Rainwater harvesting system using alternative energy sources in climate change scenarios in the State of Parana – Brazil

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Abstract. The aim of the research was to evaluate a rainwater harvesting system for a single-family residence considering the current climate scenario and simulate it in different scenarios of possible climate changes projected towards the end of the century according to the IPCC Fifth Assessment Report to see if it will be influenced. The system was simulated for eight localities of the State of Parana, south of Brazil and for the climate scenarios simulations was used the PGECLIMA_R software. The system was composed by a reservoir dimensioned by the Azevedo Neto method mentioned in the Brazilian Rainwater Regulation (NBR 15527), and a water tank. It also had a hydraulic pump that was powered by photovoltaic solar energy. A series of 31 years of daily precipitation and solar radiation data was used to perform the calculation of the reservoir and solar photovoltaic system respectively. All localities showed the need of increase in the size of the reservoir until the end of the century to supply the non-potable water demand of the residence. This was evidenced by the rise of annual simulated rainfall regime. About the photovoltaic energy system, all localities showed that there is no need to change the number of panels to supply the energy demand from the hydraulic pump until the year of 2100.

1. Introduction

Water is one of the determining factors for life on the planet, once plants, animals and other living beings depend on its availability [1]. Thus, according to Souza et al (2016) [2], the scarcity of water nowadays is a worldwide problem that has intensified over time and one of the factors that contribute to it is the disordered use by the population [3].

In this context, the search for alternatives to save and reuse water becomes fundamental and a rainwater catchment for non-potable use is one of the possibilities that can be utilized. The usual rainwater harvesting system consists in a scaled reservoir in which water is pumped by an electric component. Thus, a sustainable system for catchment and distribution of this water has as a prerogative the use of a renewable and non-pollutant energy source.

According to Juan et al (2018) [4], solar energy is a great choice for clean energy generation, as it comes from an inexhaustible source and does not emit pollutants. Besides that, Oliveira, Souza and Silva (2018) [5] claim that implementing systems that use solar energy through photovoltaic panels minimize environmental impacts by promoting the conservation of the regional natural patrimony, as well, contributes to the reduction of electrical energy expenditure.
Both solar radiation and precipitation are climate elements and their environmental influences may impact on human activity. Therefore, with the advent of possible climate change caused by global warming [6], it is important that sustainable systems take into consideration climatic factors, which in the future may cause an adaptation of these systems.

Given this context, it is clear that the development of sustainable buildings using rainwater harvesting systems combined with clean energy generation contributes directly in reducing environmental degradation and can generate greater savings for the society. Moreover, researches that emphasize rainwater catchment in single-family residences are very useful in diffusing the idea for a better rationalization of regional water resources. Thus, this paper had as a main objective to evaluate a rainwater harvesting system using alternative energy sources involving climate change scenarios in the State of Parana – Brazil.

2. Materials and methods

For the research were used daily climate data of precipitation, air temperature (maximum and minimum) and global solar radiation of eight localities in the State of Parana (Table 1), collected from the Institute of Meteorology (INMET), whose historical series comprised a period of 31 years (1987-2017).

| ID | Locality     | Latitude (S) | Longitude (W) | Elevation (m) |
|----|--------------|--------------|---------------|---------------|
| L1 | Campo Mourão | -24°03’      | -52°22’       | 616           |
| L2 | Castro       | -24°47’      | -50°00’       | 1009          |
| L3 | Curitiba     | -25°26’      | -49°26’       | 924           |
| L4 | Irati        | -25°28’      | -50°38’       | 837           |
| L5 | Ivaí         | -25°00’      | -50°51’       | 808           |
| L6 | Londrina     | -23°19’      | -51°08’       | 566           |
| L7 | Maringá      | -23°24’      | -51°55’       | 542           |
| L8 | Paranaguá    | -25°32’      | -48°31’       | 5             |

The State of Parana is located in the southern region of Brazil, between the parallels 22°30’58” and 26°43’00” south latitude and between the meridians 48°05’37” and 54°37’08” west longitude (Figure 1). According to the Koppen classification, Parana has two types of climate: Cfa with high temperatures during summer and precipitation volume concentrated in the warmest months, with no defined drought period; and the Cfb type climate with cooler temperatures during summer.
For this research was adopted a single-family residence model that includes one kitchen, one bathroom, two bedrooms and a living room. The model was designed for a family of four members and a roof rainwater catchment area of 70 m² was defined.

For the reservoir sizing was used the Azevedo Neto method, which is mentioned in the Brazilian Rainwater Regulation (NBR 15527) [8]. This method considers in its calculation the accumulated annual precipitation and the driest period of the year, so that the reservoir volume is estimated through equation 1.

\[
V = 0.042 \times Pa \times A \times T
\]

Where:

- \(V\) = final volume reservoir (m³);
- \(Pa\) = accumulated annual precipitation;
- \(A\) = rainwater catchment area (m²);
- \(T\) = factor of the driest period of the year.

In this research, the factor for the driest period of the year (T) was calculated by the maximum number of rainless days of a given month, for each location, as adopted by Lima et al (2015) [9].

