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Optimizing Storage Tank Size for Improved Reliability of Roof Rainwater Harvesting Systems: The Case of Goba Ward, Dar es Salaam

Joel Nobert[*]

Abstract

Residents in most parts of Dar es Salaam experience challenges in trying to get a stable supply of water. Roof-based rainwater harvesting has found a widespread adoption as one of the alternative sources to reduce water shortage in households, and has been used in sustainable urban drainage system, due to its effectiveness in dampening flood risks. However, most of the existing rainwater harvesting systems are not tailored to household requirements; instead they are built based on the availability of space and one's financial capability. This article analyses the reliability of the existing rainwater harvesting systems in Goba Ward, Dar es Salaam, using a daily water balance model. The article also evaluates the required optimum storage needed to meet a certain demand for the existing roof area and rainfall characteristics. Existing tank capacities, roof areas, and household size were obtained through a household survey. The study results show that the existing storage capacities are underestimated and, in some cases, overestimated compared to the simulated optimum storage; thereby resulting in performance inefficiencies. The methodology to determine the optimum size of the storage tanks was suggested by considering daily demand, roof area, and reliability desired; thus providing a usable tool to enhance design systems while considering local climate. The study recommends the development of standardized guidelines for optimizing rainwater harvesting storage capacity based on local rainfall variability, roof catchment area, and household water demand conditions.

Keywords: *roof rainwater harvesting, daily water balance, reliability and optimum storage*

1. Introduction

Rainwater harvesting (RWH) is widely recognized as an effective method for managing water and a valuable alternative source of water supply, especially considering the increasing demand for water, population growth, urbanization, and climate variability (Fulazzaky et al., 2022; Ndiritu et al., 2017; Liuzzo et al., 2016; Preeti & Rahman, 2021; Male & Kennedy, 2006; Dao et al., 2021). Rainwater harvesting involves collecting rainfall to satisfy various water needs in urban and rural areas. It provides benefits such as reducing a building's dependence on centralized water supplies, and lowering water bills (Kim et al., 2021; Ndiritu et al., 2017). RWH systems also help to manage storm water, save energy, and reduce the carbon footprint; thereby promoting greater independence from centralized water supplies (Kim et al., 2021; Ndiritu et al., 2017; Fulazzaky et al., 2022).

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[*] College of Engineering and Technology, University of Dar es Salaam: jknobert@gmail.com

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The most common RWH systems involve collecting rainwater from rooftops, which typically requires minimal treatment; and consists of a collection area (usually a roof), a conveyance system (gutters and downspouts), and a storage tank (Kim et al., 2021; Ndiritu et al., 2017; Liuzzo et al., 2016). The storage tank is consistently identified as the most expensive and critical component of an RWH system, as its proper sizing directly impacts the system's performance, user acceptance, and overall reliability (Khan et al., 2017; Imteaz & Shadeed, 2022).

Reliability is a crucial performance indicator for RWH systems, reflecting how consistently a system can meet a specified water demand (Lawrence & Lopes, 2016). Reliability can be expressed either as volumetric reliability, which is the ratio of the total water supplied to the total water demand; or as time reliability, which indicates the fraction of time during which the demand is fully met (Imteaz et al., 2012; Ndiritu et al., 2017; Islam et al., 2021). The performance and reliability of an RWH system are significantly influenced by various factors; including local rainfall patterns, roof area and characteristics, water demand scenarios, household size, and storage tank capacity (Liuzzo et al., 2016; Taffere et al., 2016; Kim et al., 2021; Ndiritu et al., 2017; Molaei et al., 2020).

Given that identifying an optimal storage size for an RWH system is highly dependent on specific geographic, climatic, and demand conditions, there is a continuous need for robust reliability analyses and design optimizations (Kim et al., 2021; Molaei et al., 2020; Lawrence & Lopes, 2016; Imteaz & Shadeed, 2022). Studies have shown that while increasing tank size generally improves reliability, there is often an 'operational threshold' beyond which further increases in tank size yield minimal additional benefits (Lawrence & Lopes, 2016; Imteaz et al., 2012; Molaei et al., 2020; Kim et al., 2021). This necessitates accurate estimation methods, such as daily water balance models, to avoid oversize tanks; which can be costly and impractical, especially in urban areas with limited space (Kim et al., 2021; Lawrence & Lopes, 2016; Imteaz et al., 2012; Preeti & Rahman, 2021; Imteaz & Shadeed, 2022).

Residents of Goba who have installed rooftop rainwater harvesting systems have done so based on personal experience, available space, and financial capacity. However, these installations have been made without technical guidance, which is essential for determining the optimal storage capacity of the systems. Key factors such as rainfall patterns and the surface area of the catchment (the roof) have not adequately been considered.

Although previous studies have examined the potential of RWH systems and storage tank sizing, the studies have primarily focused on estimating harvesting potential and determining required storage capacities under generalized conditions. Limited research has been conducted in the region on optimizing storage capacity by integrating key influencing factors such as rainfall variability, roof characteristics, household water demand, and system reliability. In addition, there is still a lack of practical and systematic approaches for determining optimal storage capacity that balances reliability and performance under local conditions. This study covers three main components. First, it presents the water demand analysis for the selected roof rainwater harvesting system. Second, it evaluates the reliability of the existing storage system under varying rainfall and domestic water demand conditions using a daily water balance method. Finally, the study determines the optimized storage capacity required to improve system performance and reliability.

