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Case Study

Quantifying Roof Catchment Yields for Improved Water Security in a Populated Built Dryland Ecosystem: The Case of Kitui Campus of Kenyatta University, Kenya

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Abstract

Water scarcity poses a significant challenge in semi-arid regions, with climate variability and growing demand exacerbating the strain on traditional water sources. As a contribution to sustainable water solution in a dryland region, this study reports the potential harvest from rooftop catchments in a populated built environment using Kenyatta University, Kitui Campus, in Kenya, as a case study. Roof catchment areas were computed using standard GIS procedures. Mean monthly rainfall was established using rainfall trends from 1981–2024. Estimated harvestable water was calculated standard formula for volume, but discounted for expected evaporation and seepage loses using applicable runoff coefficients. Results show that the entire campus can collect at least 11 million litres annually, with institutional buildings contributing 7.8 million litres and the staff quarters 3.4 million litres per year. With a population of about 1000 people coupled with water use efficiency, the campus can operate within a water secure scenario throughout the year. Seasonal analysis reveals that the October–December provides 361 mm of rainfall twice the volume of the March–May (MAM) which is 176 mm, necessitating strategic storage solutions to bridge dry periods. Based on the cost factor of above ground plastic tanks, this study proposes decentralized rainwater harvesting systems combining a series of large-capacity residential tanks available on the market (30,000-50,000 litres) for high-yield buildings and smaller tanks (5,000–20,000 litres) per individual residential houses. Lessons from this paper offer Kitui Campus, other learning environments, and households with ridged roof catchments, significantly opportunities through enhanced public health performance indicators and irrigation agriculture.
Keywords: Build Environment, Rainwater harvesting, Semi-arid regions, Water security

1. Introduction

Global water consumption is predicted to rise by 25% between 2020 and 2050, owing to population growth, agricultural expansion, and increased industrial production (van Vuuren et al. 2024). This surge will exacerbate water scarcity, undermining progress toward environmental, economic, and societal development goals (Mulwa et al. 2021). Similarly, supply of water is declining due to a variety of factors such as climate change, anthropogenic pollution, and unsustainable water management practices. Future projections indicate that global water demand will significantly exceed supply leading to widespread water scarcity and its negative impacts on human wellbeing (Gaikwad and Kadam 2019).

Although sub-Sahara Africa is largely medium to high potential in terms of agro-ecological zonation, water scarcity and water stress are an increasing challenge, a situation that is exacerbated by insufficient water development infrastructure, poor water governance, and overall insufficient investment in the water sector. Economic water scarcity presents a major challenge throughout much of SSA, as many populations lack the financial means to develop adequate water infrastructure. This economic imbalance stems from complex factors including political instability and ethnic tensions that have influenced wealth distribution (Gaikwad and Kadam 2019).

As such the high-water stress is estimated to negatively impact about 250 million people in Africa and to displace up to 700 million people by 2030. Further, 80% of African countries will experience sustainable water management challenges by 2030. According to van Vuuren et al. (2024), approximately 42% of the population in the African Great Lakes region does not have access to basic drinking water; which poses a high risk to public health through potentially poor sanitation management.

Sub-Saharan Africa (SSA) exhibits significant disparities in water resource distribution, with generally low per capita availability across the region.

While central African nations like the Democratic Republic of Congo, Republic of Congo, Angola, and Cameroon benefit from abundant water supplies, countries in the eastern Horn of Africa, western Sahel, and southern regions (including Kenya, Burkina Faso, Niger, and Zimbabwe) experience severe water constraints due to unreliable rainfall patterns and poor watershed management (Mutsotso et al. 2018).

Although Kenya is served by 5 major water towers that recharge the main perennial rivers namely Tana, Athi, Ewaso Ngiro, Nyando, Nzoia, Yala, Mara and Turkwell (Chepyegon and Kamiya 2018), Kenya faces a critical water scarcity crisis, exacerbated by inefficient water management systems, recurrent droughts, pollution of water sources, and rising demand due to population growth. The country's renewable freshwater availability is estimated at approximately 692 CM per capita per year, far below the United Nations threshold of 1,000 m^3 for water security (UNEP 2018).

With increasing water withdrawal rates exceeding 25% of its renewable fresh water resources, the situation can only get worse, particularly in the arid and semi-arid lands that constitute more than 70% of Kenya’s land mass (Chepyegon and Kamiya 2018). Further, with an estimated population of 54 million, 27% of Kenyans lack access to safe water and 68% lack access to a safe toilet, which increases the risk of poor sanitation especially in urban informal settlements cannot be over-emphasised.

Projections show that, without sustainable interventions, per capita water availability may decline further to 500 m^3 by 2030, reaching the threshold of absolute water scarcity (Mulwa et al. 2021). Spatial disparities in water distribution further compound the crisis. Central highland water towers such as Mt. Kenya and Mau Forest supply approximately 75% of Kenya’s surface water, yet downstream regions suffer from over-extraction, pollution from agricultural and industrial runoff, and poor infrastructure (Ongoma et al. 2018).

Climate change intensifies these pressures, with glacial retreat on Mt. Kenya reducing dry-season flows, and erratic rainfall patterns weakening rainfed agriculture, which is relied upon by over 80% of rural households (Mwenge et al. 2009).

More specifically Kitui County in general experiences severe water shortages. Some areas in the county are even more devastated by droughts leading to perennial crop failure and livestock death, leading to persistent food and nutrition insecurities and integrated human ill-being. Like most parts of Kenya, Kitui County experiences a bimodal rainfall pattern with the long rains from March to May (MAM) and the short rains from October to December (OND). The annual rainfall range in Kitui County is 500-1050mm, with a mean of 900 mm. There is however significant variability, with the eastern part receiving about 336.5 mm per year (Kahinda et al. 2007).

Mutunga et al. (2022) observed a decreasing trend in mean annual rainfall in the period 1988-2018. Although not significant, mean annual temperature too has been increasing, which is also indicative of climate change and a driver of potentially high evaporation losses.

1.1. Scenarios for the Future

Although Kenya is classified as a water scarcity country, this challenge can be reversed by harnessing optional water solutions like treatment of urban domestic effluent to tertiary purification and rainwater harvesting and saving technologies. While the former is capital intensive and requires direct involvement of the governments, harvesting rainwater can be easily facilitated at household and institution levels.

