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Impact of Domestic Water Demand Scenarios on Rainwater Harvesting System in the Andahuaylas City, Peru

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Abstract-This paper introduces a method for calculating the volume of storage tanks and analyzes demand scenarios within Rainwater Harvesting (RWH) systems. The water mass balance approach in a daily step-time was utilized to evaluate non-potable water demand across various residential rooftop areas in the city of Andahuaylas, Peru. The region is arid and experiences significant rainfall patterns during four months per year. The results demonstrated that for rooftop areas larger than 250 m^2, the demand can be fully met using commercial tanks larger than 1m^3. With system failures below 0.5%, it is possible to supply rooftop areas of 150 m^2 with a volume of 5m^3. These findings highlight crucial factors to be considered during the planning and design of RWH systems in the Andean regions of Peru.

***Keywords*:** Rainwater harvesting; daily water balance; storage tank size; demand scenarios

1. Introduction

As the urban population continues to rise and urban development proceeds without proper planning, freshwater resources are rapidly declining. Poor management of drinking water, attributed to various problems such as aging water infrastructure and water leakages, has imposed significant challenges on numerous water utilities as they endeavor to meet the regular demand for water [1]. An ancient technique called Rainwater Harvesting (RWH) for collecting and storing rainwater for self-supply in residential areas has emerged as part of an environmental sustainability trend. It is an alternative that allows for an increase in the water supply without the need to resort to new sources, and it could contribute to the reduction of situations of freshwater scarcity [2].

Rainwater collected from residential rooftops is unsuitable for drinking without treatment and is primarily intended for non-potable purposes, such as flushing toilets, laundry, vehicles washing, garden irrigation and landscaping [3]. In some countries, a process involving pre-filtration, filtration, and disinfection of rainwater has already been established as recommended in the standards [4]. The planning of the RWH system is influenced by a range of socioeconomic, environmental and technical factors, including the rainfall regime, rainwater quality, space availability, required demands and specific project criteria [5]. However, establishing a basic and generic recommendation for the size and configuration of rainwater storage systems remains challenging [3].

The RWH systems posses the potential to mitigate urban flood risk and water pollution, as seen in regions such as the Gulf Region, characterized by arid conditions with minimal annual rainfall yet occasional high-intensity rainfall episodes[6]. Additionally, a regionalization approach was utilized to develop design curves aiding the selection of suitable RWH system for specific location [7]. In a study documented in[8], an analysis was carried out to examine the effect of the current politics laws and regulations in South Korea influence the determining of storage tank sizes for RWH facilities, encompassing various water demand scenarios. In Peru, central government has implemented RWH systems in humid regions, including these systems with treatment construction projects in Amazon regions [9]. However, such initiatives are lacking in the Andean region. Our study aims to determine the necessary storage volume of rainwater harvesting system by considering diverse demand and rooftop area scenarios.

2. Data

2.1. Study area

The Andahuaylas city is situated in the southern region of Peru in the Apurímac department within the Andean region (Fig. 1). Covering an urban area of 10 km^2, it rests at an average altitude of 2926 meters above sea level. The climate is classified as Semiarid, characterize by dry winter, with temperatures ranging from 15° to 21° and an annual rainfall varying between 300 mm to 700 mm.

