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Designing Stormwater Harvesting Tanks for Residential Roof Runoff Management in Three Tropical Climate Types

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Rainwater harvesting (RWH) technology are currently utilized in many locations in the world due to the sustainable benefits that it provides to the surrounding community. Their application in tropical countries is still minimal due to high rainfall variability and intensity, making tank design difficult to apply and optimize. This research aims to design and assess the efficiency of stormwater harvesting tanks in three tropical climate types for residential roof runoff management. Ten-year historical rainfall data was collected for assessment in the three study sites in the Philippines: a Type I, Type II/IV, and Type III representative site from different locations in the country, characterized by varying dry and wet seasons throughout the year. To accommodate the 90th and 95th percentiles of historical rainfall, a 0.7-1.1 m^3 tank was recommended for construction in each residential site. A total of 59 events were then monitored on the selected sites to recalibrate the original design of the stormwater harvesting tanks. Compared with the initial size estimations, results indicate that nearly similar tank designs are recommended for the Type I and Type II/IV sites, attaining only a 7 % and 2 % decrease respectively, while a much smaller size would be deemed efficient for the Type III site, at least 59 % smaller than the original design.

1. Introduction

Utilizing rainwater through rainwater harvesting (RWH) is one way to apply sustainable architecture and raise awareness in relation to energy conservation (Mariana and Suryawinata, 2018). RWH system performance becomes more sustainable when dependability, resilience, and susceptibility progressively improve (Bañas et al., 2023). Socioeconomic, environmental, and technical considerations all have an impact on the use of RWH systems (Perius et al., 2021). The ongoing increase in residential areas due to urbanization has prompted the need to control excess runoff generated from impervious surfaces such as roofs. The probability of floods and torrents, as well as the likelihood of their effects on people and property, reduces if enough residences have an RWH system (Ortiz et al., 2022). The efficiency of RWH system depends on the rainfall, catchment area and storage tank. Designers and planners may take into consideration the recommended rainwater storage tank capacities to reduce flood peak and volume. Final decisions for storage capacity selection will necessitate additional local and regional investigation regarding population density, water demand, and future climate, as well as taking into account local and regional long-term goals (Nguyen et al., 2022).
RWH technology can decrease further the required energy demand from urban water systems such as distribution and treatment services as it provides water for various non-potable uses (Martin et al., 2015). This can be a profitable climate change adaptation strategy, especially in densely populated urban areas with low-rise buildings (Raimondi and Becciu, 2021). Its application can be difficult in tropical regions as they experience variability in climate conditions (Allan and Liu, 2019). This research aims to design and assess the efficiency of stormwater harvesting tanks in three tropical climate types for residential roof runoff management. This study

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characterizes the rainfall trends and occurrence frequency and determine the optimal tank size and capacity through hydrologic analysis and rainfall monitoring. The results from this study can help initiate research about stormwater tanks and their optimal design in varying tropical climate conditions

2. Materials and Methods

2.1 Study methodology

Figure 1 shows the summary of the methodology of the study. This involved the collection and analysis of historical rainfall data, local conditions, climate type, as well as the investigation of the site area, the roof surface, and connecting downspouts. The stormwater tank was designed based on catchment area measurements, outlets measurements, impervious surfaces, and available spacing within each residence. After the initial tank design construction, rainfall monitoring and data collection was performed to recalibrate the tank size.

