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Water supply and infrastructure challenges in rural low-Income arid and semi-arid lands (ASALs): A case study of Turkana, Kenya

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Abstract

Water supply and infrastructure challenges persist in rural, low-income arid and semi-arid lands (ASALs), where climatic variability, inadequate infrastructure, and socio-economic constraints exacerbate chronic water insecurity. This study investigates these challenges in Turkana County, Kenya, an emblematic case of extreme water vulnerability in a resource-constrained ASAL context, using a mixed-methods design integrating a cross-sectional household survey (n = 475), key informant interviews (KIIs), focus group discussions (FGDs), and water-quality assessments. Microbial analysis revealed substantial health risks, with 51% of sampled points exceeding World Health Organization (WHO) and Kenya Bureau of Standards (KEBS) thresholds for *Escherichia coli* (0.00 MPN/100 mL). Physicochemical assessments identified elevated fluoride and total dissolved solids in over 25% of samples, indicating widespread inorganic contamination with potential long-term health implications. Moderate correlations between fluoride and other parameters ($r = 0.62$; $p < 0.01$) suggest complex geogenic influences and possible anthropogenic inputs. More than 70% of households reported access challenges during the dry season, underscoring severe seasonal disparities. These vulnerabilities are compounded by the absence of treatment infrastructure, limited monitoring capacity, and fragmented governance. Together, the findings provide decision-grade evidence for diagnosing and addressing water insecurity in rural low-income ASALs and support targeted infrastructure investment, enhanced water-quality safeguards, and integrated governance reforms to improve climate resilience and accelerate progress toward SDG 6.

1. Introduction

Persistent water scarcity is among the most critical challenges in Africa's arid and semi-arid lands (ASALs), threatening millions of lives and livelihoods [1]. These regions face extreme climatic variability, erratic precipitation, high evapotranspiration,

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and mounting demographic pressures, making equitable and sustainable water access increasingly difficult [2–6]. Addressing this crisis is central to Sustainable Development Goal (SDG) 6.1, which targets universal access to safe and affordable drinking water [7]. Yet more than one-third of people in sub-Saharan Africa remain without basic drinking-water services [8,9]. Rural, low-income ASALs are particularly affected, as socio-economic marginalization and infrastructural deficiencies compound water insecurity, with far-reaching implications for public health, economic development, and environmental sustainability [10].

Globally, ASALs exhibit distinct and intersecting drivers of water insecurity, underscoring the need for context-specific interventions [11]. In semi-arid regions of Iran, for example, water stress is shaped by climate change, limited adaptive capacity, and macroeconomic instability [12,13]. Similar pressures, including resource depletion and water-quality decline affect rural ASALs in India, Indonesia, Kazakhstan, and China [14–17]. These challenges intensify in sub-Saharan Africa, where rapid population growth, pronounced rainfall seasonality, economic constraints, and infrastructural deficits heighten vulnerability [18–24]. A more nuanced understanding of local water dynamics in African ASALs is therefore critical to inform targeted interventions and coherent regional strategies.

In many rural ASALs across Africa, households rely heavily on seasonal water sources, resulting in highly unpredictable supplies, especially during dry periods [25,26]. This variability undermines both domestic and productive uses, heightening food insecurity, economic stress, and the potential for water-related conflict [20,27]. Fragile water systems are further strained by overexploitation of limited resources, which accelerates mechanical failures and infrastructure breakdowns [18,28–33]. These technical stresses are compounded by entrenched poverty and financial constraints that limit investment in preventive maintenance and impede the adoption of sustainable water-management practices [34–40].

Beyond SDG 6, water insecurity in rural ASALs intersects with multiple global goals. Reliance on unsafe and unreliable supplies elevates water-borne disease risks, undermining SDG 3 (Good Health and Well-being) [41–44]. Extended collection times, disproportionately borne by women and girls, restrict educational attainment and economic participation, reinforcing gender inequalities highlighted under SDG 5 (Gender Equality) [26,43,45–48]. The high financial and opportunity costs associated with accessing safe water erode livelihoods and household productivity, contributing to chronic poverty and directly impeding SDG 1 (No Poverty) [49–52]. Recurrent droughts and climatic extremes further threaten already fragile rural water systems, linking water insecurity directly to SDG 13 (Climate Action) [53–57]. Situating this study within these interconnected goals strengthens its policy relevance while maintaining SDG 6 (Clean Water and Sanitation) as the central analytical anchor.

Despite this alignment, research on water security in rural low-income ASALs, especially in Sub-Saharan Africa, remains fragmented. Existing studies (e.g., [18–24]) often generalize findings across broad regions, overlooking the socio-ecological complexity of remote, underserved communities. Consequently, interventions may fail to address the multifaceted nature of local water insecurity. In line with SDG commitments and the UN's global pledge to "leave no one behind" [7,58,59], there is an urgent need for empirically grounded, context-specific approaches to improve water access and resilience in these vulnerable settings.

This study addresses these gaps by focusing on Turkana County, one of Kenya's most water-insecure and infrastructurally underserved arid regions. The county faces extreme aridity, pronounced climate variability, and limited socio-economic capacity, all of which exert sustained pressure on its stressed water systems [57,60–62]. Prior research has largely examined drought dynamics (e.g., [60,63–65]), groundwater systems (e.g., [66–69]), hydrogeochemical processes (e.g., [70,71]), and lacustrine hydrology (e.g., [72–74]) as discrete domains. While valuable, these studies offer limited integrative analysis linking household water access, water quality, and infrastructure functionality, and few translate findings into actionable guidance for devolved service delivery. Systemic constraints, including pervasive poverty, fragmented governance, persistent infrastructure gaps, and upstream interventions such as damming and large-scale irrigation, further heighten vulnerability, making Turkana an exemplary case for examining the multi-scalar drivers of water insecurity in rural, low-income ASALs [72,75,76].

This study, therefore, fills critical empirical and policy gaps by generating county-scale, decision-grade evidence to inform devolved water-service planning, infrastructure development and upgrading, and SDG 6 progress monitoring. To support context-responsive and sustainable water governance, this study adopts a multidisciplinary framework informed by previous studies (e.g., [77–79]) integrating water-quality assessment, infrastructure evaluation, and governance diagnostics. Although grounded in Turkana, the findings have broader relevance for strengthening service reliability, enhancing system resilience, and advancing equitable access in similarly constrained ASAL settings.

This study is guided by four key objectives: (I) to characterize temporal variability in household water access; (II) to evaluate perceived and measured water quality and associated source characteristics; (III) to assess the physical condition and operational functionality of existing water supply infrastructure; and (IV) to examine household-level accessibility and reliability of water sources across seasons.

2. Methods

2.1. Study area: Geographic and demographic overview

This study was conducted in Turkana County, located in Northwestern Kenya, at approximately 3°N latitude and 35°E longitude [57,80]. Spanning 30,067 square miles, the county features varied elevations from 369 to 1,800 m above sea level [80,81]. The region is predominantly arid, classified as 19% semi-arid, 42% arid, and 38% very arid, with annual temperatures ranging from 20 °C to 42 °C and a mean of 30.5°C [24,57,80,82,83].

Turkana County, known as the "Cradle of Mankind" for its paleoanthropological significance, is also home to Lake Turkana, the world's largest permanent desert lake [74,84,85]. Its diverse topography comprises escarpments, hills, and expansive low-lying lakefront plains. The county receives an average annual rainfall of approximately 225 mm; however, precipitation is highly erratic, bimodal, and spatially heterogeneous [57,60]. During extreme drought years (e.g., 1992 and 2009; Fig 2B), annual rainfall has fallen below 60 mm, while intense localized storms occasionally trigger flash floods, damaging infrastructure, disrupting livelihoods, and accelerating environmental degradation [57,65,86].

