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Household-Level Assessment of Urban Rooftop Rainwater Harvesting Potential and Its Contribution to Domestic Water Supply in Al-Wahdah District, Sana'a City, Yemen

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Abstract

Sana'a City faces severe water scarcity driven by limited rainfall, rapid urban growth, and groundwater overexploitation. This study assessed the potential contribution of rooftop rainwater harvesting (RTRWH) to domestic water supply in Al-Wahdah District, Sana'a City. The methodology integrated household survey data, GIS-based rooftop digitization, roof-material information, and monthly rainfall records for 2013–2022, with an average annual rainfall of 335.4 mm. Of 374 valid surveyed buildings, 277 residential buildings were analyzed after excluding 97 non-residential or unsuitable records. Domestic demand was estimated using observed (47.5 L/c/d) household consumption and the SWSLC benchmark of 61 L/c/d. Current RTRWH use was negligible, contributing less than 1% of consumption. Under a theoretical full-rooftop utilization scenario, excluding storage constraints and first-flush losses, RTRWH could provide about 13,234 m³/year, equivalent to 19.6% of observed demand and 14.7% of estimated demand. Results show that RTRWH is a valuable supplementary source, but practical use requires storage and water-quality consideration.

Article Info

Keywords:
Rooftop rainwater harvesting , domestic water demand , GIS , urban water scarcity , Sana'a City , Yemen.

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1. INTRODUCTION

Water scarcity is one of the most serious challenges facing arid and semi-arid regions, where limited rainfall, rapid population growth, and increasing water demand place strong pressure on available freshwater resources [1, 2].

In urban areas, this problem is further intensified by population concentration, expansion of impervious surfaces, limited infrastructure capacity, and the vulnerability of conventional water supply systems to climate variability and groundwater depletion [2, 3].

Yemen is among the countries most affected by water scarcity, and Sana'a City is a critical example of urban water stress. The city mainly depends on groundwater resources, which have been overexploited for several decades. Consequently, groundwater levels have continuously declined, and public water supply services remain limited and intermittent. Consequently, many households rely on private tanker water and other alternative sources, which increases household expenses and places additional pressure on already depleted groundwater resources [3, 4]. only approximately 35-45% of households have access to the municipal water network, forcing the majority of residents to rely on alternative and often costly sources, such as private water tankers [5].

Rooftop rainwater harvesting (RTRWH) is a practical decentralized technique that can supplement domestic water supplies in water-scarce urban environments. The system collects rainfall from building rooftops, conveys it through gutters and pipes, and stores it for future use. In addition to improving household water availability, RTRWH can reduce dependence on tanker water, decrease pressure on public water supply systems, and contribute to storm water management by reducing direct runoff from urban surfaces [6, 7]. However, the effectiveness of RTRWH systems depends on local factors such as rainfall amount and seasonality, rooftop area, roof material, runoff coefficient, household size, and domestic water demand.

Al-Wahdah District was specifically selected for this case study because its dense residential fabric, widespread flat reinforced-concrete rooftops, and acute reliance on private tanker water make it a highly representative model for evaluating Sana'a's urban water stress and decentralized supply potential.

Previous studies in Sana'a City have shown that RTRWH can provide a meaningful supplementary source of water. For example, city-scale assessments [8, 9] estimated that rooftop rainwater harvesting could theoretically contribute approximately 20% of a city's domestic water demand and total supply. Similarly, Salleh and Taher (2012) demonstrated its strategic role, estimating a potential reduction in groundwater dependence of approximately 22% [10]. However, these macro-level studies relied on aggregated rooftop areas and generalized water demand assumptions. Such approaches are useful for estimating the overall potential, but they do not fully represent household-level variability in roof sharing, occupancy, water-use behavior, and existing water supply sources.

Therefore, a detailed household-level assessment is needed to provide more realistic evidence of the practical contribution of RTRWH in densely populated urban districts. This study assessed the potential contribution of RTRWH to the domestic water supply in Al-Wahdah District, Sana'a City, Yemen, by integrating household survey data, GIS-based rooftop digitization, roof material information, and monthly rainfall records from 2013 to 2022. It should be noted that this study focuses strictly on the hydrological quantity of harvested water and its contribution to domestic demand; water quality considerations, contamination risks, and treatment requirements are beyond the scope of this study. The specific objectives were to estimate domestic water demand, identify existing water supply sources, quantify potential harvestable rooftop rainwater, and evaluate the contribution of RTRWH to household water supply on annual and monthly scales. The main contribution of this study is its building-level approach, which incorporates actual household water consumption, rooftop characteristics, rooftop area per capita, and seasonal rainfall. This provides a more realistic basis for evaluating RTRWH as a supplementary water source and supports evidence-based planning for decentralized urban water management in Sana'a.

