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Rooftop Rainwater Harvesting Feasibility at a High-Altitude University Campus in Northeast India: Meteorological Analysis, Field Collection and Groundwater Recharge Potential

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ABSTRACT

Water scarcity during dry months paradoxically affects areas of high rainfall; Shillong, Meghalaya, receives over 2000 mm annually yet faces critical water shortages from October to March. This study evaluates the feasibility of rooftop rainwater harvesting (RWH) as a groundwater recharge and supplemental water supply strategy at North-Eastern Hill University (NEHU), Shillong, using meteorological analysis, field-based rainfall collection and a campus infrastructure audit. Daily meteorological data from the India Meteorological Department (IMD), Shillong, covering 31 March to 26 June 2024 (1023.3 mm total; 57 rainy days) were analyzed alongside 36 field collection events on the rooftop of the Department of Environmental Studies. Total field-collected volume was 2775.60 L, with May (1376.33 L) and June (1317.79 L) accounting for 97.1% of the total. An audit of campus water infrastructure,12 drill pumps, 6 reservoirs and over 80 buildings, confirmed near-total groundwater dependence. Campus-wide harvestable rooftop potential was estimated at 20,031,609 L for the study period and approximately 39.15 million L annually (runoff coefficient Cf = 0.85; 2% first-flush loss). These findings indicate that a systematically implemented RWH network at NEHU could substantially reduce groundwater extraction, particularly through monsoon-season storage for dry-season use. Implementation of a campus-wide RWH system would contribute to sustainable campus water management, reduce pressure on the shallow fractured aquifer beneath the Shillong Plateau, and provide a replicable model for other high-rainfall highland institutions facing seasonal water insecurity.

Keywords Rainwater harvesting, Groundwater recharge, Shillong, Northeast India, Campus water management.

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INTRODUCTION

Freshwater constitutes only 3% of total global wa-

ter resources, of which roughly 69% is frozen in glaciers and ice caps; accessible groundwater and surface water together represent less than 1% of the Earth's total water (UNESCO 2022). This scarcity is compounded by accelerating urbanization, population growth and climate-driven variability, creating acute stress on local water systems even in regions of nominally high rainfall (Grafton *et al.* 2017). The Northeastern hill states of India exemplify this contradiction. Meghalaya, home to Cherrapunji and Mawsynram, among the wettest places on Earth, nonetheless faces severe dry-season water shortages (Majaw 2023). Shillong, the state capital, averages over 2000 mm of annual rainfall, yet inadequate storage infrastructure means that communities and institutions face frequent supply disruptions from October through March (Liansangpuii *et al.* 2024). This temporal mismatch between supply and demand is the central water management challenge of the region.

Rainwater harvesting (RWH) is a technology with demonstrated effectiveness across diverse climatic and socio-economic contexts for bridging this seasonal gap. Defined as the collection, storage and utilization of precipitation at or near the point of fall, RWH encompasses rooftop systems, surface runoff collection and sub-surface infiltration structures (Huang *et al.* 2021). For institutional settings, rooftop RWH is particularly attractive because large, impermeable roof areas concentrate rainfall into manageable flow paths, runoff coefficients are high (0.80–0.90 for concrete), and the resulting stored water can serve non-potable or, after treatment, potable purposes (Mishra *et al.* 2020).

University campuses represent ideal pilot environments for RWH systems. Their large roof areas, predictable water demand patterns, institutional capacity for monitoring and maintenance, and potential as demonstration sites for environmental education make them high-priority targets for sustainable water infrastructure (Silvia *et al.* 2021; Murthy *et al.* 2021). Recent institutional-scale RWH studies confirm that large-footprint establishments represent underutilized collection opportunities even in water-secure climates (Naik *et al.* 2024). North-Eastern Hill University (NEHU), Shillong, operates a sprawling campus that includes academic buildings, hostels, residential quarters, service structures and recreational areas, all currently served entirely by groundwater extracted through 12 drillpumps and distributed via 6 large reservoirs. Despite the obvious relevance of RWH to NEHU's sustainability goals, no systematic assessment of the campus's rooftop collection potential has previously been published. This study addresses that gap through : (i) Analysis of IMD daily meteorological data for the pre-monsoon and early monsoon period (March–June 2024), (ii) A field rainfall collection experiment on the rooftop of the Department of Environmental Studies; (iii) An audit of campus water infrastructure, and (iv) Quantitative estimation of harvestable volumes under current roof area conditions.

