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Assessing reliability and rainfall reduction of a rainwater harvesting system in Metro Manila's rail infrastructure

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Abstract. Rainwater harvesting is explored as a potential aid in supplementing both water supply and stormwater management in urban public spaces. LRT-1 Doroteo Jose Station in Manila, Philippines was selected as the study area given the presence of large roof catchment areas, high passenger demand, as well as medium to high flood risk and history. The storage component is designed by employing mass balance calculations using rainfall data, roof parameters, and water consumption data. YAS Algorithm was performed for four design cases corresponding to 1-, 5-, 10-, and 15-year design periods along with full station roof use. User-defined performance indicators are employed to evaluate tank performance, namely reliability and rainfall reduction. The optimal tank storage capacity was calculated at about 20 to 30 cubic meters when the entire station roof area of 2,887.26 square meters is used. Reliability is at 53% to 58%, rainfall reduction is at 74% to 75%, and overall performance is at 64% to 67% for the designed system.

1 Introduction

Rainwater harvesting (RWH) is the process of collecting rainwater over a roof surface to be stored for future use. It involves components such as the roof catchment, the pipe conveyance system, and the storage tank among others. RWH can be traced back to pre-historic times when small jars with a sand filter were used for washing and cleaning. Larger wells were eventually built to collect rainwater for flood control and water supply during seasonal variations [1].

In 2013, Necesito et al. explored rainwater harvesting applications in Metro Manila, where it is mostly practiced for non-potable uses such as gardening and toilet flushing [2]. Aside from aiding the water supply from Angat Dam and supplementing groundwater recharge, RWH has the potential for reducing urban floods. Lagmay et al. (2017) studied several flood-prone areas in Metro Manila and identified that they are typically in locations of low topography where streets and creeks intersect [3]. Among these places, Taft Avenue and Rizal Avenue are where LRT-1 is situated. The railway stations provide

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large available roof catchment areas where RWH can potentially be practiced. Doroteo Jose Station is primarily selected as the study area given its flood risk and high water demand from passenger traffic as suggested by the Light Rail Manila Corporation (LRMC), the company that manages the operations and maintenance of LRT-1.

This research aims to strengthen the practice of rainwater harvesting as an alternative and sustainable means to not only supply water but also reduce flooding in LRT-1 stations. Urban street floods have resulted in damages costing up to billions of pesos in the Philippine economy, particularly to the transportation sector, yet RWH is rarely explored as a solution despite its long history of use for stormwater management [3]. The presence of RWH is also lacking in urban public spaces as it is commonly facilitated in private buildings or houses which hinders public use and awareness [4]. Most importantly, given that climate change has made rainfall patterns more intense and freshwater scarcity an even greater concern, RWH addresses both these issues by diverting rainfall-runoff out of roads and into the system while simultaneously providing water supply.

2 Trends and Methods

The main objective of this study is to identify the appropriate storage capacity of an RWH system that can be implemented in LRT-1 D. Jose Station to supply non-potable water demand and reduce flooding. This can be achieved by analysing rainfall and water consumption patterns in the station to identify demand and supply, then performing mass balance calculations to optimize the storage that can effectively serve its two purposes.

The storage tank is the most important component in rainwater harvesting design since the functionality of RWH depends on the amount of rainwater stored. Compared to probabilistic and statistical models which have limited applications, simulation models are more commonly used in designing storage capacity. This approach imitates the physical behaviour of the RWH system by simulating its operation through time steps using mass flow algorithms [5]. Analysis of the tank capacity shall also be employed by using performance indicators to quantify the two system functions.

2.1 Storage tank sizing

2.1.1 Water demand distribution

Demand based on water consumption, is the primary basis for whether the RWH system is useful mainly for the provision of toilet water. Figure 1 shows the water demand from 2015 to 2021, which served as the basis for forecasting demand until the year 2040 for the mass balance calculations. The daily water consumption data was derived based on the billed water volume in LRT-1 D. Jose Station as provided by LRMC. Potable consumption is neglected in the calculations. Outlier data were neglected and incomplete monthly data was predicted using time series forecasting with a two-year moving average. Annual water consumption for the following years was computed, and the daily water consumption was assumed constant within each month due to limitations in measuring water demand up to a monthly period only. The type of study area can also be factored in given that demand distribution differs in residential areas compared to transportation and industries due to the population and schedule of consumers [6].

