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Cistern Project for Domestic Water use in Semi-Arid Regions

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***Abstract*- Water scarcity in semi-arid regions compromises the quality of life, principally human health, in these regions. The use of cisterns with adequate dimensions, that ensure the minimum of water required to meet human needs, is a practice recommended for these regions. This paper aims to estimate, considering the regional variability of precipitation, the most appropriate relationship between the capacity of cistern and the catchment area to ensure access to water considering the minimum recommended by WHO. A case study is presented for the Brazilian semi-arid region. A curve representing the relationship between these two variables was created for each region with similar precipitation conditions. In regions with low annual average precipitation, increasing the cistern capacity was found less efficient if there was no increase in the catchment area, while in areas with higher annual precipitation and longer periods of drought, the increased cistern capacity was the best alternative. Large differences in the relation between the cistern capacity and the catchment area were obtained in regions where the total precipitation and seasonal variability of precipitation throughout the year showed an intermediate behavior.**

***Keywords* - Rainwater Harvesting, Drinking Water, Water Supply For Human Consumption, Minimum Water Requirement For Human Health**

I. INTRODUCTION

Access to safe drinking water is one of the targets of the 7th Millennium Development Goals (MDGs), which is to halve, by 2015, the proportion of the population without access to improved sources of water. Brazil had already reached the target for drinking water in 2007, considering the whole country. However, when data of some regions from Brazil (states, municipalities and rural areas) are analyzed, then this target is not yet a reality, considering that the regional and socioeconomic inequalities still remain at high levels [1]. This means there is still need for improvement.

The water scarcity is more critical in the semiarid region of Brazil, where 22 million habitants live, representing about 11.8% of the Brazilian population [2] and over half (58%) of the country's poor [3]. This is one of the most populated semi-arid regions.

The lack of rainfall is not responsible for the inadequate supply of water to the area, but an irregular spatial and temporal distribution of rain and a high evaporation rate are the leading causes [4]. Although the Brazilian semi-arid region appears to be homogeneous due to drought conditions, [5] identified seven homogeneous sub-regions in the semi-arid region, based on the variability of precipitation.

The water scarcity in the region is aggravated by the presence of a crystalline layer in about 80% of the region [6]. The crystalline rock does not have pores where water can be retained. The layer above the rock is usually quite shallow, and often less than 1 m. Generally, the groundwater that is available has a low yield, and, in most cases, is improper for human consumption because of high salinity.

Recently, efforts have been made by the Government of Brazil to mitigate drought impacts in this region. The “One Million Cisterns Project” (P1MC) is an example at the federal level, whose objective is build cisterns in the semi-arid region to supply drought-proof drinking water. Each cistern has a capacity to store 16 m^3 of water, which, according to the Ministry of National Integration, is sufficient to sustain a family of five for a dry period of up to six months.

However, these government efforts have not been able to solve the recurring problems of water shortage for the local population. According to [7], in order for the population to have access to water it is necessary that the actions and measures implemented recognize the heterogeneity and local context of each municipality and community of the Brazilian semi-arid region.

The interventions in improving access to safe water can be an effective part of poverty reduction strategy [8]. Investments in water supply and sanitation can yield, in addition to social benefits, economic benefits, because in many regions, the reduction of costs with health problems resulting from missing or poor water quality exceeds the costs of investments [8]. Several studies show the importance of water access for human health [9,10,11,12].

Based on data from the Brazilian Ministry of Health, UNICEF reports that one out of every four children who die in the semi-arid region will lose their life as a result of diarrhea after ingesting water unfit for human consumption [13]. According to [14], the direct and indirect costs of this situation, financial and social, are immense and repeat with an unacceptable frequency.

Health and other benefits from improved water supply are significantly greater when there is a supply of continuous access to safe drinking water [15].

The World Health Organization (WHO) has defined that 20 liters of water per person per day are needed to meet the basic needs of a person, although this consumption is still associated with a high risk of health problems [15]. These can be minimized, according to WHO, with a consumption of 50 liters/person/day.

Rodriguez et al. (2015) [16] ascertain that even in regions where the local population can have greater water use, this does not guarantee meeting the basic needs of a person, as recommended by WHO. Therefore, there is a need to adapt the characteristics of the project of cisterns, for example, the roof area (catchment area) and sizing of the cistern, so the local population has access to the minimum amount of water required for daily use due to the great water scarcity in the region.