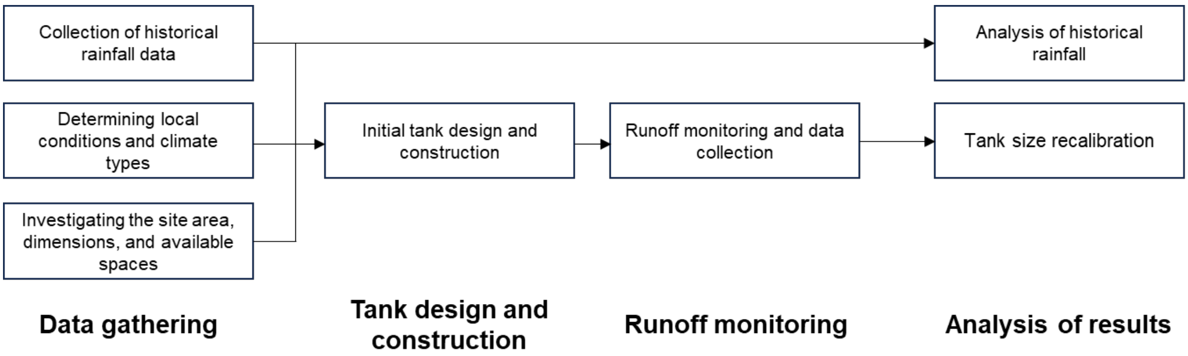

Figure 1: Rain tanks constructed in the (a) Type I site, (b) Type III site, and (c) Type II/IV site

2.2 Study area

This study was conducted in the Philippines, where three residential sites have been selected as the representative climate types of each selected region. Firstly, the Type I site is in Quezon City, National Capital Region (14°40'58.5008", 121°03'36.2808") has a roofing area of 26.1 m^2. A Type I climate is characterized by two pronounced seasons: dry from the months of November to April and wet for the rest of the months and experiences an average temperature of 27.0 °C. Secondly, the Type II/IV site is in Baybay, Leyte on the eastern side of the country (10°41'00.2400", 124°48'21.2400"), having a roofing area of 26.6 m^2. Both Type II and Type IV climates experience an average temperature of 26.8°C, although the Type II site has a pronounced rain period from November to January while a Type IV climate has an evenly distributed rainfall throughout the year. Lastly, the Type III site located in Cebu City, Cebu (10°18'11.3796", 123°53'50.2404") has a slightly larger roofing area, estimated at 39.7 m^2. A Type III climate has seasons that are not very pronounced, having a short dry season and then wet throughout the rest of the year. They commonly experience an average temperature of 27.2 °C.

2.3 Rainfall data

Rainfall data were collected for the years 2010 - 2020 from the nearest rain gauge in each site, namely the Science Garden rain gauge in Quezon City (14° 38' 42.2592", 121° 2' 39.4146") for the Type I site, the Mactan rain gauge in Cebu (10° 19' 20.3838", 123° 58' 48.4248") for the Type III site, and the Tacloban rain gauge in Leyte (11° 13' 32.001", 125° 1' 30") for the Type II/IV site. The 90^{th} and 95^{th} percentiles of historical rainfall in each location were computed to analyze the amount of rain that each area receives and to initially design a stormwater collector tank for residential roof runoff management. The Weibull Plotting Position was utilized in this study to calculate the selected rainfall percentiles for each year as this distribution method is commonly used in estimating rainfall amounts in LID-related research, such as modeling studies (Garbanzos and Maniquiz-Redillas, 2022). Eq(1) displays the equation of the Weibull Plotting Position. Tanks were then constructed based on these values in each selected site to monitor actual rainfall events for tank size recalibration.

$$P = \frac{r}{n+1} \quad (1)$$

Where *P* is the probability of occurrence, *r* is the rank number, and *n* is the number of observations.

2.4 Runoff monitoring

Runoff monitoring has been conceived as an essential part of stormwater management as it provides in-situ data for real-time assessment and knowledge for future adjustments (Saini et al., 2022). In this study, monitoring was performed manually in each site during rainfall events. Figures 2a to 2c show the constructed tanks in the Type I, Type III, and Type II/IV sites respectively. The monitoring period occurred from August to October 2022 in all sites, and the assessed parameters included the rainfall depth, duration, intensity, and maximum and peak flow rate. Flood level depth markers were situated near each constructed tank to measure the increase in water level and rainwater levels were recorded. Rain gauges were set up in each site to estimate the total roof runoff generated. Determining the total volume of roof runoff was based on the recorded water levels in each tank, and downspout was used to record the flow from select rainfall events. An outlet for the tank was also placed to empty the tank if necessary. Daily samples were also taken at set intervals at the end of monitored events to avoid inconsistencies in data due to various factors such as evaporation. A total of 59 events were monitored during the study period: 20 events in the Type I site, 19 events in the Type II/IV site, and 20 events in the Type III site.