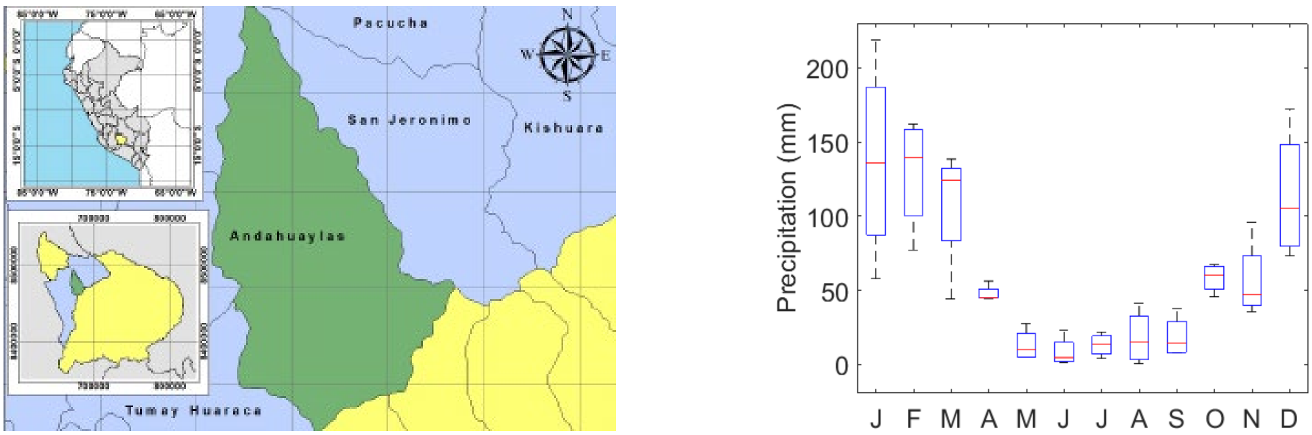


Fig. 1:Localization of the Andahuaylas city and monthly mean precipitation.

Daily precipitation data was extracted from gridded PISCO SENAMHI (Peruvian Interpolated Data of the SENAMHI's Climatological and Hydrological Observations) dataset for a period from 2015 to 2019. A single station point within the dataset was chosen to represent the delimited area. Additionally, Fig. 1 illustrates the monthly mean precipitation, depicting considerable temporal variability. The period from April to November are recognized as the dry season, while the months from December to April are identified as the wet season.

2.2. Determination of demand

According to the *Instituto Nacional de Estadística e Informática* (INEI) of 2017, the Andahuaylas city has an average of 4 inhabitants per household. In accordance with the guidelines set by the World Health Organization (WHO) for basic needs, the average total domestic water usage was is established to rangue 50 to 100 liters per inhabitant per day. For the purpose of calculations, a conservative value of 100 liters per inhabitant per day was adopted, resulting in a total water demand of 400 liters per day per household.

Considering the consumption patterns of Andahuaylas inhabitants, it is estimated that 20% of the total domestic water volume is used for potable purposes, while the remaining 80% is allocated for non-potable uses, including toilet flushing, garden irrigation, car washing and cleaning external areas, totalling an estimated 320 liters per day for non-potable uses.

3. Methodology

The water mass balance approach was adopted to calculate the storage tank capacity. The inflow volume to the tank was determined using Eq (1), which requires input data such as rainfall, rooftop area, and runoff coefficient:

$$V_t = \frac{P_t . C . A}{1000} \quad (1)$$

where, V_t is the inflow volume to tank (m^3) at time step t (day); P_t is the rainfall (mm); A is the rooftop superficial area in (m^2) and C is the rooftop runoff coefficient. Subsequently, storage over at time of the RWH system is calculate, considering the Equation 2 based on water mass balance model subject condition that storage is positive value.

$$S_t = S_{t-1} + Q_t - D_t \tag{2}$$
$$\text{Subject to } 0 \leq S_t \leq S \tag{3}$$

where, S_{t-1} is the final storage (m^3) in the tank at time step $t-1$; S_t is the storage in the tank (m^3) at time step t; D_t is the demand (m^3) at time step t; S is the storage tank capacity (m^3) in the tank. The losses due to evaporation were considered negligible. The storage tank is full in the first step time.
The procedure to determine storage tank capacity (S) is considering that the total demand is fully met and no service failures occur. The initial value for the storage tank capacity (S) is assumed. The following is the procedure for calculation tank capacity for each time step daily :

- Define the daily records of non-potable water demand.
- Calculate the inflow volume (m^3) to the tank from the rainfall depth over rooftop, following the Eq (1).
- Calculate the storage in the tank following the Eq. (2).
- Calculate el storage tank capacity (S) by trial and error process, here Solver Excel was used.

The failure was chosen as an indicator to compare the results between scenarios throughout the simulations when the capacity of the storage tank is known and constant. It could also indicate the guarantee of rainwater supply in a household.

$$\text{Failure} = \left(\frac{\sum_{i=1}^{nf} f_i}{N_t}\right) \times 100\% \tag{4}$$

where f is value of 1 when storage is equal to zero, N_t is the total number of simulation, in this case is 1826 days.