Thus, this paper aims to estimate, considering the regional variability of precipitation, the most appropriate relationship between the capacity of cistern and the catchment area to ensure access to water, considering the minimum amount recommended by WHO (20 L/person/day), and present a case study for the Brazilian semi-arid region.

II. METHODS AND MATERIALS

To support the cisterns projects to ensure access to water for population in the semi-arid regions, was adjusted the most appropriate relationship between the capacity of cistern and the rainwater catchment area, which was based on the daily water balance in the cistern. The sequence of methods used is described in the following section:

A. Characterization of study area and data used in the study

According to official data from the Brazilian Ministry of National Integration, the semi-arid region of Brazil covers an area of approximately 969,589 km² (11.4% of the Brazilian territory) and comprises 1,133 municipalities across nine Brazilian states [4].

The average annual rainfall in the region is approximately 800 mm and surpasses rainfall in the rest of the world, where average annual rainfall is half of the total rainfall in the Brazilian semi-arid region. But there is a highly irregular annual and inter-annual variability of rainfall: one year it could receive 974 mm of rainfall, while in a drought year it may only receive 185 mm [17], with the rainy season centered in only a few months per year – about five months. Rodriguez et al. (2016) [16] ascertained that in regions with highest annual precipitation, there is the highest monthly precipitation variability, where from January to May 86 % of the total annual precipitation volume rains.

Due to this variability of precipitation, [5] identified seven homogeneous sub-regions in the semi-arid region of Brazil (Fig. 1), thus, allowing to adapt water management to the characteristics of each location of the semi-arid region.

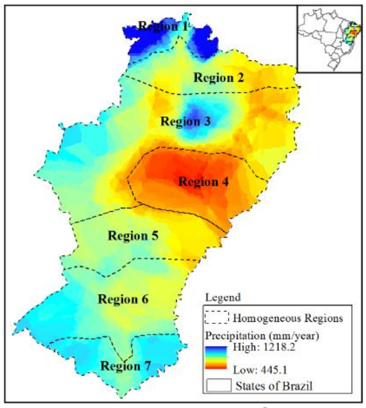

Fig. 1. Homogeneous region in semi-arid region in Brazil.

This study used the data of 290 pluviometric stations, which are part of the hydrometeorological network of the Hydrological Information System (Hidroweb) of the National Water Agency of Brazil.

B. Estimation of water volume in the cistern

The amount of water accumulated in the cistern on each day is based on the analysis of the amount of water entering the cistern and the amount demanded. The analysis is performed on a daily basis, using Eq. (1), discussed in [18],

$$S_{t+1} = S_t + Q_t - D_t \qquad 0 \le S_{t+1} \le C \qquad (1)$$

where S_{t+1} is the storage volume in the cistern at the end of t-th day (L/day); S_t is the storage value at the beginning of t-th day (L/day); Q_t is the runoff from the roof into the cistern on the t-th day (L/day); D_t is the total demand for water on the t-th day (L/day); and C is the active tank capacity.

The daily time period is important to ensure that there is sufficient water to meet the domestic demand connected to rainwater use as far as possible. The analysis is performed for a period of 10 years. The water evaporation from the cistern is not considered as the cistern is closed. The simulation starts with the cistern being considered completely full. When the water storage level (S_{t+1}) in the cistern on a particular day is greater than its capacity (C), the excess water is discarded, and the cistern storage level at the end of the day will be reset as equal to C.

The amount of water entering the cistern depends on the amount of rainfall and the characteristics of the water collection system, given as:

$$Q_t = (R_i - R_{ff})\, A_t\, k \qquad (2)$$

where Q_t is the daily runoff (L/day); R_i is the rainfall on day i (mm); R_{ff} is the first flush on day i (mm); A_t is the area in horizontal projection of the roof of the residence (m^2); and k is the runoff coefficient (decimal).

The first flush corresponds to the initial discard of a fixed portion of rainfall to improve water quality, once that the initial discharge from the roof catchment washes the roof where dirt is deposited from birds and animals, and dust. Studies have shown that the disposal of 1 to 2 mm from each rainfall event allows maintaining a better water quality [19, 20, 21, 22]. Thus, the value adopted is discarded rainfall equal to 2 mm.

