Technical Note

Water demand and sizing for rainwater harvesting: a pilot project in SFERA@UMS, Sabah, Malaysia

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ABSTRACT

Rainwater harvesting systems (RWHS) are practical solutions for supplementing conventional water supplies, particularly where piped infrastructure is absent or uneconomical. With rising urbanization and population growth, demand for clean water is increasing, often leading to shortages and flooding from disrupted hydrological cycles. This technical note, the first in a two-part series, documents the design and construction of a pilot RWHS at the Sustainable Forest Education & Research Area (SFERA@UMS), Universiti Malaysia Sabah (UMS). The system was intended to supply water for washing, toilet flushing, showers, and limited drinking. Annual water demand was estimated at 97,951 L (93,031 L non-potable, 4,920 L potable). Based on a 50 m² roof catchment and 2,718 mm annual rainfall, the theoretical collection potential is 122,314 L, exceeding demand by 24%. Monthly surplus, deficit analysis showed shortfalls in August and September, which could be mitigated by additional 4,500 L storage tanks to capture surplus from preceding wet months. Commissioning confirmed effective operation, with the first-flush device and treatment unit producing potable water that met quality expectations. The incremental RWHS cost was approximately RM 30,000, yielding a simple payback of about 9 years compared with tanker deliveries. Practical lessons include the importance of storage flexibility, cost-effective local materials, and the system's value as a demonstration tool for sustainable water management. The SFERA@UMS project highlights the feasibility of small, modular RWHS in high-rainfall tropical settings and provides a replicable design reference for campus and community applications.

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1. INTRODUCTION

Rainwater harvesting systems (RWHS) collect rainwater for domestic, commercial, and industrial use, serving as a primary or supplementary water source (Department of Irrigation and Drainage 2011). As urbanization, industrialization, population growth, agricultural expansion, and changing consumption patterns continue, the demand for clean water rises, causing water shortages and floods due to disruptions in the natural hydrological cycle (Department of Irrigation and Drainage 2017; Lani et al. 2018; Nainar et al. 2021; Judeh et al. 2022; Yahya et al. 2023; Abdelkareem et al. 2024). Rainwater harvesting offers a viable solution to meet this deficit.

The adoption of RWHS varies globally, influenced by factors such as climate, water availability, infrastructure, water demand, and cost-benefit considerations. Where domestic water supply is abundant and inexpensive, RWHS is implemented only as a supplementary non-potable source, if at all. Slow adoption results from minimal incentives and lengthy return-on-investment periods. In contrast, arid regions or areas with prolonged dry spells rely heavily on RWHS as a primary water source. These systems are also crucial in regions with distinct wet and dry seasons, mitigating flood risks during rainy periods and providing water during droughts (Judeh et al. 2022; Abdelkareem et al. 2024). RWHS can be integrated into stormwater management systems, reducing runoff and enhancing water storage (Department of Irrigation and Drainage 2011). Studies suggest coupling stormwater retention with RWHS to improve economic viability (Kim and Yoo 2009; Fewkes 2012; Dallman et al. 2016).

In Malaysia, adoption is further shaped by economic and policy factors. Domestic water tariffs remain among the lowest in Southeast Asia, Malaysia charges approximately RM 1.22 per m³ on average, the fourth lowest in ASEAN (The Edge Malaysia, 2024; The Star, n.d.). Government subsidies help keep prices low, but many water operators note that current tariffs do not fully cover supply and treatment costs (The Edge Malaysia, 2024). Tariff structures provide limited incentives for conservation, for example, many domestic users receive unchanged rates up to moderate consumption volumes, and steeper rates begin only at higher usage tiers, such as 35 m³ and above in some states (Shari, 2025). Although increasing-block tariffs (IBTs) are used in many Malaysian states, the differences between blocks are often small, offering weak economic motivation to reduce consumption when usage remains within the lower to mid blocks (Lee, 2005).

The appeal of RWHS is likely to grow as global water tariffs increase due to resource scarcity, rising demand, and expanded infrastructure (Kim and Yoo 2009; Vieira et al. 2014; Yahya et al. 2023). These trends highlight the potential benefits of investing in RWHS.