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2. MATERIALS AND METHODS

2.1. Study Area

The study was conducted in the Al-Wahdah District, Sana'a City, Yemen (Figure 1). The district is located in the western part of Sana'a City between approximately 15°19′00″N and 15°21′00″N and 44°09′09″E and 44°12′59″ E. It covers approximately 10 km^2 and lies at an elevation of approximately 2,200-2,300 m above sea level. The Al-Wahdah District is characterized by dense urban development, high residential building concentration, extensive impervious surfaces, and widespread flat reinforced concrete rooftops, which are suitable for rooftop rainwater harvesting (RTRWH). Rainfall in Sana'a is limited and seasonal. Based on the dataset of this study, the average annual precipitation was 335.4 mm. The majority of this rainfall occurs during the primary rainy season in July (130.4 mm) and August (103.8 mm), with a secondary season in April and May, and the remaining months are relatively dry.

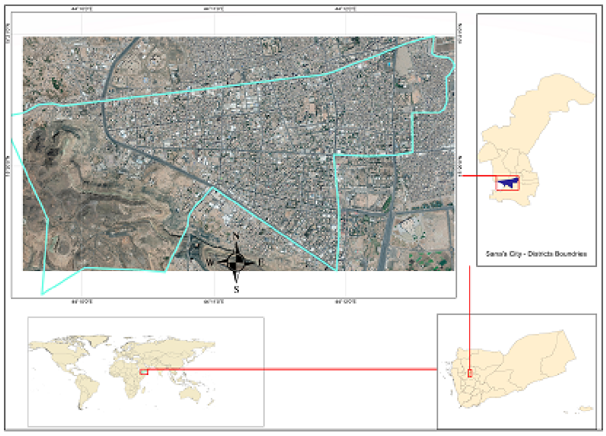

Figure 1. Location map of Al-Wahdah District, Sana'a City, Yemen.

2.2. Data Sources

This study used both primary and secondary data. Primary data were collected through a structured household survey conducted in the Al-Wahdah District in 2025. The questionnaire collected information on building characteristics, household occupancy, rooftop material, existing water supply sources, monthly water consumption, current use of rainwater harvesting, and willingness to adopt RTRWH systems in the community.

Secondary data included rainfall records, water supply information, and spatial data. Monthly rainfall data for 2019–2022 were obtained from the Civil Aviation and

Meteorology Authority (CAMA) observation station in Sana'a. To ensure a continuous and robust 10-year climatic baseline, CHIRPS version 2.0 satellite rainfall data were used to fill the missing records for 2013–2018 after applying a monthly ratio bias-correction method using the observed CAMA data. The 2013–2022 period was selected as it represents the most recent continuous dataset available after bias correction.

Water supply information and the domestic water demand benchmark of 61 L/c/d were obtained from the Sana'a Water and Sanitation Local Corporation (SWSLC). Rooftop areas were digitized using GIS tools, and roof material information was collected through field surveys.

2.3. Sampling and Field Survey

The total number of buildings in the Al-Wahdah District was 13,679. Buildings were selected as the primary sampling units because the RTRWH potential depends mainly on the rooftop area and building-level characteristics. The required sample size was calculated using a finite-population sample-size formula at a 95% confidence level, 5% margin of error, and 0.5 population proportion. The calculated minimum sample size was approximately 374 completed questionnaires were collected.

To account for non-response, 416 buildings were selected using simple random sampling method. A pilot survey was conducted from April 29 to May 7, 2025, to test the questionnaire and train the survey team. The main field survey was conducted from May 28 to July 24, 2025, through face-to-face interviews. A total of 374 complete responses were collected. However, 97 of these buildings (25.9%) were non-residential structures, including commercial offices, educational facilities, government buildings, and mosques. Because this study focuses strictly on domestic (household) water demand, these 97 non-residential buildings were excluded to prevent a selection bias. The final analysis evaluated 277 residential buildings.