MATERIALS AND METHODS

Study area

NEHU is located at approximately 25.58°N, 91.89°E in Shillong, Meghalaya, at an elevation of roughly 1500 m above mean sea level (Fig. 1). The University campus is set on the Shillong Plateau, underlain by Archaean crystalline basement rocks and Precambrian gneisses, which support shallow fractured aquifers recharged primarily by monsoon precipitation. Shillong experiences a humid subtropical highland climate (Köppen : Cwb), with a distinct monsoon from June to September, a dry winter from October to February and a transitional pre-monsoon in March–May. The Department of Environmental Studies, located within the campus, served as the primary field site for this study.

Meteorological data acquisition

Daily meteorological data for Shillong were obtained from official bulletins published by the IMD Shillong Regional Meteorological Center (https://mausam.imd.gov.in/shillong/) for the period 31 March to 26 June 2024 (88 days). Parameters recorded included: Maximum and minimum daily temperature (°C), average temperature (°C), relative humidity (%), wind speed (km/h) and direction, and 24-hour cumulative rainfall (mm) measured at 0830 IST. "Trace" values (below the 0.1 mm instrumental resolution) were treated as zero for quantitative analysis. Monthly

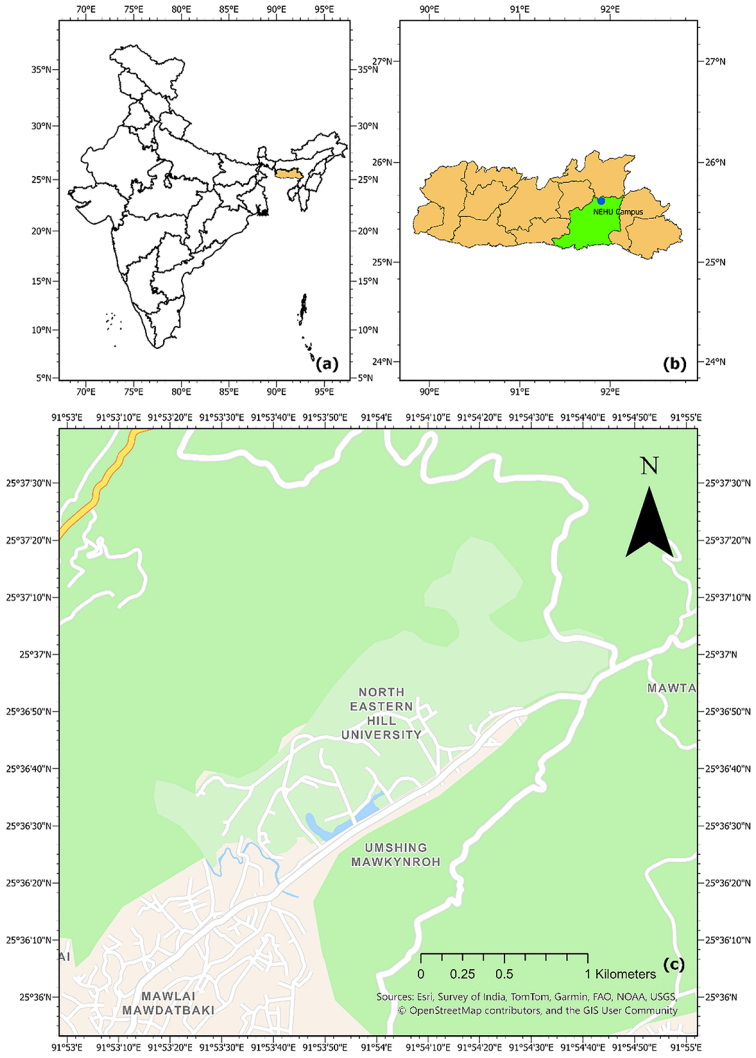


Fig. 1. Study area map (a) Meghalaya, (b) East Khasi Hill district with NEHU location, (c) NEHU campus in the Northern Shillong region.

aggregates, means and maxima were computed for all parameters.

Field rainfall collection

A controlled collection experiment was conducted on the rooftop of the Department of Environmental Studies using a rectangular container (length 58.4 cm × width 27.5 cm × height 30 cm; catchment area = 0.1606 m²; maximum capacity ≈ 48.2 L). The container remained in a fixed position on the rooftop throughout the study period (31 March–25 June 2024) and was not relocated between events. The container collected rainfall during precipitation events and was measured the following morning or, for afternoon events, the same day. Volume was computed as V = l × w × h, where h is the measured standing-water depth in the container, and converted to liters (1 L = 1000 cm³). Collection spanned 36 rain events from 31 March to 25 June 2024. The water level in the container was recorded daily ; on days without rainfall, the standing water depth was verified to re-

main unchanged, confirming that evaporation losses between rainfall and measurement were negligible over the short overnight interval.