According to the demand for non-potable water used in the single-family residence, as specified by Tomaz (2005) [10], it was sized according to Barbosa et al (2017) [11], the hydraulic pump and the electricity consumption to pump the stored water from the reservoir for distribution in the residence. Based on the need of electricity to supply the hydraulic pump, the number of photovoltaic panels was determined, according to the methodology described in Marques et al (2012) [12]. The Figure 2 represents a schematic section of the proposed system.
Figure 2. Schematics of the rainwater harvesting system.

Three different climate scenarios were simulated for each of the eight locations as a function of the average global temperature increase, using the PGECLIMA_R Software [13]. This tool creates weather scenarios by simulating daily rainfall and air temperature. Given that solar radiation is a variable that will not change significantly until the end of the century (Sgarbossa, 2019) [7], this factor was not simulated.

Future climate scenarios were simulated until the year 2099. Two of the scenarios were based on possible climate change, taking into account the projections of the IPCC Fifth Assessment Report [6]. According to this report, there is a relation between rising air temperature and increasing levels of precipitation. This relation was also established by Pyke (2005) [14], who associated a 10% variation in the amount of precipitation for each varied degree Celsius.

Thus, the first simulated scenario (S1) considered a progressive monthly increase of 1.7 °C until the end of the century, that is the most optimistic scenario established by the IPCC, with a consequent increase of 17% in precipitation levels. In the second scenario (S2), with the worst perspective of IPCC, it was considered a monthly increase of 4.8 °C in the air temperature, what can lead to a 48% increase in precipitation levels by the end of the year 2099.

A third scenario (S3) was elaborated considering the trend analysis of the 31-year historical series of the selected locations. Although in a previous analysis using the Mann-Kendall Test [15] most of the months in the analyzed localities did not present statistically significant trends of temperature variation, an increase or decrease in air temperature was estimated by linear regression for each month and place, with consequent impact on precipitation levels, as in other scenarios.

The reservoirs were dimensioned based on the simulated data of scenarios projected through 2018-2039, 2040-2069 and 2070-2099. Graphics were elaborated to support the analysis.

3. Results and discussion
According to values used to forecast consumption of non-potable water as Tomaz (2005) [10], a daily demand of 293.8 liters was obtained, with a monthly total of 8.8 m³ for the residence, presented in Table 2. The value was close to that found by Costa (2016) [16] that used the same methodology to estimate the demand for a house. Moreover, Novakoski et al (2013) [17] indicates that a simple single-family residence has an average rainwater demand of approximately 9 m³ per month, which ratifies the
value found in this research. A 310 liters water tank that is commercially available can supply the daily rainwater demand of the home.

### Table 2. Calculation of rainwater demand.

| Description       | Daily Total (L) | Monthly Total (m³) |
|-------------------|-----------------|--------------------|
| Toilet flush      | 240.0           | 7.2                |
| Garden watering   | 17.3            | 0.5                |
| Sidewalk washing  | 16.5            | 0.5                |
| Car washing       | 20.0            | 0.6                |
| **TOTAL**         | **293.8**       | **8.8**            |

The value of daily rainwater demand was used to determine the more adequate model of hydraulic pump for the system, as in Barbosa et al. (2017) [11]. Thus, were identified three commercially available pump models that would be able to supply the building’s rainwater demand and their respective monthly average electricity consumption. The data is presented in Table 3.

### Table 3. Available hydraulic pumps.

| Hydraulic Pump | Power (W) | Energy Consumption (kWh/month) |
|----------------|-----------|--------------------------------|
| Model A        | 184.0     | 2.8                            |
| Model B        | 245.0     | 3.7                            |
| Model C        | 368.0     | 5.5                            |

The average annual precipitation of the historical period for the eight locations ranged from 1572 mm to 2310 mm. According to data, Castro is the driest location and Paranaguá the wettest because it is a coastal city.

According to simulations of the three future scenarios there is a tendency of an increase in the rainfall volume, as shown in Figure 3. However, the increase did not occur lineally over the period due to the great variability of precipitation, as stated by Costa (2016) [16]. Considering all selected locations, the most optimistic scenario (S1) showed a discreet increase compared to the most pessimistic scenario (S2). In the location of Castro the S1 presented 1761 mm, the lowest average of rainfall, while the S2 presented 2198 mm. In terms of highest precipitations, the S1 of Paranaguá presented 2561 mm and the S2 presented 3257 mm. The obtained data is in agreement with the historical averages calculated previously.

The S3 scenario was determined by linear regression and it showed in the simulation a varied increase in precipitation. For some localities the annual accumulation was above S1 while in others it was below S1, such as the case of Campo Mourão and Irati (Figures 3a and 3d). This fact refers to the regression estimation that happened in localities where there was a temperature rising in some months and a decrease in others. Thus, the average increase in temperature influences in rainfall frequency.