The policy frameworks for this exist such as water being a basic right (CGK 2023), enhanced accessibility as provided for in the Water Act 2016, increased affordability as envisioned in Sessional Paper No. 1 of 2021 on National Water Policy, and pursuing sustainability dimension as articulated in the National Water Master Plan 2030 and Vision 2030. The moot question is however why actualisation of these visions and missions remain a perpetual pipe dream particularly in the current context of climate change and its impacts on livelihoods.

For Kitui County, water access was flagged as the 2nd pillar out of 6 in its development conceptual framework, with focus on dams, sand dams, bore holes and pipelines. The dimension of roof catchments, which every household should ideally have, appears marginalised. It may not therefore surprise that in 2019 Kitui county had an overall Human Development Index (HDI) of 0.480 compared to the national level of 0.520, which was indicative of poor to average performance.

The role of water scarcity in this HDI cannot be overemphasised. In an attempt to contribute to sustainable water solutions in the county, this paper focused on the potential of roof catchments in built environment using Kitui Campus of Kenyatta University as a case study. The university is expected to provide a showcasing environment of appropriate technology and its adoption. The guiding specific objectives were:

i. To quantify total available roof catchment areas for rainwater harvesting

ii. To quantify potential water yields based on seasonal rainfall patterns

1.2. Gap analysis

Previous studies on rainwater harvesting (RWH) in Kenya and similar semi-arid regions have primarily focused on household-level systems, agricultural applications (in-situ techniques such as zai pits, fanya juu terraces, and sand-storage dams in Kitui County), and general adoption factors. For instance, Kahinda et al. (2007) and Mwenge et al. (2009) modelled domestic RWH potential and tank sizing in rural South Africa, while studies in Kenya (Wanyonyi et al. 2015 in Machakos schools; Mutschinski and Coles 2023) assessed adoption among smallholders and schools, highlighting socio-economic barriers and modest water bill reductions. Sand dam research in Kitui has emphasized community-scale surface water harvesting for agriculture.

However, rarely integrated long-term satellite-derived rainfall trend analysis (Mann-Kendall and Sen's slope) with site-specific roof inventories, nor did they offer tailored decentralized storage recommendations for university campuses or similar large institutions in ASAL regions. Most importantly, many lacked comprehensive integration of seasonal variability (MAM vs. OND), building-level yield mapping, and policy alignment with IWRM at the institutional level.

This study fills these gaps by conducting a detailed GIS-based assessment of rooftop catchment areas across all major buildings at Kenyatta University Kitui Campus, quantifying potential yields, analyzing 44-year rainfall trends, and proposing practical decentralized RWH implementation strategies. It provides a replicable framework for other educational and public institutions in Kenya's arid and semi-arid lands.

2. Methodology

2.1. Computation of roof catchment areas and potential harvests

Roof footprints were mapped using ArcGIS 10.8 software. High-resolution satellite imagery (Google Earth Pro / Sentinel-2, ~10 m resolution, 2023) was georeferenced to GPS ground control points collected with a Garmin GPSMAP 64s. Polygons were digitized manually at a scale of 1:500–1:1000, then projected from WGS 84 (GCS) to UTM Zone 37S. (Figs. 1 and 2) Actual roof surface area was calculated as 1.15 × footprint area / cos 25°. While different blocks have different pitch angles, a pitch of 25 degrees was chosen as a reasonable general estimate for Kitui campus for being within the typical range for residential houses in Kenya of 15-45 degree (Okinyo 2025).

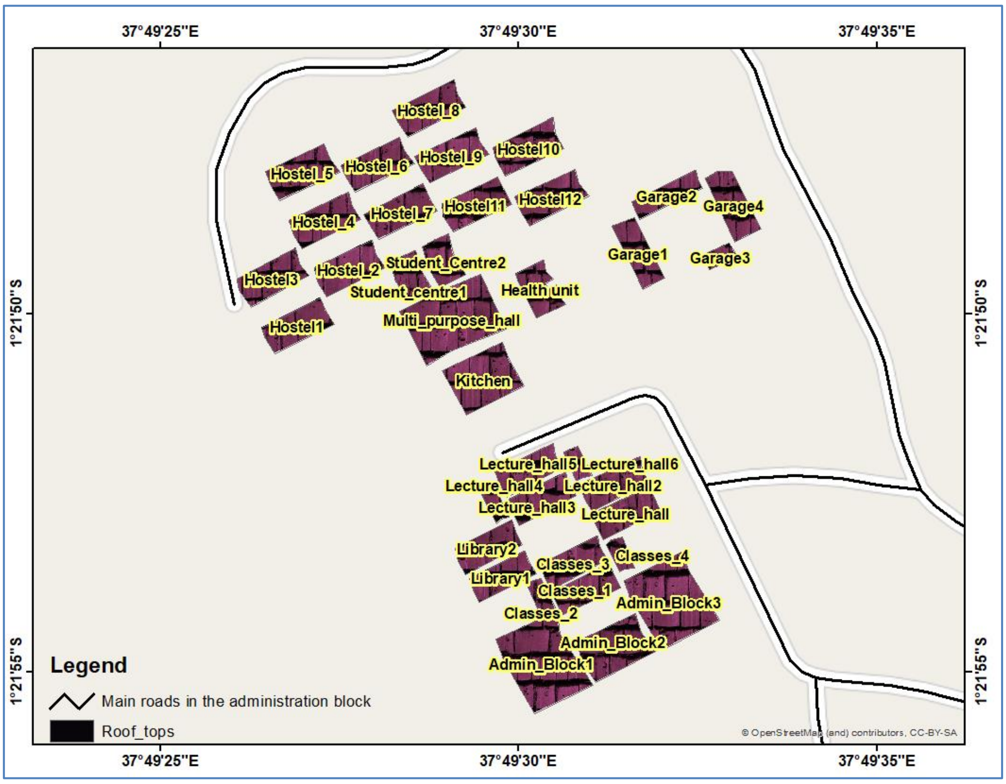

Fig. 1. Digitized satellite roof footprints of campus blocks

Fig. 2. Digitized Satellite roof footprints of Staff Quarters

2.2. Rainfall data analysis

Monthly rainfall data for Kitui County was obtained from CHIRPS data and analysed for seasonal and annual trends. Historical rainfall data for the study area (1981–2024) was obtained from NASA's POWER (Prediction of Worldwide Energy Resources) project via the https://power.larc.nasa.gov portal. The dataset provides gridded monthly rainfall estimates derived from satellite observations and re-analysis models, ensuring consistency and spatial coverage in arid and semi-arid environments. After extraction, the data was cleaned and aggregated annually in Microsoft Excel

Trend analysis was primarily based on non-parametric methods (Mann-Kendall test and Sen's slope estimator), which do not require assumptions of normality. The linear trend slopes reported for RAI are used for descriptive purposes to indicate direction and magnitude of change.