Campus infrastructure audit

A systematic inventory of campus water storage was conducted from official records of the University's Engineering and Works Department, covering residential quarters (30 entries), academic buildings (27 entries) and service buildings (9 entries). Data collected included PVC tank capacities (300–5000 L) and RCC tank capacities (up to 700,000 L).

Rooftop harvesting potential estimation

Theoretical harvestable volume was estimated using the standard volumetric equation (Sample and Liu 2014, Krishna 2005) :

$$V = R \times A \times Cf \times (1 - Ff) \quad (1)$$

Where, V is the harvestable volume (m^3), R is total rainfall depth (m), A is roof catchment area (m^2), Cf is the runoff coefficient (0.85 for concrete/RCC rooftops; Krishna 2005) and Ff is the first-flush loss factor (0.02, i.e. 2%). Rooftop areas were estimated by zone based on direct field measurements of building footprints conducted during the campus infrastructure survey, cross-verified against available engineering drawings where accessible: Department of Environmental Studies = 500 m^2; academic buildings = 8,500 m^2; residential quarters = 12,000 m^2; service buildings = 3,000 m^2; total campus = 23,500 m^2. Calculations were performed for (a) the study period (R = 1.0233 m) and (b) annualized values using the long-term mean of 2000 mm/year for Shillong.

RESULTS AND DISCUSSION

Meteorological characteristics of the study period

The study period (31 March–26 June 2024) encompassed the late dry season, pre-monsoon transition and monsoon onset over Shillong. A total of 1023.3 mm of rainfall was recorded by the IMD station over 88 days, of which 57 days, or 65% of the study period, recorded measurable precipitation. Monthly meteorological parameters are summarized in Table 1.

Temperature showed a declining trend from April through June (Table 1, Fig. 2), with mean daily values dropping from 22.9°C in April to 20.3°C in May and 20.6°C in June, reflecting the cooling influence of monsoon precipitation. Relative humidity increased markedly with monsoon advance, rising from 66.7% in April to 90.2% in June (Fig. 3). This pattern is consistent with the documented seasonal progression of the Bay of Bengal monsoon branch across the Shillong Plateau (Liansangpuii *et al*. 2024).

May 2024 was the highest rainfall month, with 565.1 mm recorded over 31 days, 24 of which received measurable precipitation (77%). The single highest daily event was 242.4 mm on 28 May 2024, coinciding with the passage of post-Cyclone Remal weather systems across the North-Eastern states. June recorded 405.9 mm over 25 rainy days (96% of the month), confirming established monsoon conditions. A remarkable 47% of total study-period rainfall fell on only five days (5.7% of the period), underscoring the episodic, high-intensity character of rainfall in this region and the critical need for high-capacity storage infrastructure.

Field rainfall collection results

Over the 36 collection events, a total of 2775.60 L was harvested on the rooftop of the Department of Environmental Studies (Table 2). The mean volume per event was 77.10 L (standard deviation: 113.17 L), reflecting the high variability typical of tropical monsoon rainfall regimes (Huang *et al.* 2021). May and June together accounted for 97.1% of total collected volume (2694.12 L), consistent with the IMD rainfall distribution.

The event-by-event distribution of collected volumes is shown in Fig. 4. The single largest event recorded 520.29 L on 27 May 2024, associated with pre-monsoon convective activity and Cyclone Remal aftermath. The five largest events collectively contributed 1520.79 L, representing 54.8% of the total collected volume. This strongly skewed distribution is a characteristic of humid subtropical highland climates and has direct implications for RWH system

Table 1. Monthly meteorological summary, Shillong, March–June 2024 (IMD data; RH = relative humidity).