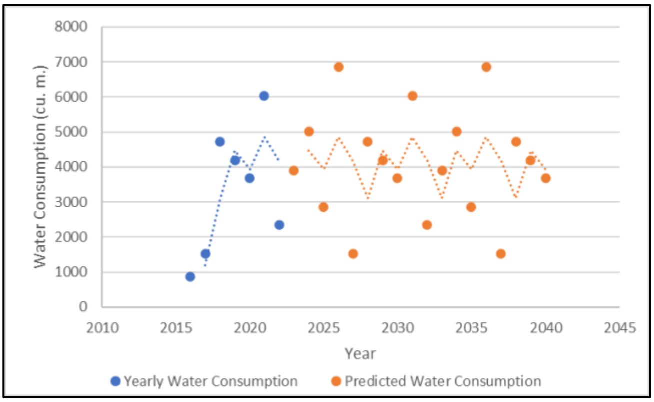

Fig. 1. Annual water consumption distribution at LRT-1 D. Jose Station.

2.1.2 Rainwater supply distribution

The rainfall distribution of the study area is essential in identifying the feasibility of rainwater harvesting since it dictates the amount of water supply available for utilization. Rainfall data is provided by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration – Climatology and Agrometeorology Division. It was collected from the nearest rain gauge station to the study area at Port Area, Metro Manila located about 2.4 km away from D. Jose Station. 20 years' worth of data from 1 January 2001 until 31 December 2020 was gathered. The same time series forecasting procedure and partitioning annual rainfall into daily values until the year 2040 was performed, as illustrated in Figure 2.

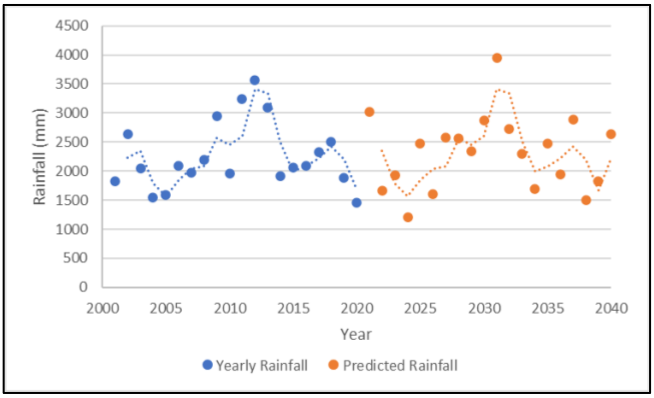

Fig. 2. Annual rainfall distribution at LRT-1 D. Jose Station.

To quantify the effective rainwater intake from the rainfall amount, the rational formula is used. The volume of rainwater is equal to the product of the rainfall amount, the roof area, and the roof runoff coefficient which depends on the roof material and slope [7]. The roof material used for LRT-1 stations, including D. Jose, is concrete and the roof is also oriented at a slope. Thus, the corresponding roof runoff coefficient (RC) can be in the range of 0.9 – 0.95 and the mean of $RC = 0.925$ is selected in the study [8].

2.1.3 Mass balance calculations and YAS algorithm

Although it is not possible to accurately depict the simultaneous processes inside a storage tank, simulation models estimate water intake, yield, and spillage of the RWH system on a time-step basis to select the optimal storage. The most common behavioural model is yield-after-spillage (YAS). In YAS, rainwater intake is added first, then spillage is calculated before yield is extracted based on water demand [5]. This process is mathematically represented by Equations (1) and (2).

$$Y_t = \begin{cases} S_{t-1} + I_t & , \quad S_{t-1} + I_t \le D_t \\ D_t & , \quad S_{t-1} + I_t > D_t \end{cases} \tag{1}$$

$$S_t = \begin{cases} S_{t-1} + I_t - Y_t & , \quad S_{t-1} + I_t - Y_t \le V \\ V - Y_t & , \quad S_{t-1} + I_t - Y_t > V \end{cases} \tag{2}$$

where Y_t: volume of rainwater yield within time step $t \ge 1$ (m^3)
S_t: volume of storage remainder at the end of time step t (m^3)
I_t: volume of rainwater intake within time step t (m^3)
D_t: water demand within time step t (m^3)
V: design volume or capacity of RWH storage (m^3)

The YAS Algorithm was used to identify the daily remaining storage of the RWH tank. The tank is initially set to empty, and routing begins on the first day of June which is the beginning of the wet season to maximize tank operations when rainfall is consistent, based on the forecasted rainfall values. Daily storage distributions were created for a design period of 1, 5, 10, and 15 years where the entire roof area of D. Jose Station was utilized for rainwater harvesting. These are selected since the typical life expectancy of a polymer plastic water storage tank is between 10 and 15 years according to information from various manufacturers and suppliers.