2. Theoretical Perspective

This study is informed by the socio-hydrological theoretical perspective proposed by Sivapalan et al. (2012), which recognizes the dynamic feedback and co-evolution between human societies and hydrological systems. The concept recognizes that water availability, infrastructure performance, and human water demand continuously influence each other under changing climatic and socio-economic conditions. The study operationalizes the concept by integrating rainfall characteristics, roof catchment area, household water demand, and storage tank capacity to assess the reliability of existing RWH systems under varying climate and demand conditions, and optimizing storage capacity.

3. Methodology

3.1 Study Area

Goba is an administrative ward in Ubungo District, Dar es Salaam Region, Tanzania. The ward is located at latitude 6° 44′ 26″ South and longitude 39° 9′ 40″North (Figure 1), and at an elevation of 100m above mean sea level.

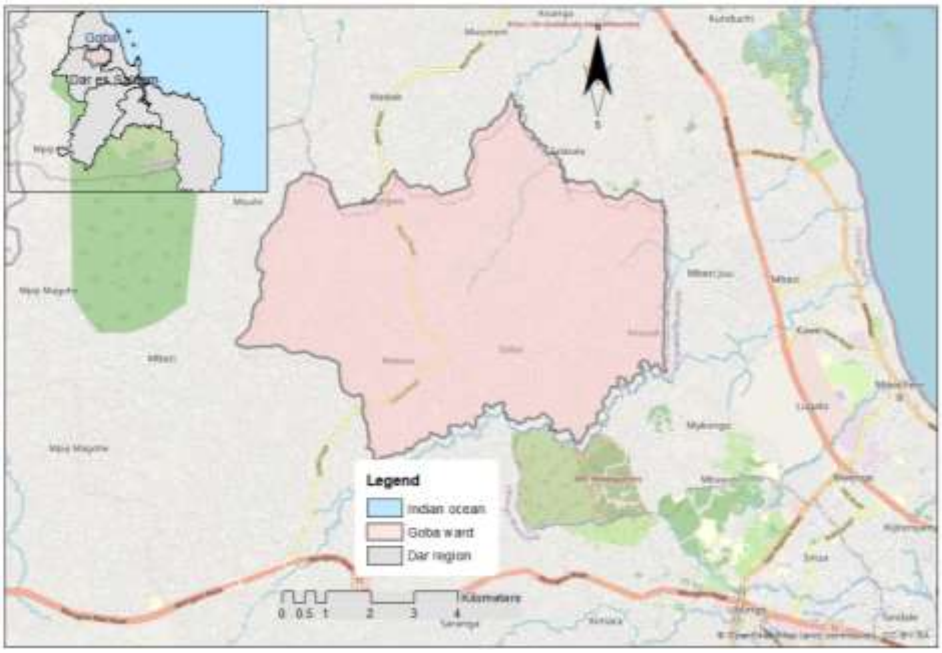

Figure 1: Location Map of Goba Ward in Dar es Salaam, Tanzania

Dar es Salaam experiences bimodal rainfall distribution (Figure 2). The long rains occur from March to May, with April recording the highest rainfall of over 220mm. This is followed by a dry period from June to September. The short rains occur from October to December, with rainfall gradually increasing and peaking in December. The mean annual rainfall is about 1030mm.

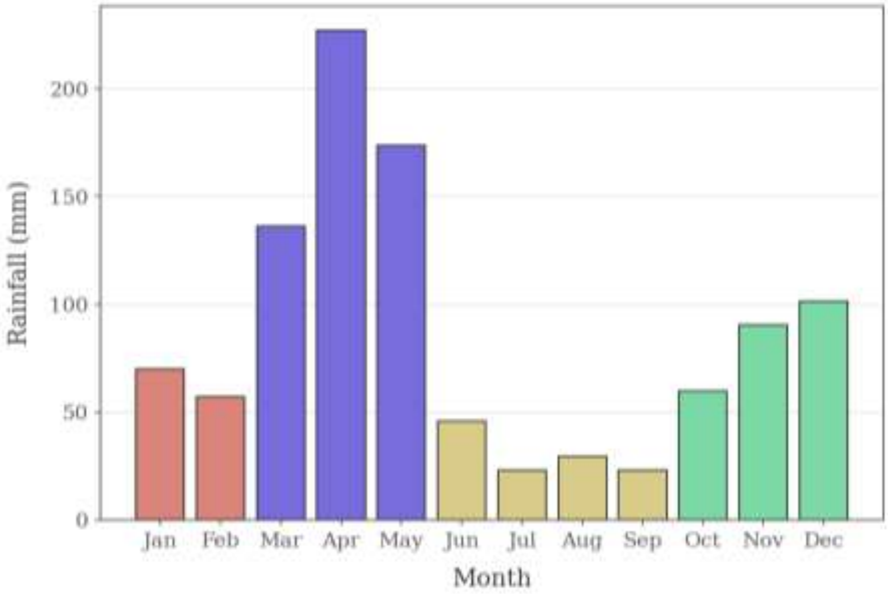

Figure 2: Mean Monthly Rainfall for UDSM Station (1976–2008)

