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Research paper

Multiple household water sources and uses in rural ASALs: Evidence and proposed solutions from Turkana, Kenya

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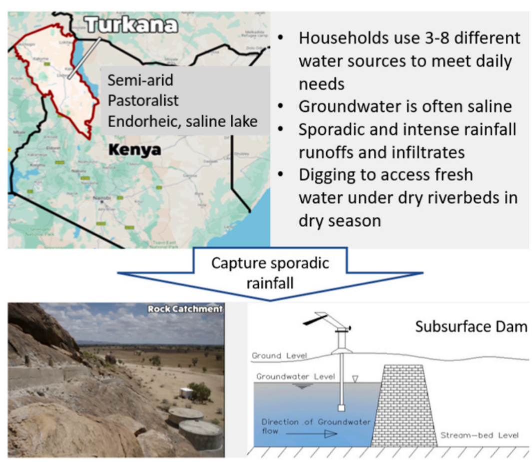
HIGHLIGHTS

- 475 households (HHs) surveyed in the semi-arid, pastoralist Turkana County, Kenya.
- Most HHs report 4–6 water sources, with major source and use changes across seasons.
- Boreholes serve 94.1 % of HHs but water quality and functionality pose challenges.
- HHs reported using much less water for handwashing and hygiene in the dry season.
- Scaling up rock catchments and subsurface dams can potentially meet HH water needs.

GRAPHICAL ABSTRACT



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ABSTRACT

Water scarcity remains a pressing issue in arid and semi-arid lands (ASALs), often compelling households to rely on multiple water sources to meet their daily water needs. While widespread in many low and middle-income settings globally, the specific extent and dynamics of this practice remain underexplored. This study addresses this gap by examining multisource water use in Turkana County, a predominantly pastoralist and rural low-income ASAL in Kenya. A cross-sectional survey of 475 households revealed universal reliance on multiple water sources, with usage patterns largely influenced by seasonal availability. Despite operational and water quality constraints, boreholes were the most utilized source, supporting 94.1 % of households. Other prevalent sources included rivers/streams, shallow hand-dug wells on dry riverbeds, water pans, springs, water vendors, and the saline Lake Turkana. Roof-based rainwater harvesting also supported a substantial proportion of households (19.4 %), although it was constrained by housing design. While pronounced disparities in water access were observed between rural townships and more remote areas, statistical analysis revealed significant

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seasonal associations between water source use and household activities across Turkana. This study proposes implementing alternative rainwater harvesting techniques: macro and rock catchments, and subsurface dams to address water scarcity and flood risk in Turkana. Findings highlight the critical role of multiple water source use in rural low-income ASALs and its potential to inform research, global water management, health outcomes, and resilience-oriented interventions.

1. Introductionn

Despite global progress in safe water access, rural areas in developing countries, particularly in Africa, face substantial challenges (The Sustainable Development Goals Report, 2022). Nearly 418 million people in Sub-Saharan Africa currently lack access to basic drinking water services, while projections suggest that up to two-thirds of the continent's population may face severe water scarcity in the coming decades (UNICEF and Africa to drastically accelerate, 2022; Falkenmark et al., 1989; Mason et al., 2019). Classified as a high-water risk region by the World Resources Institute (WRI) Aqueduct tool, Africa faces acute vulnerability, especially in its arid and semi-arid lands (ASALs), where climate change, erratic rainfall, and rapid population growth continue to intensify water stress (Falkenmark et al., 1989; Mason et al., 2019; Few et al., 2015a; Wambua, 2019; Kalele et al., 2021). These pressures have also contributed to declining water quality, highlighting the urgency of the region's water crisis.

There is a pressing need for empirical evidence on the widespread practice of multiple water source use (MWSU) to meet daily household needs in African ASALs. This gap is especially pronounced in rural low-income settings, which remain underrepresented in the literature despite several studies (e.g. (Van Koppen, 2020; Katsi et al., 2007; Bolade et al., 2023; Kelly et al., 2018; Nyong et al., 2001; Almedom et al., 1994; Thompson, 2001),) examining household water use in broader rural contexts. The oversight is particularly consequential in pastoral communities, where water is required for both human and livestock use amid chronic scarcity and economic marginalization, factors that further constrain access and management. Existing research in these contexts (e.g. (Kelly et al., 2018; Hoque et al., 2018; Balfour et al., 2020; Libey et al., 2022; Ford et al., 2023),) remains limited in scope, typically documenting only four to eight source types and rarely disaggregating use by season or function.

Although widespread, MWSU remains largely overlooked in water policy and planning frameworks. Global monitoring systems, such as the WHO/UNICEF Joint Monitoring Programme (JMP), classify households by a single "main" water source, oversimplifying household strategies, masking seasonal vulnerabilities, and underestimating water insecurity (Progress on household drinking water, 2021; Bartram et al., 2014). This neglect has practical consequences: it promotes one-dimensional interventions that frequently misalign with household practices or ecological realities, resulting in unsustainable infrastructure, inefficient resource allocation, and persistent inequities (Hope et al., 2020; Mwihaki, 2018; Heo, 2025). This study captures seasonal MWSU dynamics to provide actionable evidence for designing decentralized, equitable, and climate-resilient water interventions that more accurately reflect the coping strategies of vulnerable populations in ASALs. Situating these dynamics within Kenya's devolved rural water governance and SDG 6 monitoring frameworks further underscores how MWSU evidence can inform anticipatory planning, strengthen equity, and improve responsiveness to vulnerable populations (Mwihaki, 2018; Progress on household drinking water, 2023; James Origa Otieno et al., 2023).

Acknowledging these persistent challenges, this study presents a seasonally disaggregated assessment of MWSU in Turkana County, Kenya, a rural, low-income ASAL emblematic of chronic water stress in Sub-Saharan Africa (Water and Sanitation, 2025; Opiyo et al., 2015). Drawing on structured survey data from 475 households, the study captures thirteen distinct water source types and seven functional uses, offering rare, high-resolution insights into household water use under conditions of ecological scarcity and infrastructural fragmentation.

This study aims to contribute to localized SDG 6 monitoring by generating disaggregated data on seasonal dynamics and functional household water use, dimensions rarely captured in national reporting systems (Progress on household drinking water, 2023). By examining how households navigate ecological and infrastructural constraints, the study seeks to inform decentralized service planning and improve responsiveness to vulnerable populations in climate-stressed ASALs, aligning with Kenya's devolved rural water governance model (Mwihaki, 2018; James Origa Otieno et al., 2023; Mwang'ombe et al., 2010; Ngetich et al., 2022). Integration of seasonal variability further strengthens the evidence base for anticipatory planning and resource allocation, as emphasized in the national resilience and adaptation strategies (Hope et al., 2020; Mwang'ombe et al., 2010; Nunow, 2024).

This study is grounded in a dual conceptual framing that integrates the Multiple-Use Water Services (MUS) framework and socio-ecological resilience theory. The MUS framework emphasizes the functional diversity of household water needs and the corresponding reliance on multiple sources (Koppen et al., 2009; Renwick, 2007). Resilience theory complements this by demonstrating how households reorganize water access in response to environmental variability, institutional fragmentation, and long-term resource stress (Berkes et al., 2008; Walker et al., 2004; Folke, 2006). Together, these frameworks provide a systems-level perspective on household water strategies in Turkana's complex and dynamic context, offering a more nuanced understanding of resilience and vulnerability in arid, resource-constrained settings.