First, the Rainfall Anomaly Index (RAI) was calculated to classify each year as extremely wet, very wet, near normal, or dry. This involved computing deviations of annual rainfall from the long-term mean, with anomalies scaled against the mean of the ten driest and ten wettest years, following the method of van Rooy (1965).

Second, the Mann-Kendall (MK) trend test, a non-parametric method widely used in climatological studies, was applied to detect the presence of monotonic trends in the annual rainfall series without assuming a specific data distribution.

Third, the Sen's slope estimator was used to quantify the magnitude of the trend identified by the MK test by calculating the median of all pairwise slopes in the time series. The MK test analysed the monthly, seasonal and annual rainfall data and detected any significant statistical trend. Sen's slope (Q_r) determined the nature of the trend. MK test statistic (Z) was done using the mathematical relation by Bluman (2009) shown in Eq. 1:

$$s = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad (1)$$

where:

$_j$ and x_k = time series observation

n = length of time series

sgn (x) defined by function expressed in Eq. 2:

$$sgn(x) = \begin{cases} 1 & if\ x > 0 \\ 0 & if\ x = 0 \\ -1 & if\ x < 0 \end{cases} \quad (2)$$

The variance (VAR) and *S* were used to estimate the value of standardized test statistics (Z) as shown in Eq. 3 and Eq. 4 respectively.

$$VAR\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5) \right] \quad (3)$$

where t_p is the number of ties at p^{th} value and q is the number of tied groups.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \quad (4)$$

The values of *Z* indicate the presence of statistical significance in the time series. The *Z* positive value indicates an upward trend in the time series. The *Z* negative value indicates a downward trend in the time series. Statistical significance was evaluated at the 95% confidence level ($\alpha = 0.05$). Trends with p-values less than 0.05 were considered statistically significant, while those with $p \geq 0.05$ were considered non-significant.

2.3. Calculation of potential roof harvests

Calculating harvest potential was based on the standard procedure, where harvestable water = Rainfall × Catchment Area × Collection Efficiency**.** Since effective rainwater collection never achieves 100% efficiency due to various loss factors like evaporation, seepage due to porosity and first flush effects, flush losses were estimated at 0.1 to 0.2 inches, which reduces overall collection volume by 10-20% depending on rainfall patterns and frequency.

Runoff coefficients for different surfaces have been discussed by among others the Engineering Tool Box (2023), US Green Building Council (1996-2026) and Oxfarm Wash (2026) whose figures range from 0.6-0.95 for tiles and iron sheet roofs.

Since Kitui Campus roofs are tiled, a runoff coefficient of 75% was adopted as a reasonable estimate based on typical runoff coefficients provided by among others Mwenge et al. (2009) and Kumar (2004). Due to seasonality dynamics water yields focussed on the County's two main rainy seasons of March to May (MAM) and October to December (OND).

3. Results and Discussion

3.1. Annual rainfall trend analysis

The analysis of Kenyan rainfall trends reveals significant hydro-climatic shifts with critical implications for water resource management. Annual precipitation for Kitui campus revealed a non-significant increasing trend (Sen's slope β = +1.12 mm/year, p = 0.15), consistent with observed intensification of rainfall extremes across East Africa (Ongoma et al. 2018).

The data exhibit high inter-annual variability (Fig. 3), with extreme wet years (2006: 935.6 mm) contrasting sharply with drought episodes 2005: 336.6 mm), mirroring the increased climate variability documented in Mutsostso et al. (2018) assessments. The non-significant increasing trend (Sen's slope +1.12 mm/yr, p=0.15) masks high inter-annual variability (CV ≈ 25–30%), with extreme wet, which indicates the need for storage due to high variability to buffer droughts.

3.2. Analysis of rainfall anomaly index (RAI)

Analysis of the Rainfall Anomaly Index (RAI) (Fig. 4) for Kitui County from 1981 to 2024 reveals a concerning trend of increasing rainfall variability and a growing frequency of below-average rainfall years. The non-significant increasing trend (Sen's slope +1.12 mm/yr, p=0.15) masks high inter-annual variability (CV ≈ 25–30%), with extreme wet (2006: 936 mm) and dry (2005: 337 mm) years. High variability underscores the necessity of storage to buffer droughts.

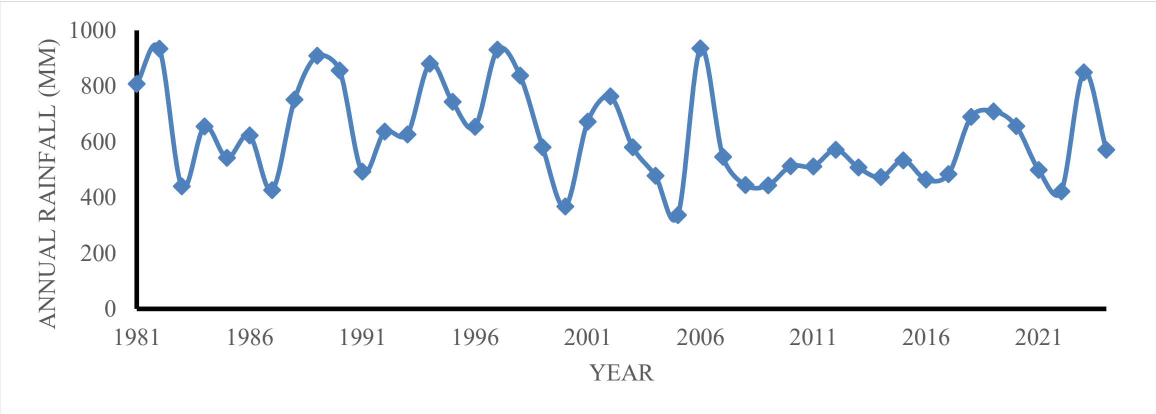

Fig. 3. Annual Rainfall Trend (1981–2024) at Kitui Campus (NASA POWER data).

