 720,60                            |
| Cajazeiras     | Alto Sertão      | 16                | 893,03                            |

Source: Authors (2024).

Considering the region's marked seasonality, with rainfall concentrated in just a few months each year, the values for recovery of cistern functionality, expressed by resilience, seem relatively low. Unlike a large reservoir, such as a dam, where both the demand to be met and the storage capacity are considerably higher, a cistern recovers very quickly from a failure. To meet the demand assumed in this study (0.075 m<sup>3</sup>), a precipitation event of only 2.5 mm/day is sufficient, *i.e.*, very low precipitation, but it represents the level of supply for that day to be considered satisfactory. In several cases, rapid, but not continuous, recovery can be observed, *i.e.*, recovery occurs one day, but soon after there is a sequence of failures again (Figure 8).

**Figure 8:** Simulation of the water balance of a cistern for the municipality of Campina Grande – PB.



Source: Authors (2024).

On April 28, 1993, there was a recovery after 10 days of failures in Campina Grande (Figure 8); however, this recovery was not maintained, and another sequence of 22 days of failures occurred. What is argued here is that for the cistern the condition of failure recovery as a day with its demand is met does not actually represent a recovery, even if that day is essential for users in meeting their needs. Instead, it should be the situation in which, for some days, a localized failure occurs, but the recovery is fast and continues for a long period, remaining without failures and guaranteeing service to users.

Therefore, a new assessment of the resilience indicator was proposed based on the following conceptualization: the minimum guarantee to be met is considered to be a percentage of the cistern volume. For example, by adopting 10% there is a total of  $1.6 \text{ m}^3$ . For the volume considered, with this value, there are approximately 21 days of uninterrupted supply, that is, it is considered that the system recovery occurs with the supply of 21 uninterrupted days. Resilience was also simulated considering a minimum storage, *i.e.*, 20% (42 days) and 30% (63 days), as shown in Table 2 (columns labeled with “40 m<sup>2</sup>”). In this work, this modified concept of resilience is proposed as more realistic for the case of domestic cisterns.

**Table 2:** Modified resilience (in days) of cisterns for some SAPB municipalities, for roof areas of 40 m<sup>2</sup> and 60 m<sup>2</sup>.

| Municipality   | Region           | Resilience (10%) (days) |                   | Resilience (20%) (days) |                   | Resilience (30%) (days) |                   |
|----------------|------------------|-------------------------|-------------------|-------------------------|-------------------|-------------------------|-------------------|
|                |                  | Roof                    |                   | Roof                    |                   | Roof                    |                   |
|                |                  | 40 m <sup>2</sup>       | 60 m <sup>2</sup> | 40 m <sup>2</sup>       | 60 m <sup>2</sup> | 40 m <sup>2</sup>       | 60 m <sup>2</sup> |
| Campina Grande | Agreste          | 119                     | 95                | 164                     | 111               | 221                     | 122               |
| Sumé           | Cariri/Curimataú | 140                     | 101               | 198                     | 167               | 249                     | 185               |
| Patos          | Sertão           | 119                     | 75                | 132                     | 91                | 153                     | 103               |
| Cajazeiras     | Alto Sertão      | 85                      | 28                | 92                      | 28                | 92                      | 28                |

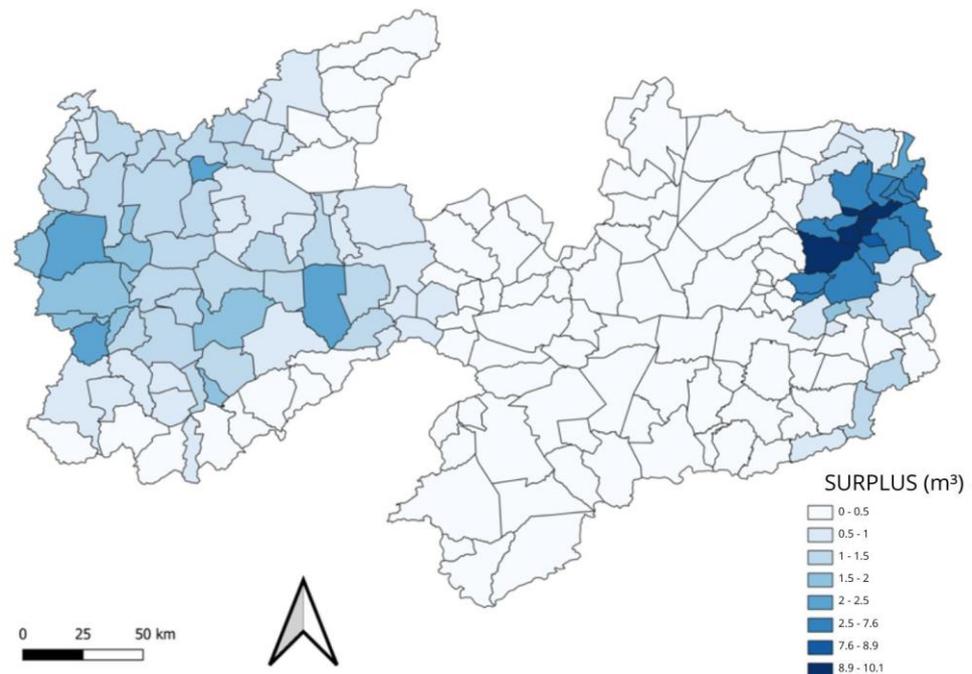
Source: Authors (2024).