RWHS is not only sustainable but also cost-effective. Rainwater is typically less contaminated than surface or groundwater, requiring minimal treatment to meet potable standards (Yahya et al. 2023). When rainwater is used as a supplementary source, simple debris traps often suffice for treatment, making it even more economical. The harvested water can be used for activities such as washing, gardening, and toilet flushing. Moreover, RWHS reduces energy consumption and carbon footprints, as it requires significantly less energy to deliver water compared to conventional domestic water supply systems (Vieira et al. 2014; Ghimire and Johnston 2019; Musz-Pomorska et al. 2021; Zang et al. 2021; de Sá Silva et al. 2022).

The complexity of RWHS depends on intended use and budget. For external washing and irrigation, minimal treatment, including debris traps and first-flush mechanisms, is adequate. Indoor uses such as toilet flushing and showers require additional filtration for hygiene and maintenance. For drinking purposes, advanced filtration including nano-membrane filters, ultraviolet purification, and carbon filters is necessary to ensure safety and quality. A key advantage of RWHS is that performance depends mainly on roof catchment area and rainfall characteristics, making the system largely independent of ground conditions such as soil type or underlying vegetation.

Since the Sustainable Forest Education and Research Area, Universiti Malaysia Sabah (SFERA@UMS) was designated as a forest reserve and conveyed to the Faculty of Tropical Forestry on 22 June 2022, continuous upgrades, maintenance, and activities have been carried out in the area. A network of jungle trails has been established for educational, research, and recreational purposes. One of these trails now connects to an existing hiking trail frequently used by students, staff, and visitors, including international tourists, to access UMS Peak. The forest reserve is utilized for field experiments and educational activities involving students and both resident and international researchers. Additionally, numerous university- and state-level events have been held in the area. As a result, a shed incorporating a Rainwater Harvesting System (RWHS) was developed to provide a gathering space and a reliable water supply for SFERA@UMS users, including students, lecturers, researchers, and the general public.

This first paper in a two-part series outlines the construction, design, and performance of a rainwater harvesting and treatment system at the Sustainable Forest Education and Research Area (SFERA@UMS). The companion paper will present the production of potable water from the harvested rainwater. Presented as a Technical Note, the primary objective is to document the design, sizing calculations, and implementation of a pilot RWHS within a tropical forest reserve. Unlike hypothesis-driven research articles, the contribution lies in providing a replicable reference design, including climate-based optimisation, demand estimation, and cost analysis, that can be adopted or adapted for similar equatorial settings. Published examples of detailed and openly accessible RWHS designs for high-rainfall tropical environments remain limited, particularly those that integrate sizing calculations with climate considerations and cost constraints. By sharing a fully worked case study together with an accompanying sizing calculator, this note addresses that practical gap and supports practitioners, researchers, and policy makers seeking reliable design guidance.

2. BRIEF SITE DESCRIPTION

The Sustainable Forest Education and Research Area (SFERA@UMS) is a 37-ha forest reserve located within the Universiti Malaysia Sabah campus in Kota Kinabalu, Sabah (5°57′ N, 116°04′ E). The site is characterised by lowland mixed dipterocarp forest interspersed with secondary vegetation and recreational trails. Although no dedicated hydrological measurements were collected prior to the rainwater harvesting project, the design team conducted a basic site survey to evaluate roof placement, drainage routes, and accessibility.

Previous ecological assessments provide minimal but relevant background on the site's biophysical setting. Floristic surveys recorded more than 150 plant species including dipterocarps and pioneer taxa within the campus forest patches (Majuakim et al., 2018). Wildlife observations, including studies on the Sunda pangolin (Manis javanica), describe a humid tropical environment with annual rainfall exceeding 2,500 mm and a mixed forest canopy structure (Kodoh et al., 2024; Sompud et al., 2023). These reports confirm the presence of intact vegetation and a humid equatorial climate that is favourable for rainwater harvesting.

The RWHS design was therefore based on the site survey combined with long-term rainfall records from the Kota Kinabalu meteorological station rather than on new in-situ hydrological measurements. It was built within a small open-canopy clearing, ensuring unobstructed roof exposure and minimal organic debris on the catchment surface. The site lies on the coastal plain of Kota Kinabalu within a humid equatorial climate, where temperature and humidity remain relatively uniform year-round. Consequently, local factors such as soil texture, vegetation cover, or microclimatic gradients exert little influence on system sizing or operation compared with the dominant regional rainfall pattern.

3. DESIGN AND SIZING METHODOLOGY

The rainwater harvesting system was designed by considering several key factors, including water demand calculations, rainfall amount, rainfall characteristics, and monitoring and maintenance requirements. Figure 1 shows a process flowchart for designing and constructing the RWHS.