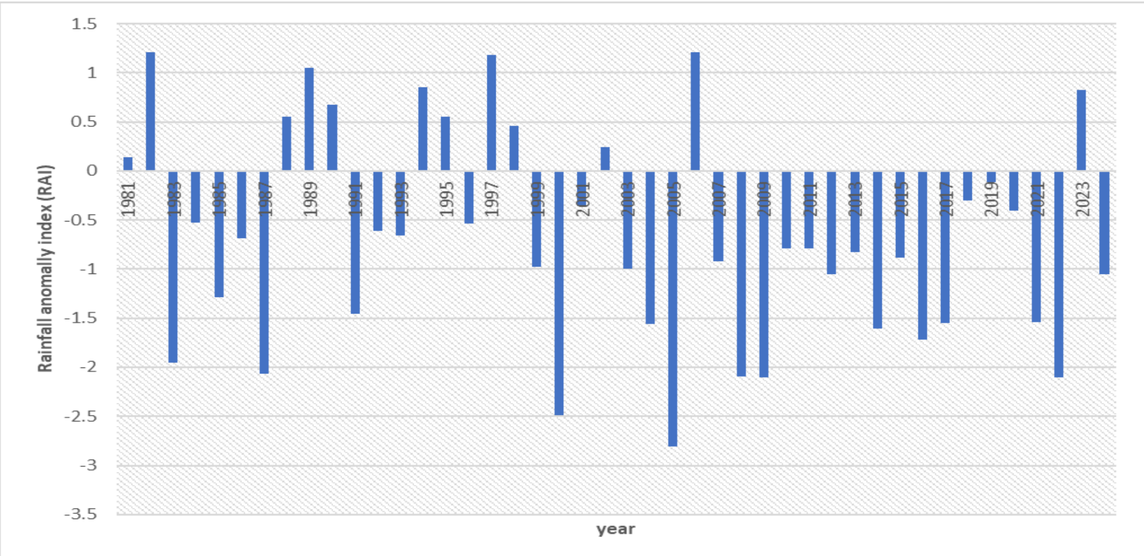

Fig. 4. Rainfall Anomaly Index (1981-2024) at Kitui Campus Kenyatta University

The Fig. 4 indicates that while positive rainfall anomalies implying wetter-than-normal conditions occurred intermittently in years such as 1985, 1989, 1997, 2006, and 2023, the overall pattern is dominated by negative anomalies. Particularly severe drought years were recorded in 1984, 2000, 2009, and 2022, all of which had RAI values below -2.0, signalling extreme rainfall deficits. These years correspond with major drought events that had widespread socio-economic impacts in Kenya, especially in semi-arid counties like Kitui.

The 1984 drought was one of the worst of the 20th century, resulting in widespread crop failure, famine, and loss of livestock across Eastern Kenya (Ongoma et al. 2018). Similarly, the 2000 drought was driven by the failure of both the short and long rains and affected over 4 million people nationally, with Kitui among the hardest-hit regions due to its dependence on rain-fed subsistence agriculture (CGK 2023).

The 2009 drought, also linked to a strong negative Indian Ocean Dipole phase and weak El Niño conditions, resulted in severe food shortages, depleted water sources, and emergency aid appeals (Mutsotso et al. 2018). Most recently, the 2022 drought was part of a multi-year dry spell driven by consecutive failed rainfall seasons and exacerbated by the La Niña phenomenon, which suppresses rainfall in East Africa (FAO 2022).

These droughts not only highlight meteorological extremes but also underscore the region's vulnerability to hydrological shocks.

In Kitui, such droughts result in cascading impacts including crop failure, acute food insecurity, malnutrition, water scarcity, increased livestock mortality, and reduced household incomes (Opiyo et al. 2015). They also intensify environmental degradation as communities turn to charcoal production and deforestation for livelihood coping.

The frequency of such extreme droughts is increasing, and their intensities are being amplified by broader climate change dynamics, particularly the warming of the western Indian Ocean and shifting atmospheric circulation patterns that disrupt the reliability of both the MAM and OND rainy seasons (Nicholson 2017). This underscores the need for targeted climate adaptation strategies in Kenya's arid and semi-arid lands (ASALs), including Kitui, to strengthen resilience against recurring droughts and rainfall variability.

3.3. Seasonal Rainfall Analysis

An analysis of seasonal rainfall trends in Kitui reveals diverging patterns between the March–May (MAM) and October–December (OND) seasons (Table 1). The MAM season exhibits a slight decreasing trend (mean = 176.6 mm, standard deviation = 52.3 mm), with a linear RAI slope of –0.028 units per year ($p = 0.10$). This trend is not statistically significant at the conventional 95% confidence level ($p < 0.05$) nor at the 90% level. In contrast, the OND season (mean = 361.1 mm, standard deviation = 92.4 mm) shows a moderate downward trend (slope = –0.045 RAI units/year, $p = 0.03$), which is statistically significant at the 95% confidence level.

This suggests a real and concerning reduction in OND rainfall over time, with implications for seasonal water availability, particularly since OND is historically the more reliable and productive rainy season in the region. This agrees with the Rainfall Anomaly Index (RAI) which further identifies 2000–2005 as a prolonged drought period, in line with the "Millennium Drought" trends noted by Opiyo et al. (2015). No formal normality tests were conducted prior to linear regression on the RAI series, as the Mann-Kendall test (non-parametric) was the primary trend detection method and is robust to non-normality. The linear regression on RAI was used for slope interpretation.

This study reveals that rainfall patterns have a notable deviation from the broader national climatic trend in which the March–May (MAM) season is traditionally regarded as the "long rains" and typically more productive than the October–December (OND) "short rains." Contrary to this national pattern, Kitui often experiences higher rainfall during the OND season than during the MAM season, as reflected in the seasonal averages, where OND rainfall (361.1 mm) exceeds that of MAM (176.6 mm).

Several factors account for this inversion; first, Kitui lies in the rain shadow of the Aberdare ranges and Mount Kenya, which causes the southeast trade winds, dominant during the MAM season, to lose much of their moisture before reaching the region (Ngaina and Mutai 2013). In contrast, the OND season is strongly influenced by large-scale ocean-atmosphere interactions, particularly the

Indian Ocean Dipole (IOD) (William and Funk 2011). A positive IOD event, characterized by warmer-than-normal sea surface temperatures in the western Indian Ocean, enhances convection and moisture transport over Eastern Africa, often resulting in increased OND rainfall (Behera et al. 2005; Black et al. 2003). Additionally, the seasonal migration of the Intertropical Convergence Zone (ITCZ), which brings convective rainfall as it shifts across the equator, sometimes has a stronger presence over Eastern Kenya during OND than MAM, further amplifying precipitation in Kitui during this period (Nicholson 2017).