When reanalyzing the indicator, it is possible to observe a significant increase in the recovery time of the systems. The municipality of Sumé presents the highest value in days in all scenarios. In the scenario with the largest storage (30%), the municipality of Sumé reaches approximately eight months (249 days) to recover the guarantee of supply to families. This long period highlights the need to implement other sources or other water supply systems to guarantee access to water for these users. With the new formulation of resilience, it is possible to demonstrate the sensitivity of the SDAAC to the desired water security.

#### 4.4 Surplus

The surplus, that is, the average volume overflowed from the cistern, for the municipalities studied (Figure 9), reaches a value of around 1.2 m<sup>3</sup> per year. The numbers show the potential for increasing the number of tanks in parallel or for sizing the tank by assessing the potential of the region to be implemented. Due to the establishment of a single volume of cisterns for the P1MC, this surplus water captured by the roof ends up not being used in many cases because there is not enough storage capacity.

**Figure 9:** Average annual surplus of cisterns for SAPB municipalities.



Source: Authors (2024).

## 4.5 Discussion

The four indicators proposed in this work were selected to provide a comprehensive view of the performance of SDAACs in the Brazilian semi-arid region. The methodology applied in this study is based on the premise that the combination of these four indicators is complementary and necessary to understand different dimensions of water supply and demand in regions with challenging rainfall characteristics. Multidimensional assessment is a recent trend in studies on these water systems. For example, Quon and Jiang (2023) recommend multicriteria comparative assessment of technological alternatives using scenario generation, while Jesus *et al.* (2020) and Teston *et al.* (2024) use life cycle analysis to assess the impact and performance of SDAAC in the Brazilian semi-arid region and in urban areas, respectively.

Although some results demonstrate a similarity between reliability and efficiency, the two indicators present conceptual distinctions, since while reliability measures the frequency of meeting the minimum demand, efficiency assesses the extent of this service, especially on days of partial failure, which may be more relevant in climate change scenarios (Alamdari *et al.*, 2018; Rocha *et al.*, 2022). The fact that these two indicators presented similar, but not identical, results indicates that, for the current patterns of precipitation, capacity and, mainly, demand of SDAAC in the Brazilian Semi-arid region, both indicators are influenced by similar aspects of the performance of cisterns in meeting the water demand of users, even if the focus of each indicator is different. Most national and international studies, as previously mentioned, use only the reliability indicator (e.g., Yu *et al.*, 2023). However, as demonstrated here, reliability alone does not allow a satisfactory characterization of the performance of the systems.

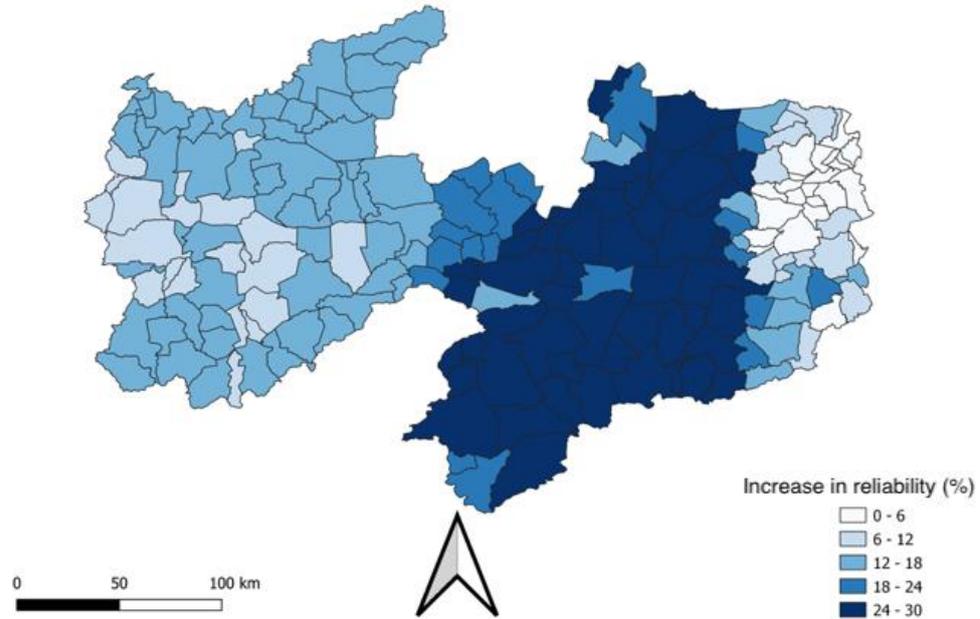
The surplus can inform the possibilities of increasing the use of local precipitation potential, as also concluded by Silva *et al.* (2024), when proposing a similar indicator. Resilience has proven to be a key indicator for SDAAC in semi-arid regions, as it characterizes the intermittency in meeting demands, whether during the rainy season, during the so-called “veranicos”, or in the dry season, due to annual seasonality. To the authors' knowledge, the specific literature on SDAAC has not yet considered this indicator.