For this reason, the S3 scenario of Campo Mourão was very close to the historical of 1710 mm, since in the regression analysis a small increase in temperature was determined. On the other hand, the localities of Curitiba, Ivaí and Londrina (Figures 3c, 3e and 3f) presented a S3 very close to S2. So, it is possible to see that their verified trends show a greater change in temperature. None of the cities presented in S3 a result as pessimistic as evidenced in S2, showing that if a regional warming occurs, it will be closer to the most optimistic scenario of the IPCC.
Figure 3. Average annual accumulated precipitation and reservoir volumes.
According to the IPCC projection, in S1 there will be an increase of 1.7 °C by 2099 and as Pyke (2005) [14], this implies an increase of 17% in the rain. In the simulation performed by the PGECLIMA_R Software, for this scenario, increase percentages close to 17% were found, as shown in Figure 4, indicating the validity of the simulation.

In turn, S2 estimates the increase of 4.8 °C, determining an alteration of 48% in the precipitation. The simulation performed by the Software also obtained percentages close to the IPCC.

On the other hand, S3 presented a random trend with a varied percentage of increase in rainfall. The highest value was 41% for Curitiba and the lowest was 6% for Campo Mourão, which is explained by the higher and lower tendency of change in the calculated temperature, respectively.

With the annual accumulated precipitation average values presented above, the reservoir volumes were estimated by the Azevedo Neto method. Comparing the results from all localities, it is clear that the smallest reservoir volume considering the historical series was 3.4 m³ for the Castro locality, agreeing with the fact that it is historically the city with less precipitation and the largest volume was 4.5 m³ for Paranaguá, evidenced by the fact that it is the rainiest city.

Regarding the historic, all locations showed a need for an increase in the reservoir volume at the end of the century, as shown in Figure 3, but there was no evidence of a linear trend.

This is due to the fact that, according to the adopted method, the reservoir volume calculation is based on three direct variables: the rainwater catchment area, the accumulated annual precipitation and the factor of the driest period of the year. As in this research the first factor remained constant (being the roof area of 70 m²), the volume changed according to the last two variables mentioned.

In order to supply the demand for electricity required for the operation of the hydraulic pump, was dimensioned the necessary photovoltaic panels. For this, the “Model C” pump of Table 3 was chosen, as it is the highest power model. Thus, if there is an increase in rainwater demand up to certain parameters, the same pump can still supply the need. With this, a commercially available photovoltaic panel with a power of 54 W and an area of approximately 0.42 m² was chosen, as it is indicated for use in hydraulic pumping systems according to the manufacturer.

According to Marques et al (2012) [12], the calculation for the determination of photovoltaic panels take into account the historical average incidence of solar radiation and the energy consumption...
in question of 5.5 kWh/month. The Figure 5 shows the average global solar radiation of the months of the historical series and the average electricity generation through the panels. It can be noted that in all localities there was a decrease in the incidence of solar radiation in the coldest months (May, June, July and August) and the most evident increase in the hottest months (January, November and December) referring to the summer season, when the Sun’s rays intensify in the southern hemisphere, same result found by Sgarbossa (2019) [7]. The locality of Maringá presented the highest average radiation incidence, which was 5.1 kWh/m² and Paranaguá the lowest, of 3.8 kWh/m².

It is noticeable that electric power generation is directly related to solar radiation incidence, as evidenced by Gnoatto et al. (2008) [18]. Therefore, it is visible that warmer months present higher power generation, the direct opposite of colder months.

![Incidence of solar global radiation (Rg) and average electricity generation (Eg)](image)

**Figure 5.** Solar radiation incidence (Rg) and average electricity generation (Eg).
As shown in Figure 6, all localities presented a surplus in warmer months to supply the demand for electricity while in colder months there was a deficit. However, considering the annual average, there is an attendance percentage of approximately 98% for all localities.

Although this deficit exists in some periods of the year, the surplus values balance the months of low electricity production, because there is an energy compensation mechanism. This way, the photovoltaic system can be connected to the public grid (on-grid) and what is overproduced is transferred to the grid, generating credits for when the energy production is not enough to attend the demand. Thus, the system is weighted and does not generate extra expenses with electricity from the grid.

4. Conclusion
The objective of this paper was to evaluate a rainwater harvesting system that uses alternative energy sources. Considering the results obtained in the research it is clear that for an adequate dimensioning of reservoirs it is fundamental to take into account the influence of climate change. These changes may indicate the need to increase the volume of reservoirs and, by doing that, it is possible to ensure a longer system life and to provide greater savings to users by reducing water consumption from the public network.

It can also be reported that the estimation of the production of solar energy in function of the average incidence of radiation in the locality is an important aspect to consider the viability of installation of photovoltaic systems in residences. The State of Parana showed a great potential for the installation of a solar power generation system, since the percentage of attendance of the photovoltaic energy showed annual values of about 98% for all the localities.

In conclusion, a rainwater harvesting system combined with a photovoltaic system seems to be a good way to reduce environmental impacts. The rainwater harvesting contributes to reduce the use of potable water, mitigating the effects of scarcity - which has been accentuated over the years - and it can also provide greater savings for society.
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