Table 1. Mean monthly rainfall for March-May and October - December

Season	Mean Rainfall (mm)	Std Dev (mm)	Linear Trend Slope (RAI units/year)	p-value	Interpretation
MAM	176.6	52.3	-0.028	0.10	Slight decreasing trend, not statistically significant at 95% level
OND	361.1	92.4	-0.045	0.03	Moderate decreasing trend, statistically significant at 95% level

Moreover, recent studies suggest that the influence of climate change is exacerbating the variability and weakening of the MAM rainfall season in East Africa, including Kitui. Increased warming in the western Indian Ocean has been linked to more frequent and intense positive IOD events, disproportionately enhancing OND rainfall while suppressing MAM rains (Wainwright et al. 2021). This shift has significant implications for rain-fed agriculture, water resource planning, and climate adaptation in semi-arid counties like Kitui.

3.4. Rainwater harvesting potential

As expected, larger roof catchment areas are associated with higher volumes of rainwater harvested, owing to the increased surface area available for collecting precipitation during rainfall events (Mwenge et al. 2007). Combined roof catchments for the main campus blocks can harvest at least 7,839,360 litres (7839 CM) of water during the two rainy seasons per year (Table 2).

With a population of about 1000, water availability per capita per year can easily reach 1000 CM, which would place campus water scenario away from water scarcity classification. Integration of water use efficiency can further shift the campus into water security classification.

Since the campus blocks have different roof footprints, designing a water harvesting system that integrates environmental aesthetics and uniformity would entail working with average yields for clustered blocks: Administration block (416,060 CM), Lecture Hall (48,160 CM), Hostels (188,290 CM) and the Amphitheatre (497, 470 CM). The Kenyan market does not however manufacture plastic tanks for residential purposes beyond 30, 000 litres capacity.

In these cases, spatial mapping to erect a series of inter-connected tanks would be the feasible solution. Based on campus spatial map, each space between blocks can have two 30,000 litre tanks. The apparent excess water that would be form the spillway discharge can be directed into one main underground tank, whose water can be pumped to a central tank before it flows to different application points by gravity.

For the individual staff quarters, whose mean yield is 123,072 litres per year (Table 3), one 30,000 litres tank would be practical based on available space. Excess water from these individual houses can also be directed to the central underground water tank alluded to above.

In essence potential water harvests at Kitui campus can meet all domestic needs and irrigation agriculture focusing on early maturing crop varieties recommended for such dryland ecosystems. The benefits to public health and sanitation in such a high population learning space cannot be overemphasised.

In terms of extension of technology to the surrounding communities, raised plastic tanks of at least 5000 litres are recommended based on household income levels. The excess water from roofs can similarly be directed to sizeable pits or underground tanks for storage (Kathula and Abdinoor 2024).

This study affirms this as there is substantial variability in rainwater harvesting (RWH) potential across institutional and residential structures at the Campus. The RWH potential was estimated at 75% efficiency and mean rainfall based on the MAM of 176 mm OND of 361 mm (Table 2).

Institutional buildings such as the amphitheatre have average potential of about ~497,000 litres, admin blocks ~416,000 litres, and the kitchen ~302,000 liters recorded the highest annual harvests, attributable to their large, sloped roofs and uninterrupted catchment areas (Fig. 5). These findings are consistent with previous studies such as Kahinda et al. (2007), which highlight roof area and surface slope as the most critical determinants of RWH performance in semi-arid regions.

Large structures (Amphitheatre, Admin) dominate yields, supporting centralized storage, while variability reflects roof size differences. Conversely, classrooms had the lowest average yield (~104,000 litres), likely due to their smaller individual roof areas and fragmented distribution. Nonetheless, the staff quarters, although modest in individual yield ranging from 49,000 to 161,000 litres, collectively contribute over 3.45 million litres annually, a value that rivals the combined total of several institutional buildings. Similar observations were made by Mwenge et al. (2009) in South Africa and Mugume et al. (2016) in Uganda, where decentralized RWH systems in residential areas proved essential in buffering municipal supply and improving household water security.

Using a runoff coefficient range of 0.70–0.85, accounted for variability in tile condition, slope, and first-flush losses and total annual harvest varied between 7.3 – 8.3 million litres. The base case of 0.75 is conservative for well-maintained tiled roofs but may decrease with dust accumulation or poor maintenance. These findings highlight a strong case for tiered RWH interventions, where large public buildings serve as centralized hubs and residential units employ distributed systems. Such hybrid approaches have been found to enhance reliability, resilience, and cost-effectiveness in institutional water management (Wanyonyi et al. 2015; Umukiza et al. 2023). In addition to individual block harvests, plenty of water can be made available for environmental greening, micro-irrigation agriculture and campus sanitation.

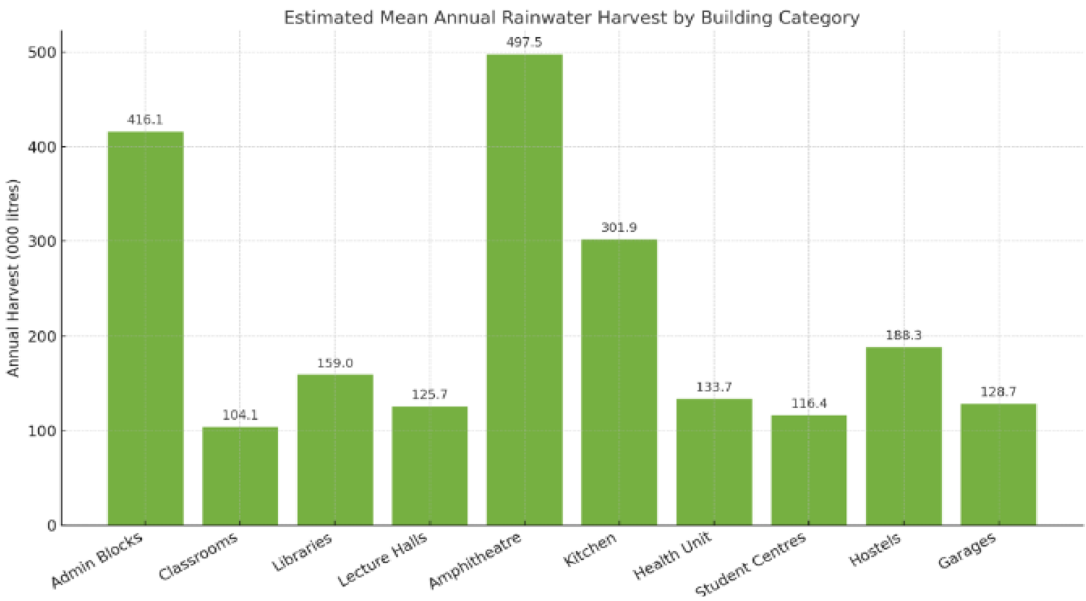

Fig. 5. Mean annual roof harvest for main institutional blocks

Table 2. Water yields from main blocks (March-May and October-December Seasons)