Economically, Turkana is Kenya's poorest county, with over 75% of its population falling within the lowest national wealth quintile [76]. Its population of approximately one million is predominantly rural and pastoralist, and sparsely distributed across six sub-counties: Loima, Turkana North, South, East, West, and Central [57,64,81,87]. The county also hosts over 200,000 refugees and supports an estimated 11 million livestock [87].

2.2. Survey design and data collection methods

This study employed a mixed-methods design integrating quantitative and qualitative approaches. Primary data were collected through a cross-sectional household survey (n = 475) using stratified random sampling to ensure spatial coverage across sub-counties. To complement this, key informant interviews (KIIs) were conducted with national and county officials, non-governmental organizations (NGOs) practitioners, and community leaders to capture institutional and operational perspectives on water-service delivery. Additionally, six gender-stratified focus-group discussions (FGDs) elicited community insights on household water use, source reliability, and management challenges.

Fieldwork was conducted primarily during the wet season owing to logistical and safety constraints associated with dry-season conditions, including extreme temperatures, population mobility, and the complex logistics of accessing sparse, unreliable, and distant water sources [26,60]. To capture seasonal variation, retrospective accounts of dry-season water access and infrastructure performance were elicited through KIIs, FGDs, and respondents' recall across seasons. Triangulation across these instruments ensured that key dimensions of seasonal dynamics were represented while maintaining methodological consistency and data quality.

2.3. Water quality sampling and testing

Water quality testing complemented the primary data collection. Sampling followed a purposive strategy targeting frequently used water points identified through local knowledge, field observations, and logistical feasibility. Although not ecologically stratified, this approach captured the most commonly utilized sources across the county.

Samples were collected in sterile 240 mL bottles, immediately sealed, labeled, and stored in a cooler box. To maintain sample integrity, all pre-incubation procedures were completed within six hours of collection, and onsite microbial testing, conducted by the first author. A subset of samples was re-analyzed in the laboratory to verify result consistency (only for physicochemical properties), with no discrepancies observed. Importantly, procedures adhered to institutional and funder protocols, and no concerns regarding the sampling or testing were reported across study sites.

2.3.1. Microbial testing. Microbial water quality was assessed by quantifying the Most Probable Number (MPN) of *Escherichia coli* (*E. coli*) and total coliforms (TC) per 100 mL of water, with 95% confidence intervals calculated. The Aquagenx Compartment Bag Test (CBT) Kit was selected for its cost-effectiveness, field reliability in low-resource settings, and alignment with World Health Organization (WHO) standards [88].

2.3.2. Physicochemical testing. Physicochemical parameters were measured using calibrated field instruments. pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and resistivity were assessed using the Apera PC60-Z Smart Water Tester. Fluoride concentrations were quantified using the Hanna High Range Fluoride Checker HC HI739, while nitrate (NO_3^-) and nitrite (NO_2^-) were determined using LaMotte Insta-Test 2996 analytic strips. To complement and contextualize field findings, secondary data were obtained from Turkana County and national government water quality reports. Observations during site visits were also used to validate results and strengthen the study's conclusions.

2.4. Data analysis procedures

Descriptive statistical methods (e.g., means, range, and standard deviations) were applied to summarize survey and water quality results. Spearman's rank correlation was used to evaluate associations within the physicochemical dataset. All analyses and visualizations were performed using Python and GraphPad Prism. Triangulation was achieved by cross-referencing household responses with administrative records and by comparing field measurements with potable water standards defined by the WHO and Kenya Bureau of Standards (KEBS).

2.5. Ethical Considerations

This study obtained ethical clearance from the University of Alabama Institutional Review Board (IRB) and the Kenya National Commission for Science, Technology, and Innovation (NACOSTI). Additional permissions were also obtained from the Turkana County government and local administrative leaders. All participants provided informed consent, with clear communication on voluntary participation and the right to withdraw at any time.

3. Results and discussion

This section synthesizes quantitative and qualitative evidence to elucidate the multidimensional nature of water insecurity in Turkana County. Through an integrated analysis of household survey data, water quality metrics, infrastructure audits, and institutional diagnostics, structured around the study's core objectives, the results reveal how intersecting climatic, infrastructural, and governance constraints shape chronic water scarcity in this rural low-income ASAL setting.

3.1. Seasonal variability in household water access

Water source availability in Turkana County exhibited pronounced seasonal variability, directly influencing household access patterns, source preferences, and collection burdens [26]. During the wet season, most surveyed households accessed water within 0.6 miles of their homes. In contrast, dry-season conditions imposed substantially longer round-trip distances and extended collection times (**Fig 1**) [26]. These spatiotemporal disparities underscore the chronic burden of seasonal variability on household water access, and reflect broader dynamics observed across drought-prone regions of sub-Saharan Africa, where climatic variability, infrastructural deficits, and socio-economic constraints converge to shape water security outcomes [18,21–23,89–91].

Among the surveyed households (n = 475; 3 nonresponsive), the mean collection distance was 0.97 ± 0.03 miles (95% CI: 0.91–1.03 miles), with a corresponding mean collection time of 67.4 ± 1.2 minutes (95% CI: 64.9 – 69.8 minutes). Both metrics exceeded the SDG 6.1 threshold, which defines basic access as a round-trip collection time under 30 minutes from a source within 0.62 miles [92]. They also surpassed regional benchmarks, 33 minutes for rural sub-Saharan Africa and 49 minutes for Kenya's Rift Valley, underscoring the acute access challenges facing households in Turkana County [48,93].

Disaggregated data further reveal stark seasonal disparities: while 73% of households met the SDG distance threshold during the wet season, more than 70% exceeded it in the dry season. This variability imposes elevated opportunity costs, suppresses per capita water consumption, and heightens household vulnerability [94]. In particular, women and children disproportionately bear the physical and temporal burdens of water collection in the region, reinforcing gendered labor inequities and limiting overall household productivity [26,45–47].

3.2. Water supply and infrastructure challenges

3.2.1. Limited access to improved water sources. Stark disparities in water source quality in Turkana County reveal entrenched infrastructural inequities, with only eight source types classified as improved (i.e., protected from external contamination and fecal matter), compared to eleven categories of unimproved sources (**Fig 2A**). Improved sources

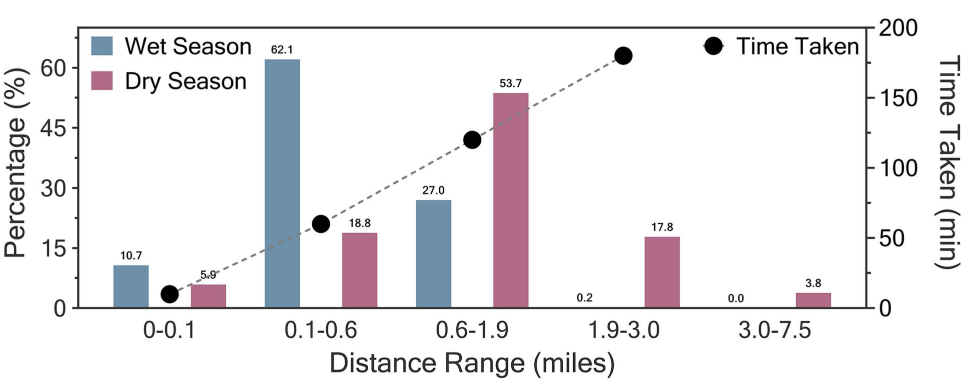

Fig 1. Water Collection distance and time across different seasons in Turkana County.