Figure 1. Flowchart of RWHS design and construction at SFERA@UMS

3.1. Water Demand Calculations

The usage of the area can be categorized into daily regular usage, special events, and forestry camps. It is estimated that, over the course of one week, there will be a single day during which approximately 50 users are present in the area for field education. This is in addition to the variable number of sporadic tourists and visitors, currently estimated at 50 people per week. It is anticipated that some of these users will utilize the toilet facilities. The calculations for daily water usage (toilet, non-potable) are as follows:

Toilet usage:

Vol. per flush	= 4.5 L
Est. no. of area users per week	= 100 persons
Est. no. of toilet users per week	= 50 persons (50% of no. of area users)
Vol. of toilet water needed per week	= 4.5 L x 50 persons = 225 L
Vol. of toilet water needed per day	= 225 L / 7 days = 32.14 L
Vol. of toilet water needed per year	= 32.14 L x 365 days = 11,731.1

In a year, it is estimated that there will be four university- and/or state-level special events (e.g., International Day of Forests, Tree Planting Campaign, field trips by local schools, etc.), with an estimated 100 participants per event. The calculations for water usage are as follows:

Toilet usage:

Vol. per flush	= 4.5 L
Est. area occupancy per special event	= 100 persons
Est. no. of toilet users per special event	= 50 persons (50% of area occupancy)
Vol. of toilet water needed per special event	= 4.5 L x 50 persons = 225 L
Vol. of toilet water needed for special events per year	= 225 L x 4 times = 900 L

Drinking water:

Vol. per user	= 0.3 L
Est. no. of users per event	= 100 persons
Vol. of drinking water needed per special event	= 0.3 L x 100 persons = 30 L
Vol. of drinking water needed for special events per year	= 30 L x 4 times = 120 L

The estimated drinking water volume for special events (0.3 L per person) reflects the short duration of these gatherings (typically ≤ 2 hours), during which many attendees do not consume water.

Moreover, two rounds of Forestry Camp, involving students and staff from the Faculty of Tropical Forestry, are held annually as part of the faculty's curriculum. Each round is attended by 120 participants (100 students and 20 staff) who camp for 10 days in the area. The calculations for water usage are as follows:

Toilet:

Vol. per flush	= 4.5 L
Est. no. of users per camp event	= 120 persons
Vol. of toilet water needed per user per day	= 13.5 L (Assume 3 flushes/person/day)
Vol. of toilet water used per day	= 13.5 L x 120 persons = 1,620 L
Vol. of toilet water used per camp event	= 1,620 L x 10 days = 16,200 L
Vol. of toilet water used for camp events per year	= 16,200 x 2 = 33,400 L

Washing & shower:

Vol. of water needed per user per day	= 20 L (survival training)
Est. no. of users per camp event	= 120 persons
Vol. of washing water needed per day	= 20 L x 120 persons = 2,400 L
Vol. of washing water needed per camp event	= 2,400 L x 10 days = 24,000 L
Vol. of washing water needed for camp events per year	= 24,000 L x 2 times = 48,000 L

Drinking water:

Vol. per user	= 2 L
Est. no. of users per camp event	= 120 persons
Vol. of drinking water needed per day	= 2 L x 120 persons = 240 L
Vol. of drinking water needed per camp event	= 240 L x 10 days = 2,400 L
Vol. of drinking water needed for camp events per year	= 2,400 L x 2 times = 4,800 L

Table 1. Summary of annual water input and demand

Rain (mm)	Collection (L)	Annual Demand (L)			Total Annual Demand (L)
		Toilet	Washing	Drink	
2,718.1	122,314.5	45,031.1	48,000.0	4,920.0	97,951.1

For forestry training camps, water-use assumptions are based on regulated quotas used for survival training, where daily washing and shower allowances are intentionally restricted to 20 L per person and toilet use is limited to approximately three flushes per day. Water consumption figures were adapted from standard Malaysian civil and mechanical engineering guidelines for non-residential facilities (GreenBuildingIndex, 2025; GreenRE, 2025). In summary, the total water demand per year is 97,951.1 L, with 93,031.1 L being non-potable water (washing, shower, and toilet flushing) and 4,920 L being potable water (Table 1).