Building ID	(E) Est annual harvest (litres) = 1000 (C+D)	(D) OND harvest (m^3)	(C) MAM harvest (m^3)	(B) Actual Roof Area (m^2) 1.15A/Cos 25^o	(A) Roof Foot print (m^2)
Admin Block1	498,320	335.00	163.32	1,237.30	979.08
Admin Block2	272,920	183.47	89.45	677.62	536.20
Admin Block3	476,950	320.63	156.32	1,184.20	937.06
Mean (Adm)	416,060	279.70	136.36	1,033.04	817.45
Classes 1	156,130	104.96	51.17	387.68	306.77
Classes 2	49,540	33.30	16.24	122.99	97.32
Classes 3	160,660	108.00	52.66	398.91	315.66
Classes 4	50,230	33.77	16.46	124.72	98.69
Mean (Cls)	104,140	70.01	34.13	258.58	204.61
Library 1	152,490	102.51	49.98	378.63	299.61
Library 2	165,560	111.30	54.26	411.08	325.29
Mean (Lib)	159,030	106.91	52.12	394.86	312.45
Lecture hall 1	165,370	111.17	54.2	410.61	324.92
Lecture hall 2	172,700	116.10	56.6	428.81	339.32
Lecture hall 3	162,540	109.27	53.27	403.57	319.35
Lecture hall 4	45,860	30.83	15.03	113.86	90.10
Lecture hall 5	15,9420	107.17	52.25	395.83	313.22
Lecture hall6	48,160	32.38	15.78	119.6	94.64
Mean (Lec Hall)	125,680	84.49	41.19	321.05	246.93
Amphitheatre	497,470	334.43	163.04	1,235.21	977.43
Kitchen	301,940	202.98	98.96	749.71	593.25
Health unit	133,670	89.86	43.81	331.91	262.64
Student Centre1	113,930	76.59	37.34	282.07	223.84
Student Centre2	118,840	79.89	38.95	295.07	233.49
Mean	116,390	78.24	38.12	288.57	228.67
Hostel 1	183,920	123.64	60.28	456.65	361.35
Hostel 2	190,580	128.12	62.46	473.22	374.46
Hostel 3	191,710	128.88	62.83	476.01	376.67
Hostel 4	190,480	128.05	62.43	472.93	374.23
Hostel 5	195,830	131.65	64.18	486.24	384.76
Hostel 6	180,680	121.46	59.22	448.60	354.98
Hostel 7	182,550	122.73	59.82	453.3	358.7
Hostel 8	187,570	125.73	61.84	464.37	367.46
Hostel 9	185,630	124.79	60.84	460.91	364.72
Hostel 10	194,590	130.81	63.78	483.15	382.32
Hostel 11	184,680	124.15	60.53	458.53	362.84
Hostel 12	191,000	128.4	62.6	474.23	375.26
Mean	188,290	126.53	61.73	467.35	369.81
Garage 1	157,550	105.91	51.64	391.18	309.54
Garage 2	127,000	85.38	41.62	315.34	249.53
Garage 3	45,430	30.54	14.89	112.81	89.27
Garage 4	184,790	124.23	60.56	458.82	363.07
Mean	128,690	86.52	42.18	319.54	252.85
Total	7,839,360	5,269.66	2,569.70	19,461.98	15,401.31

Table 3. Yields from staff quarters (March-May and October–December Seasons)

Object ID	(A) Roof footprint (m^2)	(B) Actual Roof Area (m^2) = 1.15A/Cos 25°)	(C) MAM harvest (m^3)	(D) OND harvest (m^3)	(E) Est annual harvest (litres) = 1000(C+D)
1	297.66	376.16	49.65	101.85	151,500
2	313.91	396.70	52.36	107.41	159,770
3	294.91	372.69	49.19	100.91	150,100
4	356.24	450.19	59.43	121.89	181,320
5	224.90	284.21	37.52	76.95	114,470
6	199.51	252.13	33.28	68.26	101,540
7	240.40	303.80	40.10	82.25	122,350
8	239.22	302.31	39.91	81.85	121,760
9	235.08	297.08	39.21	80.43	119,640
10	200.60	253.51	33.46	68.64	102,100
11	214.06	270.52	35.71	73.24	108,950
12	234.28	296.07	39.08	80.16	119,240
13	173.45	219.20	28.93	59.35	88,280
14	212.44	268.47	35.44	72.69	108,130
15	290.58	367.22	48.47	99.42	147,890
16	213.90	270.31	35.68	73.19	108,870
17	240.55	303.99	40.13	82.31	122,440
18	269.08	340.05	44.89	92.07	136,960
19	277.17	350.27	46.24	94.84	141,080
20	267.92	338.58	44.69	91.67	136,360
21	316.54	400.02	52.80	108.31	161,110
22	249.08	314.77	41.55	85.22	126,770
23	219.56	277.47	36.63	75.13	111,760
24	251.48	317.80	41.95	86.04	127,990
25	210.68	266.24	35.14	72.08	107,220
26	264.34	334.06	44.10	90.45	134,550
27	166.18	210.01	27.72	56.86	84,580
28	96.84	122.38	16.15	33.13	49,280
Total	6,770.56	8,556.21	1,129.41	2,316.6	3,446,010

For Tables 2 and 3, Values assume mean seasonal rainfall; actual yields will vary ±15–25% due to inter-annual rainfall uncertainty in satellite products and runoff efficiency.