2.2 Storage tank performance indicators

Tank performance indicators must be evaluated along with the complete mass balance calculations to identify the optimal tank size so that iterations can be terminated. In developing appropriate performance variables for the RWH system, both water demand fulfilment and stormwater reduction were factored in. Based on water demand, it is ideal that the storage is always at least the demand which is assessed through reliability. For rainfall reduction, rainwater collection must be maximized while spillage must be minimized which is quantified by the change of rainfall to runoff. These performance indicators are defined mathematically in Equations (3), (4), and (5).

$$Reliability = \frac{T(S_{t-1}+I_t \ge D_t)}{T} \tag{3}$$

$$Rainfall\ Reduction = \min\left(\frac{V-S_{t-1}}{I_t}, 100\%\right) \tag{4}$$

$$Performance = 50\% \times Reliability + 50\% \times Rainfall\ Reduction \tag{5}$$

where T: total number of time steps $t \ge 1$

In this study, reliability and rainfall reduction were treated with equal significance in the tank performance. Thus, the reliability and rainfall reduction for an assumed volume were averaged to develop the overall performance rating curve. Based on the curve behaviour, the optimal tank size is the assumed storage size with the maximum performance value.

3 Results and discussion

3.1 Demand and supply distributions

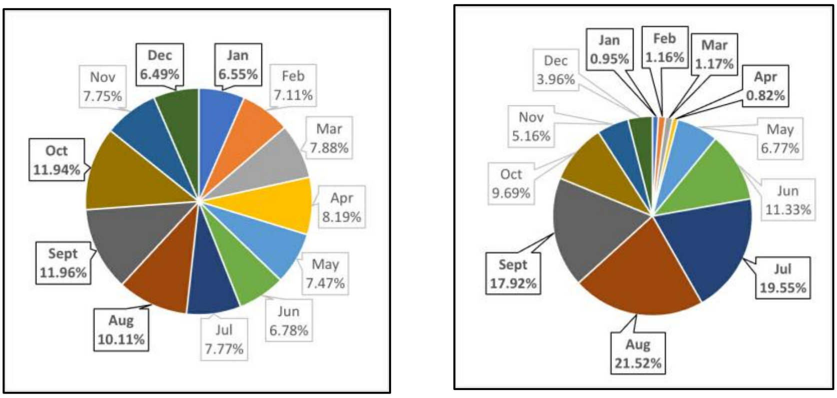

Fig. 3. Monthly distribution of (a) water demand and (b) rainfall.

The demand and supply patterns can be assessed through the monthly trends presented in Figure 3. Water consumption in D. Jose Station is generally consistent – lowest in December and January while highest from August to October (Figure 3a). Given that train riders are mostly students (44%) and employees (31%), months of highest water demand are typical during simultaneous school operations and lowest on vacation and holiday months [9]. For rainfall, it is insignificant from January to April, begins in May, peaks from July to September and decreases from October to December (Figure 3b). This trend is consistent with the Type 1 Climate, characterized by a distinct dry season and wet season [10].

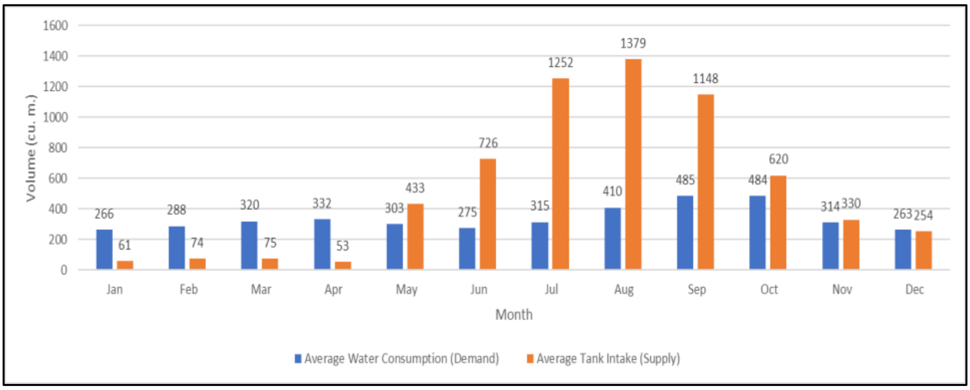

Fig. 4. Average monthly demand and supply.