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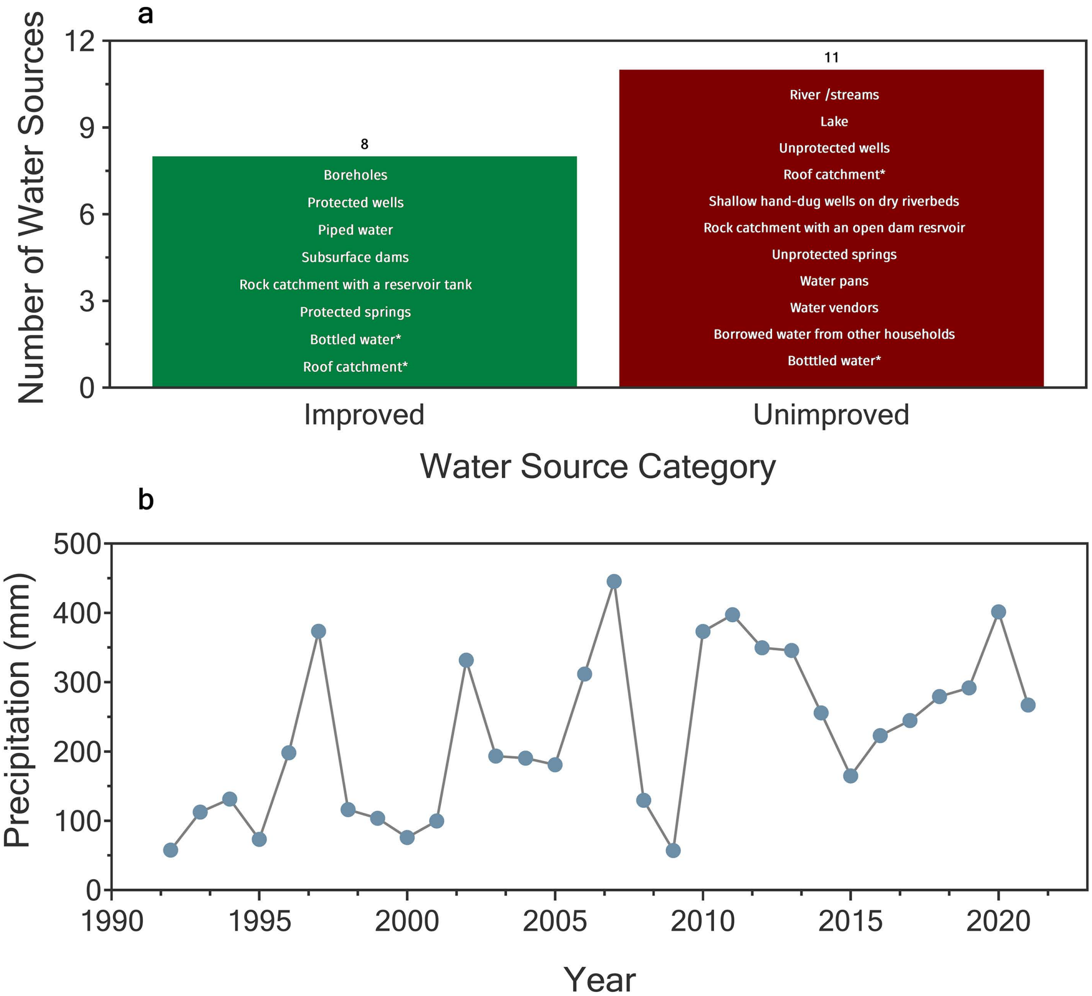

Fig 2. (A) Turkana's Water Source Categories and (B) Turkana County's Annual Precipitation from 1992 to 2021.

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such as piped water, boreholes, and bottled water were more common in rural township settings [26,95]. In contrast, more remote areas relied predominantly on unimproved sources, including unprotected springs and wells, rivers/streams, shallow hand-dug wells on dry riverbeds, and water pans. With over 61% of the population still reliant on unimproved sources [67], strategic investment in safe, protected infrastructure is essential for expanding equitable access and mitigating public health risks.

3.2.2. Geographical and environmental constraints. Turkana's arid and semi-arid landscape imposes severe constraints on sustainable water resource management driven by (i) limited and seasonally variable water sources; (ii) erratic rainfall patterns (**Fig 2B**); and (iii) elevated evaporation rates [70,83,96,97]. These interrelated factors reduce surface water availability, inhibit groundwater recharge, and exacerbate regional water scarcity, collectively placing substantial pressure on already strained infrastructure. The county's remoteness and rugged terrain further hinder service delivery, while underlying geological heterogeneity contributes to pronounced spatial disparities in water quality, evidenced in elevated fluoride and salinity concentrations across numerous sources (see **Section 3.3.2**) [68,70,71].

3.2.3. Governance fragmentation, power dynamics, and their implications. Water supply infrastructure in Turkana County involves multiple actors, including the national government through the Lodwar Water and Sanitation Company

(LOWASCO), the county government, non-governmental organizations (NGOs), and local Water Resource Users Associations (WRUAs). While this multi-stakeholder landscape offers potential for collaboration, overlapping mandates, unclear lines of authority, and fragmented planning undermine coordination, leading to duplication, idle assets, and weak oversight, patterns widely documented in rural water governance [98–100].

Within this fragmented environment, political incentives and power asymmetries strongly shape priority-setting and operational decisions. KIIs highlighted how investments are often skewed toward politically visible capital projects, with some representatives citing ambiguous ownership and limited mandate over legacy systems as disincentives to rehabilitation. This expansion-oriented bias places disproportionate burdens on women and remote households and hinders progress toward SDG 6, perpetuating the very vulnerabilities that devolution was intended to address [26,45,48,101–103].

Regional hydro-political dynamics further amplify these challenges. Upstream abstractions, persistent security constraints, refugee–host pressures, and fragmented donor cycles narrow planning horizons and channel support unevenly across wards, deepening spatial inequities [72,81,104]. Limited community voice in planning and oversight further weakens accountability and local ownership, reducing system sustainability [105]. Strengthening WRUAs and other community-based operators offers a pathway to rebalance power relations, enhance accountability, and improve equity in service delivery [106,107].

3.2.4. Infrastructure functionality and maintenance. Ensuring functional reliability remains a persistent challenge in Turkana County's water sector. As the primary water source for many households, boreholes become especially vital during the dry season when ephemeral sources fail, thereby intensifying the consequences of borehole malfunction [26]. Of the 1,554 installed boreholes, 23% were non-functional, primarily due to mechanical breakdowns (64%), vandalism (8%), and abandonment (8%) (**Table 1**, **Fig 3**, **Fig 4A**, **Fig 4B**, and **Fig 4C**), reflecting broader trends across rural sub-Saharan Africa, where mechanical and security-related failures are widespread [98,108–110]. Another 144 remained unequipped, lacking functional water-abstraction mechanisms, while limited groundwater recharge in several areas further constrained sustainable supply [111].

Piped water systems also faced compounding operational deficiencies, including limited production capacity, recurrent spare parts shortages, and a scarcity of local technical expertise. These constraints contributed to frequent service interruptions and underutilization. The absence of essential components, such as treatment units and water-quality testing facilities, further undermined system reliability and increased public health risks. As a result, households frequently reverted to unimproved sources, heightening their exposure to microbial contamination.

Table 1. Reasons for Borehole Non-functionality in Turkana County Table 1 Reasons for Borehole Non-functionality in Turkana County.