The specific objectives of this study are to: (I) describe the number and types of household water sources in Turkana County and their respective uses; (II) assess seasonal changes (wet vs. dry) in water source preferences and usage; (III) investigate household-level water management practices and their seasonal dynamics; and (IV) discuss the implications of these findings for water supply planning, policy development, and climate-resilient interventions in rural low-income ASALs.

2. Methods

2.1. Geographical and demographic overview

Turkana County spans 30,067 sq miles (77,873 km^2) and supports approximately 1 million people and 11 million livestock across its six sub-counties: Loima, Turkana North, South, East, West, and Central (Rusiniak et al., 2021; Population and Housing Census of, 2019). Predominantly rural and pastoralist, the population is spread across dispersed, kinship-tied clustered settlements (Fig. 1a) (Asokan et al., 2025). Notably, over 75 % of residents fall within Kenya's lowest national wealth quintile, reflecting widespread poverty (Kenya Demographic and Health Survey, 2022).

This study covered all six sub-counties. Turkana West is the most populous, with over 239,000 residents and more than 200,000 refugees, while Lodwar Town in Turkana Central has the largest rural township population (approximately 82,970) (Population and Housing Census of, 2019). As refugees are not officially counted in the county's permanent population, the household sample focused exclusively on long-term residents.

Surrounded by hills, mountainous ranges, and the coastal plains along Lake Turkana, the county is predominantly arid to semi-arid. It receives an average annual rainfall of 225 mm, concentrated in two short rainy seasons separated by prolonged hot and dry periods (Kenya Meteorological Department data). Rainfall variability is extreme, ranging from as low as 57 mm during drought years to sudden, flood-triggering events. These conditions reflect intensifying climate variability, evidenced by Lake Turkana's transition from a freshwater lake to a saline, endorheic basin with increasing frequency and severity of droughts (Opiyo et al., 2015; Avery, 2010; Johnson et al., 2009; Schilling et al., 2014).

The combination of fragile hydro-ecology and fragmented infrastructure is typical of rural (Van Koppen, 2020; Katsi et al., 2007; Bolade et al., 2023; Kelly et al., 2018; Nyong et al., 2001; Almedom et al., 1994; Thompson, 2001) and other low-to-middle-income contexts across Africa (Hoque et al., 2018; Tucker et al., 2014; Adekalu et al., 2002; Howard et al., 2002; Vedachalam et al., 2017; Dos Santos et al., 2015; Oyerinde et al., 2022); however, Turkana's extreme aridity, marked by some of the lowest rainfall and highest water stress indices in Sub-Saharan Africa, amplifies these challenges, making it a critical case for examining multi-source household water use under systemic stress.

2.2. Survey design and data collection

This study employed a mixed-methods design, integrating structured cross-sectional household survey with qualitative inquiry to capture both quantifiable patterns and contextual depth. Data collection involved in-person interviews using questionnaires with both closed- and open-ended questions, supplemented by direct observation. The household served as the primary unit of analysis, with interviews conducted with both spouses or available adult men and women. To validate household responses and situate findings within institutional contexts, key informant interviews (KIIs) were conducted with county and national water officers, NGO personnel, and community leaders. All data were self-reported and included respondents' recall across all seasons.

A two-stage probability cluster sampling strategy was employed. Clusters were delineated in consultation with sub-county water officers, using shared water resources and settlement distribution as criteria to ensure ecological and socio-spatial diversity. Within each cluster, households were randomly selected to achieve both statistical rigor and geographic representation.

The survey questionnaire was designed for clarity and translated into the local language. It captured data on water sources, usage preferences, collection patterns, treatment methods, and satisfaction with water quality and quantity. Uses were classified as consumptive (drinking, cooking) or non-consumptive (other household tasks) to enable disaggregated analysis. Respondents could also specify "Other" sources and uses to capture additional inputs.

Questions on water source access and utilization addressed (1) the primary person responsible for water collection, (2) distance to sources, (3) total trip and queuing time across seasons, (4) perceived water quality comparisons, and (5) source use by season and function. The survey aligned with core indicators from the WHO/UNICEF JMP for Water, Sanitation, and Hygiene (WaSH) (Bartram et al., 2014; WHO/UNICEF, 2006). It also captured data on point of use, source reliability, contamination events, and climate variability. Only data amenable to self-reported recall were included.

Volumetric water use for household activities was estimated using 1-, 2.5-, and 5-gallon jerricans to ensure contextual accuracy. These values were cross-validated and converted to liters for consistency. Per-activity volumetric estimates were then used to approximate consumption trends, providing insight into seasonal and spatial variability, although

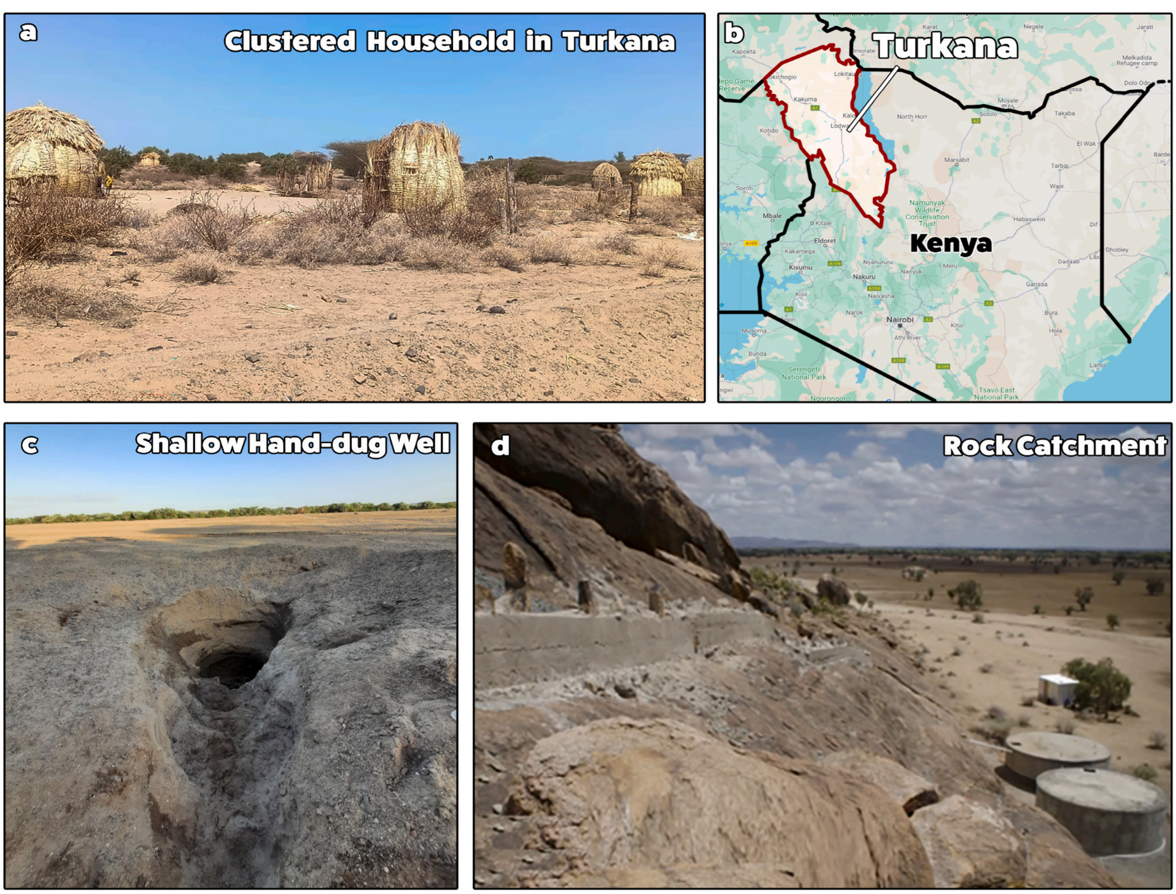

Fig. 1. (a) Clustered settlement pattern showing dome-shaped houses in Turkana County (b) Geographical location of Turkana County. Water collection methods in Turkana County: (c) Shallow Hand-Dug Well on a Dry Riverbed, and (d) Rock Catchment.

total per capita use was not the primary focus.