2.4. Questionnaire Design and Validation

A structured questionnaire was designed to support household-level RTRWH assessment. The questionnaire included four main sections: building characteristics, domestic water supply and consumption, RTRWH practices and awareness, and community perceptions. The questionnaire was reviewed by academic and professional experts to ensure its content validity. It was then tested through a pilot survey prior to final implementation. Reliability was assessed using Cronbach's alpha, which produced a value of 0.71, indicating acceptable internal consistency. Therefore, the validated questionnaire was considered suitable for collecting household-level data on urban RTRWH conditions in Sana'a.

2.5. Domestic Water Demand Estimation

Domestic water demand was estimated using two methods. First, the estimated domestic demand was calculated using a normative benchmark of 61 L/c/d. This value was derived from the internal water network design criteria and expert consensus of the engineering staff at the Sana'a Water and Sanitation Local Corporation (SWSLC). Although not formally published, it serves as the utility's operational baseline for adequate urban domestic water planning in Sana'a. The monthly estimated demand was calculated using Eq. (1):

$$D_e = \frac{N\text{x}61\text{x}30}{1000} \tag{1}$$

where (D_e) is the estimated monthly domestic demand in cubic meters, (N) is the number of occupants, 61 is the per-capita daily demand in liters per capita per day, and 30 is the assumed number of days per month.

Second, the observed domestic water demand was calculated from household survey data by summing the reported monthly water consumption from all domestic water supply sources. Comparing the observed and estimated demands allowed the study to evaluate the gap between actual water consumption and the normative demand benchmark.

2.6. Estimation of RTRWH Potential

The potential monthly volume of rooftop rainwater harvesting was estimated using the standard water balance equation shown in Eq. (2):

$$Q = \frac{P\text{x}A\text{x}C}{1000} \tag{2}$$

where (Q) is the monthly harvestable rainwater volume in cubic meters, (P) is the monthly rainfall in millimeters, (A) is the rooftop area in square meters, and (C) is the runoff coefficient. The rooftop area was obtained through GIS digitization, and runoff coefficients were assigned according to the roof material type based on field observations and technical guidance for rooftop rainwater harvesting systems [11]. The albedo values were 0.85 for concrete rooftops (66.1% of buildings), 0.75 for traditional mud rooftops (32.9%), and 0.90 for insulated and metal rooftops (1.1%). Monthly values were aggregated to estimate the annual RTRWH potential.

2.7. Contribution of RTRWH to Domestic Water Demand

The contribution of RTRWH to domestic water demand was calculated by comparing the estimated harvestable rainwater volume with both observed and estimated domestic water demand, as shown in Eq. (3):

$$\text{RTRWH Contribution}(\%) = (\frac{Q}{D})\text{x}100 \quad (3)$$

where (Q) is the estimated RTRWH volume in cubic meters, and (D) is the domestic water demand in cubic meters. The calculation was performed on monthly and annual scales to evaluate both the total contribution and seasonal performance of RTRWH.

2.8. Data Processing and Analysis

The survey data were compiled, cleaned, and analyzed using Microsoft Excel and SPSS. Incomplete and inconsistent records were reviewed prior to the analysis. All datasets were standardized in terms of units: rainfall in millimeters, rooftop area in square meters, and water volume in cubic meters. Spatial processing and rooftop digitization were performed using ArcGIS 10.8.1. Descriptive statistics, percentages, and comparative analyses were used to evaluate domestic water demand, existing water supply sources, RTRWH potential, and the contribution of RTRWH to the household water supply.

2.9. Scope and Limitations of the Assessment

This study evaluated the gross theoretical potential of RTRWH to establish a quantitative hydrological baseline for the Al-Wahdah District. The methodology assumes full capture of the harvestable runoff and does not include a daily water balance model or storage-sizing reservoir simulation. Given the highly seasonal nature of rainfall in Sana'a, the actual utilized volumes will be constrained by the physical space available for large storage tanks in a dense urban environment, likely resulting in overflow losses during the peak months of July and August. Furthermore, the calculations do not account for first-flush diversion losses, nor does this study assess the microbiological or physicochemical quality of the harvested water for domestic safety.