3.2 Data Source

The primary data were collected through household survey questionnaires. and included roof catchment area, existing storage tank capacity, and household size. The existing storage capacity data were necessary for assessing the reliability and performance of the current RWH systems. The household size data were used to estimate domestic water demand based on per capita water demand values. These data were essential for evaluating the adequacy of existing storage systems, and for optimizing storage tank capacity under varying rainfall and household demand conditions. The sample size was determined using a standard formula for estimating proportions in a population (Kothari, 2004); which is expressed as:

$$n = \frac{Z^2.p.q}{e^2}$$

Where: n = minimum required sample size, z =standard normal deviate at the desired confidence level, p = estimated proportion of population possessing the characteristic of interest, $q = 1 - p$ = proportion of the population without the characteristic, and e = acceptable margin of error.

A 90% confidence interval was adopted to allow for a smaller and more manageable sample size, which is appropriate for exploratory or baseline assessments and acceptable error level of 10%, leading to a sample size of about 50 households.

The roof areas for each household were estimated from Google Earth Pro. The daily water demand was estimated based on per capita water demand as per DCOM Ministry of Water, 2020. The rainfall data used for the analysis were obtained from the University of Dar es Salaam weather station. The summary of data used for the analysis is as shown in Table 1.

Table 1: Data Used for the Analysis and Sources

S/N	Data required for analysis	Data source
1	Daily rainfall data	University of Dar es Salaam (UDSM) meteorological station
2	Existing storage capacity for each household	Survey questionnaire
3	Household population	Survey questionnaire
4	Roof area of each household	Google Earth Pro
5	Total daily water demand for each household	Estimated based on per capita water demands as per DCOM Ministry of Water

3.3 Water Balance Simulation

Figure 3 shows the key components of an RWH system and its water balance.

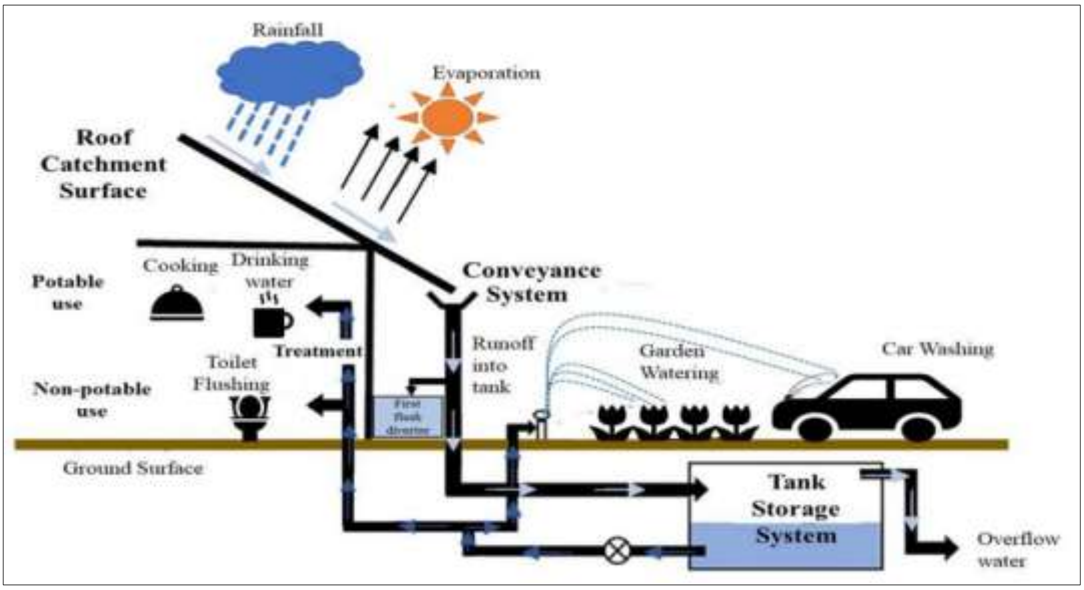

Figure 3: Underground Rainwater Harvesting System

Source: Zabidi et al. (2020)

As Figure 3 shows, rainfall is collected from the roof catchment area, and conveyed through a system that includes a first flush diverter to remove initial contaminants. The harvested water is stored in a storage tank, which determines the system's capacity to retain water for later use. The stored rainwater is used for both potable purposes (e.g., drinking and cooking after treatment); and non-potable uses (e.g., toilet flushing, garden irrigation, and car washing).

A spreadsheet-based daily water balance model was developed considering daily rainfall, contributing catchment (roof) area, storage (tank) volume, and water uses. At each time-step, the roof runoff during the time-step is added to the volume of the water in the tank; and then user consumption and overflow is subtracted. Equation 1 shows the simulation of daily water balance for a tank:

$$V_t = V_{t-1} + Q_t - D_t - O_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where: V_t is the cumulative volume of water in the tank at present, V_{t-1} is the cumulative volume of the water in the tank that remained from the previous time-step, Q_t is the rainwater captured at present, D_t is the total consumption per day, and O_t is the outlet overflow volume from the tank.

If $V_t \leq 0$, then $Q_t = 0$; if $V_t > 0$, then the water supply is limited by the cumulative water stored and inflow quantity in the tank. If $V_t \geq V_s$, then the tank is full and there is overflow from the tank.