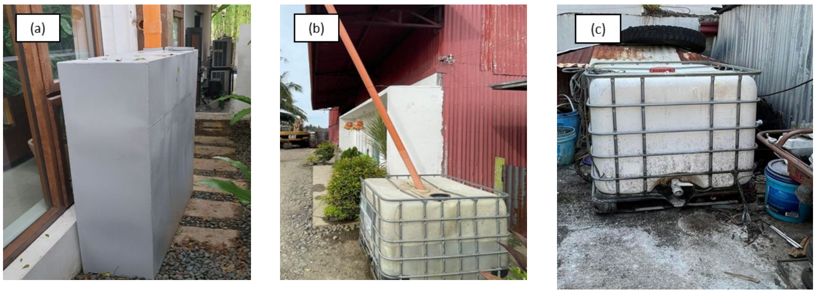

Figure 2: Rain tanks constructed in the (a) Type I site, (b) Type III site, and (c) Type II/IV site

3. Results and discussion

3.1 Rainfall trends and occurrence frequency

Analyzing the rainfall characteristics of a site is essential in rainwater harvesting research as it is dependent on the local climate (Onderka et al., 2020). Due to potential fluctuations that could cause the estimates of storage tank dimensions, the current phenomenon of climate change should also be taken into account (García-Ávila et al., 2023). The cumulative rainfall data was firstly assessed in each site as it could help characterize the area's potential for rainwater harvesting and help in differentiate the rainfall amount in each site, which could later suggest a difference in tank design. Figure 3 shows the characteristics and patterns of monthly rainfall of the three sites.

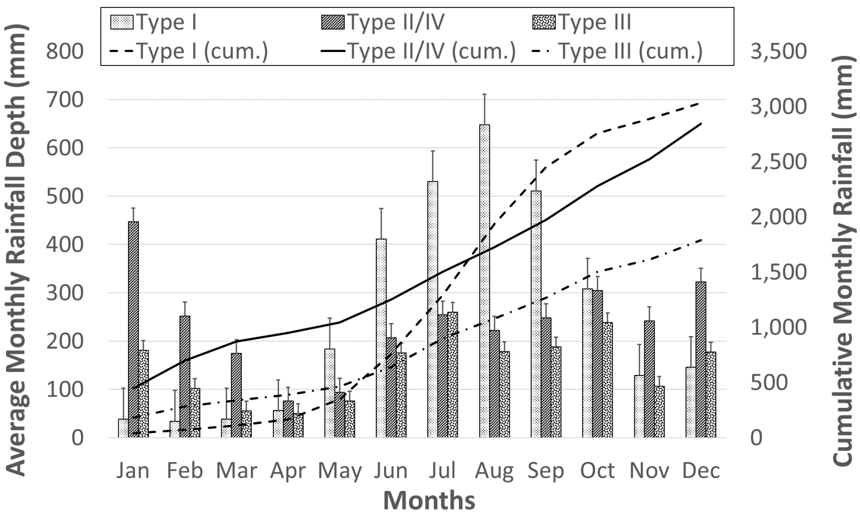

Figure 3: Monthly trends of rainfall collected

The Type I site appeared to have intense and frequent rainfall from June to October and a pronounced dry season from November to April. This contrasts the Type II/IV site which received stable rainfall amounts throughout the middle of the year, with generally no definitive dry or wet seasons throughout the year. The Type III site experienced more stable rainfall throughout the year and yielded the least cumulative rainfall. Peak monthly rainfall is mainly observed in the Type I climate from July to September. This implies that different rain tank sizes are needed for each site even though they are all categorized as tropical climates. Figure 4 shows the frequency of rainfall events at the three sites. Most recorded events show that all sites mainly experienced small amounts of daily rainfall in all areas. Little variability was observed in the daily frequency count among the three sites, all having amounts predominantly ranging from 0 to 5 mm. Rainfall with intensity greater than 80 mm also occurred rarely in all sites. Given the number of prevalent low-intensity events in the areas, this suggests that rain barrels could be utilized to help manage excess runoff for rainfall capture and storage.