Not all the water that falls on the roof drains into the cistern, part of it ricochets off the roof or is blown and a small portion back to the atmosphere. Most installers of cistern have an efficiency of 75% to 90% [23]. For corrugated iron roofs well-constructed, the runoff coefficients range of 0.8 to 0.85 [24], for concrete-lined ground catchments, ranges from 0.73 to 0.76 [24, 25]. Therefore, it is appropriate to adopt a runoff coefficient value of 0.8 [26, 27].

According to [28], when reservoirs are analyzed with a historic data record at the project site, a single estimate of the capacity and other indexes is obtained, however, such an approach does not give a measure of risk for these indexes caused by natural uncertainty from inflow or operation. This fact, along with the high lack of data on the historical series of rainfall in arid and semi-arid regions, especially in underdeveloped countries and in developing countries, limits the application of the methodology presented. Thus, this study is based on a smaller dependence on the characteristics of the database available and can make it a more comprehensive method for overcoming the limitations related to the dependence on the starting year of the series and the impossibility of associating certain parameters analyzed for a return period.

For this, daily rainfall for each of 290 pluviometric stations is obtained based on synthetic rainfall series generated by the program Cligen developed by USDA - United States Department of Agriculture. The Cligen is a stochastic weather generator which produces daily estimates of precipitation, temperature, dewpoint, wind, and solar radiation for a single geographic point, using monthly parameters (means, SD's, skewness, etc.) derived from historic measurements.

The daily water demand (D_t) from the cistern will depend on the number of persons in the family and the water consumption per capita, given as:

$$N_{p,f}\, q_c \qquad (3)$$

where $N_{p,f}$ is the number of persons in the family; and q_c is the per capita water use (L/person/day).

For the Brazilian semi-arid, the water demand was estimated for a family with five individuals.

C. Relationship between capacity of cistern and catchment area

As most people cannot last more than three days without water [29], the cistern capacity was estimated, so that a consumption of 100 L/day in the residence results in 3 consecutive days without water in the cistern associated with a return period (T) of 10 years.

Rodriguez et al. (2016) [16] ascertain that a cistern of 16 m^3 and with 70 m^2 of catchment area (original Project data) are not sufficient to ensure water demand in the semi-arid region of Brazil. In order to determine the best relationship between the cistern capacity and the catchment area, seeking to meet the minimum requirement of water recommended by the WHO, we estimated the cistern capacity associated with a catchment area of 100 m^2, 120 m^2, 140 m^2, 160 m^2 and 180 m^2.

Based on the variation of water volume in cistern (Eq. 1), the cistern capacity associated with a given catchment area was estimated in each simulated year for each location corresponding to the gauging stations.

The annual series of cistern capacity associated with a water catchment area, for each locality, was simulated statistically, in order to identify the probabilistic model that best fitted the data. The distributions considered were: Log-Normal with two and three parameters, Pearson III, Log-Pearson III, and Weibull.

The selection of distribution models for each series was performed using the Kolmogorov-Smirnov (KS) test at the 5% level. In the KS test, comparison was made between the maximum deviation, in modulus, resulting from the differences between observed and theoretical values of frequencies, with the tabulated value based on sample size and significance level. For the model probabilities to be considered appropriate, the calculated values should be equal to or lower than the tabulated value for the KS test.

After the selection of the probability distribution with the goodness-of-fit to the data of cistern capacity, the value of cistern capacity associated with a return period of 10 years was obtained for a given catchment area in each locality.

Based on these data, the mean value of the cisterna capacity associated with a catchment area in each homogeneous region was estimated. To obtain measures of uncertainty of the data analyzed in each region confidence interval for the mean was estimated, which enables to better analyze the error involved in the analysis.

Although the confidence interval does not permit to calculate the actual magnitude of an individual error, it is possible to group several estimates from different locations and then observe the distribution of these errors.

When the parameter of interest is the population mean (μ), the confidence interval (CI) for the parameter with probability 1 - α (significance level) that the interval contains true parameter can be given as:

$$C.I.(1-\alpha): \bar{X} - D\,\frac{s}{\sqrt{n}} \le \mu \le \bar{X} + D\,\frac{s}{\sqrt{n}} \qquad (4)$$

where $\bar{X}$ is the sample mean; s is the sample standard deviation; n is the sample size; and D is the statistical distribution selected.