Generally, the equation used is:

$$0 \leq V_t = V_{t-1} + Q_t - D_t < V_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: V_s is the storage capacity of the tank.

Q_t was calculated through the following formula:

$$Q_t = C \times R_t \times A \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where: C is the runoff coefficient, R_t is the average daily rainfall, and A is the catchment area (roof).

Reliability of Rainwater Harvesting

The reliability of rainwater harvesting is a crucial performance indicator. For this study, the reliability of a rainwater harvesting system was evaluated using time-based reliability.

$$\text{Reliability} = \left(1 - \frac{\text{sum of all failure days}}{\text{total number of days in the simulation period}}\right) \times 100\% \ \ldots\ldots\ldots (4)$$

3.4 *Optimum Storage Capacity*

The optimal storage tank capacities for the existing rainwater harvesting systems were determined using a daily water balance model, taking into account prevailing climatic conditions. The model incorporated key variables, including daily water consumption, roof catchment area, catchment permeability represented by the runoff coefficient, and the existing storage volume. Daily water balance models were widely adopted due to their accuracy and conservative analysis results (Kim et al., 2021).

The optimal capacity for the existing rainwater harvesting system was determined through a trial-and-error approach, whereby the storage volume was progressively adjusted while monitoring changes in system reliability. This process continued until further increases in storage volume no longer resulted in improvements in reliability; indicating that the system had reached its maximum achievable performance. The resulting optimal storage capacity thus represents the minimum volume required for the system to operate at its highest efficiency under the prevailing climatic conditions.

3.5 *Sizing of Optimum Storage Capacity for a Particular Geographical Location*

A proper estimation of the required storage capacity is crucial for designing an efficient rainwater harvesting system, especially considering the associated storage costs. For any given geographical location, it is important to generate a summary graph that relates rainfall, water consumption, and required storage capacity (van der Zaag, 2000). This approach allows for a comparative assessment and optimization of storage tanks based on household water use and roof size for a given geographical location with known rainfall patterns. This graphical representation includes the Relative Water Consumption (RWC) on the horizontal axis, expressed in millimetres (mm) of water layer per day; and the Relative Storage Capacity (RSC) on the vertical axis, also expressed in millimetres (mm) of water layer. The RWC is calculated as the daily water consumption divided by the roof catchment area:

$$RWC = \frac{Q}{A}$$

Where: RWC = relative water consumption (mm/day), Q is daily water consumption (litres/day), and A is roof area (m^2). It is noteworthy that since 1mm of water over $1m^2$ equals 1 litre, this formula expresses daily water consumption in terms of water depth over the catchment area.

The relative storage capacity (RSC) is defined as the ratio of storage volume to the roof area:

$$RSC = \frac{S}{A}$$

Where: RSC is relative storage capacity (mm), S is the storage capacity in litres, and A is the roof area in m^2.

The study employed quantitative data because the analysis required numerical assessment of rainfall harvesting potential, household water demand, storage capacity, and system reliability. The quantitative data enabled objective measurements and comparisons of variables such as roof area, storage volume, household size, and estimated water demand, which were necessary for conducting reliability analysis and storage optimization. The quantitative approach focused mainly on measurable variables and numerical relationships, which may overlook social and behavioural factors affecting water use and storage decisions.

4. Results and Discussion

4.1 Existing Storage Tanks

The relationship between roof catchment area and storage capacity is as shown in Figure 4, indicating the extent to which roof area influences storage capacity. Figure 5 shows the relationship between storage capacity, household size, and roof area. The correlation analysis shows that storage tank capacity has a very weak correlation with both roof area (r = 0.08) and daily water demand (r = 0.15) (Figures 6–7). These findings suggest that the sizing of storage tanks among most households is not driven by technical design considerations such as available catchment area, anticipated water demand, or climatic conditions. Instead, it is likely that storage decisions are predominantly influenced by practical constraints, including available physical space and financial capacity.

Taffere et al. (2016) noted that traditional RWH systems in semi-arid Mekelle, Ethiopia, were unreliable partly because their designs underestimated daily water demand and household size. This finding is also supported by Kim et al. (2021), who pointed out that the optimal storage size for RWH systems depends on factors such as water demand, climatic conditions, and existing infrastructure.