Cause of Non-Functionality	Number of Boreholes	Percentage of Total (%)
Broken Down	229	63.6
Abandoned	29	8.1
Vandalized	28	7.8
Bad Water Quality	20	5.6
Collapsed	18	5.0
Pump Burnt Out	10	2.8
Dried out	8	2.2
Low Yield	6	1.7
Pump Not Installed	4	1.1
Capped	4	1.1
Swept by floods	3	0.8
Silted	1	0.3

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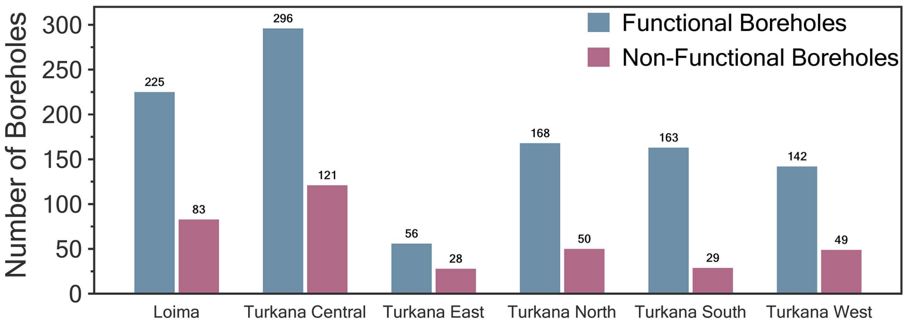

Fig 3. Borehole Functional and Non-Functional Data by Sub-County in Turkana County.

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Fig 4. Boreholes abandoned due to: (A) poor water quality, (B–C) breakdown, (D) Turkana residents fetching water from a broken piped water supply.

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Findings from KIIs and FGDs reinforced these observations, with many supply systems reported to fail within three years of installation. National-level data reflect similar patterns: across Kenya's ASALs, two-thirds of rural water systems become dysfunctional within 3–5 years, and roughly one-third remain non-functional at any given time, underscoring the acute challenges of sustaining water infrastructure in marginalized, resource-constrained regions [112,113].

3.3. Water quality analysis

This study sampled multiple water sources, including piped water, surface waters (Lake Turkana, rivers, open-reservoir rock catchments, and water pans), boreholes, bottled water, springs, shallow hand-dug wells in dry riverbeds, subsurface dams, and vendor-supplied water. Microbial and physicochemical analyses revealed widespread public-health risks, with several samples exceeding WHO and KEBS drinking-water quality thresholds [41,114]. Microbial contamination results are presented in Fig 5A, Fig 5B, Table A in S1 Text, and Table B in S1 Text, while physicochemical findings are summarized in Table 2.

3.3.1. Microbial analysis. ***Escherichia coli (E. coli).*** Among the 91 sampling points, 49% had no detectable *E. coli* (0.0 MPN/100 mL; **Fig 5A**). Fecal contamination was detected in the remaining samples: 18% fell within intermediate-risk categories (6% probably safe, 1.0–3.7 MPN/100 mL; 12% possibly safe, 3.1–9.6 MPN/100 mL), 22% within high-risk categories (14% possibly unsafe, 13.6–17.1 MPN/100 mL; 8% probably unsafe, 32.6–48.3 MPN/100 mL), and 11% were classified as unsafe, exceeding 100 MPN/100 mL.

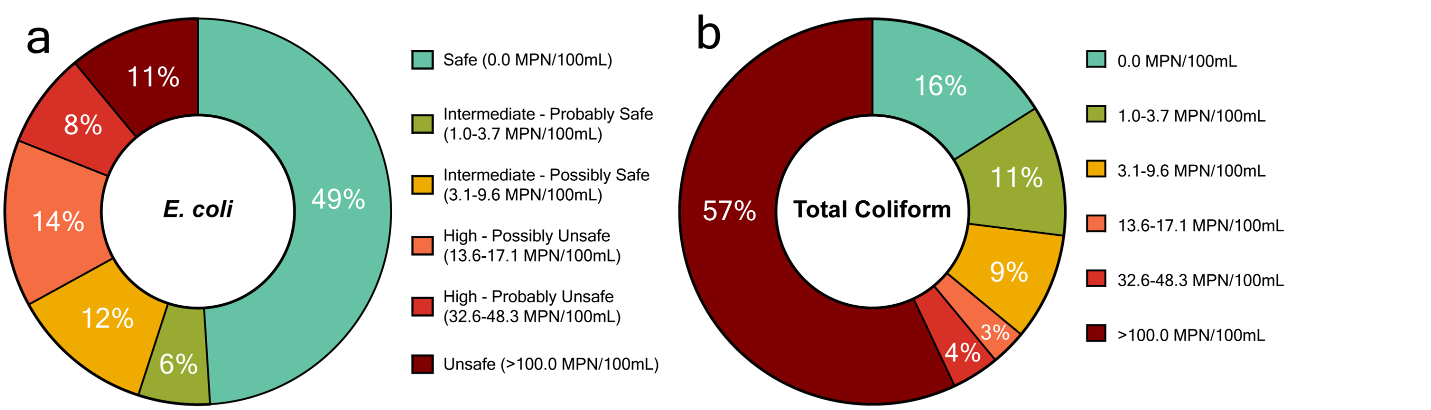

Fig 5. (A) *E. coli* risk categories and (B) total coliform concentration levels in 91 mixed-source water samples from Turkana County.

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Table 2. Physicochemical parameters of water samples from Turkana County.

Test Parameters	Units	Range	Mean± Std Deviation	Coefficient of Variance %	WHO Guideline
pH (-)	–	5.92-9.79	7.95 ± 0.64	8.09	6.5-8.5
Electrical Conductivity (EC)	[μS]	11.3-10380	1444.02 ± 1911.52	132.37	1500
Total Dissolved Solids (TDS)	ppm	23.9-7310	1006.56 ± 1315.48	130.69	<300
Salinity	ppt	0.02-5.14	0.71 ± 0.93	131.46	–
Resistivity	kΩ	0.008-24.5	2.04 ± 2.84	139.33	–
Fluoride	ppm	0.0-16.9	1.69 ± 2.69	159.35	1.5
Nitrite (NO2-)	ppm	0-0.5	0.01 ± 0.05	1000.00	3
Nitrate (NO3-)	ppm	0-50	2.47 ± 7.83	314.80	50

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Total Coliform (TC). Only 16% of samples were free of TC (0.0 MPN/100 mL), while more than half (57%) exceeded 100 MPN/100 mL (**Fig 5B**). The remaining samples ranged from 1.0 to 48.3 MPN/100 mL, indicating widespread sanitary breaches across multiple source types.

Risk stratification by source type revealed comparatively lower microbial contamination in subsurface dams, bottled water, boreholes, and piped supplies (Table A in S1 Text and Table B in S1 Text). However, high-use boreholes, particularly those located in school compounds, marketplaces, and livestock watering points, showed elevated *E. coli* levels compared with infrequently used, saline boreholes, raising concerns about borehole safety given their designation as improved sources (Fig 2A). Surface waters also presented the highest risk, with 83% of samples exceeding safe *E. coli* thresholds, corroborating community accounts linking contamination to widespread open defecation near water points, unrestricted livestock access, crowding at collection points, and unhygienic handling during collection and storage, conditions typical in pastoral settings [115,116].

Although this study did not isolate specific contamination pathways, the presence of *E. coli* in over half of the samples indicates pervasive fecal pollution associated with inadequate sanitation, aging infrastructure, and unsafe water-handling practices [115]. FGDs described routine use of shared dipping utensils and open storage containers, while seasonal narratives highlighted long collection times and fallback to unimproved sources during shortages, as conditions that intensified exposure risk during the dry season.

Variability in contamination levels along the supply chain (from source to point of use) also reflected converging behavioral, infrastructural, and institutional drivers. While common in pastoral contexts [116], the detection of *E. coli* in piped supplies and TC concentrations of 13.6 MPN/100 mL in refilled bottled water is particularly concerning, revealing critical weaknesses in water treatment and distribution (Table A in S1 Text and Table B in S1 Text). KIIs reported intermittent chlorination, inconsistent residual testing, and weak handling practices, noting that vendors frequently refill branded bottles without adequate cleaning or post-treatment, underscoring the need for stricter quality control and regulatory oversight.