3.2. Basic Rainfall-Based Catchment Sizing

Long-term rainfall records for Kota Kinabalu (Deutscher Wetterdienst n.d.; World Meteorological Organization n.d.) were analyzed to determine annual totals and seasonal distribution, which form the basis of the catchment sizing calculations described below:

Given that,

Annual rain	= 2,718 mm
Runoff coefficient	= 0.9 (for metal roof)
Intended collection volume	= 9.75911×10^{10} mm^3 (97,951.1 L)
Surface area	= Intended collection volume / (Annual rain x Runoff coefficient)
	= 9.75911×10^{10} mm^3 / (2,718 mm x 0.9)
	= 39,894,980 mm^2
	= 39.89 m^2

3.3. Designed Catchment and Estimated Yield

During the initial planning of the project, it was stipulated that a small shed be constructed alongside the RWHS to accommodate a small crowd. The shed was designed and built with roof dimensions of 10 × 5 m (50 m²), exceeding the minimum requirement. The physical layout of the catchment and conveyance system was designed to ensure efficient rainwater collection and ease of maintenance, as outlined below.

| Collection volume	= Surface area x Annual rain x Runoff coefficient
	= 50,000,000 mm^2 x 2,718 mm x 0.9
	= 122,314.5 L (24,363.4 L excess)

Monthly rainfall patterns and the resulting surplus/deficit analysis are presented in Section 3 as part of the system performance evaluation.

3.4. First-flush system

Before entering the primary collection tank and undergoing filtration, rainwater passes through a first-flush device. This device captures and retains the initial rainfall, releasing it after the rain event. The initial portion of rainwater, which is not harvested, triggers a valve upon reaching a certain volume, thereby allowing the collection of cleaner rainwater. The first-flush system prevents the initial, more polluted rainwater, contaminated by debris and dirt from washing the roof, from entering the primary tank. While this device increases the overall cost of the system, its benefits, including improved water quality and extended filter service life, outweigh the financial expense. Various designs and mechanisms for first-flush devices exist, such as manual-emptying, passive auto-emptying, spring-loaded, cyclone, and electronic systems. For this project, a passive, auto-emptying, float-type first-flush device from Blue-Mountain Co, Rain Harvesting was selected (Figure 2).

Since the first-flush system operates based on storage and timed release, a retention chamber is required to temporarily store the initial rainwater. The retention chamber, which forms the bottom portion of the device, is customizable to accommodate varying water volumes (Figure 2). According to current guidelines (Department of Irrigation and Drainage 2011), 2 mm of rainfall is recommended for first-flush. With a roof size of 50 m², the required retention chamber volume can be calculated as follows:

First-flush total volume	= First-flush rain depth x Roof area
	= 2 mm x 50,000,000 mm^2
	= 100,000,000 mm^3
	= 100 L
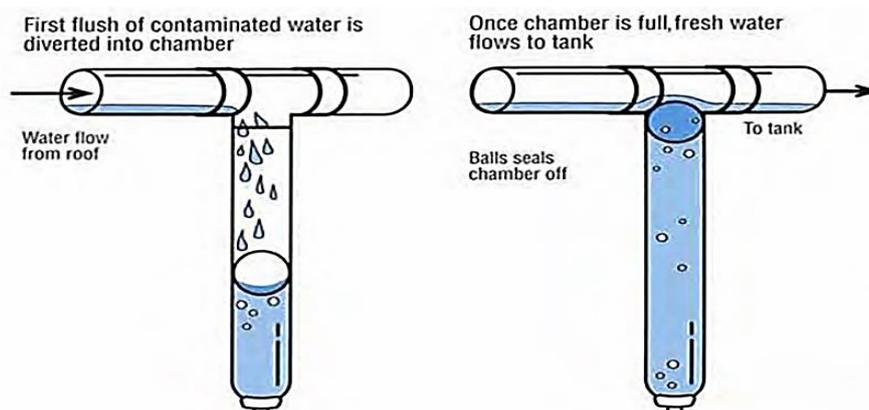
Figure 2. Principles of operation of the first-flush-system in use (Source: (BlueMountain Co))

The retention chamber should have a capacity of at least 100 L. For this construction, the chamber consists of two connected PVC pipes clamped to the shed's pillar (Figure 3). Each pipe measures 152.3 mm in diameter and 3.3 m in length, resulting in a total chamber volume of 120.4 L.