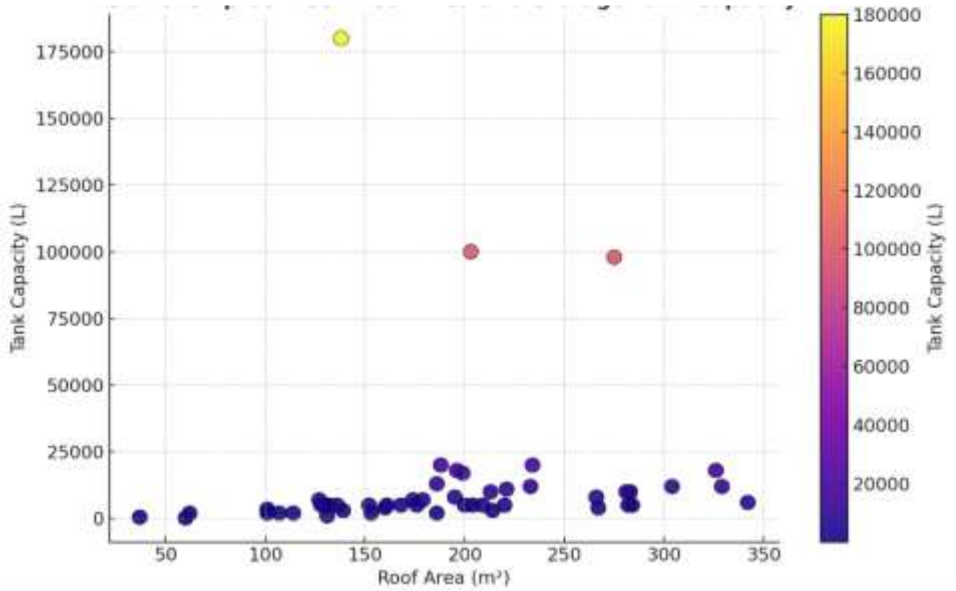

Figure 4: Relationship between Storage Tank Capacity and Roof Area

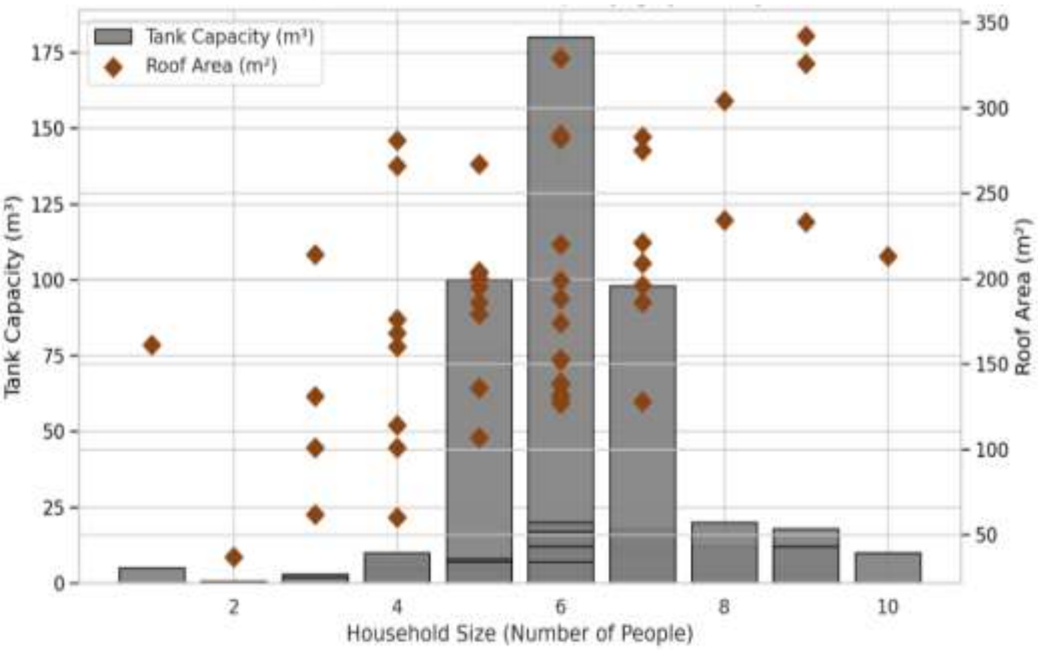

Figure 5: Roof Area and Storage Capacity by Household

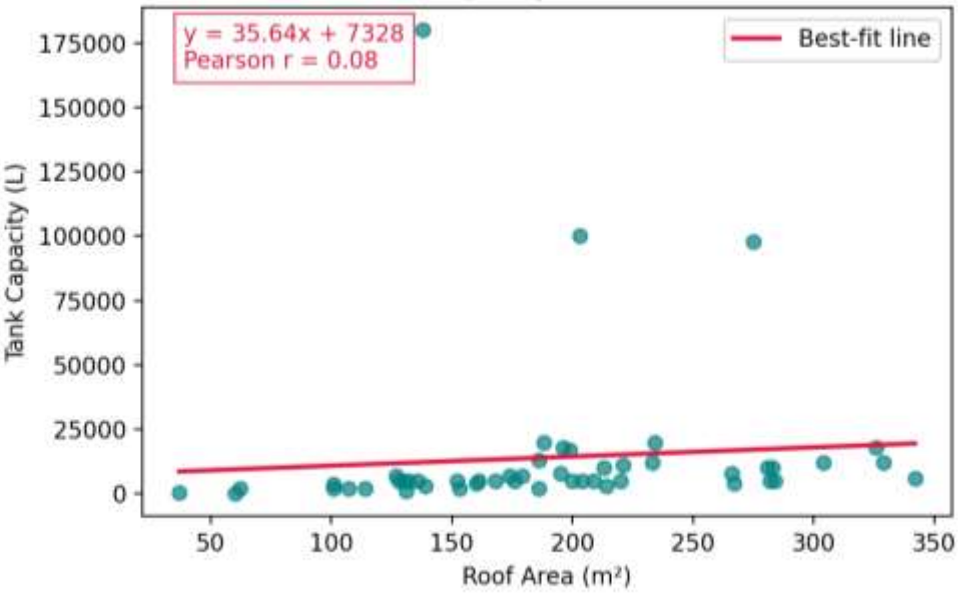

Figure 6: Correlation between Storage Capacity and Roof Area

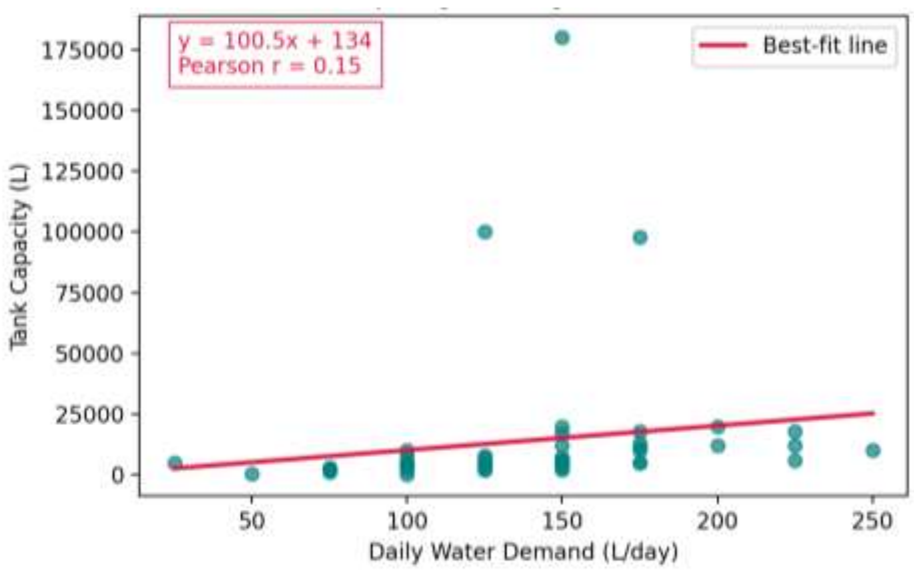

Figure 7: **Correlation between Existing Storage Capacity and Water Demand**

Figure 8 illustrates the reliability of existing storage capacities. Households that achieved high reliability (above 80%) typically had large storage tanks relative to their water consumption, along with spacious roof areas that enhanced rainwater collection. The lowest reliability