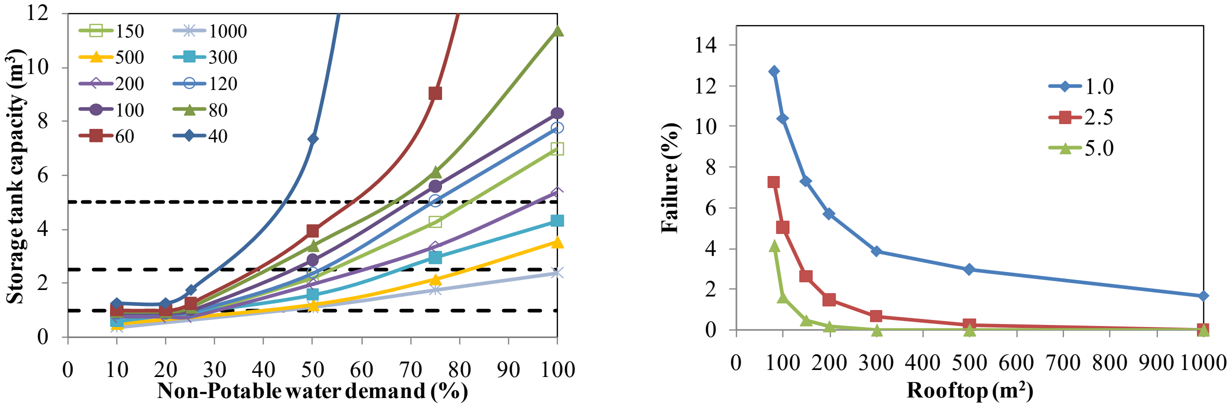
4. Results

The Table 1 shows the necessary values for the scenarios in order to obtain the storage tank capacity for an average household in the city of Andahuaylas. The daily demand for the months from April to November was considered as 5% of the non-potable daily demand. For the months from December to March, the demands vary between 10% to 100% of the non-potable daily demand. Rooftop areas vary from 40 m2 to 1000 m2 and the runoff coefficient is 0.95, where the material is corrugated iron with slope. Although the roof area of a typical house varies between 80 to 150 m2, larger areas were included to observe the potential storage capacity.

Table 1:Parameters of simulation for calculation of storage tank capacity and failure of system.

Description	Values	Unit
Demand water per house	400	liters.d^{-1}
Demand water potable per house	80	liters.d^{-1}
Demand water non-potable per house	320	liters.d^{-1}
Runoff coefficient	0.95	-
Non-Potable demand for dry period	5	%
Non-Potable demand for humid period	10, 20, 25, 50, 75, 100	%
Rooftop areas	40, 60, 80,100, 120, 150, 200, 300, 500, 1000	m^2

The Fig. 2(a) shows the results of the storage tank capacity based on the non-potable water demand and the roof area. It also displays three horizontal lines indicating three of the commercial tank volumes available in the market, which are 1.0, 2.5, and 5.0 m3. From the results, it is observed that when the demand is less than 25%, the tank capacities range from 0.6 m3 to 1.75 m3. For a 50% demand, roofs larger than 60 m2 have capacities ranging from 1.19 m3 to 3.92 m3. At 75% demand, roofs greater than 120 m2 have capacities ranging from 2.16 m3 to 5.03 m3. Finally, at 100% demand, roofs larger than 300 m2 have capacities ranging from 2.38 m3 to 4.3 m3.The Fig. 2(b) shows system failure based on roof area for three sizes of commercial volume considering a 100% non-potable demand for humid period. This figure shows that failures exceed 1.7% for a 1 m^3 volume for roof areas. However, for volumes of 2.5 m^3 and 5 m^3, the system shows no failures for roof areas larger than 500 m^2. For these two volumes, areas smaller than 500 m^2, the failures increase to 7.28% and to4.16% for 2.5 m3 and 5 m3, respectively. The Fig. 3 shows the system failure based on various scenarios of non-potable water demand for commercial tank volumes of 1.0, 2.5 and 5.0 m^3. The figure demonstrates that there is no system failure for demands below 20%, 40%, and 60% for the volumes of 1m^3, 2.5m^3, and 5m^3, respectively. The total simulation period is five years equivalent to 1826 days, the failure rate of 0.5% equal to 9 days in the system not supplying water is limit. Based on this criterion, roof areas larger than 500 m^{2}and 150 m^{2}could store 2.5 m^{3}and 5m^3, respectively.