The t-distribution should be used when the population standard deviation (σ) is not known and the sample size is small (n<30). Otherwise, the normal distribution should be used. For better accuracy of results, a value of α was adopted as equal to 0.005, corresponding to the 95% confidence levels, i.e., 95% confident that the interval contains the true population mean.

A curve based on average data of the cistern capacity associated with the catchment areas was fitted for each homogeneous region and for the data associated with lower and upper limits of the 95% confidence interval. These curves serve as support for decision-making in order to adapt the dimensions of project (cistern capacity and catchment area) according to the characteristics of each homogeneous region within the semi-arid region.

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III. RESULTS

A. Variation of water volume in the cistern – project data

The variation in cistern-water volume throughout the year differed among homogeneous regions due to the variability of average annual precipitation and the seasonal variability of precipitation throughout the year. Fig. 2 shows the 10-year variation in cistern-water volume, considering the precipitation data from a station located in the homogeneous region 1. This represents the highest yearly total precipitation among the seven homogeneous regions identified. The cistern capacity was 16 m^3, with a catchment area of 70 m^2, and the demand of residence of 100 L/day, corresponding to 20 L/person/day.

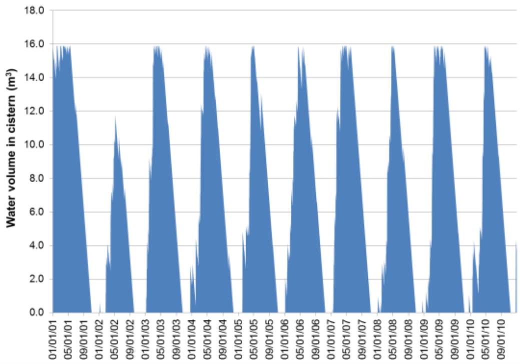

Fig. 2. Water volume variation in the cistern in 10 years considering the precipitation data of a station located in the homogeneous region 1. Cistern capacity was16 m^3, with a catchment area of 70 m^2, and the demand of the residence of 100 L/day.

During the simulated period there was a water demand of 100 L/day (consumption of 20 L/person/day, as recommended by WHO, for a family of 5 people) that would cause a daily withdrawal of water from the cistern. The cistern was completely filled in all the simulated years, except in the second year when the water volume reached only 74.3% of its capacity. This results from the lower precipitation in this year, which is approximately 64.3% of the average annual precipitation (Fig. 3a).

Considering the cistern dimensions initially adopted (tank capacity of 16 m^3 and water catchment area of 70 m^2), and water consumption of 100 L/day, the cistern would be empty for 664 days (18% of simulated period), representing a lack of water to meet basic human consumption for about 60 days per simulated year. Therefore, despite that it is possible to have the cistern filled every year, the water demand of 100 L/day is unmet throughout the year.

By April, there was usually water recharge in the cistern, but in May the cistern begins to empty despite the small contribution from roof-water runoff in this month, which is insufficient to offset the withdrawal of water. The average rainfall that occurs in the period from June to December (corresponding to 55.9 mm or 7% of the average annual total) is insufficient to recharge the cistern as the total demand during these seven months (equivalent to 21.4 m^3) far exceeds the amount of water that is entering the cistern (Eq. 2). The imbalance between water recharge and water demand in this period resulted, for most simulated years, in the absence of water in the cistern beginning in October, although in some years there is already water scarcity in this month.

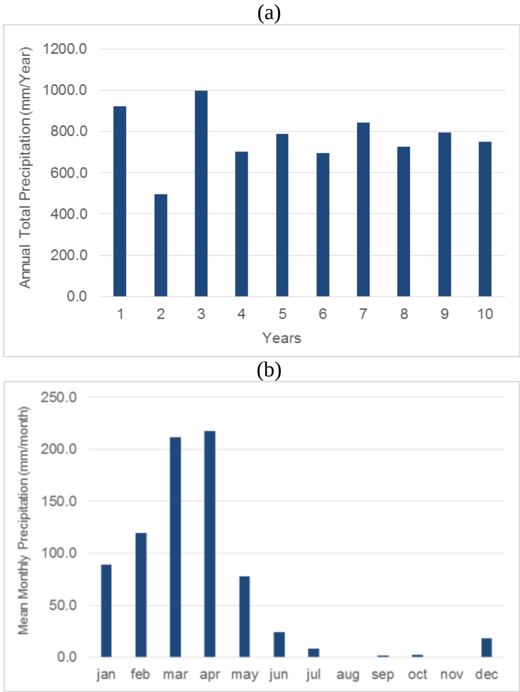

Fig. 3. Annual total precipitation (a) and mean monthly precipitation (b) simulated for the 10-years period considering precipitation data of a station located in the homogeneous region 1.