recorded was 17.7%; which was associated with a household that had a daily demand of 100 litres but only a 200-litre tank, and a small roof area of 60m². Similarly, Tafere et al. (2016) noted that the size and characteristics of a catchment area, such as the roof, are crucial for the quantity of collected water. Generally, larger roof areas lead to greater rainwater capture and storage (Imteaz et al., 2022).

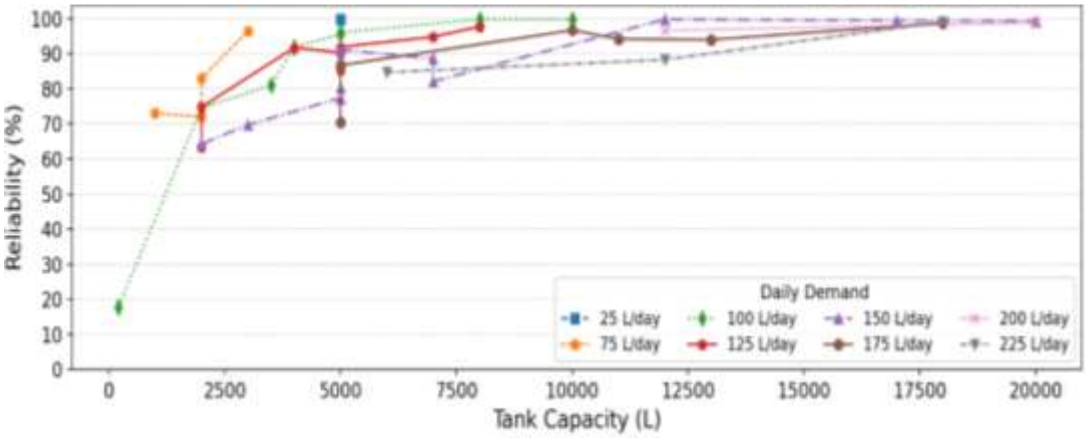

Figure 8: **Reliability of Existing Storage Tanks**

4.2 Optimum Storage Capacity

The comparison between existing and simulated optimum storage capacities for varying daily water demand levels shows significant differences for a given roof area (Figure 9).