In 2023, the Brazilian Federal Government announced resources for the reactivation of the Cisterns Program (updated nomenclature for the former P1MC), implementing more than 50 thousand new cisterns in the semi-arid region of Brazil. Previous studies (e.g., Cohim, 2013; Toosi *et al.*, 2020; Rocha *et al.*, 2022) have recommended increasing the roof area for rainwater collection, when necessary to increase reliability. This study corroborates this recommendation, exemplifying, in Figure 10 and Table 2 (columns “60 m<sup>2</sup>”), the improvement in reliability and resilience values for the semi-arid region of Paraíba, by adding 20 m<sup>2</sup> of roof area to homes that had an area equivalent to the standard of 40 m<sup>2</sup>. The municipalities most sensitive to this addition of catchment area were those in the Cariri/Curimataú region, the driest in the state. For example, in the municipality of Alcantil, there was an increase of almost 30% in reliability, increasing it from 59.73% (40 m<sup>3</sup>) to 89% (60 m<sup>2</sup>). On average, for the region studied, this would reach an increase of 16.11% in reliability. For resilience, the recovery time drops significantly for the drier regions, e.g., municipalities of Sumé, Campina Grande and Patos.

The expansion of the roof area and addition of complementary storage tanks could be determined on a case-by-case basis to bring the reliability and resilience indicators to their optimal values, also considering the surplus, as recommended by Silva *et al.* (2024). The

resources for the expansion of roof areas and increase in storage capacity could come not only from the Cisterns Program, but from an action coordinated with other programs to improve production infrastructure, such as storage and processing environments for agricultural production, for example.

**Figure 10:** Increase in the reliability of cisterns for a catchment area of 60 m<sup>2</sup> compared to the situation with a catchment area of 40 m<sup>2</sup>.



Source: Authors (2024).

## 5 Conclusions

This study analyzed the supply-demand relationship provided by domestic rainwater harvesting systems in the semi-arid region of Paraíba. The standard system type of the 1 Million Cisterns Program was studied, including the demand predicted by it. These systems were numerically simulated for all 194 municipalities in the region, subjected to 30 years of historical daily precipitation series, generating four indicators that reflect the supply provided by the systems. The supplied demand reflects the magnitude and temporal distribution characteristics of rainfall in each municipality.

Due to the low daily demand, the reliability and efficiency indicators were highly redundant. Due to the low rainwater collection capacities on small roofs and storage in cisterns, the classic resilience indicator has been modified to represent the long periods after the rainy season when the systems are unable to meet demand regularly, and this has yielded satisfactory results.

The indicators proposed in this work can be used to design new systems or to adapt and expand existing systems. A small increase in roof area could substantially increase the reliability and resilience of the systems. On the other hand, in municipalities where overflows occur during rainy periods, this surplus in supply can be used by increasing storage capacity. Failures in meeting demands, recovery time after failures, and possible surpluses can guide early warning systems.

Since this is a simulation-based study, there are some limitations. The main sources of uncertainty are related to the precipitation data, which come from spatial interpolation combining conventional surface measurements with satellite estimates and are assumed to be only one sample point per municipality, to the simulation of user behavior by uniformly consuming the reference demand established in the P1MC, and to the consideration of the infrastructure of the standardized system. Such limitations, however, do not compromise the conclusions of this study, since the spatial patterns of the supply-demand relationship, as characterized by the proposed indicators, are quite evident and informative.

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