Month	Total Rainfall (mm)	Mean Daily Rainfall (mm)	Max Daily Rainfall (mm)	Mean Avg Temp (°C)	Mean RH (%)	Rain Days
March 2024	0.4	0.40	0.4	23.0	86.0	1
April 2024	51.9	1.73	26.4	22.9	66.7	7
May 2024	565.1	18.23	242.4	20.3	84.7	24
June 2024	405.9	15.61	54.0	20.6	90.2	25
Total/Mean	**1023.3**	**11.88**	**242.4**	**21.0**	**80.1**	**57**

design: Storage tanks must be sized to handle peak monsoon inflows, while retaining water through the seven-to-eight month dry period. April and March together yielded only 81.48 L (2.9% of total), confirming the near-complete absence of exploitable rainfall outside the monsoon window. Comparable studies from Mizoram (Majaw 2023) and campus-scale RWH assessments in Indonesia (Silvia *et al.* 2021) report similar monsoon concentration patterns.

A direct monthly comparison between IMD-recorded rainfall and field-collected volume further illustrates the strong seasonal signal governing harvesting potential at NEHU (Fig. 5). While the two datasets are expressed in different units, rainfall depth in millimeters and collected volume in L from a 0.1606 m² container, their monthly trajectories are closely aligned, confirming the representativeness of the field collection experiment. May recorded the highest values in both datasets (565.1 mm IMD; 1376.33 L collected), followed by June (405.9 mm; 1317.79 L), while March and April together contributed negligibly to total collection. The proportional difference between May and June is more pronounced in the field collection data than in the IMD record: Despite June receiving 71.8% of May's total IMD rainfall, field collection in June reached 95.7% of May's volume. This convergence likely reflects the sustained high-intensity events that characterised the established monsoon in June (mean relative humidity: 90.2%), which produced more efficient runoff per unit rainfall than the convective pre-monsoon storms

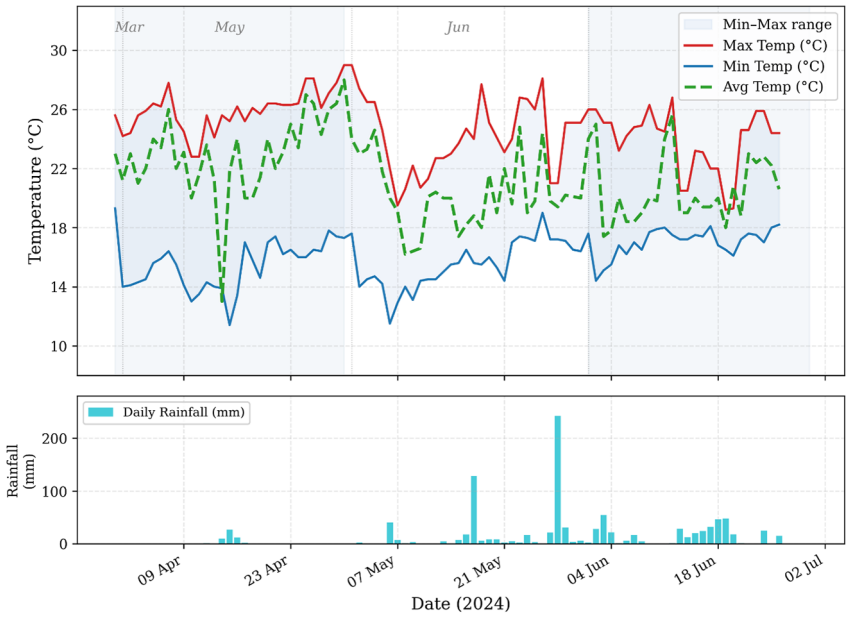


Fig. 2. Daily temperature trends at Shillong, March-June 2024 (Source: IMD).

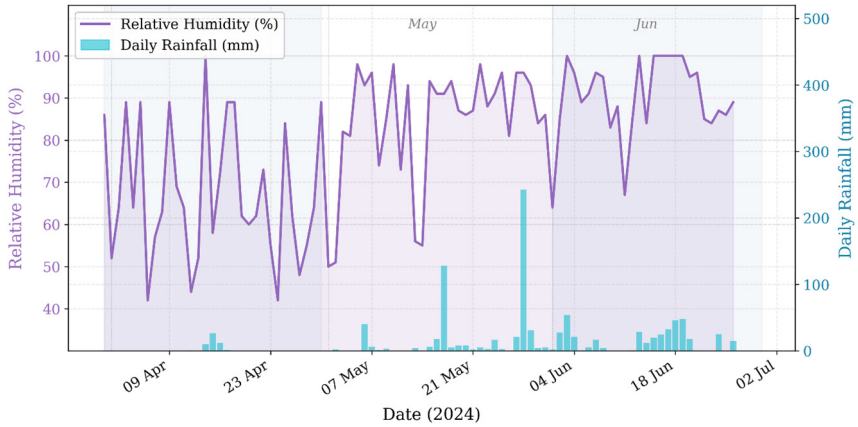


Fig. 3. Daily Relative Humidity and Rainfall at Shillong, March-June 2024 (Source: IMD).