Two interconnected 152.3 mm pipes, 3.3 m

Figure 3. First-flush retention chamber

4. RESULTS AND DISCUSSION
4.1 Climate-Based Optimization and Monthly Surplus/Deficit

Total rainwater collection and water demand, however, represent only one aspect of the water balance and are insufficient for designing an effective RWHS. Although the area has an equatorial climate, hot and humid year-round, rainfall is characterized by seasonality and monsoonal phases (Mahali et al. 2020; Tanaka et al. 2023). The Northeast Monsoon typically begins in early November and lasts until March, bringing steady winds from the east or northeast (10–30 knots) and increased rainfall in Kota Kinabalu. The Southwest Monsoon, lasting from late May or early June to September, brings lighter winds, below 15 knots, from the southwest and is relatively drier than the Northeast Monsoon. Between these major monsoon periods, two inter-monsoon phases occur: late March to early May and October to mid-November, characterized by light, variable winds and frequent afternoon thunderstorms (Toosi et al. 2020). In terms of resultant rainfall, January to May are relatively dry months, while June to December are wetter. February (78 mm) and March (93 mm) are particularly dry, whereas June to November is especially wet (278–387 mm).

Due to the temporal heterogeneity of rainfall and water demand, long-term averages of monthly rainfall and water demand are required to determine the appropriate water storage capacity. Using long-term averages of monthly rainfall (Deutscher Wetterdienst n.d.; World Meteorological Organization n.d.), the total possible water collection by month

was calculated. These figures were then compared with the calculated monthly water demand to determine periods of surplus or deficit (Table 2; Figures 4 and 5).

Referring to Table 2, a water surplus occurs in all months except August and September. Without additional water storage facilities, this RWHS can supplement 12,537 L (28.76%) and 12,929 L (29.68%) of the water demand in August and September, respectively, making the design highly viable. Considering the volume of water surplus in the three months preceding August (31,432 L), seven 4,500-L water tanks would be required to fully meet the water demand in August. Fourteen such tanks, seven additional tanks, would be sufficient to meet the water demand for both August and September, with collection starting from December of the preceding year. However, even without additional water storage tanks, the system can significantly reduce dependency on the domestic water supply.

The recommended addition of seven to fourteen 4,500-L polyethylene tanks is feasible because the tanks are installed externally beside the shed rather than within the gathering space itself. Each tank requires only a small level base, approximately 1.4 m in diameter, and can be positioned along the cleared perimeter without affecting the shed's use for educational or recreational activities. Installation is modular, allowing tanks to be added incrementally as funding permits. Based on prevailing local prices, a single 4,500-L tank with basic fittings costs approximately RM 1,000–1,200, giving an estimated additional investment of RM 7,000–17,000 depending on the final number of units. Plumbing connections can be integrated into the existing conveyance system with minimal disruption to current operations.
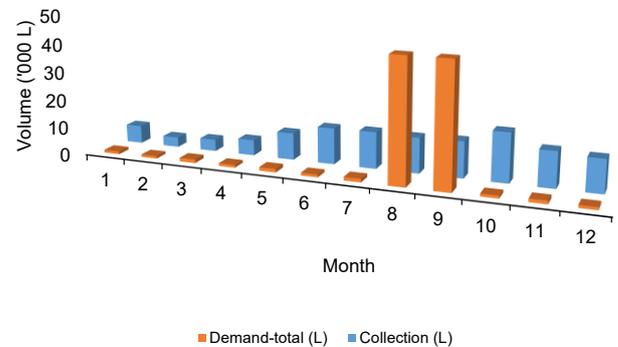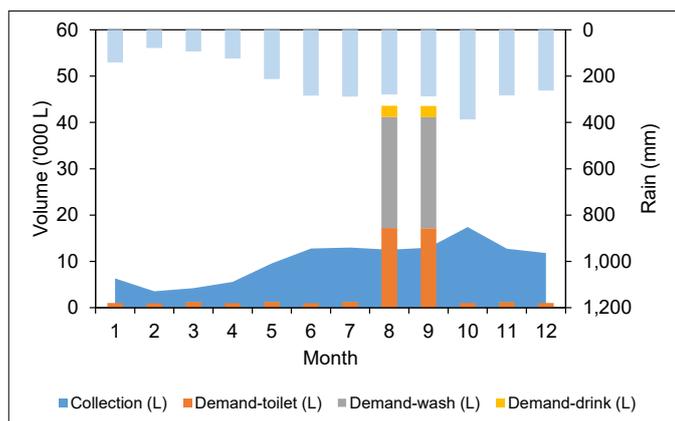