3. RESULTS AND DISCUSSION

3.1. Building Characteristics and Water Demand

The analysis focused on 277 residential buildings from the completed household surveys. The surveyed buildings showed considerable variation in occupancy, rooftop area, and roof material characteristics, all of which directly influence rooftop rainwater harvesting (RTRWH) potential. Table (1) presents the mean rooftop area of approximately 172 m^2 per residential building, while the mean rooftop area per capita was about 16.3 m^2/person. This variation indicates that the potential benefit of RTRWH is not uniform across households but depends strongly on the relationship between the roof area and the number of occupants.

Domestic water demand was evaluated using both observed household consumption and the SWSLC normative benchmark of 61 L/c/d. The observed average domestic water consumption was approximately 45.7 L/c/d, which is approximately 25% lower than the SWSLC benchmark. This difference reflects constrained water use under conditions of limited supply rather than necessarily lower household water needs. The comparison between the observed and estimated demand is important because it shows that households in the Al-Wahdah District are already consuming less than the normative requirement, indicating the presence of unmet domestic water demand.

Table[1]: Summary of main water demand and RTRWH indicators for the sampled residential buildings.

Indicator	Value
Sampled residential buildings	277
Number of apartments	876
Number of occupants	4,111
Total rooftop/building area	47,652 m^2
Average rooftop/building area per residential building	172.0 m^2/building
Average rooftop area per capita	16.3 m^2/person
SWSLC domestic demand benchmark	61 L/c/d
Observed domestic water consumption	45.7 L/c/d
Total observed domestic demand	67,656 m^3/year
Total estimated domestic demand	90,276 m^3/year
Current RTRWH contribution	0.7%
Tanker-water contribution	74.2%
SWSLC contribution	20.7%
Annual RTRWH potential under full rooftop utilization	13,234.4 m^3/year
RTRWH contribution to observed demand	19.6%
RTRWH contribution to estimated demand	14.7%

3.2. Existing Water Supply Sources

The results show that the domestic water supply in the Al-Wahdah District depends mainly on private tanker water. As shown in Table (2) and Figure (2), tanker-delivered water accounts for approximately 74.2% of the total residential water consumption, whereas the public water network operated by SWSLC contributes approximately 20.7%. Other sources accounted for less than 5% of the total consumption. Current rainwater harvesting contributes only approximately 0.7%, indicating that RTRWH is currently used at a very limited level.

This supply structure highlights the vulnerability of the

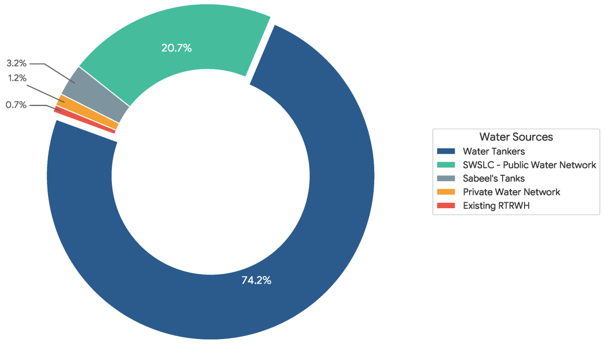

Figure 2. Contribution of different water supply sources to total residential water consumption in Al-Wahdah District.

Table[2]: Residential Water Consumption

No.	**Water source**	**Residential Water Consumption**	
		(%)	**(m^3/month)**
1	**SWSLC – Public network**	**20.7%**	**1,164.5**
2	**(Non-SWSLC) Private water sources (total)**	**79.3%**	**4,473.5**
2.1	|– Tankers	74.2%	4,182.0
2.2	|– Private network	1.2%	70.0
2.3	|– Sabeel's tanks	3.2%	183.0
2.4	|– Existing RTRWH	0.7%	38.5
Total (all sources)		**100.0%**	**5,638.0**

existing urban water systems. Heavy dependence on tanker water increases household expenditure and indirectly contributes to further groundwater abstraction because tanker water is commonly supplied from wells outside or around the city. The low contribution of existing RTRWH practices indicates a large untapped opportunity for improving household water resilience through the wider adoption of rooftop harvesting systems.