The problem reported in region 1 aggravates further in region 4, where the annual total precipitation is the lowest among the seven homogeneous regions of the semi-arid region. Fig. 4 shows the variation of water volume in the cistern (16 m^3 capacity) in 10 years, considering the precipitation data of a station located in the homogeneous region 4. The catchment area was 70 m^2 and the demand of the residence was 100 L/day. As the simulation starts, considering the cistern completely filled, the stored volume near its capacity is only observed in the first simulated year.

The water volume in the cistern only exceeds half of its storage capacity in the years 2, 5 and 8. This results from the concentration of the annual total precipitation in a few events, making it possible to meet water demand and store water in the cistern, which would not be possible otherwise.

The cistern remained without water for 1,757 days (48% of the total simulated days), which correspond to approximately 176 days/year (Fig. 4). The seventh and the tenth simulated years showed the lowest rainfall, corresponding to approximately 65% (252.6 mm/year) and 49% (188.3 mm/year) of the average annual (387.4 mm/year), respectively (Fig. 5a). Thus, the cistern remained dry (or empty) for 228 days in the former and for 295 days in the latter year.

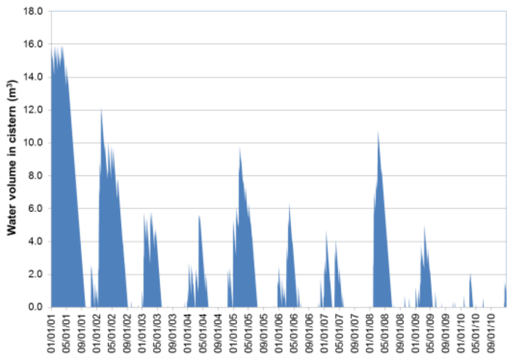

Fig. 4. Variation of cistern-water volume in 10 years considering the precipitation data of a station located in the homogeneous region 4. Cistern capacity = 16 m^3; catchment area = 70 m^2; residence-water demand = 100 L/day.

The rainfall that occurred from May to November (Fig. 5b) was insufficient to meet the established demands leading to a reduction of water volume in the cistern. In general, the water recharge that occurred before May was enough to support the demand of one family through June. However, rainfall was still insufficient to meet such demands in December.

(a)

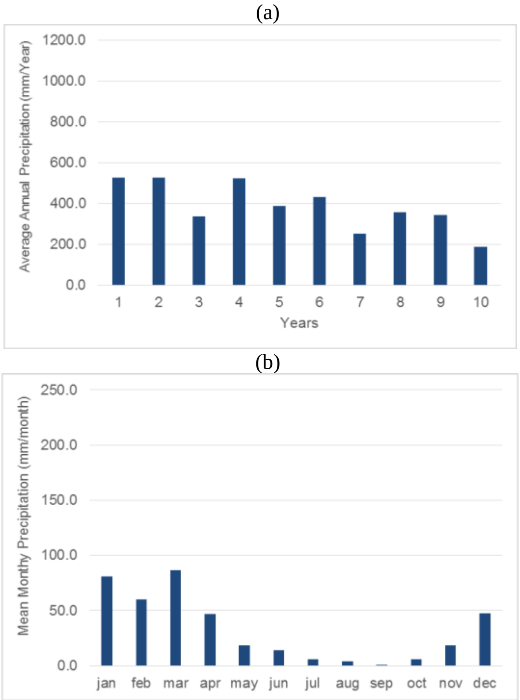

Fig. 5. Annual total precipitation (a) and mean monthly precipitation (b) simulated for the 10-year period considering the precipitation data of a station located in the homogeneous region 4.

B. Cistern Dimensioning

Table 1 shows the average capacity of the cistern necessary to meet a demand of 100 L/d in each homogeneous region, considering a catchment area of 70 m^2.

TABLE 1. Average capacity of the cistern (m^3) required to meet a demand of 100 L/d in each homogeneous region of the Brazilian semi-arid considering a catchment area of 70 m^2.