Figure 4. Monthly water collection and total demand

Table 2. Monthly rain, water collection, and water demand

Hydrological component	Month												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Rain (mm)	141	78	93	123	212	284	288	279	287	387	283	262	2,718.1
Collection (L)	6,332	3,515	4,190	5,553	9,554	12,776	12,974	12,537	12,929	17,429	12,749	11,781	122,314.5
Demand-toilet (L)	996	900	1,221	964	1,221	964	1,221	17,196	17,164	996	1,189	996	45,031.1
Demand-wash (L)	0	0	0	0	0	0	0	24,000	24,000	0	0	0	48,000.0
Demand-drink (L)	0	0	30	0	30	0	30	2,400	2,400	0	30	0	4,920.0
Demand-total (L)	996	900	1,251	964	1,251	964	1,251	43,596	43,564	996	1,219	996	97,951.1

Figure 5. Monthly rain, water collection, and water demand (toilet, washing, and drinking)

In addition to water demand and rainfall characteristics, factors such as practicality, scalability, and economics were also considered. Economic constraints influenced the size of the shed and roof catchment, thereby affecting the potential rainwater collection volume. The entire project, including the construction of a 10 × 5 m shed, rainwater collection and filtration system, potable water treatment system, and a four-cubicle toilet, had to be completed within a budget of RM 90,000 (USD 19,106.25 at the time of writing). The resultant construction is shown in the attached as-built drawing in the Appendix.

The sizing calculations proved effective, as sufficient water was harvested and stored for the intended usage without any issues of water stress. The calculation of potential rainwater harvesting volume was based on the Department of Irrigation and Drainage Malaysia formula (Department of Irrigation and Drainage 2011; 2017). Water demand values, such as per capita usage and flushing volume, were adapted from standard values commonly used in Malaysian civil and mechanical engineering practices, as well as in the construction field. For ease of use, a public-access online calculator was developed and hosted at https://sites.google.com/view/rwhscalculator/home. This calculator is maintained by the author, with periodic revisions and updates available.

4.2. Further Discussion

Testing and commissioning of the rainwater harvesting system (RWHS) demonstrated its functionality and effectiveness. The first-flush mechanism, designed to capture and release the initial rainfall to flush contaminants from the roof, worked as intended. Observations showed that the first-flush containment chamber was filled after each rain event, thus indicating the successful initiation of rainwater collection. Laboratory tests confirmed that the potable water treatment system produced water safe for consumption, meeting expected quality standards. Despite these positive outcomes, the implementation and operation of the system highlight several aspects worthy of further discussion.

Although no flow meter was installed during the pilot phase, routine observations during events and daily use showed that the 4,500 L primary storage tank was never completely depleted, indicating that harvested rainwater consistently met the calculated demand. This qualitative performance is consistent with the surplus–deficit analysis based on long-term rainfall data. Future upgrades will incorporate volumetric flow monitoring and routine water-quality sampling to provide continuous quantitative records of system yield and treatment performance.

The current rainwater harvesting system (RWHS) offers several advantages and some limitations. Among its key benefits, the system is cost-effective due to the use of locally sourced materials, such as PVC pipes and metal roofing, which help to significantly reduce construction costs. Its modular design allows for scalability, enabling future expansion, such as adding more storage tanks to accommodate increased demand. Additionally, the system contributes to sustainability by relying on gravity for water distribution, which minimizes energy input and reduces its carbon footprint (Ghimire and Johnston 2019; Musz-Pomorska et al. 2021; Zang et al. 2021; de Sá Silva et al. 2022). Furthermore, the system holds substantial educational value, serving as a practical demonstration tool for students and researchers, fostering awareness of water conservation practices. However, the system also has certain drawbacks. It requires regular maintenance of the first-flush mechanism, filters, and storage tanks to maintain optimal performance. The current storage capacity may prove insufficient during extended dry periods or high-demand events, such as forestry camps. Moreover, the use of cost-effective materials like PVC could lead to reduced durability, necessitating replacements over time.

The choice of materials and design elements significantly impacts the performance and cost of the RWHS. For instance, using concrete roofing instead of metal would have altered runoff characteristics. Concrete surfaces typically have lower runoff coefficients due to their porosity, leading to reduced water collection efficiency. Additionally, concrete roofing is heavier and requires a more robust structural framework, increasing construction costs. Similarly, underground storage tanks, while protecting water from temperature fluctuations and algae growth, involve higher installation and maintenance costs. Such a design might be preferable in urban environments, but is less practical for the educational and recreational purposes of SFERA@UMS (Minnesota Pollution Control Agency n.d.; Centre for Science and Environment n.d.; García-Ávila et al. 2023).