Figure 4 presents a comparison of monthly demand and supply based on the projected volume estimates. RWH is unreliable within January to April where supply is significantly lower than demand. By May, supply begins to overtake demand, particularly during the last few weeks and days as the wet season comes about. An oversupply of rainwater is observed from June to October which necessitates optimal tank sizing. As rainfall evens out with demand during November and December, the oversupply from previous months can assist in satisfying water demand as rainfall decreases.

3.2 Storage distributions

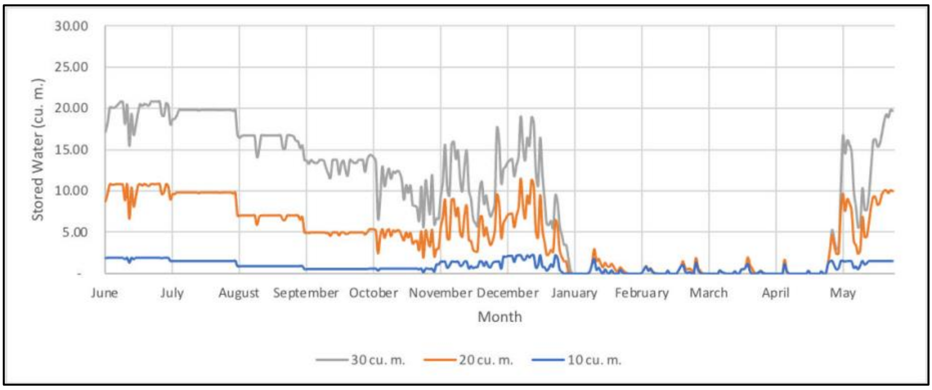

Fig. 5. Average 1-year storage distributions of varying commercial tank sizes.

The annual storage volume distribution, shown in Figure 5, is derived from mass balance calculations conducted with a daily time step. For typical commercial tank sizes, as the capacity is increased, the remaining storage distribution also increases consistently with the same trend. This is because yield is independent of the tank size. Yield is subtracted from the stored water in the tank, which is almost always full during the wet season. During the dry season, the tank is almost always empty due to the lack of rainfall for all iterations. The flat segments of consistent storage capacity from June to October represent days when the tank is always full before yield. In contrast, remaining storage became erratic during November and December since rainfall begins to decrease in these months.

3.3 Performance analysis

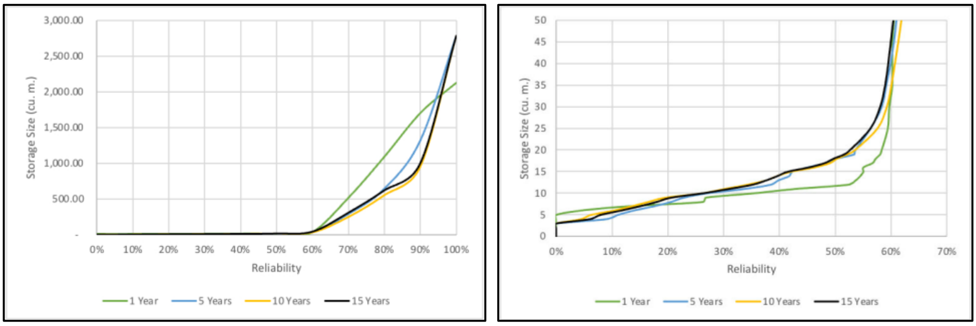

Fig. 6. Storage size vs. reliability – (a) complete plot and (b) magnified plot from 0% to 60% (right).

Reliability is defined as the number of days during the simulation period when the storage is sufficient to meet water demand. As illustrated in Figure 6a, full reliability is achieved with a storage capacity of 2,783.11 cu.m., whereas at 45.42 cu.m., reliability is already at 60%. This sharp increase is in contrast with the gradual trend observed from 0 to 60% reliability, which is satisfied with storage volumes ranging from 5 to 30 cu.m. (Figure 6b). Note that the average daily water consumption is at 11.23 cu.m which falls well within this range.