3.3.2. Physicochemical properties. Physicochemical analysis of sampled water points provided critical insights into the chemical quality of drinking water sources in Turkana County. Results revealed pronounced spatial variability, with pH values ranging from 5.9 to 9.8 (mean = 8.0 ± 0.6). While 82% of the samples met WHO and KEBS drinking water pH standards (6.5–8.5), deviations in some samples suggest potential localized geochemical or anthropogenic influences (**Table 2**, **Fig 6A**) [41,114].

Fluoride concentrations ranged from 0.0 to 16.9 ppm (mean = 1.7 ± 2.7 ppm), exceeding the WHO and KEBS threshold of 1.5 ppm in over 25% of the samples (Table 2, Fig 6B) [41,114]. This trend aligns with findings from the Rift Valley, where naturally occurring fluoride-bearing geological formations are commonly linked to elevated groundwater fluoride levels [70,71,117–121].

Electrical conductivity (EC) and total dissolved solids (TDS) levels also exhibited wide variations, with EC ranging from 11.3 to 10,380.0 µS/cm (mean = 1444.0 ± 1911.5 µS/cm) and TDS from 28.9 to 7310.0 ppm (mean = 1006.6 ± 1315.5 ppm) (Table 2, Fig 6C, and Fig 6D). While 83% of samples met the KEBS EC threshold for potable water (2500 µS/cm), 17% exceeded this limit. Similarly, 67% and 22% of TDS values surpassed WHO (<300 ppm) and KEBS (<1500 ppm) thresholds, respectively, highlighting variation in mineral content and salinity across Turkana's water sources [41,114].

Consistent with established hydrochemical relationships, statistical analysis revealed strong positive correlations between EC, TDS, and salinity ($r = 0.95$ to 1.00, $p < 0.001$), supporting the inference of a common hydrogeogenic origin. However, moderate correlations between fluoride and these parameters ($r = 0.62$ to 0.63, $p < 0.01$) suggest the presence of additional contributing factors beyond general mineralization and salinization, warranting further investigation [70,119,121].

3.4. Community perceptions and participation in water management

Community perceptions and participation play a critical role in shaping household water-use behaviors and the long-term sustainability of water interventions in Turkana County. Despite widespread awareness of contamination risks, many

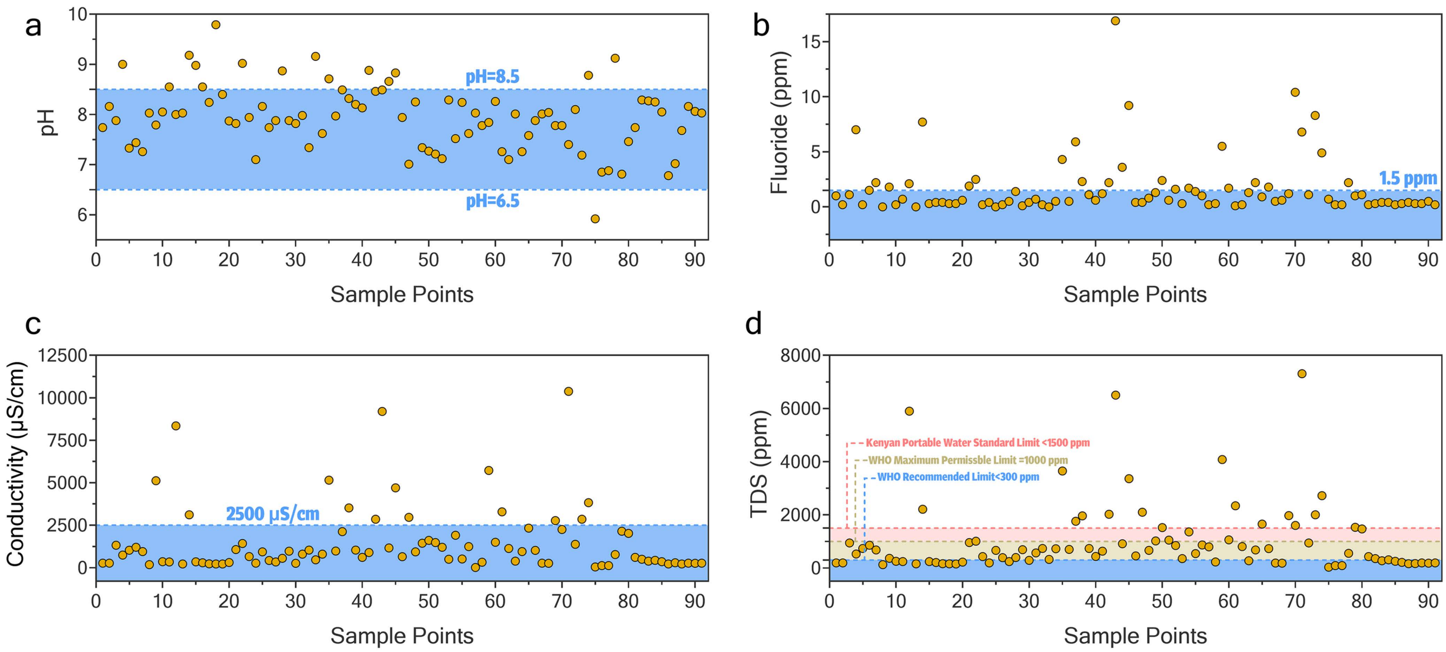

Fig 6. Physicochemical characteristics of 91 mixed-source water samples from Turkana County, with sample points presented in mixed order: (A) pH, (B) fluoride concentration, (C) electrical conductivity (EC), and (D) total dissolved solids (TDS). The shaded bands indicate applicable drinking-water standards: WHO-recommended pH range (6.5–8.5) in **(A)**; WHO maximum permissible fluoride concentration (1.5 ppm) in **(B)**; Kenyan drinking-water standard for EC (<2,500 µS/cm) in **(C)**; and WHO-recommended (<300 ppm), WHO maximum permissible (1,000 ppm), and Kenyan potable-water standard (<1,500 ppm) TDS thresholds in **(D)**.

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households continue to rely on unimproved sources, driven by limited availability of improved supplies, taste preferences, elevated salinity in boreholes, and distrust in the reliability of formal systems, particularly recurrent mechanical failures that often led to system abandonment (**Fig 4A**, **Fig 4B**, **Fig 4C**, **and Fig 4D**) [26]. These preferences frequently diverge from measured water quality (**Section 3.3**) and recommended safety standards, with sources perceived as "safer" or "better-tasting" often exhibiting microbial or chemical contamination [41,114]. Similar patterns have been documented in other rural settings, where sensory perceptions routinely outweigh health-based safety standards [122–126].

Equally consequential are deficiencies in community participation in water management. Insights from KIIs and FGDs revealed that limited involvement of local communities in the planning, implementation, and maintenance of water systems erodes local ownership and compromises long-term sustainability. These findings align with evidence from other rural low-income settings, where externally driven interventions with minimal community engagement frequently experience premature failure and accelerated infrastructure degradation [98,109,110]. Together, these insights underscore the need for participatory approaches that promote community ownership, build local technical capacity, and enhance accountability to ensure the durability and effectiveness of water interventions over time.

3.5. Coping strategies to water supply challenges in Turkana county

To cope with chronic water scarcity, particularly during the dry season, households in Turkana County employed a range of adaptive strategies, including water source diversification, inter-household sharing arrangements, and the prioritization of essential over non-essential uses [26]. Some households also adopted alternative hygiene practices, including applying mixtures of animal fat, red ochre, and locally sourced scented leaves for skin care, using twig-based toothbrushes, and wiping dishes with newspapers in response to limited water availability [26]. While effective in the short term, these strategies heighten microbial risks, undermining both public health and the sustainability of water security efforts [127–129].