3.3. Rainfall Characteristics and RTRWH Potential

Rainfall in Sana'a is limited and highly seasonal. As Shown in Table (3), the main rainfall periods occur during April–May and July–August, whereas rainfall during the remaining months is low or nearly absent. This seasonal pattern strongly influences the temporal performance of RTRWH systems. Therefore, monthly analysis is more informative than annual totals alone, especially in arid and semi-arid urban environments such as the UAE.

Under the full rooftop utilization scenario, the estimated RTRWH potential for the 277 residential buildings was approximately 13,234.4 m³/year. This result indicates that a considerable amount of rainwater can be captured from existing rooftops if appropriate collection and storage systems are installed. However, because most harvestable rainfall occurs within a few months, the usefulness of this volume depends strongly on the adequate storage capacity and system design.

3.4. Contribution of RTRWH to Domestic Water Demand

The estimated annual RTRWH potential was compared with both the observed and estimated domestic demand. The total observed domestic water consumption for the 277 residential buildings was approximately 67,656 m³/year, whereas the estimated demand based on the SWSLC standard was approximately 90,276 m³/year. Under full rooftop utilization, the RTRWH could provide approximately 19.6% of the observed annual demand and 14.7% of the estimated annual demand.

These results confirm that although RTRWH cannot replace existing water supply systems, it can provide a meaningful supplementary source. The higher contribution relative to observed demand reflects the fact that current household consumption is constrained by limited water availability. When compared with the normative demand benchmark, the same harvested volume represents a smaller proportion of the total water needs.

Figure (3) illustrates that the RTRWH contribution varies considerably on a monthly scale. During the peak rainfall months, particularly July and August, harvested rainwater could meet a large share of household demand, reaching approximately 91.3% of the observed demand in July and 72.7% in August. During April and May, the contribution was moderate, reaching approximately 30.8% and 18.1% of the observed demand, respectively. In contrast, during the extended dry period from September to February, the monthly contribution is generally very low, often below 2% of the demand.

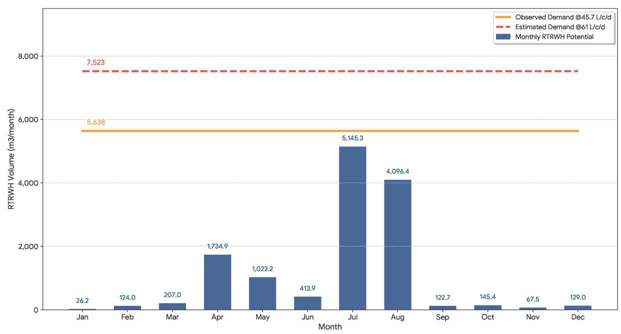

Figure 3. Monthly RTRWH potential compared with observed and estimated domestic water demand for the sampled residential buildings.

This seasonal behavior demonstrates that RTRWH is most effective as a supplementary source during the rainy season. Without sufficient storage, some of the harvested water during the high-rainfall months may be

Table[3]: Monthly Rainfall (mm), 2013–2022

Month	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Average
Jan.	0.5	0.5	1.5	0.7	0.6	0.6	0.0	2.0	0.3	0.0	**0.7**
Feb.	1.7	1.8	7.7	2.8	4.6	2.9	2.5	0.0	7.6	0.0	**3.1**
Mar.	5.1	2.0	9.7	5.7	6.1	3.8	5.3	1.5	0.0	13.4	**5.2**
Apr.	41.6	17.6	36.1	79.7	28.4	71.1	47.4	88.2	20.8	8.9	**44.0**
May.	12.9	26.0	7.4	22.1	57.7	17.8	71.6	32.4	11.1	0.0	**25.9**
Jun.	7.3	6.4	31.1	7.4	7.4	12.8	1.2	27.9	0.0	3.4	**10.5**
Jul.	78.1	29.9	78.2	258.0	254.2	103.0	37.0	206.1	122.2	137.5	**130.4**
Aug.	102.1	65.6	3.7	152.0	130.0	139.7	34.8	119.0	83.4	207.9	**103.8**
Sep.	2.5	2.2	4.0	2.8	3.5	3.8	7.7	4.6	0.0	0.0	**3.1**
Oct.	4.5	4.3	4.0	3.2	3.2	4.6	2.1	0.0	13.8	0.0	**3.7**
Nov.	1.9	1.6	1.1	1.8	1.1	1.0	5.5	0.2	0.0	0.0	**1.7**
Dec.	3.4	3.4	0.7	3.3	3.3	4.2	0.0	0.0	0.0	14.4	**3.3**

lost through overflow. Therefore, storage capacity, first-flush systems, filtration, and regular maintenance are essential for maximizing the practical benefits of RTRWH systems.