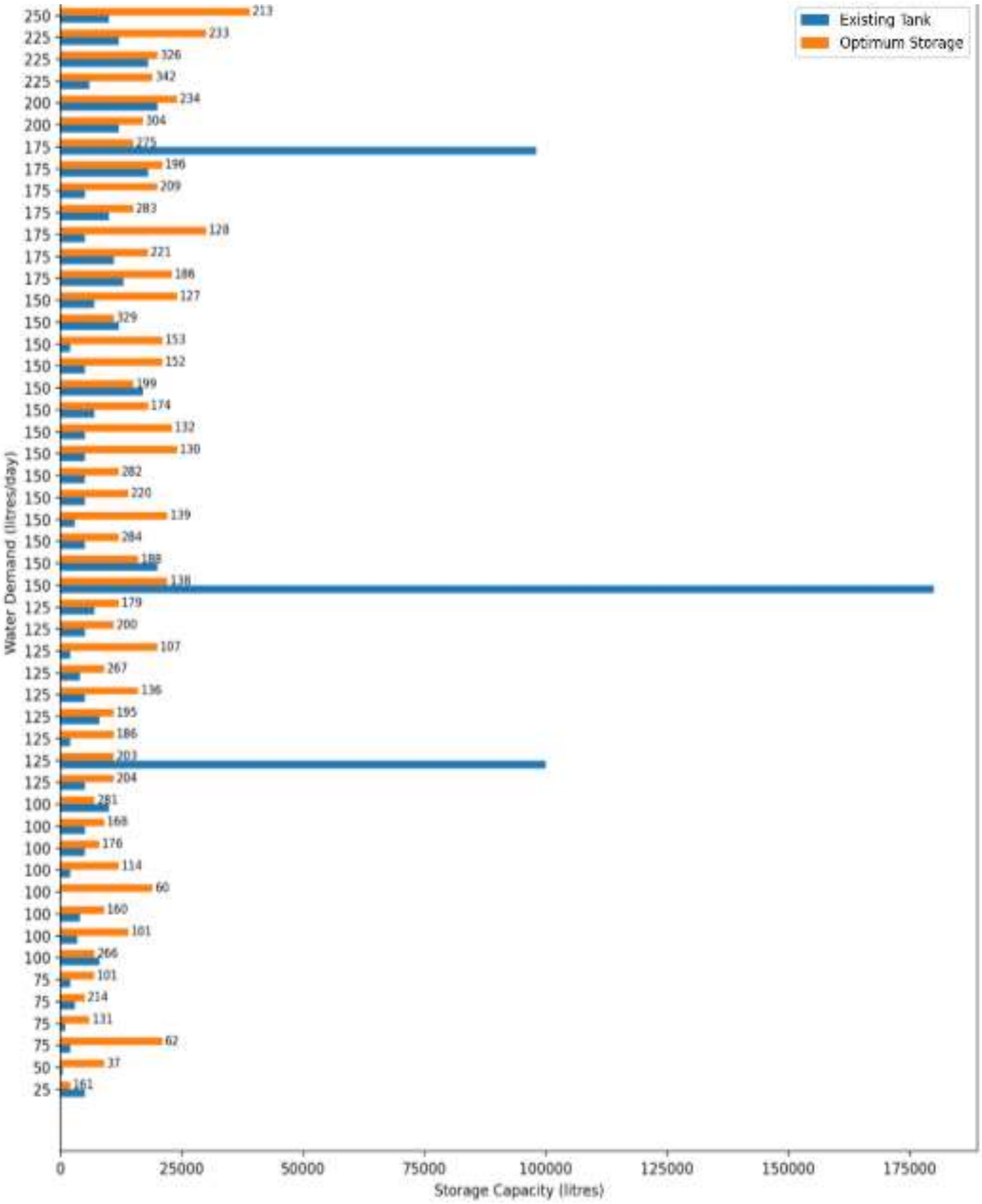

Figure 9: Comparison of Existing and Optimum Storage Tanks for Different

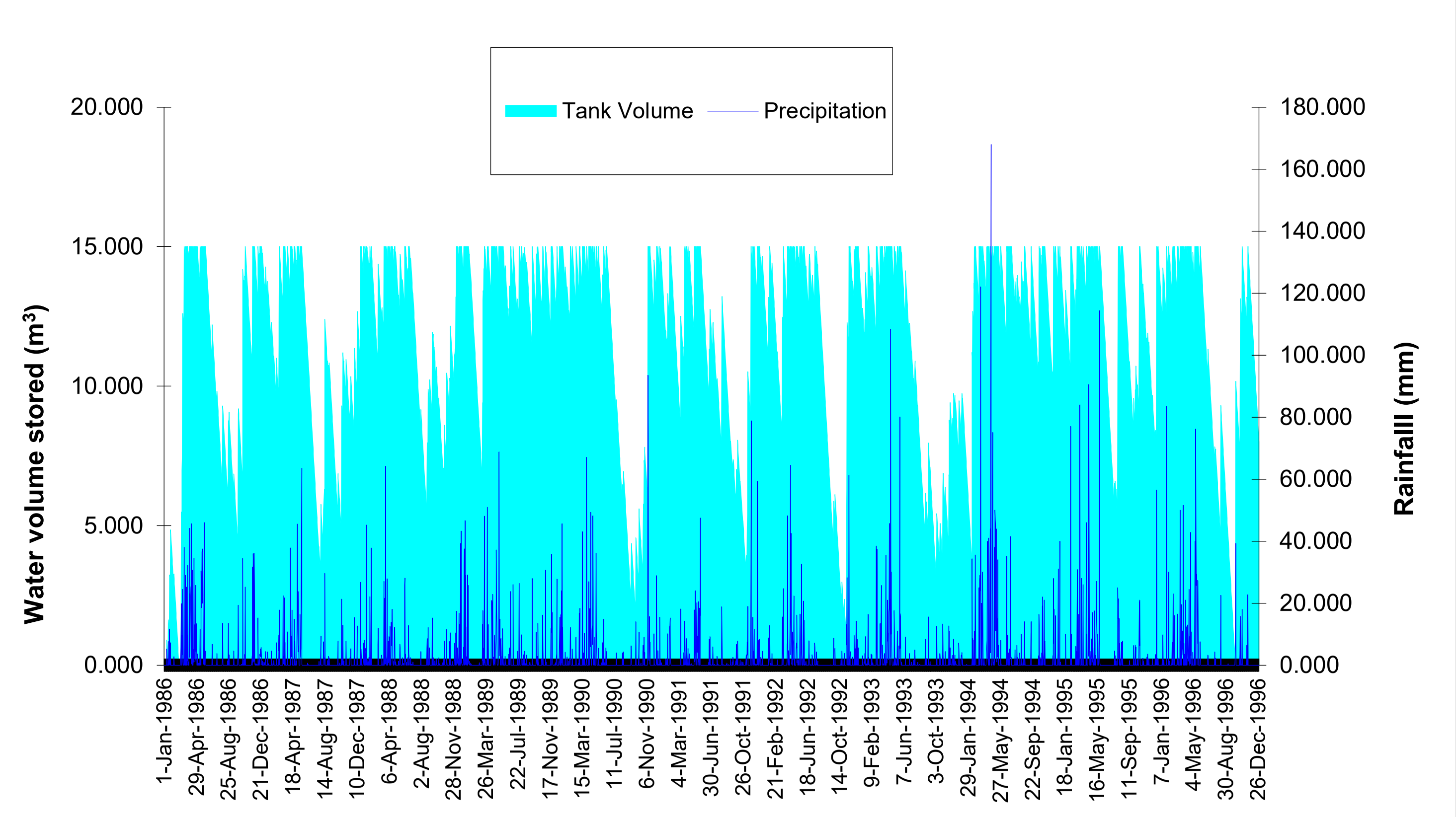

Figure 10: The Plot of Rainfall and Simulated Water Storage

While optimum storage capacities increase proportionally with demand to ensure high reliability, the capacities of existing household storage tanks do not follow this trend; they often fall short or, in some cases, exceed requirements without added benefits. This difference suggests that many existing systems were not designed based on water balance assessment. The simulation results show that optimal storage sizing must consider not only household water demand, but also the existing catchment area (roof size) and prevailing rainfall characteristics. Integrating these factors through simulation-based analysis ensures more reliable, efficient, and climate-responsive rainwater harvesting system designs.

This aligns with the research conducted by Kim et al. (2021), which emphasizes that the ideal storage capacity is significantly influenced by factors such as water demand, seasonal variations, financial considerations, and the available infrastructure in a specific geographical area. Figure 10 presents the results of a water balance analysis conducted for a household with a daily water consumption of 175 litres, and a catchment area of 275m^2. The simulation aimed to evaluate