2.3. Survey implementation summary

The survey included 475 households, with 20 % (94 households) drawn from rural townships—characterized by closely-knit, medium-density settlements with basic public services—and 80 % (381 households) from more remote areas. The sampling strategy ensured inclusivity and representativeness, capturing a cross-sectional snapshot of the county's diverse household population. Each clustered settlement was represented, with participation from both male and female adults, providing insights into intra-household variation by gender, though findings were not explicitly disaggregated beyond that dimension. Importantly, community participation was motivated by interest in future water projects, but participants were informed that the study was academic, involved no direct benefits, and that findings would be shared with relevant authorities to inform future interventions. The findings presented herein derive exclusively from the structured household survey (n = 475). While KIIs provided contextual insights for the broader research study, they were not systematically analyzed in this article.

2.4. Data analysis procedures

Quantitative analysis was led by the first author, with iterative validation from the co-author team. McNemar's test, for paired categorical data, was used to assess seasonal variation in source use. Phi coefficients examined associations between source types and household activities, while the Chi-square test of independence evaluated relationships between source choice and reported seasonal transitions in availability. Statistical significance was determined by comparing computed values of Phi (ϕ) and Chi-Square (χ^2) against critical thresholds. Divergent or ambiguous results were reviewed collaboratively to ensure contextual validity. Due to limited variability, "Farming" was excluded from statistical correlation analyses.

Qualitative data from open-ended survey responses were coded thematically using grounded coding to enrich the interpretation of behavioral adaptations and institutional dynamics.

2.5. Conceptual framing and analytical framework

The dual conceptual framing informed all phases of the study through an integrated mixed-methods approach. The MUS framework shaped the structure of the household survey, enabling functional disaggregation of water uses, seasonal tracking of source reliance, and classification of improved versus unimproved sources. This supported a systematic analysis of multi-source strategies across diverse ecological and infrastructural contexts. Socio-ecological resilience theory complemented this by shaping the inclusion of variables related to reliability, seasonal substitution, access constraints, and user preferences, facilitating the identification of adaptive trade-offs in resource-scarce environments. Both frameworks were jointly operationalized to guide the interpretation of household water practices, enabling a structured assessment of how users adapt to intersecting ecological and institutional stressors.

2.6. Ethical considerations

This study obtained necessary approvals from the University of Alabama's Institutional Review Board (IRB) and the Kenyan government through the National Commission for Science, Technology & Innovation (NACOSTI). Additional permissions were granted by the County government of Turkana and local community leaders. All participating households signed Informed Consent Statements, emphasizing voluntary participation and the right to withdraw at any time. The household questionnaire tool is provided as Supplementary Material (Appendix A) for reference.

Table 1
Water Sources available in Turkana County and their Standards (listed per WHO standards).

Improved Water Sources	Unimproved Water Sources
Boreholes/Protected wells	Rivers/streams
Roof catchment[a]	Lake
Piped water	Shallow hand-dug wells on dry riverbeds
Subsurface dams	Water pans
Rock catchment (with reservoir tanks)[a]	Water vendors
Springs (Protected)[a]	Borrowed water from other households
Bottled water[a]	Springs (Unprotected)[a]
	Unprotected wells[a]
	Roof catchment[a]
	Rock catchment (with open dam reservoir)[a]
	Bottled water[a]

[a] Classified both as improved or unimproved depending on quality and safety.

3. Results

This section is organized into nine interrelated subsections that build a cumulative empirical narrative. Section 3.1 introduces the diversity of water sources across the study area. Sections 3.2 to 3.5 explore seasonal and spatial patterns in water access, behavioral adaptations, and source-use assignments, including statistical associations between water sources and household activities. Sections 3.6 to 3.9 examine factors influencing source selection, dry-season coping strategies, and household-level practices related to hygiene, storage, and water treatment.

3.1. Household water sources and collection dynamics

A typical household comprised five to seven members, with adult females primarily responsible for water collection and related decision-making in 97.3 % of surveyed households. Female children also participated actively in water collection and related activities in 92.3 % of these households.

This survey identified 13 distinct water sources (Table 1), supporting seven specified household uses. Groundwater sources were the primary contributors to household water needs, with boreholes being the most prevalent (94.1 %). However, functionality limitations (22.9 %) and water quality concerns (42.5 %) posed significant challenges (Fig. 2; Table S1 and S2). Other groundwater sources included shallow hand-dug wells on dry riverbeds (48.6 %; Fig. 1c), springs (39.4 %), and subsurface dams (24.8 %) (Fig. 2).

Surface water sources, including rivers/streams (63.4 %), water pans (44.6 %), and Lake Turkana (33 %), also played key roles in meeting seasonal water demands. Additionally, sources such as rock catchments (30.7 %; Fig. 1d), vendor-purchased water (34.3 %), bottled water (22.7 %), and water borrowed from other households (65.7 %) further

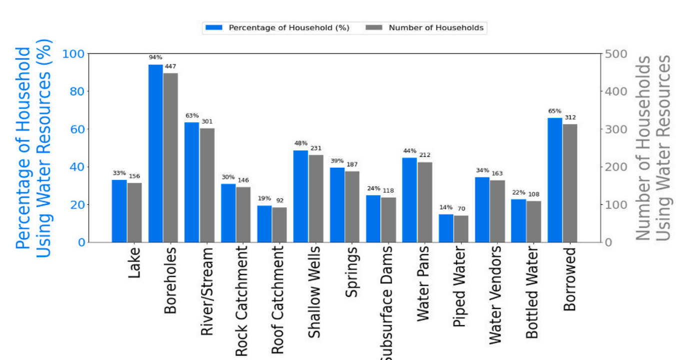

Fig. 2. Percentages of households using different water sources in Turkana County during the wet and/or dry season (households reported multiple sources, so the sum is more than 100 %).

Table 2
Water source availability by location.