Homogeneus Regions	Average Capacity Cistern (m^3)
Region 1	35.3
Region 2	49.5
Region 3	54.4
Region 4	120.8
Region 5	77.0
Region 6	48.4
Region 7	34.7

With 70 m^2 of catchment area, a greater storage capacity for the cistern would be required in order to meet the minimum water demand recommended by WHO. Nevertheless, increasing storage capacity would pose a risk to the structure of the cistern as a maximum of 20 m^3 of storage capacity has been suggested to minimize the risk of cracking [30]. This represents a major concern, as even for region 1 and region 7 with greater water availability, the cistern capacity would have to be 77% and 74% greater than 20 m^3, respectively. In the case of homogeneous region with higher water scarcity, the cistern capacity would exceed 4 (region 5) to 6 times (region 4) that recommended by [30].

In addition to the risk of cracking, the construction of cisterns with such dimensions would be economically unfeasible, given the low socioeconomic status of the population.

Therefore, increasing the catchment area is an alternative for minimizing costs and to ensure a safe dimensioning. In areas where the house roof is not large enough to collect the water needed for a family of five, the catchment of water from floors and pavements may be implemented. In this system, the rainwater that falls on paved areas is collected in channels and drains, directed to a filter and finally to a reservoir similar to that used to collect water from the roof.

Fig. 6 represents the best fit potential regression curve of the average data of the cistern capacity and catchment area for each homogeneous region and the curves associated with lower and upper limits of the 95% confidence interval. For the curves of average data, the variation of the cistern capacity is shown with increasing catchment area from 100 m^2 to 110 m^2 and from 170 m^2 to 180 m^2.

The slopes of the curves are more pronounced for smaller catchment areas. Thus, an increase in the catchment area from 100 m^2 to 110 m^2 represents a great benefit with respect to the reduction in cistern capacity when compared to increasing a larger catchment area (e.g., 170 m^2 to 180 m^2)

The slope is more pronounced for regions with lower annual total precipitation and lower seasonal variability of precipitation throughout the year, as it occurs in the region 4 and region 5 (Fig. 7 and Fig. 8).

In region 4, where the average annual rainfall (565.3 mm/year) is the lowest among all homogeneous regions of the semi-arid, the variability of precipitation throughout the year is smaller compared to region 1. In the rainiest months (December-January), the precipitation in region 4 is well below that of other regions, ranging from 59.8 to 109.1

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mm/month, while the driest months (August-October) the precipitation is higher than in other homogeneous regions, such as region 1 (with highest rain in semi-arid) ranging from 10.3 to 18.0 mm/month. Thus, even in the dry period, the daily precipitation is sufficient to wash the catchment surface (2 mm), and for a small recharge in the cistern which is proportional to the catchment area. Although it may be insufficient to meet the daily demand for water (100 L), this recharge helps to slowdown the depletion of water in cistern. Considering the behavior depicted in Fig. 4, it is evident that when the catchment area is small (70 m^2) the water volume entering the cistern is insufficient for filling it completely, even at the end of the rainy season in the 10-year simulated period. Therefore, increasing the cistern capacity is meaningless, if catchment area is not increased accordinly.

In region 1, which has the highest annual average precipitation (1009 mm/year) and where 86% of this total occurs from January to May, there is a lack of water entering the cistern in the dry season, once the average precipitation during the most critical months (August-November) is only 4.4 - 7.7 mm/month, nearly corresponding to the total precipitation used for washing the catchment area. However, even considering a small catchment area (70 m^2), the amount precipitated in the rainy months is enough to completely fill the cistern in each year (Fig. 2). Therefore, because the existence of a larger catchment area would not increase water storage in the cistern, as its capacity would have been exceeded during rainy months, increasing the cistern capacity is the best alternative to guaranty water supply during the dry period (4 months).