The total project cost was approximately RM 90,000, which covered construction of the 10 × 5 m multipurpose shed, four-cubicle toilets, and the rainwater harvesting and treatment system. Because the shed and toilets would have been built regardless of the RWHS, the incremental cost attributable to the RWHS is about RM 30,000. Based on an annual harvested demand of roughly 98 m³, purchasing equivalent tanker water at RM 700 per 20,000 L would cost approximately RM 3,430 per year, whereas the same volume from a municipal connection (if available) would cost only approximately RM 118 per year at the current Sabah domestic tariff of RM 1.20/m³ (rate for government facilities) (JANS, 2025). Using the incremental RWHS cost, the simple payback period is about 9 years compared with tanker purchase, while the cost per litre of harvested rainwater over a 20 year design life falls to RM 0.015 per litre (RM 15/m³). Because the SFERA@UMS site has no municipal water connection, the relevant economic benchmark is the delivered cost of tanker water, and the rainwater harvesting system provides a practical and cost-competitive alternative to regular tanker deliveries while ensuring a reliable on-site supply.

In the absence of measured collection volumes, the SFERA@UMS system can be compared with other tropical installations in terms of design ratios and theoretical collection potential. For example, the roof-area-to-annual-demand ratio at SFERA@UMS is 0.51 m² per 1,000 L of annual demand, which is similar to ratios reported for small-scale systems in

Singapore (0.55 m² per 1,000 L) and southern India (0.48 m² per 1,000 L) (Lim and Lu 2016; Khan et al. 2023). Likewise, the planned storage volume represents roughly 45% of the mean monthly rainfall input, a proportion comparable to design recommendations for high-rainfall equatorial climates. These cross-site comparisons suggest that the SFERA@UMS design provides a conservative yet efficient balance between catchment size and storage, despite the absence of direct yield measurements.

One potential issue with the RWHS is its dependence on consistent rainfall. While the equatorial region of Sabah, Malaysia, experiences high annual rainfall, seasonal variations, such as drier months during the Southwest Monsoon, could lead to temporary water deficits, particularly if storage capacity is insufficient. This situation underscores the importance of designing systems with adequate storage to bridge periods of low rainfall (Toosi et al. 2020). Another concern is the maintenance of the first-flush mechanism and filtration system. Accumulated debris and sediment in the first-flush chamber and filters can reduce system efficiency and require regular cleaning. Neglecting maintenance could result in reduced water quality and flow rates (Mat Daud et al. 2021). Additionally, the use of PVC pipes for the first-flush retention chamber, while cost-effective, may pose durability concerns over long-term exposure to UV radiation and weather conditions.

Rainwater harvesting systems are widely used across the globe, particularly in regions facing water scarcity. For instance, RWHS projects in arid regions of Australia and India often incorporate large underground storage tanks and concrete catchments to maximize water retention and minimize evaporation losses (Mehrabadi et al. 2013; Chubaka et al. 2018; Habibullah et al. 2023; Khan et al. 2023). In contrast, our project employs a metal roof catchment and above-ground storage tanks, which are suitable for the high rainfall and humid conditions of Sabah. While underground systems provide better insulation against temperature variations, they are more expensive to construct and maintain compared to above-ground alternatives. In urban settings, such as Singapore, RWHS are often integrated with green roofs and stormwater management systems to address both water conservation and urban flooding issues (Lim and Lu 2016). Compared to these urban systems, our design is simpler and more cost-effective, prioritizing functionality and scalability for educational and recreational purposes rather than urban infrastructure challenges.

Although direct volumetric measurements are not yet available for this project, comparable case studies help situate the design. A household-scale system in a humid tropical setting (Bangladesh) reported ≈313,800 L yr⁻¹ from an ≈171.9 m² roof (1,850 ft²), equivalent to approximately 0.55 m² per 1,000 L yr⁻¹ under local rainfall conditions (Rahman et al. 2014). At a Malaysian university residence block (Perlis), a ~998 m² roof yielded 1,124.74 m³ over four wet-season months (May, Aug–Oct), demonstrating the high short-term potential in monsoonal climates. On a per-period basis this is approximately 0.89 m² per 1,000 L for that 4 month interval (Yahya et al. 2016). For larger roofs, modelling and field-calibrated studies in Malaysia indicate that tank sizing and reliability, for example a 160 m³ tank for a 20,000 m² roof at approximately 60% supply reliability, are dominant drivers of performance, reinforcing the importance of storage relative to catchment area in high-rainfall settings (Lani et al. 2018). Using the same ratio for SFERA@UMS (design demand 97,951 L yr⁻¹, roof 50 m²), the roof-area-to-demand metric is approximately 0.51 m² per 1,000 L yr⁻¹, which sits within the range implied by these cases. Together, these comparisons support the sizing logic adopted here and emphasise storage flexibility as the key lever for bridging short dry spells even where annual rainfall is high.