Water scarcity also reshaped intra-household labor dynamics and resource allocation. Children were sent to government- or NGO-supported institutions to access free meals and drinking water, while adult males and older boys migrated with livestock in search of pasture and water. Meanwhile, women and girls, primarily responsible for domestic water collection, walked long distances to secure supplies, intensifying both their time burden and physical strain (Section 3.1).

3.6. Health and socio-economic implications

3.6.1. Microbial contamination and disease burden. The absence of water treatment and routine quality-monitoring infrastructure in Turkana County (**Section 3.2.4**) significantly amplifies existing public health vulnerabilities. Raw, untreated water—often classified as "improved" based solely on its source—is supplied directly to households, heightening the risk of microbial contamination [95]. Reflecting this gap, widespread contamination was detected at several sampling points along the distribution pathway, with concentrations frequently exceeding WHO and KEBS drinking-water safety thresholds (**Table A** in S1 Text and **Table B** in S1 Text) [41,114]. Since WHO guidelines require drinking water to be free of *E. coli* and TC, these elevated levels highlight the need for targeted interventions. This urgency is underscored by regional records of high mortality during past waterborne disease outbreaks [130,131].

Addressing microbial contamination is therefore essential not only to prevent recurrent outbreaks but also to mitigate child malnutrition, reduce household and system-level expenditures, and relieve pressure on under-resourced health facilities. KIIs and FGDs described reliance on unimproved water sources as the principal driver of diarrhoeal disease and cholera outbreaks, particularly among young children and older adults. Healthcare professionals corroborated these accounts, frequently attributing clinical cases to consumption of contaminated surface water, in line with prior research linking pathogen exposure to unsafe water and inadequate household-level treatment practices [132–136]. Notably, chronic microbial exposure in early childhood has been linked to nutrient malabsorption and growth stunting among children under five in Turkana [134].

3.6.2. Chemical contaminants and long-term health risks. Beyond microbial contamination, chemical pollutants in drinking water sources (**Section 3.3.2**) pose substantial long-term health risks. Fluoride concentrations exceeded WHO and KEBS thresholds in over 25% of sampling points, heightening the risk of dental and skeletal fluorosis (**Table 2**, **Fig 6B**) [41,114]. This is particularly concerning given the irreversible and well-documented health effects reported in Turkana County and across the Rift Valley [73,117,119,137,138]. Although local healthcare personnel recognized fluoride-related conditions, FGDs revealed limited community awareness, with many residents unaware that their symptoms were attributable to prolonged exposure to chemically contaminated waters.

Similarly, while not classified as acutely hazardous, the elevated TDS levels observed (Fig 6D) may contribute to kidney dysfunction, disrupt mineral homeostasis, and increase dehydration risk, particularly among vulnerable populations [139,140]. Community narratives also linked borehole salinity to joint pain in adults, suggesting possible chronic health impacts. These concerns align with previous findings among Turkana pastoralists, where a 100 mg/L increase in water salinity was associated with a 45% rise in hypertension risk and a 33% increase in impaired renal function [141]. Collectively, these fluoride- and salinity-related conditions extend beyond individual morbidity: chronic exposure elevates household healthcare costs, increases demand for long-term care, and places additional strain on understaffed, resource-constrained health facilities, contributing to a growing burden of chronic disease in already vulnerable populations [118,119].

3.6.3. Socio-economic implications. Water scarcity and contamination in Turkana County have far-reaching socio-economic consequences. The high incidence of water-related illnesses, including cholera, typhoid, diarrhoeal disease, and fluoride-related bone deformities, reduces labour productivity and amplifies economic shocks, placing additional strain on already fragile rural economies (**Sections 3.6.1 and 3.6.2**) [142–144]. Seasonal displacements during extended dry periods (**Section 3.9**) further disrupt household structures, erode social cohesion, and disproportionately burden women and girls, limiting access to education, employment opportunities, and broader economic participation [26,46,47].

Deteriorating water quality also undermines public trust in formal infrastructure, discouraging community engagement in future interventions and weakening prospects for long-term system stewardship. The cumulative effect of these dynamics reinforces cycles of poverty, deepens socio-economic inequality, and exacerbates entrenched gender disparities, underscoring the urgent need for sustainable, community-informed water solutions [46,93,142,145].

4. Limitations

This study's focus on Turkana County, with its distinct geographic, climatic, and hydrological characteristics (**Section 3.2.2**), may limit the generalizability of findings to other ASALs. Logistical constraints, including the inaccessibility of highly remote or insecure areas and a limited number of sampled water points, may have introduced sampling bias and underrepresented spatial heterogeneity in water sources. To mitigate this, field reconnaissance, logistical feasibility, and community input guided site selection to ensure inclusion of commonly used sources across diverse settlement zones. Future studies should employ stratified, spatially randomized sampling to improve representativeness and external validity.

The cross-sectional wet-season design limits capture of seasonal variability; therefore, dry-season vulnerabilities may be underrepresented. While FGDs and KIIs offered retrospective context on dry-season conditions, these accounts cannot substitute for direct, seasonal measurements. Longitudinal monitoring with higher temporal resolution, integrated climatic data, and participatory approaches, supported by agency–community collaboration, is needed to characterize seasonal dynamics and strengthen adaptive management.

Water quality assessment was also limited to microbial indicators and selected physicochemical parameters, excluding trace metals, specific salts, and emerging contaminants. Future studies should incorporate a broader suite of chemical and biological indicators, as well as related health assessments, to strengthen risk characterization.

Reliance on self-reported data may have introduced recall or reporting bias, particularly for historical access and infrastructure functionality. Although triangulation with administrative records and field observations helped reduce this risk, real-time monitoring tools and digital tracking systems would enhance accuracy in future research.

Finally, while this study identifies institutional fragmentation and highlights key governance and power dynamics influencing water service delivery, it does not fully examine the socio-political processes shaping these outcomes. The primary focus on environmental, infrastructural, and water-quality dimensions limited deeper exploration of the social, economic, and political drivers of water insecurity. Future research should adopt participatory, multidisciplinary approaches to better illuminate governance structures, conflict dynamics, and systemic factors underpinning water insecurity in rural low-income ASALs.

5. Recommendations

Addressing water supply and infrastructure constraints in Turkana County demands a coordinated, context-specific, and multi-dimensional strategy. Persistent challenges, including limited access, pronounced seasonal variability, infrastructural deficiencies, water quality concerns, and complex geographical constraints, pose serious public health and socio-economic risks. Overcoming these challenges requires integrated interventions that strengthen local water security, climate resilience, and long-term sustainability.

Water security should be recognized as foundational to rural economic stability, food security, and poverty reduction [7,146]. Aligning water sector strategies with national development priorities, led by the Turkana County Government and supported by the Ministry of Water, Sanitation, and Irrigation, can help mitigate the drivers of seasonal migration, displacement, and livelihood disruption. Sustained, diversified financing, anchored in national and county frameworks and supported by public, private, and international actors, is essential for improving infrastructure, strengthening governance, and advancing climate adaptation.

Rehabilitating and expanding water infrastructure remains critical. The county government, in collaboration with local utilities such as LOWASCO and development partners, should prioritize the restoration of non-functional systems, invest in decentralized supply networks, and institutionalize preventive maintenance. Integrating modern monitoring technologies through partnerships with research institutions and the Water Resources Authority will enable adaptive, evidence-based water management grounded in reliable, time-sensitive data.

To address the seasonal dynamics that compromise water availability and system performance, targeted investments in diversified, climate-resilient supply systems are urgently needed. National and county governments, in partnership with NGOs and donor agencies, should scale up rainwater harvesting infrastructure, including rock catchments, macro catchments, and subsurface dams, to expand storage capacity [147–149]. Complementary measures such as groundwater recharge and small-scale desalination can further diversify supply, improve quality, and build resilience across both surface and groundwater systems.