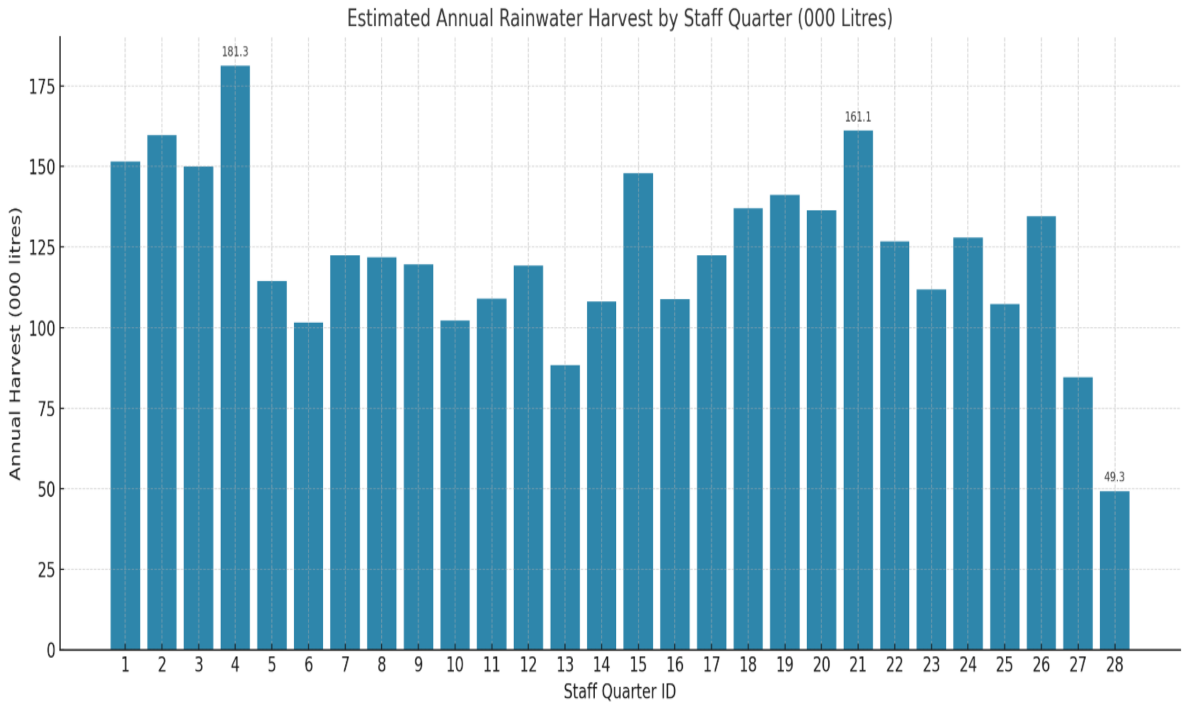

Fig. 6. Staff quarters potential roof harvest

3.5. Drought-informed storage sizing

Recommended tank sizing was determined by integrating annual harvest potential, seasonal yield variability, and the need to buffer extreme drought events (RAI < -2.0 in 1984, 2000, 2009, and 2022) and prolonged dry spells such as 2000–2005. The OND season (mean 361 mm) contributes more than twice the rainfall of the MAM season (176 mm), making effective storage of OND surpluses critical. A simplified cumulative water balance approach was used, assuming non-potable demand of 40–80 m³ per month for large institutional buildings and 5–15 m³ per month per staff quarter household (based on typical university benchmarks for sanitation, cleaning, landscaping, and limited irrigation in semi-arid conditions). Dry-period scenarios considered 3–4 months of minimal rainfall (< 20 mm/month) or extended 6–8-month deficits during severe droughts (Table 4). Recommended storage capacities prioritize carry-over from strong OND seasons: High-yield institutional buildings (Amphitheatre and Admin blocks, > 400,000 L annual potential): 150,000–250,000 L tanks. These can buffer 3–5 months of essential non-potable demand during moderate droughts and 2–4 months in severe drought years. Staff quarters (individual yields 49,000–161,000 L/yr): 10,000–20,000 L modular tanks, providing 1–3 months of autonomy. Shared systems are recommended for lower-yield units.

Table 4. Estimated annual harvest versus recommended tank capacity

Estimated Annual Harvest (L)	Recommended Tank Capacity (L)	Estimated Drought Buffer (Months)	Use Case & Rationale
>400,000	150,000–250,000	3–5 months (severe: 2–4)	Amphitheatre, Admin blocks – Centralized storage for peak institutional demand
250,000–400,000	80,000–150,000	2–4 months	Kitchen, large lecture halls
100,000–250,000	20,000–50,000	2–3 months	Libraries, high-yield staff quarters
50,000–100,000	10,000–20,000	1–2 months	Classrooms, medium quarters
<50,000	5,000–10,000 or shared	1 month (with rationing)	Small units – Community/shared systems

Buffer estimates assume 50–70% of annual harvest is stored from the OND season and conservative demand. These recommendations align with the National Water Harvesting and Storage Strategy (2020–2025), UN-Habitat (2011) and WMO (2022). Actual performance depends on maintenance, first-flush systems, and site-specific demand audits. Full dynamic modelling using daily rainfall and actual campus consumption data is recommended for future optimization (Ngigi 2003).

3.6. Practical storage standards and implementation considerations

Tank sizing also considered commercial tank availability, cost implications, space constraints, and building-specific usage. Emphasis is placed on integrating storage with first-flush diverters and basic filtration units to maintain water quality, especially given potential rooftop contaminants and proximity to agricultural areas. Although large centralized buildings like the Amphitheatre should use tanks ranging from 50,000 to 250,000 litres, while residential units can utilize modular storage of 5,000–20,000 litres per household, effective tank size is dictated by what the market offers – not bigger than 30,000 litres. Therefore, shared tank systems can improve water storages and reduce the water footprint.

3.7. Comparative analysis of rainwater harvesting studies

To contextualize the findings of this study, selected RWH studies in terms of scale, methods, and outputs were compared (Table 5). This highlights the contribution of the current GIS-based institutional assessment in semi-arid areas.

Table 5. Comparison of rainwater harvesting studies – methods, scale, and outputs

Study / Reference	Scale	Methods	Key Outputs / Findings	Context / Location
Kahinda et al. (2007)	Household	Hydrological modelling + socio-economic surveys	Domestic RWH potential to improve rural water supply; Runoff coefficients and tank sizing guideline	Rural South Africa
Mwenge Kahinda et al. (2007)	Household & Community	Modelling of roof & surface catchments; Efficiency factors	Challenges & opportunities; High potential in semi-arid areas with iron-sheet roofs	South Africa
Wanyonyi et al. (2015)	Institutional (Schools)	Field assessment + water demand surveys	40–60% reduction in water bills; Improved reliability in schools	Machakos, Kenya
Mugume et al. (2016)	Institutional (Urban)	Multifunctional flood resilience modelling	Enhanced urban flood resilience + water supply through RWH	Uganda
Mutschinski and Coles (2023)	Household (Smallholders)	Adoption & resilience assessment	Improved climate resilience for small landholders; Scalable low-cost intervention	Kenya