(a) (b)

Fig. 2:Storage tank capacity in function of non-potable water demand in percentage.

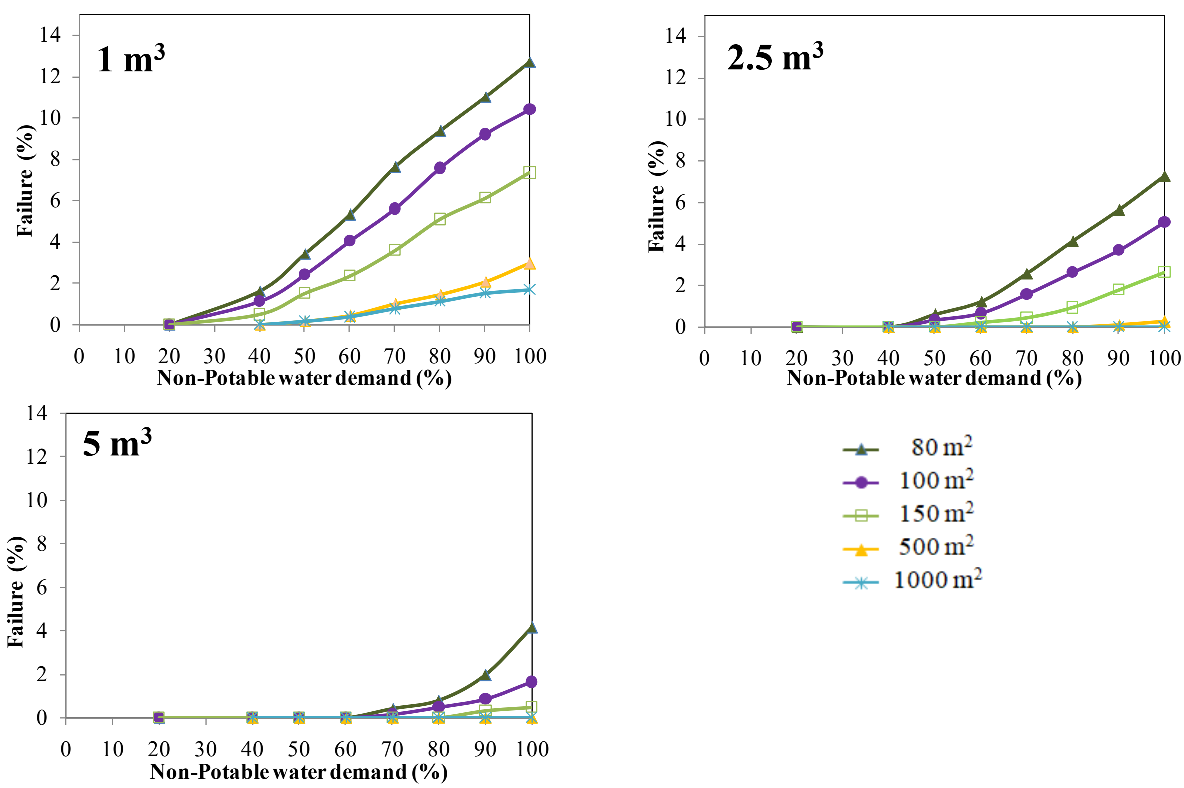


Fig. 3: Failure of system in function of non-potable water demand in percentage and roof area.

5. Conclusion

This paper aims to analyze various scenarios of non-potable water demand for humid period and household roof areas to collect rainwater in the city of Andahuaylas, Peru. To supply demand, the required storage tank capacities were viable for commercial volumes of $1m^3$, $2.5m^3$, and $5m^3$, provided that the roof areas were larger than 250 m^2. However, roof typical areas in the region are less than 150 m^2, in which case only 80% of the non-potable water demand can be supply. For failures below 0.5% are tolerable, tanks with capacities of $2.5m^3$ and $5m^3$ supply for roof areas larger than 500 m^2 and 150 m^2, respectively. For typical households, it's feasible to supply with $5m^3$ tanks for 150 m^2 areas. These results rely on rainfall patterns of Andahuaylas city. The findings of this study can be fundamental for future projects and strategies concerning rainwater harvesting in other regions of Peru. This research contributes to sustainable water management by promoting the efficient utilization of alternative water resources and advocating for reduced dependence on traditional water sources in the city of Andahuaylas

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