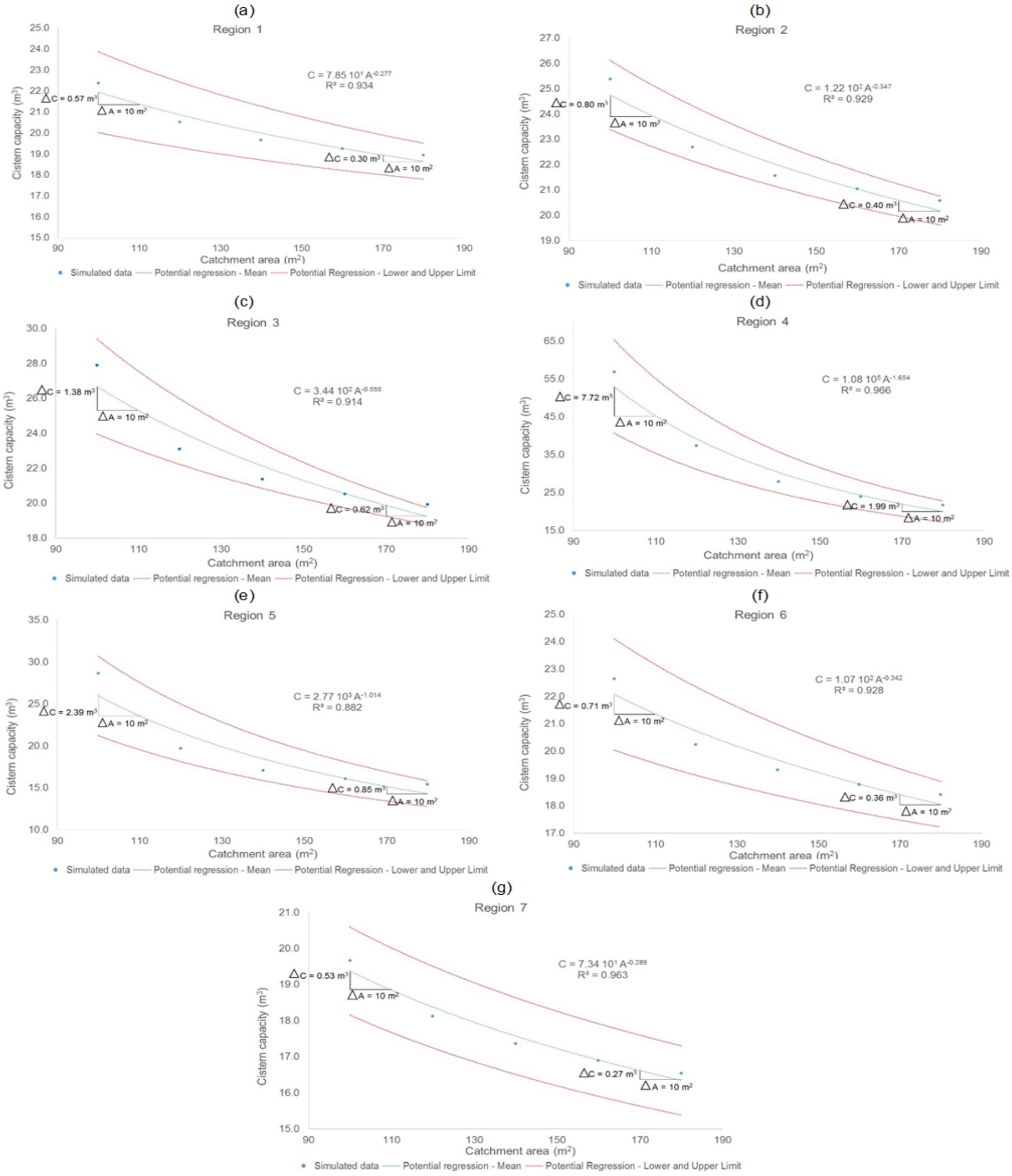

Fig. 6. The best fit potential regression curve between the capacity of cistern and the catchment area to meet a demand of 20 L/person/day, and the curves associated with lower and upper limits of the 95% confidence interval for (a) region 1; (b) region 2; (c) region 3; (d) region 4; (e) region 5; (f) region 6; (g) region 7 of the Braziliansemi-arid.

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The strong effect that the long period without water recharge in cistern has on project conditions becomes more evident by a comparative analysis between the behavior evidenced in region 1 with that observed in the region 7. The annual average precipitation in region 7 is 869 mm/year, which corresponds to 86.1% of the total precipitation in region 1. In both regions, even considering a small catchment area (70 m^2), the amount of water that enters the cistern is sufficient to ensure its total filling at the end of the rainy season. However, in region 7, the driest period of only three months (June-August) is less than the four driest months in region 1, and the average monthly precipitation in these three months in region 7 varies from 10.9 to 13.3 mm/month. This is sufficient to ensure some water recharge into the cistern as observed in region 4. Because of such differences, a lower cistern capacity is required in region 7 relative to region 1 (Fig. 8).