Sub-County	No of Wards	Wards/Locations	Rural/Rural Township	Total No. of Households Surveyed	Water Sources Available
Loima	4	Kotarur/Lobei	Rural	58	Boreholes
		Turkwel	Rural		Rock catchment
		Loima	Rural		Rivers/Streams
		Lokiriama/Loren Gippi	Rural		Shallow hand-dug wells on dry riverbed
					Piped water
					Borrowed water
Turkana North	6	Kaeris	Rural	61	Boreholes
		Lake Zone	Rural		Lake
		Lapur	Rural		Springs
		Kaaleng'/Kaikor	Rural		Rock catchment
		Kibish	Rural		Shallow hand-dug wells on dry riverbeds
		Nakalale	Rural		Subsurface dams
					Water pans
					Water vendors
					Borrowed water
Turkana South	5	Kaputir	Rural	74	Boreholes
		Katilu	Rural		Rivers/Streams
		Lobokat	Rural		Piped water
		Kalapata	Rural		Subsurface dams
		Lokichar	Rural Township		Shallow hand-dug wells on dry riverbeds
					Water vendors
					Bottled Water
					Borrowed water
Turkana West	7	Kakuma	Rural Township	120	Boreholes
		Lopur	Rural		River/Stream
		Letea	Rural		Rock catchment
		Songot	Rural		Roof catchment
		Kalobeyei	Rural		Springs
		Lokichoggio	Rural Township		Shallow hand-dug wells on dry riverbeds
		Nanaam	Rural		Subsurface dams
					Water pans
					Piped water
					Water vendors
					Bottled water
					Borrowed water
Turkana East	3	Kapedo/Napeito M	Rural	54	Lake
		Katilia	Rural		Boreholes
		Lokon/Kochodin	Rural		Rivers/Streams
					Shallow hand-dug wells on dry riverbeds
					Water pans
					Piped water
					Borrowed water
	5	Kerio Delta	Rural	108	Lake
Turkana Central		Kang'atotha	Rural		Boreholes
		Kalokol	Rural Township		Piped water
		Lodwar Township	Rural Township		Roof catchment
		Kanamkemer	Rural Township		Water vendors
					Bottled water
					Borrowed water

supplemented household water needs (Fig. 2).

Roof catchment rainwater harvesting was limited due to the prevalence of dome-shaped housing structures, constructed from wooden sapling frameworks and covered with grass, palm leaves, or animal skin (Fig. 1a). Despite these structural constraints, roof catchment supported 19.4 % of surveyed households (Fig. 2).

Piped water was predominantly available in rural townships, serving 14.7 % of surveyed households (Fig. 2); only 5.4 % of these were located in more remote areas.

3.2. *Seasonal and geographic variability of* ***water sources***

Household access to water sources in Turkana County exhibited marked spatial variation as shown in Table 2. Seasonal variation was also pronounced, with rivers/streams, springs, shallow wells, and roof-based rainwater harvesting primarily accessed during the wet season. In contrast, subsurface dams, rock catchments, and water pans, though recharged by rainfall, functioned mainly as dry-season sources. Piped water, boreholes, and vendor-supplied sources remained consistently accessible year-round, while shallow hand-dug wells on dry riverbeds were used exclusively during the dry season.

3.3. *Seasonal adaptations and perceptions of water availability*

Households in Turkana adjusted their domestic water use patterns in response to seasonal shifts in availability. During the wet season, activities such as bathing and laundry were conducted both at home and at the water source, whereas in the dry season, they were performed primarily at the source. Notably, non-consumptive uses exhibited nearly twice the seasonal fluctuation compared to consumptive uses (Fig. 3a).

Perceptions of water availability also varied significantly between seasons ($\chi^2 = 633.6$; $p < 0.05$), with 93.5 % of households reporting scarcity during the dry season, compared to only 12.5 % in the wet season. Perceived water quality similarly shifted: more than half rated it as poor in the dry season, whereas in the wet season, 52.0 % considered it fair and 46.2 % good.

Water source preferences were shaped by aesthetic qualities, perceived health risks, and taste. In rural townships, boreholes, roof catchments, and piped water were consistently rated highest. In contrast, households in remote areas favored rivers/streams and springs

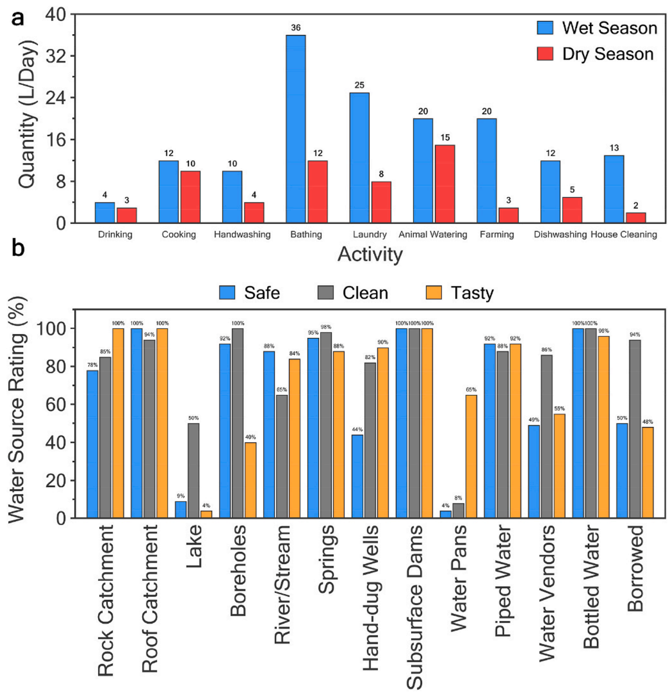

Fig. 3. (a) Seasonal variation in the quantity of domestic water usage in Turkana County, (b) Households' source ratings in Turkana County.

over boreholes, primarily due to superior taste (Fig. 3b).

3.4. Water source access and utilization

A total of 894 water points were reported, of which 18 were located in inter-ethnic conflict zones and deemed inaccessible. Of the remaining 876 accessible sources, 868 (99.1 %) were utilized for at least one purpose, while 8 were not used due to poor water quality. Consequently, 26 water points (18 inaccessible and 8 of poor quality) were excluded from the dataset and subsequent analyses.

Water use patterns in Turkana County were highly diverse, with 94.7 % of surveyed households utilizing four or more water source types year-round. Seasonal shifts in reliance were evident, with 44.8 % of households (primarily in more remote areas) depending on a single source, often rivers or streams, in the wet season. In contrast, all households reported multi-source use during the dry season, with 72 % relying on five to six different types (Fig. 4). No household reported year-round dependence on a single source, demonstrating adaptive strategies in response to seasonal variability.

Clear differences emerged between rural townships and more remote settlements. Township households accessed an average of 4.49 sources (SD = 1.12), primarily private or shared boreholes, piped water, and roof catchment. During the dry season, adaptations included vendor-supplied and bottled water. In more remote areas, households accessed an average of 5.67 sources (SD = 0.97), including public boreholes and wells, springs, seasonal rivers/streams, water pans, and shallow hand-dug wells on dry riverbeds. Use of rock catchments and subsurface dams varied by site-specific availability.

These patterns were also reflected in sub-county disparities. Source diversity peaked in Turkana West, with 23 households utilizing up to eight different source types. Conversely, in Turkana Central, 25 households relied consistently on only three sources: piped, bottled, and vendor-supplied water (Fig. 4).

3.5. Mapping sources to uses across seasons

The assignment of water sources to household activities exhibited

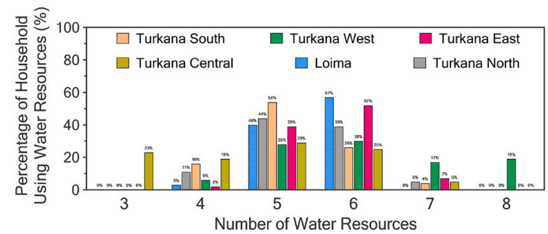

Fig. 4. Percentage of households by location, using different sources as reported by respondents from 475 households surveyed in Turkana County. Water Source types and availability by location are listed and described in Table 2.

clear seasonal variation and statistically significant associations. In the wet season, rivers/streams were the most common sources for cooking (53.3 %) and drinking (52.4 %), followed by boreholes (cooking: 48.6 %, drinking: 40.4 %) and springs (cooking: 27.8 %, drinking: 26.9 %) (Table 3). During the dry season, reliance shifted markedly to boreholes (cooking: 90.7 %, drinking: 82.3 %), with additional use of shallow hand-dug wells on dry riverbeds (35.6 %) and water vendors (34.3 %) for cooking, and rock catchments (30.7 %) and subsurface dams (24.8 %) for drinking. Borrowed water emerged as a key coping mechanism during the dry season, primarily for drinking (65.7 %), with limited use for cooking (17.5 %) and animal watering (11.6 %) (Table 3).