Reducing the burden of water collection is vital to improving educational attainment and economic participation, particularly for women and children [46,47]. Expanding decentralized distribution networks, led by the county government and supported by community-based organizations, can substantially reduce collection burdens. Local water resource planning must also address inequalities shaped by governance and socio-political dynamics. Community education and awareness campaigns remain essential for mitigating contamination risks, reducing the socio-economic burden of unsafe water use, and encouraging sustained adoption of safe water and sanitation practices.

To address widespread microbial contamination, the Ministry of Health, in collaboration with the Ministry of Water and development partners, should invest in centralized treatment facilities, regional laboratories, and robust quality control systems. Where centralized options are not feasible, the county government and NGOs should support the rollout of affordable, context-appropriate household and community-level treatment technologies to overcome persistent logistical and economic barriers.

Proactive monitoring and regulation of chemical contaminants, particularly fluoride, must also be prioritized. Regulatory agencies and research institutions should collaborate to institutionalize routine water-quality surveillance, track contamination trends, and inform health and infrastructure investments.

At the governance level, Turkana County should adopt an integrated framework to strengthen stakeholder coordination and service delivery. Key actions include clearer institutional mandates, improved interagency collaboration, and shared asset registries, guided by the County Department of Water, the Water Services Regulatory Board (WASREB), and Water Resource Users Associations (WRUAs). Embedding water governance within broader health, education, and development systems can unlock cross-sectoral synergies [56,146]. Strengthening the role of WRUAs and community-based organizations in system planning and maintenance will further reinforce local ownership and support sustained infrastructure performance [150].

Advancing research and innovation is essential for strengthening long-term water security in Turkana County and other ASALs. Future work should build on these findings by developing context-specific technological and management solutions and integrating scientific evidence into local planning and decision-making. Embedding adaptive approaches within county and basin-level institutions will enhance their capacity to respond to climatic uncertainty and system variability. The adoption of Integrated Water Resource Management (IWRM) principles [151,152], guided by national and regional water agencies, remains critical for ensuring environmentally, socially, and economically sustainable water systems across the region.

6. Conclusion

This study integrates water-quality evidence, infrastructure assessments, governance diagnostics, and community insights to generate decision-grade evidence for one of Kenya's most water-insecure regions. It demonstrates how environmental constraints, geographic isolation, and governance and power asymmetries converge to shape inequitable and unreliable water access, positioning water insecurity in rural ASALs as both a technical and socio-political challenge. By linking infrastructural deficiencies with microbial and chemical risks and situating these within fragmented governance systems, the study provides one of the most detailed county-scale assessments of rural water insecurity in Turkana. The findings offer actionable guidance for devolved planning, performance monitoring, and investment prioritization under SDG 6. Realizing meaningful improvements will require coordinated investment, strengthened governance, climate-resilient management, and sustained institutional commitment tailored to ASAL socio-ecological realities. Progress will also depend on research-driven innovations and inclusive multi-stakeholder collaboration, particularly with community-led initiatives, to enhance service quality and ensure long-term system sustainability.

Supporting information

S1 Text. Supporting Information.
(DOCX)

S1 Checklist. Inclusivity in global research.
(DOCX)

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References

1. Leal Filho W, Totin E, Franke JA, Andrew SM, Abubakar IR, Azadi H, et al. Understanding responses to climate-related water scarcity in Africa. Sci Total Environ. 2022;806(Pt 1):150420. https://doi.org/10.1016/j.scitotenv.2021.150420 PMID: 34571220
2. Falkenmark M, Lundqvist J, Widstrand C. Macro-scale water scarcity requires micro-scale approaches. Aspects of vulnerability in semi-arid development. Nat Resour Forum. 1989;13(4):258–67. https://doi.org/10.1111/j.1477-8947.1989.tb00348.x PMID: 12317608
3. Mason N, Nalamalapu D, Corfee-Morlot J. Climate change is hurting Africa's water sector, but investing in water can pay off. World Resources Institute; 2019.
4. Few R, et al. Vulnerability and adaptation to climate change in the semi-arid regions of East Africa. 2015. http://idl-bnc-idrc.dspacedirect.org
5. Wambua BN. Analysis of the current and potential future climate hazards and their impacts on livelihoods and adaptation strategies in arid and semi-arid lands. AJAFS. 2019;7(4). https://doi.org/10.24203/ajafs.v7i4.5835
6. Kalele DN, Ogara WO, Oludhe C, Onono JO. Climate change impacts and relevance of smallholder farmers' response in arid and semi-arid lands in Kenya. Scientific African. 2021;12:e00814. https://doi.org/10.1016/j.sciaf.2021.e00814