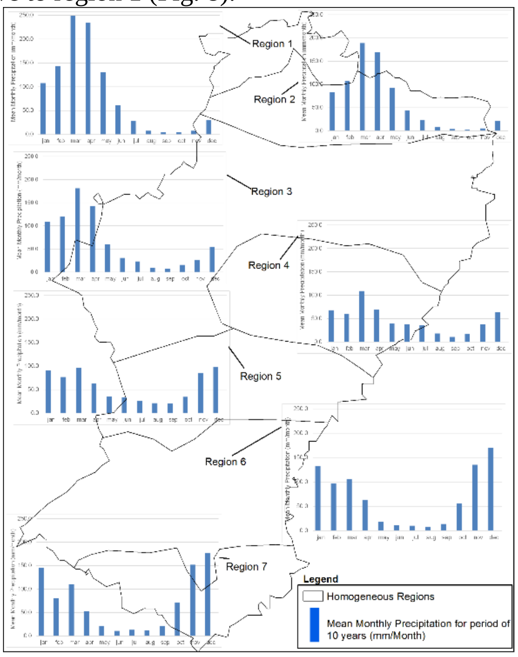

Fig. 7. Mean monthly precipitation simulated to the period of 10 years in each homogeneous region of semi-arid of Brazil.

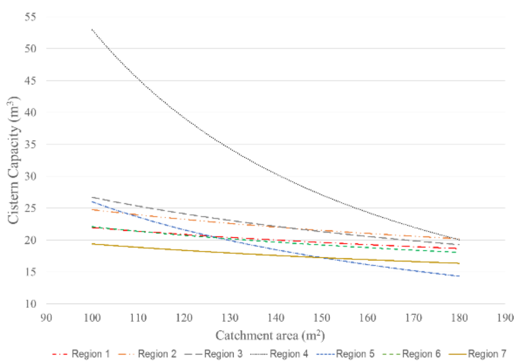

Fig. 8. The best fit potential regression curve between cistern capacity and catchment area in each homogeneous region

Another behavior that is important to mention is related to region 5. Despite having the lowest yearly total precipitation (about 681.6 mm/year) among the seven homogeneous regions identified, region 5 shows a more regular distribution of precipitation throughout the year (Fig. 7). Consequently, even in periods of low precipitation (July-September, from 20.7 to 26.0 mm/month), there is still a recharge in the cistern. Such higher uniformity of precipitation in region 5 makes project conditions strongly influenced by both the catchment area and the cistern capacity. For instance, for a catchment area higher than 150 m^2, the cistern capacity required to meet the demand in this region is the lowest among all seven homogeneous regions.

IV. CONCLUSIONS

Most of the population living in semi-arid regions of the world have lack of access to safe portable water, which is vital for the life' quality. The storage and use of rainwater represents the main and cheapest alternative of supplying water in these regions, and it has been implemented by several governmental programs in Brazil. Yet, the cistern projects currently adopted in the Brazilian semi-arid are unable to ensure enough water to meet the basic needs of a person (20 L/person/day; WHO), regardless of the high risks of health problems still associated with its consumption.

Therefore, the development of a curve representing the relationship between cistern capacity and catchment area, such that water supply is assured, provides feedback for decision-making, thereby benefiting the population and maximizing the return on the investment.

The behavior of the fitted curve reflects rainfall characteristics of each region within the semi-arid region, depending on both the annual precipitation volume and the variability of rainfall throughout the year.

In regions in which annual average precipitation is insufficient to ensure the total filling of the cistern at the end of the rainy season, increasing cistern capacity is found to be less efficient, if catchment area remains the same. In this case, larger catchment areas will enable not only the total filling of the cistern at the end of the rainy season, but also will ensure water recharge in the cistern during the dry season.

In regions having sufficient precipitation in the rainy season to ensure total filling of the cistern but marked with longer periods of drought, increasing the catchment area is found to be less efficient. Because affluent water into the cistern during the rainy season is enough to ensure its total filling and the water contribution in the dry season is less relevant for this condition, increasing the cistern capacity in this region is the best opition.

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