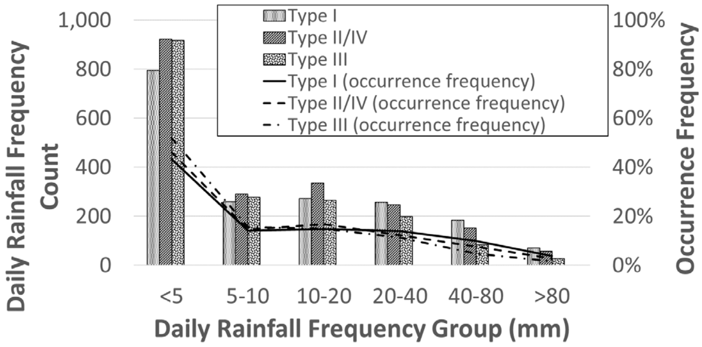

Figure 4: Occurrence frequencies of rainfall from the three study sites

3.2 Initial tank size calibration

Rain tanks were then constructed on each site based on the 90th and 95th percentiles of historical rainfall of each site. Using the Weibull Plotting Position, the percentile values were computed each year with available rainfall data to determine what tank size is sufficient for placement on the site. Figure 5 shows the theoretical tank sizes estimated in the two percentiles across the three sites.

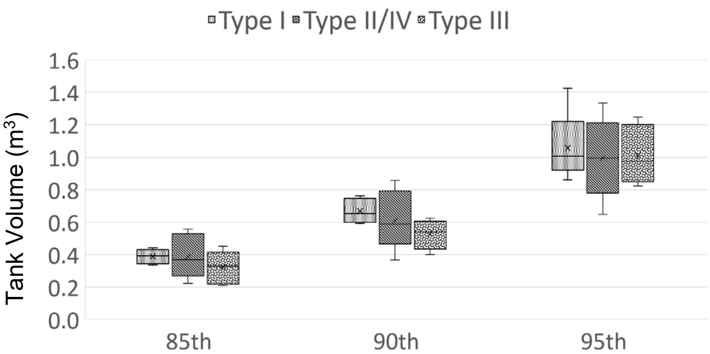

Figure 5: Initial tank size estimation based on rainfall percentile

This figure also includes a hypothetical 85th percentile scenario for comparison. On average, a 0.6 to 0.7 m^3 stormwater harvesting tank is required to cater to the 90th percentile of rainfall, while the 95th percentile requires a 1.0 to 1.1 m^3 tank. The Type I climate requires slightly larger tank sizes as opposed to the two climates in both percentiles. Larger discrepancies between median tank sizing were also seen in the 90th percentile as compared to the 95th percentile, whose median values were prominent. Smaller boxes were also observed in Type I and Type III sites, indicating that their percentile values for each year are more consistent as opposed to the Type II/IV site, which generated a larger range of options. Rain tanks were then constructed in the sites based on the percentiles. Tank sizes computed are as follows: a 0.76 m^3 (760 L) welded steel sheet tank in the Type I site, a 1.0 m^3 (1,000 L) intermediate bulk container (IBC) tank in the Type II/IV site, and a 1.0 m^3 (1,000 L) IBC tank in the Type III site for rainfall monitoring and further size recalibration.

3.3 Rainfall monitoring and tank size recalibration

Stormwater monitoring was then performed on all three sites to assess and further recalibrate the estimated tank volumes. A total of 59 rainfall events were monitored in the sites and were quantified further by obtaining the roof runoff and rainfall depth of each rain event. Figure 6 shows the relationship between the ratio of captured over the total runoff volume versus the intensity of the monitored event. In this figure, the total rainfall is defined as the total rainfall volume of each event based on the rainfall gauge in each site while the captured roof runoff is defined as the volume collected in each site's constructed tank. Results show that all built rain tanks were efficient in capturing small volumes of water. This was mainly evident in the Type I site, but the Type II/IV and Type III sites had greater variations in captured efficiency across comparable rainfall amounts. This signifies that the Type I rain tank was efficient in capturing roof runoff, as opposed to the spread-out values observed in the other two sites. The Type III site generally scored the lowest ratios among the three, implying that the tank size constructed was not efficient for capturing rainfall in the site.