the effectiveness of an RWH system using historical rainfall data, and to maximize its benefits by incrementally adjusting the storage capacity until no additional benefits were gained. The analysis determined that the optimal storage capacity was 15m^3 (15,000 litres). With this capacity, a system achieved a reliability level of 99.6%; indicating that, on average, each household had access to water 99.6% of the days during the simulation period.

4.3 Storages Capacity and Reliability

Figure 11 illustrates the relationship between relative water consumption (RWC) and relative storage capacity (RSC) at various levels of a system reliability.

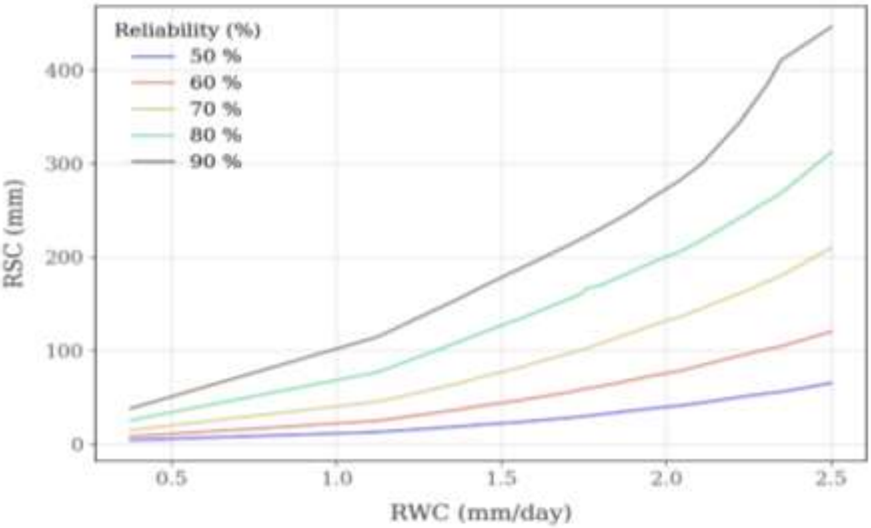

Figure 11: Relative Storage Capacity and Relative Water Consumption for Different Reliability Levels

The current practice of sizing tanks based on available space and financial capacity—rather than considering household demand, catchment area (such as the roof), and rainfall characteristics—often results in systems that are inefficient and underperforming. Thus the methodology developed in this study for optimal storage sizing enhances rainwater harvesting design. The study recommends the development of standardized guidelines for optimizing rainwater harvesting storage capacity based on local rainfall variability and household water demand conditions.

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