Phi coefficient analysis revealed strong and statistically significant positive associations across most source-activity pairings. Boreholes, rivers/streams, springs, rock catchments, and water vendors were strongly associated with both consumptive uses (cooking and drinking; $\phi = 0.531$ to 0.981; $p < 0.0001$) and non-consumptive activities (e.g., handwashing and bathing; $\phi = 0.580$ to 0.987; $p < 0.0001$). Shallow hand-dug wells on dry riverbeds and water pans showed moderate to strong correlations across all uses ($\phi = 0.240$ to 0.851; $p < 0.0001$), while piped water exhibited consistently strong correlations across nearly all household uses ($\phi = 0.699$ to 0.719; $p < 0.0001$). Although some sources had weaker associations with animal watering and select consumptive uses (cooking; $\phi = 0.187$ to 0.408; $p < 0.0001$, drinking; $\phi = 0.093$ to 0.405; $p < 0.0001$), all correlations were statistically significant, and no negative associations were identified.

3.6. Factors influencing water source access and choices

Seasonal dynamics and proximity were critical determinants of household water access and choice in Turkana County. During the wet season, 72.8 % of surveyed households accessed water sources within 0.6 miles, with round-trip trips taking less than 60 min. In the dry season, accessibility declined sharply, with only 24.6 % of households accessing water within the same distance and time constraints. Instead, 53.7 % of households undertook round trips of 0.6–1.9 miles, lasting approximately 60–105 min, while 18 % traveled up to 3 miles, requiring 2–3 h. A smaller proportion (3.7 %) traveled over 3 miles, with the longest reported round-trip reaching 7.5 miles. Estimating the duration for these longer distances was challenging. Despite these seasonal shifts in access, 52.7 % of surveyed households prioritized closer, lower-quality water sources over more distant, higher-quality options.

Geographic and economic factors also played key roles in household water access and selection. In rural townships, 97.9 % of households reported purchasing vendor-supplied water, compared to only 18.1 % in more remote areas. Additionally, rural township households reported higher water consumption rates than their more remote counterparts. However, preferential access to nearby reliable water sources (within 0.6 miles) was primarily limited to affluent township residents and non-local individuals, who were also more likely to supplement their supply with vendor-supplied or bottled water.

Table 3
Percentage of households reporting utilization of the different water sources and their respective purposes across the two seasons in Turkana County.

Water Source	Wet Season (% of Households)									Change from Wet Season to Dry Season (Percentage Point Change)							
	% HH that use (Anytime)	Any Use	Drink	Cook	Hand Wash	Bath	Laundry	Animal watering	Share with Others	Any use	Drink	Cook	Hand Wash	Bath	Laundry	Animal watering	Share with Others
Boreholes	**94.1**	56.4	40.4	48.6	51.6	44.2	40.6	12.0	23.2	+37.4***	+41.9***	+42.1***	+37.9***	+32.6***	+30.9***	+23.4***	+12.8***
Rivers/Streams	**63.4**	63.4	52.4	53.3	54.5	61.5	60.2	63.4	7.6	−51.4***	−51.2***	−50.1***	−50.7***	−52.0***	−50.3***	−51.4***	−5.1***
Rock catchment	**30.7**	8.8	8.8	3.8	9.3	5.9	8.4	8.7	0.8	+21.9***	+21.9***	+18.1***	+18.3***	+11.2***	+5.9**	+10.7***	+10.5***
Roof catchment	**19.4**	19.4	19.4	19.2	14.3	2.7	7.8	3.8	8.6	−16.4***	−16.4***	−18.9***	−14.3***	−2.7***	−7.8***	−3.8***	−7.6***
Shallow hand-dug wells on dry riverbeds	**48.6**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+48.6***	+13.5***	+35.6***	+43.4***	+44.4***	+48.5***	+25.1***	+2.9***
Subsurface dams	**24.8**	9.9	9.9	6.3	4.0	2.3	0.6	2.1	7.2	+14.9***	+14.9***	+13.5***	+6.5***	+1.1	+2.1**	−0.4	+12.2***
Springs	**39.4**	34.4	26.9	27.8	27.8	39.4	39.3	34.1	13.7	−30.9***	−23.6***	−24.2***	−24.0***	−29.3***	−28.2***	−32.0***	−11.2***
Water pans	**44.6**	6.9	0.0	0.6	2.1	2.9	3.8	6.9	0.0	+37.7***	+4.2***	+15.2***	+28.6***	+32.4***	+33.5***	+37.7***	+3.4***
Piped water	**14.7**	14.7	14.7	8.0	8.0	8.0	7.8	1.1	7.8	−6.5***	−0.4	−4.4***	−5.7***	−6.5***	−6.9***	−0.8	−2.9**
Water vendors	**34.3**	7.2	1.5	7.2	6.9	5.7	3.6	0.0	0.0	+27.1***	+24.4***	+26.5***	+24.2***	+22.9***	+24.0***	+4.4***	+2.5**
Bottled water	**22.7**	10.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	+12.2***	+12.2***	–	–	–	–	–	–
Borrowed water	**65.7**	16.0	16.0	1.7	0.4	0.0	0.0	0.0	6.9	+49.7***	+49.7***	+15.8***	−0.4	–	0.4	+11.6***	+1.5
Lake	**33.0**	4.4	0.0	0.0	0.4	1.1	2.7	4.4	0.0	+28.6***	+0.4	+1.7*	+4.2***	+4.8***	+23.2***	+28.6***	+4.2***

Note. The change from wet to dry season is shown as a percentage point change. The negative changes reflects a reduction in source use, while positive changes reflect an increase.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.7. Seasonal changes in handwashing

In response to recurrent waterborne disease outbreaks and public health campaigns, households in Turkana County demonstrated heightened awareness of handwashing practices. Most households placed water containers outside their homes specifically for handwashing, with 96.2 % recognizing its importance before meals, 88 % after toilet use, and 64.1 % before cooking. However, during the dry season, daily water volumes allocated for handwashing dropped considerably from 10 L to 4 L (Fig. 3a), as larger 2.5-gallon jerricans were replaced with smaller 1-gallon jerricans.

Seasonality significantly influenced the availability of handwashing sources ($\chi^2 = 8.92$; $p = 0.0028$), with 11.6 % of households reporting no handwashing sources during the dry season, compared to only 6 % in the wet season. Notably, rivers/streams (54.5 %), boreholes/wells (51.6 %), and springs (27.8 %) were the primary sources for handwashing during the wet season (Table 3). Dry-season reliance shifted to boreholes (89.5 %), shallow hand-dug wells on dry riverbeds (43.4 %), water vendors (31.8 %), and water pans (30.7 %). This transition included significant increases in borehole use for handwashing (>35 percentage points (pp); $= 0.313$; $p < 0.0001$), along with marked declines in the use of rivers/streams (−50.7 pp), springs (−24.0 pp), rainwater (−14.3 pp), and piped water (−5.7 pp) for the same purpose (Table 3).