3.8. Operational and environmental implications

The integration of rooftop rainwater harvesting (RWH) systems offers significant operational and environmental benefits for institutions in semi-arid environments like Kitui. By capturing rooftop runoff, the campus can reduce dependence on municipal and borehole water, resulting in cost savings, greater water security, and improved drought resilience. Decentralized systems can effectively meet non-potable demands for sanitation, cleaning, irrigation, and flushing. Environmentally, RWH reduces storm water runoff, erosion, and downstream sedimentation while supporting potential groundwater recharge through controlled overflow (Gould and Nissen-Petersen 1999). It also lowers energy consumption associated with water pumping and decreases the carbon footprint of water supply. Water quality remains a key consideration, particularly near agricultural areas. Implementation of first-flush diverters, sediment traps, screens, and basic filtration is essential to minimize contaminants from dust, bird droppings, and agrochemicals (Mendez et al. 2011; WHO 2006; UN-Habitat 2011). The modular and scalable design of RWH systems enables phased implementation and shared storage, enhancing flexibility and system resilience (Wanyonyi et al. 2015). Overall, RWH promotes sustainable water use practices among campus users while aligning with climate adaptation objectives.

3.9. Strategic implications for integrated water resources management

The decentralized rooftop rainwater harvesting (RWH) strategy proposed in this study aligns closely with the core principles of Integrated Water Resources Management

(IWRM) - demand management, source diversification, environmental sustainability, and stakeholder participation (UN-Water 2018). It also supports Kenya's National Water Master Plan 2030 and the National Water Harvesting and Storage Strategy (2020–2025). RWH enhances demand-side management by reducing institutional reliance on boreholes and municipal supplies, thereby improving water-use efficiency in semi-arid Kitui, where erratic rainfall and high evapotranspiration exacerbate water scarcity (CGK 2023). The Kitui County Integrated Development Plan (CIDP) could benefit from adopting rooftop RWH as a complementary, low-cost intervention alongside dams and boreholes (Malesu et al. 2007).

The strategy promotes source diversification by introducing a distributed, climate-resilient water source that buffers against droughts, energy shortages, and system failures (Kahinda et al. 2009; UN-Habitat 2011). Environmentally, it reduces pressure on aquifers and rivers, lowers energy consumption, and supports green infrastructure. Furthermore, the approach contributes to Sustainable Development Goal 6 by increasing water availability for non-potable uses. As centres of innovation, educational institutions like Kenyatta University Kitui Campus can serve as demonstration hubs, promoting stakeholder engagement, water literacy, and behavioural change in surrounding communities (Mutschinski and Coles 2023).

However, these findings are context-specific to the campus's tiled roofs, rain-shadow location, and OND-dominant rainfall. Generalization to other ASAL ecosystems with similar rainfall pattern is plausible. In dissimilar agro-climatic zones, caution is encouraged based on site-specific assessments. Nonetheless, roof catchment yields are always directly proportional to roof footprints across climatic zones. As such, these findings till offer key lessons on rainwater harvesting whether in institutions or independent residential areas that have ridged roof catchments.

3.10. Limitations of the study and areas for further research

While this study provides robust estimates of rooftop RWH potential, several limitations should be acknowledged. First, rainfall data were sourced from NASA POWER (via CHIRPS), which offers excellent spatial coverage in data-scarce semi-arid regions but carries inherent uncertainties. Satellite-based estimates can exhibit biases, particularly in semi-arid environments with high spatial variability, convective rainfall, and topographic influences; validation studies in East Africa indicate that CHIRPS/POWER products generally perform well at monthly/annual scales but may under- or overestimate event-based rainfall compared to ground stations. Future work should validate these against local rain gauge data where available. Second, the analysis focused on supply-side potential (roof area × rainfall × 0.75 efficiency) but did not include a detailed water demand analysis for the campus (per-building or per-capita consumption for sanitation, irrigation, cleaning, or drinking). Matching supply with actual demand profiles would refine tank sizing and system design. Third, no economic analysis i.e, cost-benefit, payback period, or life-cycle costing of tanks and installation was conducted. Such analysis would strengthen the case for investment, especially given potential cost savings on municipal/borehole water.

Although rooftop runoff can contain contaminants from dust, bird droppings, roofing materials, or nearby agricultural activities, tiles and iron roof in Kenya as generally accepted as of insignificant risk, this dimension was outside the scope of this study. The necessity of first-flush systems, filtration, and periodic testing for microbial and chemical parameters before use, particularly for portable applications cannot be overemphasised (WHO 2006; Mendez et al. 2011).

4. Conclusion

This study underscores the critical role of rooftop rainwater harvesting (RWH) as a practical and sustainable intervention to enhance water security and climate resilience at Kenyatta University's Kitui Campus in semi-arid Kenya. Using GIS-based roof mapping and 44 years (1981–2024) of rainfall data, the analysis reveals that the campus can potentially harvest approximately 7.8 million litres of rainwater annually at 75% collection efficiency. Institutional buildings, particularly the amphitheatre and admin blocks, show the highest yields (up to 497,000 litres per year), while staff quarters collectively contribute 3.45 million litres.

A major finding is the pronounced seasonal variability, with the October–December (OND) season delivering more than double the rainfall of the March–May (MAM) season (361 mm vs 176 mm). This imbalance, together with historical extreme droughts and a statistically significant declining trend in OND rainfall, highlights the importance of strategic storage. Drought-informed modeling recommends 150,000–250,000 L tanks for high-yield institutional buildings (buffering 3–5 months of non-potable demand) and 10,000–20,000 L modular tanks for staff quarters.

The study advocates a decentralized hybrid RWH system; combining centralized storage for major buildings with distributed units for residential areas, to reduce dependence on unreliable municipal and groundwater sources. This approach aligns with Integrated Water Resources Management (IWRM) principles, Kenya's National Water Master Plan 2030, the National Water Harvesting and Storage Strategy (2020–2025), and Sustainable Development Goal 6.

Operational benefits include potential cost savings, improved water availability for sanitation, cleaning, and irrigation, as well as reduced stormwater runoff and groundwater pressure. However, the findings are context-specific to the campus's tiled roofs, location in the rain shadow of Mt. Kenya, and OND-dominant rainfall regime. Transferability to other institutions or counties requires site-specific validation.

In conclusion, rooftop rainwater harvesting offers a feasible, low-cost, and climate-resilient strategy for semi-arid educational institutions. Its implementation at Kitui Campus can serve as a valuable demonstration site and replicable framework for similar settings in Kenya's arid and semi-arid lands (ASALs), provided it is supported by policy integration, stakeholder engagement, and phased investment.

5. Conflict of Interest

The authors declare no conflict of interest over this paper.

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