The successful implementation of this RWHS highlights the potential for similar systems in other regions with comparable climatic conditions. The design principles can be adapted to suit varying water demands, rainfall patterns, and budgetary constraints. Future improvements could include the integration of automated monitoring systems to track water levels and quality, reducing manual maintenance efforts (Tolossa et al. 2020; Raimondi et al. 2024). Furthermore, incorporating renewable energy sources, such as solar panels, to power water pumps and filtration systems could enhance sustainability. Additional studies comparing the long-term performance and cost-effectiveness of different materials and designs would provide valuable insights for optimizing RWHS in diverse settings.

Long-term climate projections for Sabah indicate a likely increase in the intensity and variability of rainfall events, with some models suggesting drier inter-monsoon periods but more frequent extreme downpours during the wet season (Huang et al. 2023; Leong et al. 2024). Such changes could affect rainwater harvesting systems by increasing short-term collection potential while lengthening dry spells between major events. For SFERA@UMS, this underscores the importance of adequate storage capacity and flexible system expansion to buffer against extended dry periods, even under a generally high annual rainfall regime.

4.3. Key Findings & Outcomes

The performance of the SFERA@UMS rainwater harvesting system demonstrates that a relatively small roof catchment (50 m²), combined with above-ground storage tanks, can supply the calculated annual water demand of 97,951 L under the prevailing equatorial climate. The monthly surplus–deficit analysis shows that only August and September experience potential shortfalls, which can be mitigated by adding storage tanks to capture excess rain from preceding wet months. System commissioning confirmed that the first-flush mechanism and treatment unit consistently produced potable water that met quality standards.

From a design perspective, three practical lessons emerged:
1. Storage flexibility is essential for coping with seasonal rainfall variability despite high annual totals.
2. Simple construction materials, such as metal roofing and PVC piping, provide a cost-effective balance between functionality and ease of maintenance.
3. Educational value is significant, as the system serves as a live demonstration of sustainable water management for students and visitors.

These outcomes underscore the feasibility of small-scale RWHS for non-potable and limited potable uses in high-rainfall tropical settings, and they provide a replicable reference for similar forest-based facilities.

5. CONCLUSIONS

The pilot rainwater harvesting system (RWHS) at SFERA@UMS demonstrates that a small, modular installation can reliably meet the non-potable and limited potable water needs of an educational forest reserve under high-rainfall equatorial conditions. The sizing calculations, cost information, and design ratios provide a replicable reference for similar projects where long-term rainfall data are available but on-site hydrological records are lacking.

This project serves as a valuable model for the design and implementation of RWHS in similar contexts, advancing water-conservation efforts and resilience to water scarcity. To support broader adoption, an online RWHS calculator was developed to help users estimate the required roof size and materials based on targeted collection volumes and annual rainfall. This tool, maintained by the lead author, is accessible at https://sites.google.com/view/rwhscalculator/home. With abundant annual rainfall, rainwater harvesting represents a practical solution for equatorial regions. However, in Sabah, Malaysia, adoption is currently limited by low water tariffs; nevertheless, increasing water stress and rising tariffs may incentivize wider implementation in the future. For now, basic systems designed for non-potable uses, such as washing and sanitation, remain a feasible and viable option.

Several limitations should be acknowledged. The reported annual collection of 122,314 L is a theoretical estimate, as no flow meter was installed and routine water-quality measurements were not undertaken. The economic assessment is preliminary and based on construction costs and estimated tariffs rather than a full life-cycle cost–benefit analysis.

Future work should incorporate flow and water-quality monitoring, explore automated level sensors, and evaluate long-term climate change impacts on rainfall variability to refine system sizing. Comparative economic analyses that include municipal tariff trends and tanker-water prices would strengthen understanding of cost effectiveness.

Despite these limitations, the project offers practical lessons for campus and community water management in Malaysia and other high-rainfall tropical settings. The modular design allows incremental expansion of storage and can serve as a demonstration site for education, policy engagement, and capacity building in sustainable water management.

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