3.8. Coping strategies during the dry season

Beyond changes in handwashing practices, households also adopted broader coping mechanisms to manage acute water shortages and maintain basic daily routines. During the dry season, households prioritized critical needs such as cooking and drinking, while curtailing non-essential activities. In more remote settings, 93.5 % of households reportedly refrained from bathing and adopted alternative hygiene practices. These included using mixtures of animal fat, red ocher, and locally sourced scented leaves for skin care, along with traditional toothbrushes crafted from *Esekon* tree twigs.

In rural townships, 52 % of households reduced bathing frequency, while others implemented water-saving measures such as wiping dishes with newspapers to reduce dishwashing. To address food and water scarcity, some households simplified meals to a single daily preparation, while others sent children to schools where they could access complimentary food and water resources.

3.9. Water handling practices

Households in Turkana County commonly used 2.5- and 5-gallon jerricans for water collection and storage (Fig. 5a), citing convenience and compatibility with limited storage space. Some also utilized 5- to 10-gallon earthen pots for storing drinking water, often covering them to maintain hygiene (Fig. 5b). However, practices such as the handling of cups used to fetch water from these pots posed potential risks to water quality.

Point-of-use water treatment methods included chlorination (60 %), traditional purification techniques (43.2 %), and filtration (33 %). Boiling (11.6 %) was the least preferred method due to fuel scarcity and time constraints. However, these self-reported practices are likely to overestimate actual treatment behaviors (Rosa et al., 2017).

4. Discussion

The use of multiple water sources to meet daily household needs is widely documented in rural areas (Van Koppen, 2020; Katsi et al., 2007; Bolade et al., 2023; Kelly et al., 2018; Nyong et al., 2001; Almedom et al., 1994; Thompson, 2001) and other low-to-middle-income contexts across Africa (Hoque et al., 2018; Tucker et al., 2014; Adekalu et al., 2002; Howard et al., 2002; Vedachalam et al., 2017; Dos Santos et al., 2015; Oyerinde et al., 2022), Asia (Brown et al., 2013; Özdemir et al.,

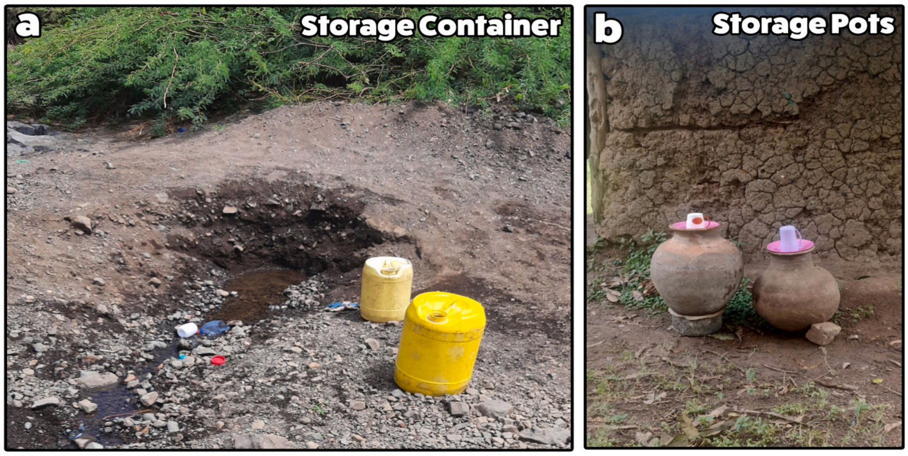

Fig. 5. (a) Common 2.5- and 5-gallon jerricans used for water collection and storage; (b) earthen pots used for drinking water storage, illustrating covered storage practices in Turkana County.

2011; Shaheed et al., 2014; Coulibaly et al., 2014; Wang et al., 1989; Ahmed et al., 1997; Madanat et al., 1993), Central America (Smith et al., 2015), and Pacific Island Countries (Elliott et al., 2017). However, these dynamics remain underexplored in rural low-income ASALs, where ecological stress, infrastructural deficits, and institutional fragmentation exacerbate water insecurity. This study addresses that gap through one of the most granular, seasonally disaggregated analyses of MWSU to date, in a rural low-income ASAL context in Kenya.

Findings reveal widespread and functionally differentiated reliance on multiple sources, with distinct seasonal shifts in use. These behaviors reflect pragmatic adaptation to fluctuating availability, perceived quality, and access constraints, consistent with the MUS framework's emphasis on functional diversity and resilience theory's framing of adaptation as iterative, context-specific, and necessity-driven (Koppen et al., 2009; Renwick, 2007; Berkes et al., 2008; Walker et al., 2004; Folke, 2006). By linking source preferences to coping strategies and seasonal trade-offs, the study advances systems-level understanding of household water dynamics in climate-vulnerable, data-scarce settings and reinforces the urgency of integrating these realities into water policy and planning (Few et al., 2015b; van der et al., 2022).

A disaggregated analysis of improved and unimproved sources (Table 1) illustrates how households reorganize water access strategies in response to intersecting ecological and infrastructural constraints, core dimensions of social-ecological resilience. Seasonal shifts in source preferences and usage patterns (Sections 3.4–3.**6**) reflect the non-linear, iterative nature of adaptation, shaped by trade-offs among water quality, accessibility, and availability (Kelly et al., 2018; Balfour et al., 2020; Hope et al., 2020). These dynamics highlight the need to integrate MWSU realities into SDG 6 monitoring and decentralized, climate-resilient WaSH planning, particularly in contexts where poverty, governance fragmentation, and environmental stress intersect to undermine water security (Progress on household drinking water, 2023; Water and Sanitation, 2025; van der et al., 2022). Frameworks built on a single "main" source fundamentally misrepresent household practices, whereas policies grounded in MWSU provide a more accurate basis for safeguarding access and reducing seasonal vulnerability (Progress on household drinking water, 2021; Progress on drinking water, 2017).

The statistical associations in Section 3.5 further validate the observed coping behaviors and provide actionable evidence for tailoring infrastructure investment and governance reform. Embedding such evidence into localized SDG 6 monitoring frameworks is essential for designing equitable, climate-resilient, and anticipatory interventions in structurally water-insecure ASALs (Wutich et al., 2014; Sadoff et al., 2015; Cairncross et al., 2010).

This study reaffirms the pivotal role of women in rural water management, consistent with prior research and development reports (Progress on household drinking water, 2023; Kenya Demographic and Health Survey, 2022; Water-related conflicts in Turkana County, 2022; Magala et al., 2015; Muok, 2020; Pike, 2019). Intra-household water responsibilities remain deeply gendered, with women and girls disproportionately tasked with collection (section 3.1). These entrenched roles, influenced by cultural and social norms, constrain mobility, reduce time for education or income generation, and perpetuate cycles of vulnerability and inequality (Sorenson et al., 2011; Pickering et al., 2012).

The heterogeneity in MWSU across Turkana County illustrates how households adapt to climatic variability, hydrological uncertainty, and resource scarcity, patterns aligning with findings from other water-insecure regions (Table 3; Fig. 2) (Sorenson et al., 2011; Adams et al., 2019). Households in more remote areas primarily relied on public shared boreholes or wells, rivers and streams, springs, shallow hand-dug wells on dry riverbeds, water pans, and Lake Turkana (Section 3.4). In contrast, households in rural townships predominantly depended on boreholes, piped water, vendor-supplied water, and bottled water. Roof catchment was also used to supplement their supply, though its utility was often constrained by the structural limitations of local housing (Fig. 1a).