At low storage sizes, only days during the wet season which have high rainfall can fulfil water demand. Increasing the storage compensates days during the wet season with less rainfall not enough to satisfy demand. A massive increase in capacity will eventually lead to enough stored water even during the dry season when there is negligible rainfall. This increase in tank size after 60% reliability, which has a great effect on cost, is not practical in constrained urban spaces. The lack of 40% reliability can be attributed to the unavailability of rainwater and tank operation from January to May.

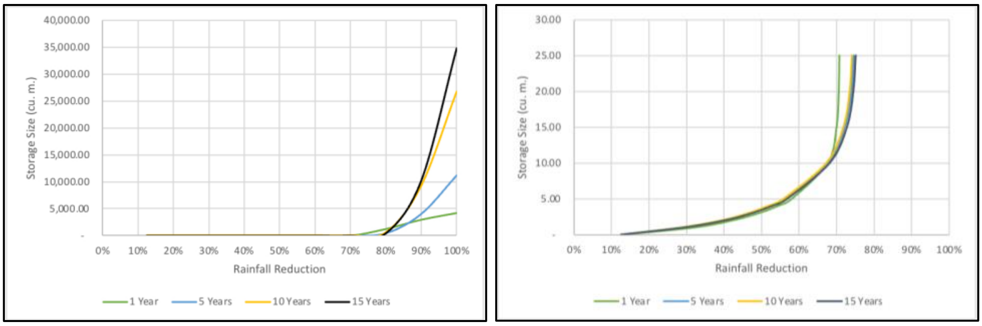

Fig. 7. Storage size vs. rainfall reduction – (a) complete and (b) magnified from 0% to 70%.

Rainfall reduction measures the percentage of rainfall received by the roof catchment that is effectively stored in the RWH tank rather than lost through spillage or runoff. Its trend closely resembles that of reliability, with complete reduction achieved at 34,807.90 cu.m. (Figure 7a). 70% reduction is already attained at only 11.53 cu.m. (Figure 7b), given an average daily rainfall volume of 17.42 cu.m. By definition of this performance indicator, there is high rainfall reduction from January to April due to negligible or low rainfall, while there is low rainfall reduction from July to September due to extremely high rainfall. Beyond the 70% reduction threshold, the slight increase in rainfall reduction does not justify the substantial increase in storage size.

4 Conclusion

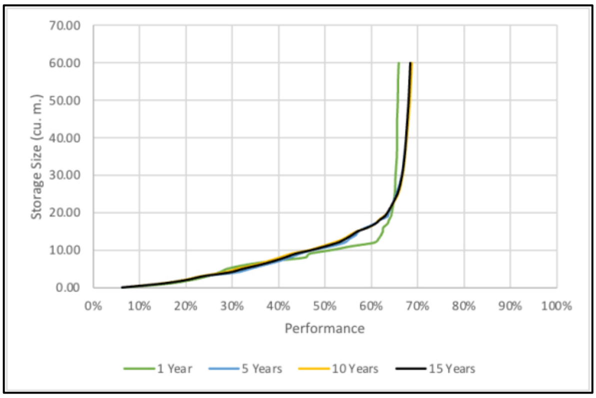

Fig. 8. Storage size vs. performance for practical tank capacities.

Performance is taken as the average of the two indicators reliability and rainfall reduction (Figure 8). By virtue of practicality and space restrictions at Doroteo Jose Station, the maximum volume is 60 cu.m. for evaluation. Based on the curve, performance increases gradually until about 65% before the curve steeps. The optimal capacity would be around 20 to 30 cu.m. with performance of about 63.52% to 66.67%. Reliability is around 52.64% to 58.04% while rainfall reduction is around 74.40% to 75.30%.

In Doroteo Jose Station, rainfall supply is high in June to September and low in January to April, while water demand is relatively uniform all year long. Moderate tank sizes maximize both reliability and rainfall reduction while avoiding diminishing returns of oversized storage. RWH is seen effective as a flood mitigation strategy together with being a water supply source.

This study recommends that RWH alone is insufficient in the dry season and requires alternative water sources to support demand. RWH should also be paired with proper drainage management to increase rainfall-runoff and flood reduction rates. Ultimately, this tank sizing framework can be integrated in local water management and flood control strategies to emphasize practices in line with sustainable development goals, particularly on Industry, Innovation, and Infrastructure (SDG 9), Sustainable Cities and Communities (SDG 11), and Climate Action (SDG 13).

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