of May. This finding has a practical implication for storage design, it suggests that the monsoon's second month (June–July) may be as important a collection window as the onset month, and that RWH tanks

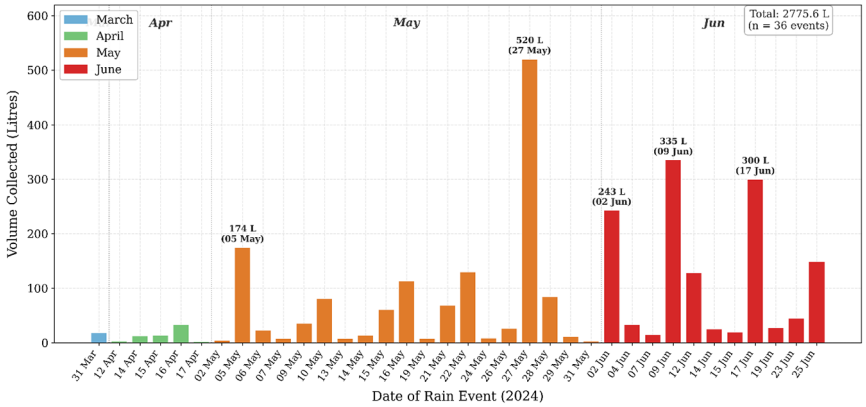


Fig. 4. Volume of rainwater collected per event – Rooftop, Department of Environmental Studies, NEHU, Shillong, 2024.

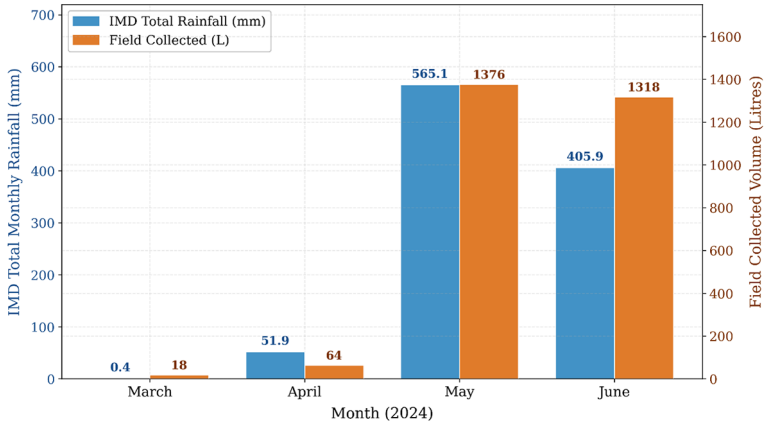


Fig. 5. Monthly IMD Rainfall vs Field-Collected Volume, Shillong, 2024.

Table 2. Summary of field-collected rooftop rainfall by month, NEHU, 2024.

Month	Events (n)	Total collected (L)	Mean per event (L)	Max Single Event (L)
March 2024	1	17.79	17.79	17.79 (31 Mar)
April 2024	5	63.70	12.74	33.21 (16 Apr)
May 2024	19	1376.33	72.44	520.29 (27 May)
June 2024	11	1317.79	119.80	335.38 (9 June)
Total	**36**	**2775.60**	**77.10**	**520.29 (27 May 2024)**

Table 3. Estimated rooftop RWH potential by campus zone (Cf = 0.85; first-flush loss = 2%).

Building/ Zone	Est. Roof Area (m²)	Study Period Potential (L)	Annual potential (L/yr)
Department of Environmental Studies	500	4,26,204	8,33,000
Academic Buildings	8,500	72,45,476	1,41,61,000
Residential Quarters	12,000	1,02,28,907	1,99,92,000
Service Buildings	3,000	25,57,227	49,98,000
Total Campus	**23,500**	**2,00,31,609**	**3,91,51,000**

sized only for the peak daily event rather than the cumulative monthly volume risk significant losses through overflow. Future work incorporating July–September data will be essential to determine the full monsoon-season harvestable window and, consequently, the minimum storage volume required to retain water through the dry season.