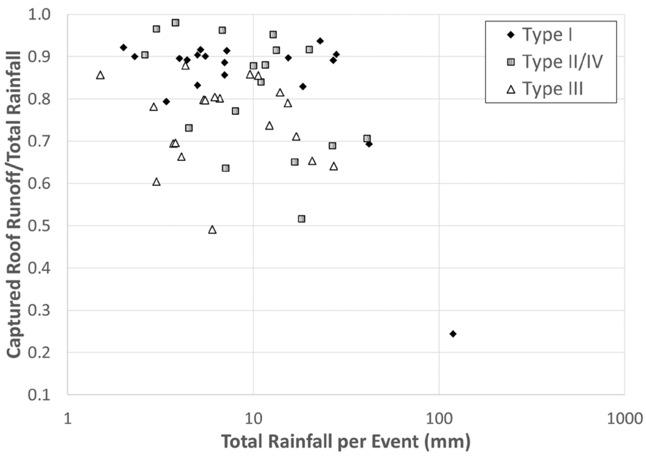

Figure 6: Rainfall and runoff volume ratio of monitored events

3.4 Tank size optimization

Recalibration was performed by computing the runoff coefficient and assessing the tank's runoff retention efficiency after each event in each site (Alihan et al., 2016). Upon assessment, the recalibrated tank sizes are as follows: a 0.706 m^3 (706 L) in the Type I site, a 0.93 m^3 (930 L) in the Type II/IV site, and a 0.412 m^3 (412 L) tank in the Type III site. Figure 7 shows the difference between the initial tank volume constructed on-site and the recalibrated volume. Smaller volumes were mainly recommended based on this recalibration. Results indicate that nearly similar tank designs are recommended for the Type I and Type II/IV sites, attaining only a 7 % and 2 % decrease respectively, while a much smaller size would be deemed efficient for the Type III site, at least 59 % smaller than the original design. This was due to the smaller rainfall amounts experienced in the Type III site, therefore smaller tank sizes could accommodate the rainfall that occurs in that site. This optimization process requires further evaluation as various spatial, physicochemical, and microbiological parameters (García-Ávila et al., 2023) could affect its potential for domestic use.

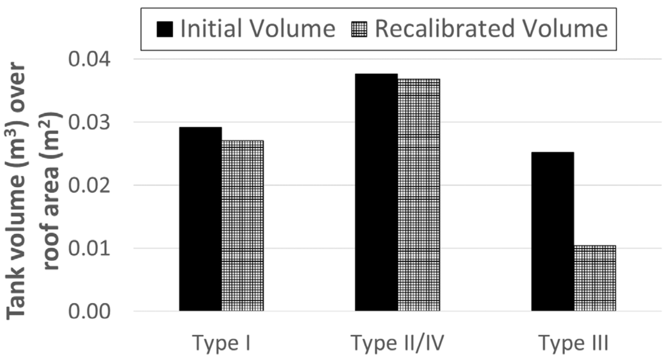

Figure 7: Comparison of the initial and recalibrated tank volume for the three sites

4. Conclusions

The design of stormwater tanks is dependent on local conditions and their supposed purpose. This study aimed to design stormwater harvesting tanks in three tropical climate types for residential roof runoff management.

Three sites were assessed in this research, namely the Type I, Type II/IV, and Type III sites based on their respective climate type in the Philippines. The rainfall amounts and patterns were highly variable in all sites, where most rainfall events were deemed to be low intensity. The initial stormwater tank design was based on the 90th and 95th percentile of historical rainfall in the site and this was optimized further after monitoring rainfall events in the three areas. Results indicate that a small decrease in tank size for Type I and Type II/IV is recommended, while a significant decrease may be effective for Type III sites. This study recommends further analysis before a design criterion can be proposed, so water collected could also be used for multiple purposes. Additional analysis about the cost aspect of tank construction is also needed to determine its economic impact.

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