3.5. Household-Level Variability Based on Rooftop Area per Capita

To further evaluate the variability in RTRWH performance, the contribution of harvested rainwater was analyzed at the building level using the rooftop area per capita (m²/person). This indicator reflects the rooftop catchment area available for each resident and is therefore more informative than the total rooftop area. The results showed substantial variation among the sampled residential buildings, confirming that the RTRWH effectiveness is strongly influenced by both building characteristics and occupancy density (Table 4).

Table[4]: Median RTRWH contribution by occupancy-density group and rooftop area per capita.

Number of buildings	Occupancy density	Rooftop area per capita (m^2/ person)	Median RTRWH/ estimated demand (%)	Median RTRWH/ observed demand (%)
70	High density	0.60–6.72	5.36	7.16
69	Medium density	>6.72–11.49	10.03	13.38
69	Low density	>11.49–21.80	19.54	26.08
69	Very low density	>21.80–71.53	41.11	54.87

As shown in Table (4), the median RTRWH contribution increased consistently as the per capita rooftop area increased. In high-density buildings, where the rooftop area per capita ranges from 0.60 to 6.72 m²/person, the RTRWH could meet a median of only 5.36% of the estimated demand and 7.16% of the observed demand. In contrast, very low-density buildings, with a rooftop area per capita greater than 21.80 m²/person, could meet a median of 41.11% of the estimated demand and 54.87% of the observed demand. This clear increase demonstrates that buildings with fewer occupants and larger rooftop areas per person have substantially higher potential for rainwater harvesting.

The median contribution relative to the observed demand was higher than that relative to the estimated demand in all occupancy density groups. This is because the observed household consumption is lower than the SWSLC normative benchmark used for estimating demand. Therefore, the same harvested volume represents a larger percentage of the observed demand than the estimated demand.

The influence of household-level variability is further illustrated in Figure (4), which shows the relationship between per capita rooftop area and the percentage of observed domestic water demand that could be met by RTRWH. The figure confirms a positive relationship between the per capita rooftop area and the RTRWH contribution. It also shows the role of rooftop material, as buildings with less porous roof surfaces, such as concrete, insulated, or metal rooftops, generally show better harvesting performance than traditional mud roofs. This is because the roof material affects the runoff coefficient and, therefore, the proportion of rainfall that can be converted into harvestable runoff.

Overall, these findings demonstrate that the per capita rooftop area is a key factor controlling the performance of RTRWH systems. Multi-family buildings or highly occupied houses may have lower per-capita harvesting benefits, even when their total rooftop area is relatively large. Conversely, buildings with fewer occupants and larger rooftop areas can achieve significantly higher contributions. Therefore, RTRWH planning should not only rely on the total rooftop area at the district or city scale; it should also consider occupancy density, rooftop material,

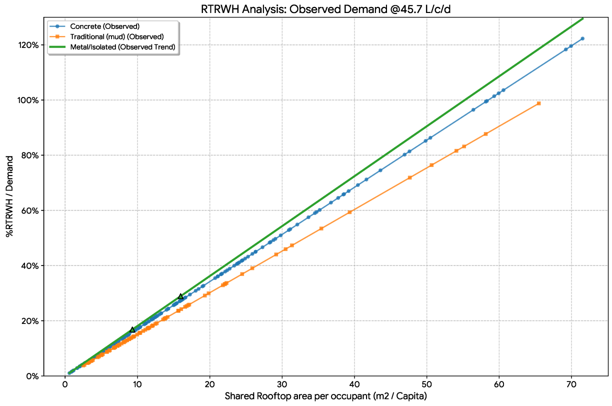

Figure 4. Relationship between rooftop area per capita and the percentage of observed domestic water demand met by RTRWH, categorized by rooftop material

and building-level variability when identifying households and locations where RTRWH systems are most effective. These results represent the theoretical harvesting potential; the actual usable volumes may be lower depending on the storage capacity, first-flush diversion, conveyance losses, system maintenance, and water quality requirements.