Boreholes emerged as the predominant year-round water source in Turkana County, despite operational and water quality limitations (Fig. 2; Tables 3, S1 & S2). Of the 1573 validated boreholes, more than one-third (667) exhibited water quality challenges, while 22.9 % were non-functional (Table S1 and S2). These findings underscore the fragility of borehole dependence and reinforce the urgent need for integrated water resource management that emphasizes infrastructure reliability, routine maintenance, water quality monitoring, and community oversight to ensure long-term sustainability.

Water access patterns in Turkana reflect broader socio-economic disparities and infrastructural limitations. Rural township households predominantly relied on improved water sources, whereas their more remote counterparts depended heavily on unimproved categories (Section 3.4). A year-round reliance on unimproved sources for consumptive purposes was also evident, with only a minority of the 13 identified water source types meeting improved standards (Table 1). This dependency, exacerbated by inadequate water handling, suboptimal water treatment practices, and frequent switching between water sources, further heightens health vulnerabilities (Section 3.9) (Vedachalam et al., 2017; Peres et al., 2020; Stoler et al., 2019). Addressing these inequities necessitates equitable and targeted water infrastructure development to strengthen water security for all communities in the county.

Cultural beliefs also influenced health behaviors and outcomes in Turkana County. Despite scientific warnings about the adverse effects of consuming fluoride-contaminated lake water, some residents attributed skeletal deformities to a "curse" (ibid p.173 as cited in (Avery, 2013)), highlighting a disconnect between scientific knowledge and local perceptions. Bridging this gap is vital, especially given historical links between waterborne diseases and elevated mortality rates (Cholera Epidemics Infects Thousands in Kenya, 2009; Water Shortages Lead to Cholera Outbreak, 2009).

The reported water sources and their utilization exhibited pronounced seasonal variations, shaped by household access, preferences, and local availability (Tables 2 and 3). During the dry season, households in more remote areas, typically dependent on rivers, streams, and springs during the wet season, transitioned to boreholes, water pans, and shallow hand-dug wells on dry riverbeds. Conversely, rural township households, which primarily relied on boreholes, piped water, and roof catchment during the wet season, experienced minimal seasonal variation, substituting roof catchment with vendor-supplied and bottled water during the dry season. These seasonal shifts reveal the interplay of structural constraints and household adaptation, reinforcing resilience perspectives and emphasizing the need for flexible, multi-source planning in ASAL contexts (Thompson, 2001; Wutich et al., 2008; Bisung et al., 2017).

Seasonal shifts in water use patterns revealed a substantial increase in reliance on boreholes (37.4 pp; $p < 0.001$), shallow hand-dug wells on dry riverbeds (48.6 pp; $p < 0.001$), water pans (37.7 pp; $p < 0.001$), and water vendors (27.1 pp; $p < 0.001$) during the dry season. Concurrently, reliance on rivers/streams, springs, and roof catchment declined significantly across key activities such as cooking, drinking, and handwashing ($p < 0.001$; Table 3). These trends emphasize the dynamic and adaptive nature of MWSU in response to seasonal scarcity, a pattern also documented in other water-insecure settings (Thompson, 2001; Wutich et al., 2008). The critical role of supplemental sources, particularly water vendors, during dry periods further highlights the need to strengthen the reliability and quality of all water supply systems to bolster household resilience (sections 3.5 and 3.7).

The utilization of predominant water sources for both consumptive and non-consumptive activities exhibited strong positive correlations, with high statistical significance ($p < 0.0001$; Table 3; Section 3.5). The absence of negative associations demonstrates that households relied on the same sources for multiple needs, reflecting fluid overlaps rather than discrete activity-specific boundaries. These multifunctional patterns, reinforced by significant seasonal shifts in source reliance, challenge conventional survey approaches that classify water use into rigid domains ("drinking" versus "other uses") or rely on narrow proxies such as cooking and handwashing to represent broader household demand (WHO/UNICEF, 2006). They also diverge from a prior study that reported clearer distinctions between use categories, underscoring the need for further research to validate and contextualize the relationships in this study (Elliott et al., 2017).

Households in Turkana County employed adaptive water management strategies shaped by seasonality, proximity, accessibility, and perceived water quality. During the dry season, borrowed water was prioritized for drinking, consistent with patterns observed in other water-insecure rural contexts (Table 3) (Elliott et al., 2017; Wutich et al., 2008). Non-consumptive activities were scaled back, with hygiene practices often replaced by culturally embedded alternatives (Fig. 3a; Section 3.8). Domestic routines were also reorganized to minimize water use, while household labor and resources were strategically redistributed to balance competing demands. Despite these adjustments, water for consumptive use remained relatively stable, while non-consumptive activities declined markedly (Fig. 3a). These patterns reflect deeper structural reorganizations of daily life, emphasizing how water scarcity reshapes behavioral norms. While effective in the short term, such adaptations increase exposure to health risks and socio-economic vulnerability, reinforcing the urgent need for sustainable water security interventions.

The adaptive patterns observed underscore the relevance of both the MUS and socio-ecological resilience frameworks. Water use across multiple sources (Table 3) reflects the multifunctionality of rural systems, a core tenet of MUS often overlooked in centralized water planning (Koppen et al., 2009; Renwick, 2007). Concurrently, seasonal source-switching, water rationing, and the prioritization of essential uses reflect resilience-based responses to hydrological and infrastructural stressors, consistent with findings from other rural ASAL across Kenya (Section 3.8; Fig. 3a; Table 3) (Berkes et al., 2008; Walker et al., 2004; Folke, 2006; Ouma, 2021; Ndiritu, 2021; Karanja, 2018). The widespread uptake of small-scale roof catchments by 19.4 % of households (Fig. 2) further exemplifies community agency and social learning in navigating systemic constraints (Bisung et al., 2014).

Seasonal variation in water acquisition behaviors also revealed pragmatic trade-offs shaped by household perceptions and constraints. Vendor reliance increased significantly during the dry season (+27.1 pp; $p < 0.001$), while reported handwashing declined (Fig. 3a; Table 3), revealing a persistent gap between hygiene awareness and practice, an issue well documented in low-resource settings (Tucker et al., 2014; Elliott et al., 2017; Curtis et al., 2011; Mosler, 2012). Perceptions of water quality also deteriorated during the dry season, with over half of households reporting poor quality, compared to more favorable assessments during the wet season (Section 3.3). Yet, accessibility often took precedence over quality, underscoring the difficult compromises households must navigate amid scarcity (Section 3.6).

While widespread, household responses to water scarcity and service variability in Turkana remain uneven, reflecting differentiated resilience shaped by material assets, ecological setting, institutional access, and social capital. These disparities reinforce the urgency of equity-driven water governance that addresses structural barriers facing marginalized groups. Strengthening resilience requires not only integrated infrastructure and behavioral interventions but also systemic reforms to decentralize service delivery, embed adaptive learning, and strengthen participatory governance. As emphasized in resilience literature (e.g. (van der et al., 2022; Van Der et al., 2020; Falkenmark et al., 2021; Gittins et al., 2021),), such reforms are essential to buffer climate shocks, reduce conflict over scarce resources, and secure long-term water sustainability in ASALs (Leaman, 2012; Pltonykova et al., 2020; Seter et al., 2018; Eckstein, 2009).