Rooftop harvesting potential and groundwater recharge implications

Application of Equation 1 to the estimated campus roof areas yields the harvesting potentials shown in Table 3. For the study period (1023.3 mm), of the campus-wide harvestable volume is estimated at over 20 million L. Annualized to Shillong's long-term mean of 2000 mm/year, the figure rises to approximately 39.15 million liters per year.

The annual campus harvestable volume of approximately 39.15 million L substantially exceeds the total documented static storage capacity of the campus (estimated at approximately 1.29 million L across PVC and RCC tanks), by a factor of roughly 30. This discrepancy highlights both the magnitude of the untapped resource and the infrastructure investment required to realize it. Liansangpuii *et al.* (2024) documented comparable scale mismatches at watershed-level interventions in Bundelkhand, where existing structures captured only a fraction of annual potential. Murthy *et al.* (2021) found a similar pattern in a Guntur municipal RWH framework, where the volumetric gap between potential and infrastructure capacity was the primary barrier to implementation.

Given that NEHU currently operates 12 drill-pumps continuously, even partial substitution of groundwater by harvested rainwater would yield measurable reductions in aquifer drawdown of the shallow fractured aquifer underlying the Shillong Plateau. Mishra *et al.* (2020) demonstrated in a similar University campus context that a rooftop RWH system could replace 40–60% of non-potable water demand. This study's data suggest comparable substitution is theoretically achievable at NEHU if adequate storage infrastructure is installed.

The strongly episodic rainfall distribution, with individual events exceeding 500 L on a single small catchment, requires first-flush diversion systems capable of handling extreme events. The 242.4 mm event on 28 May 2024 would have generated approximately 291,906 L from academic building rooftops alone. Overflow provisions and spillway design must therefore be considered integral to any RWH masterplan, rather than optional additions (Huang *et al.* 2021).

Key data gaps and recommendations

This study identifies several critical data gaps that limit quantitative conclusions. First, the study covers only the pre-monsoon and early monsoon window; dry-season data are needed to compute a full annual water balance and determine the storage volume required to bridge the October–March deficit. Second, no water quality analysis was conducted on collected rainwater; pH, turbidity, total dissolved solids, coliform bacteria and heavy metals must be assessed

before any potable application is contemplated. Third, campus roof areas were estimated from footprint measurements; accurate surveying via satellite imagery or architectural plan review would improve Equation 1 inputs. Fourth, the absence of campus water consumption records prevents a supply-versus-demand analysis, which would constitute the most powerful evidence base for investment decisions. Future work should address these gaps through an extended monitoring program, GIS-based roof area mapping, water quality testing and a structured consumption survey (Murthy *et al.* 2021, Mishra *et al.* 2020).

Meghalaya's indigenous traditions, including the bamboo drip irrigation systems of the Khasi and Jaintia communities and sacred grove management that passively maintains catchment hydrology (Das *et al.* 2023), offer complementary low-cost, community-oriented approaches that can be integrated into an institutional RWH framework at NEHU. A holistic RWH masterplan combining engineered infrastructure, traditional knowledge and policy enforcement would position NEHU as a model of sustainable water management in the Northeastern highlands.

CONCLUSION

This study presents the first systematic assessment of rooftop rainwater harvesting feasibility at North-Eastern Hill University, Shillong, combining meteorological data analysis, a controlled field collection experiment and a campus infrastructure audit. The study period (31 March–26 June 2024) recorded 1023.3 mm of total rainfall over 57 rainy days, with extreme-event intensities reaching 242.4 mm on a single day. A total of 2775.60 liters was collected across 36 field events from a rooftop container of 0.1606 m², with May and June alone contributing 97.1% of the total, underscoring the decisive role of the monsoon in determining collection viability.

Scaled to the full campus using the standard volumetric equation (Cf = 0.85; first-flush loss = 2%), the harvestable rooftop potential for the study period exceeds 20 million liters campus-wide, and the annualized estimate reaches approximately 39.15 million liters, approximately 30 times the current documented static storage capacity. These figures demonstrate that a systematically implemented RWH network could substantially reduce dependence on the 12 groundwater drill pumps that currently supply the entire campus, improve water security during the October–March dry season, and contribute to aquifer recharge beneath the Shillong Plateau.

The findings are directly applicable to other high-altitude, high-rainfall institutions in Northeast India and the broader Himalayan and sub-Himalayan belt, where seasonal mismatches between supply and demand are endemic. Immediate next steps should include year-round monitoring, precise GIS-based roof area mapping, water quality testing and a campus water demand survey to support a full feasibility plan and cost–benefit analysis for a NEHU RWH masterplan.

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