3.6. Comparison with Previous Studies

The estimated RTRWH contribution in this study is broadly consistent with previous city-scale assessments conducted in Sana'a, where rooftop rainwater harvesting was estimated to contribute approximately 20–22% of domestic water demand or total urban water supply [8–10].

Similar findings have been reported in other arid and semi-arid regions, where RTRWH performance was strongly influenced by rainfall seasonality, rooftop area, storage capacity, and household demand [12–14].

However, studies conducted in wetter or more favorable rainfall environments reported higher contributions, confirming that local rainfall conditions and roof area per capita strongly control system performance [14, 15].

In addition to water supply benefits, previous studies have emphasized the importance of water quality control, first-flush diversion, filtration, and system maintenance when harvested rainwater is intended for domestic use [16]. RTRWH can also provide stormwater management benefits by reducing runoff volume and peak discharge from impervious urban surfaces [17].

Therefore, in arid cities such as Sana'a, RTRWH should be considered a supplementary component of a diversified urban water supply system, rather than a standalone source.

4. CONCLUSIONS AND RECOMMENDATIONS

This study assessed the potential contribution of rooftop rainwater harvesting (RTRWH) to the domestic water supply in Al-Wahdah District, Sana'a City, using household survey data, GIS-based rooftop analysis, roof material information, and monthly rainfall records. The findings show that the current RTRWH practice in the study area is very limited, contributing less than 1% of domestic water consumption. However, under a full rooftop-utilization scenario, the RTRWH could provide approximately 13,234.4 m^3/year for the sampled residential buildings, representing 19.6% of the observed domestic water demand and 14.7% of the estimated demand based on the SWSLC standard of 61 L/c/d.

The results confirm that RTRWH cannot replace existing domestic water supply systems in Sana'a City, mainly because rainfall is limited and highly seasonal in this region. Nevertheless, it can serve as a meaningful supplementary source, particularly during the rainy season. The monthly analysis showed that the RTRWH contribution can be substantial during July and August, while it remains very low during the extended dry season. Therefore, the reported contribution should be interpreted as the theoretical harvestable potential under full rooftop utilization. Actual usable volumes may be lower because of storage capacity limitations, first-flush diversion, conveyance losses, system maintenance requirements, and water quality constraints.

The household-level analysis demonstrated that the performance of the RTRWH varied considerably among the buildings. The median contribution increased consistently from high-density to very low-density buildings as the per-capita rooftop area increased. In high-density buildings, RTRWH could meet a median of only 5.36% of the estimated demand and 7.16% of the observed demand, whereas in very low-density buildings, it could meet a median of 41.11% of the estimated demand and 54.87% of the observed demand. These results confirm that the rooftop area per capita is a key planning indicator because buildings with fewer occupants and larger rooftop areas per person can achieve substantially higher contributions than highly occupied buildings with limited roof areas.

Rooftop material also influences the RTRWH performance through its effect on runoff efficiency. Less porous surfaces, such as concrete, insulated, and metal rooftops, generally provide better harvesting performance than traditional mud rooftops because they generate higher runoffs. Therefore, RTRWH planning should consider not only the total rooftop area but also the occupancy density, per capita rooftop area, rooftop material, roof condition, and feasible storage capacity.

Based on these findings, this study recommends promoting RTRWH as a complementary component of urban water management in Sana'a. Local authorities, SWSLC, and relevant water institutions should encourage the inclusion of RTRWH systems in new buildings and support their gradual adoption in existing ones. Financial incentives, partial subsidies, or low-interest loans could help households overcome the initial costs of installing storage tanks, gutters, filters, and first-flush systems.

Technical guidelines should also be developed to support the appropriate design, storage sizing, filtration, first-flush diversion, and maintenance of RTRWH systems under local conditions. Public awareness campaigns are needed to improve household understanding of the benefits, limitations, and safe use of rainwater.

Future studies should evaluate storage-sizing requirements and conduct simple reservoir balance simulations to estimate the practically usable water volume under seasonal rainfall conditions. Further research should investigate the microbiological and physicochemical quality of harvested rooftop rainwater, as water quality is a key factor controlling its safe domestic use. In addition, future studies should assess the role of RTRWH in reducing urban runoff and localized flood risk, particularly in densely built districts with extensive, impervious surfaces.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this work. All co-authors have approved the manuscript and concurred with its submission to the journal.

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