4.1. Limitations

This study primarily relied on participant self-reporting and retrospective recall methods, which may have constrained the comprehensiveness and accuracy of information on water sources and utilization. Such methods are susceptible to recall bias, potentially underestimating the impacts of seasonal variations on water availability and usage patterns. To mitigate this, survey questions were anchored to specific reference periods and framed around concrete prompts to elicit memory-anchored rather than generalized responses.

While the study examined household adjustments during the dry season, its primary focus on the quantity, frequency, and timing of water use may have introduced scope bias, overlooking critical qualitative dimensions. Reported coping strategies may also have been affected by social desirability bias. Nonetheless, enumerators were trained to build rapport, ensure confidentiality, and employ indirect questioning techniques where appropriate to reduce this risk. Interviews were also conducted privately, with only household members present, and respondents were assured of anonymity to minimize response distortion. Future research should explore the broader implications of seasonal changes and water scarcity on livelihoods and health outcomes in Turkana County to complement and extend these findings.

Although this study examined household water use patterns, it did not account for the influence of cultural norms and socio-economic status, factors critical to understanding water-related behaviors in heterogeneous, resource-constrained settings like Turkana County. These dynamics often supersede environmental or technical considerations, shaping source selection, perceived quality, and gendered access, particularly where social norms and pastoralist traditions remain influential (Sorenson et al., 2011; Van Der and Voorn, 2008; Nébié et al., 2024). Their exclusion may limit the explanatory depth and obscure socially embedded adaptive strategies (Thompson, 2001; Sorenson et al., 2011). Future research should systematically incorporate these variables and disaggregate by age, disability, and economic status to better identify vulnerabilities and guide targeted interventions.

Another key limitation was the purposive selection of clusters based on safety, cost, and logistical feasibility, which excluded extremely remote areas and may limit the generalizability of the findings. However, selected clusters were designed to approximate conditions in extremely remote settings by drawing on shared water sources. While a larger sample would have strengthened representativeness, no evidence of systematic bias was identified that would undermine the validity of findings. To enhance internal validity, triangulation across survey modules was employed, and interpretation remained conservative and descriptive in scope.

5. Recommendations

Turkana County faces multifaceted challenges in water resource management, including (i) inadequate access to high-quality water, (ii) recurrent flooding, (iii) seasonal variability, (iv) reliance on water-intensive activities like pastoralism, (v) knowledge gaps in sustainable water management, and (vi) insufficient water resource data for informed decision-making. In this context, and given the necessity-driven dynamics of MWSU observed herein, policymakers should move beyond one-dimensional approaches and design flexible, complementary, and seasonally responsive water portfolios.

Turkana's diverse water sources (Table 1) present opportunities to enhance both water quantity and reliability. Solar-powered decentralized treatment systems offer viable solutions for mitigating borehole salinity and improving the quality of surface and groundwater resources (Hafeez et al., 2021; Hendrickson et al., 2020). Their strategic deployment, through coordinated partnerships between local government and NGOs, will be essential for optimizing existing supplies and securing long-term sustainability across the region. Crucially, these technologies must operate as complements rather than replacements within household water portfolios.

Alternative rainwater harvesting (RWH) systems, including macro catchments, rock catchments, and large-capacity subsurface dams, also offer scalable, cost-effective, and climate-resilient solutions to address recurrent flooding and chronic scarcity (Ishida et al., 2011; Petersen, 2013). Well-suited to off-grid, low-maintenance environments, these systems align with the county's hydrogeological and geomorphological conditions, reinforced by the prevalence of dry riverbeds (*laggas*) and mountainous rocky terrain (Water; Nissen-Petersen, 2006; Ngigi, 2003; Umukiza et al., 2023; Che-Ani et al., 2009; Stevanović, 2016; Nilsson, 1988). With more than 30 % of households already relying on small-scale variants (Fig. 2), phased expansion through county-led, community-driven models is both feasible and context-appropriate.

Although rock catchments entail higher upfront costs, cost-effectiveness improves with sub-surface storage (Nissen-Petersen, 2006; Leclert et al., 2014). Integrating managed aquifer recharge (MAR) can further strengthen the viability of subsurface systems by enhancing infiltration and reducing salinity risks (Kebede et al., 2024; Dillon et al., 2020). Scaling up these systems, however, requires site-specific hydrogeological assessments and rigorous cost-effectiveness evaluations (Stevanović, 2016; Nilsson, 1988; Ishida et al., 2003).

The effectiveness of interventions hinges on integration within seasonal household portfolios, supported by financing and governance frameworks that sustain both primary and secondary sources. A blended model, leveraging national and county-level investment with catalytic support from NGOs and development partners, will be critical for adoption at scale. Targeted technical assistance and seed funding for pilot demonstrations can accelerate implementation, while context-specific design approaches that utilize local materials, community labor, and simplified construction standards can enhance cost efficiency. Embedding these systems within community-led delivery models is essential for long-term sustainability, particularly for macro catchment systems that may require negotiated land tenure arrangements.

Beyond pastoralism (the primary economic activity), Turkana holds untapped potential for water-based enterprises, including clean water vending, private treatment services, and rainwater harvesting system provision. Promoting these ventures through targeted financial incentives, vocational training, and technical support can stimulate local economies and diversify livelihoods. Strengthened government–private sector collaboration is critical to reducing financial barriers, attracting investment, and advancing economic diversification, thereby supporting more sustainable livelihoods across the region.

Seasonal fluctuations in water quality pose serious health risks (Elliott et al., 2017), particularly in areas dependent on unimproved sources. The shifts in water use patterns documented in this study underscore the difficulty of maintaining consistent safety standards throughout the year. National public health authorities, led by the Ministry of Health in collaboration with county health departments, should implement comprehensive monitoring to detect contamination trends, assess associated risks, and guide targeted interventions. In the context of MWSU, such actions must include not only improved supplies but also secondary sources, which remain central to household portfolios and contribute substantially to health risks.

Robust data and monitoring systems are essential for tracking temporal changes in water resources and advancing SDG 6 objectives. However, persistent data gaps in remote, low-income settings such as Turkana hinder effective water governance and WaSH programming. The Ministry of Water, Sanitation, and Irrigation, in collaboration with county authorities and local research institutions, should prioritize capacity-building in data acquisition, analysis, and use. Embedding MWSU in monitoring and research frameworks is essential to ensure that evidence systems reflect lived realities, strengthening the basis for policy and planning. Future research should integrate MWSU to advance understanding of household water dynamics and guide resilience-oriented strategies across rural low-income ASAL contexts.

6. Conclusion

This study provides a seasonally disaggregated analysis of MWSU in a rural low-income ASAL, offering empirical insights into how households reorganize access and usage patterns amid scarcity, institutional fragmentation, and ecological stress. Using the MUS and socio-ecological resilience frameworks, it highlights the disconnect between lived realities and survey frameworks that assume a single "main" source or rigidly separate "drinking" from "other uses." The findings underscore the need to integrate MWSU into SDG 6 monitoring and decentralized WaSH planning while informing climate-resilient policy, service delivery, and anticipatory planning. Strengthening water security in Turkana and similar ASALs requires investment in flexible, complementary systems embedded in participatory governance structures, measures essential for resilience, public health, and climate-adaptive water governance in resource-constrained settings.

CRediT authorship contribution statement

Vivian Abungu: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kofi Adanu:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Mostafa Dadashi Firouzjaei:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Benon Wasonga:** Writing – review & editing, Resources, Project administration, Investigation. **Mark A. Elliott:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsd.2025.101531.

Data availability

If the article is accepted, we will ask our IRB for permission to share the data.

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