7. United Nations. The 2030 agenda for sustainable development. 2015. https://www.sdgs.un.org
8. Hope R, et al. Rethinking the economics of rural water in Africa. Oxon Rev Econ Pol. 2020;36(1):171–90.
9. United Nations. The Sustainable Development Goals Report 2022. 2022.
10. Gaur MK, Squires VR. Climate variability impacts on land use and livelihoods in drylands. Springer International Publishing. 2018. p. 3–20.
11. Anthonj C. Contextualizing linkages between water security and global health in Africa, Asia and Europe. Geography matters in research, policy and practice. Water Security. 2021;13:100093. https://doi.org/10.1016/j.wasec.2021.100093
12. Karimi M, Tabiee M, Karami S, Karimi V, Karamidehkordi E. Climate change and water scarcity impacts on sustainability in semi-arid areas: Lessons from the South of Iran. Groundwater for Sustainable Development. 2024;24:101075. https://doi.org/10.1016/j.gsd.2023.101075
13. Taheri Tizro A, Fryar AE, Pour MK, Voudouris KS, Mashhadian MJ. Groundwater conditions related to climate change in the semi-arid area of western Iran. Groundwater for Sustainable Development. 2019;9:100273. https://doi.org/10.1016/j.gsd.2019.100273
14. Omarova A, Tussupova K, Hjorth P, Kalishev M, Dosmagambetova R. Water Supply Challenges in Rural Areas: A Case Study from Central Kazakhstan. Int J Environ Res Public Health. 2019;16(5):688. https://doi.org/10.3390/ijerph16050688 PMID: 30813591
15. Singh O, Turkiya S. A survey of household domestic water consumption patterns in rural semi-arid village, India. GeoJournal. 2012;78(5):777–90. https://doi.org/10.1007/s10708-012-9465-7
16. Messakh JJ, Punuf DA. Study on the accessibility of water sources to meet the water needs of rural communities in semi-arid regions of Indonesia. IOP Conf Ser: Earth Environ Sci. 2020;426(1):012043. https://doi.org/10.1088/1755-1315/426/1/012043
17. Liu W, Zhao M, Xu T. Water poverty in rural communities of arid areas in China. Water. 2018;10(4):505. https://doi.org/10.3390/w10040505
18. Calow R, et al. The struggle for water: drought, water security and rural livelihoods. 2006.
19. Calow RC, Macdonald AM, Nicol AL, Robins NS. Ground water security and drought in Africa: linking availability, access, and demand. Ground Water. 2010;48(2):246–56. https://doi.org/10.1111/j.1745-6584.2009.00558.x PMID: 19341371
20. World Health Organization. Public health and environment in the African region: report on the work of WHO, 2012-2013. World Health Organization; 2014.
21. Nyong AO, Kanaroglou PS. A survey of household domestic water-use patterns in rural semi-arid Nigeria. Journal of Arid Environments. 2001;49(2):387–400. https://doi.org/10.1006/jare.2000.0736
22. Gamedze K, Tevera D, Chemhaka G. Assessment of determinants of domestic water demand in rural areas of Swaziland. Current Research Journal of Social Sciences. 2012. 4(3):196–200.
23. Muraya MW, Rambo CM. Factors influencing sustainability of rural water projects in Isiolo County, Kenya. International Academic Journal of Information Sciences and Project Management. 2019;3(4):159–83.
24. Water-related conflicts in Turkana County. Water, Peace and Security. 2022.
25. Afullo A, Danga B. The mythical nature of MDG7c to Kenya's arid and semi-arid lands (ASALS). 2013. https://repository.lboro.ac.uk
26. Abungu V, Adanu K, Dadashi Firouzjaei M, Wasonga B, Elliott MA. Multiple household water sources and uses in rural ASALs: Evidence and proposed solutions from Turkana, Kenya. Groundwater for Sustainable Development. 2025;31:101531. https://doi.org/10.1016/j.gsd.2025.101531
27. Ratemo CM, Ogendi GM, Huang G, Ondieki RN. Application of Traditional Ecological Knowledge in Food and Water Security in the Semi-Arid Turkana County, Kenya. OJE. 2020;10(06):321–40. https://doi.org/10.4236/oje.2020.106020
28. Valcourt N, Javernick-Will A, Walters J, Linden K. System approaches to water, sanitation, and hygiene: a systematic literature review. Int J Environ Res Public Health. 2020;17(3):702. https://doi.org/10.3390/ijerph17030702 PMID: 31973179
29. Harvey P, Reed B. Rural water supply in Africa: Building blocks for handpump sustainability. Loughborough University: WEDC; 2004.
30. Baumann E. May-day! May-day! Our handpumps are not working!. Rural Water Supply Network: Perspectives. 2009;1.
31. Smets S, et al. Sustainability assessment of rural water service delivery models: findings of a multi-country review. Washington, DC, USA: World Bank; 2017.
32. Tools for assessing the O&M status of water supply and sanitation in developing countries. World Health Organization; 2000.
33. Davis J, Brikké F. Making your water supply work: Operation and Maintenance of small water supply systems. IRC International Water and Sanitation Centre; 1995.
34. Gomez M, Perdiguero J, Sanz A. Socioeconomic factors affecting water access in rural areas of low and middle income countries. Water. 2019;11(2):202.
35. Abubakar IR. Factors influencing household access to drinking water in Nigeria. Utilities Policy. 2019;58:40–51. https://doi.org/10.1016/j.jup.2019.03.005
36. Nkiaka E. Exploring the socioeconomic determinants of water security in developing regions. Water Policy. 2022;24(4):608–25. https://doi.org/10.2166/wp.2022.149
37. Adelodun B, Ajibade FO, Ighalo JO, Odey G, Ibrahim RG, Kareem KY, et al. Assessment of socioeconomic inequality based on virus-contaminated water usage in developing countries: A review. Environ Res. 2021;192:110309. https://doi.org/10.1016/j.envres.2020.110309 PMID: 33045227

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38. Gómez Dávalos M. Socioeconomic indicators as determinants for water access in rural areas of developing countries: a panel data approach. Water. 2016;11(2):202.
39. Mume J. Impacts of rainwater-harvesting and socioeconomic factors on household food security and income in moisture stress areas of Eastern Hararghe, Ethiopia. Int J Novel Res Marketing Manag Econ. 2014;1:10–23.
40. Alfonso SM, Kazama S, Takizawa S. Inequalities in access to and consumption of safely managed water due to socio-economic factors: Evidence from Quezon City, Philippines. Current Research in Environmental Sustainability. 2022;4:100117. https://doi.org/10.1016/j.crsust.2021.100117
41. Guidelines for drinking-water quality: incorporating the first and second addenda. World Health Organization; 2022.
42. Edwin M. Assessment of water availability and accessibility for healthy and sustainable livelihoods in Sankuri and Central divisions, Garissa County, Kenya. Kenyatta University; 2015.
43. Ouma E. Water security risks and coping mechanisms among sedentarized pastoralists in Isiolo County, Kenya. University of Nairobi;. 2021.
44. Fo W. Nutritional and health challenges of pastoralist populations in Kenya. 2017.
45. Progress on household drinking water, sanitation and hygiene 2000-2022: Special focus on gender. UNICEF/World Health Organization; 2023.
46. Sorenson SB, Morssink C, Campos PA. Safe access to safe water in low income countries: water fetching in current times. Soc Sci Med. 2011;72(9):1522–6. https://doi.org/10.1016/j.socscimed.2011.03.010 PMID: 21481508
47. Pickering AJ, Davis J. Freshwater availability and water fetching distance affect child health in sub-Saharan Africa. Environ Sci Technol. 2012;46(4):2391–7. https://doi.org/10.1021/es203177v PMID: 22242546
48. Collecting water is often a colossal waste of time for women and girls. UNICEF; 2016.
49. Cook J, Kimuyu P, Whittington D. The costs of coping with poor water supply in rural Kenya. Water Resources Research. 2016;52(2):841–59. https://doi.org/10.1002/2015wr017468
50. Stoler J, Pearson AL, Staddon C, Wutich A, Mack E, Brewis A, et al. Cash water expenditures are associated with household water insecurity, food insecurity, and perceived stress in study sites across 20 low- and middle-income countries. Sci Total Environ. 2020;716:135881. https://doi.org/10.1016/j.scitotenv.2019.135881 PMID: 31874751
51. Water security is critical for poverty reduction, but billions will remain without water access unless urgent action is taken. World Bank; 2024.
52. Trends G. The future of water: Water insecurity threatening global economic growth, political stability. The National Intelligence Council; 2021.
53. Oleku SR. Assessing the impacts of climate change on water resources and pastoralists livelihoods in Kajiado West Sub-county, Kenya. University of Nairobi; 2024.
54. Chirisa I, Nel V. Resilience and climate change in rural areas: a review of infrastructure policies across global regions. Sustainable and Resilient Infrastructure. 2021;7(5):380–90. https://doi.org/10.1080/23789689.2020.1871538
55. Njogu HW. Effects of droughts on the delivery of infrastructure services in Kenya. Natural Resources Forum. 2022;46(2):221–44. https://doi.org/10.1111/1477-8947.12251
56. Eca U, et al. Water and climate change. 2020.
57. *Participatory Climate Risk Vulnerability Assessment Report* 2023. Turkana County Government; 2023.
58. Kabeer N. Leaving no one behind: the challenge of intersecting inequalities. Challenging inequalities: pathways to a just world. ISSC, IDS and UNESCO; 2016. p. 55–8.
59. SDG 6 synthesis report 2018 on water and sanitation. United Nations; 2018.
60. Opiyo F, Wasonga O, Nyangito M, Schilling J, Munang R. Drought adaptation and coping strategies among the turkana pastoralists of Northern Kenya. Int J Disaster Risk Sci. 2015;6(3):295–309. https://doi.org/10.1007/s13753-015-0063-4
61. Obiero K, Wakjira M, Gownaris N, Malala J, Keyombe JL, Ajode MZ, et al. Lake Turkana: Status, challenges, and opportunities for collaborative research. Journal of Great Lakes Research. 2023;49(6):102120. https://doi.org/10.1016/j.jglr.2022.10.007
62. There is no time left. Climate change, environmental threats, and human rights in Turkana County, Kenya. Human Rights Watch. 2015.
63. Heo Y. From drought to hope: Advancing water, sanitation and hygiene in Turkana County: Providing safe, clean water. 2025.
64. Asokan SM, Kweyu RM, Kalibbala MM, Obando JA. Prolonged drought and governance challenges in Turkana County, Kenya – Access to water and livelihood changes. Environmental Development. 2025;55:101193. https://doi.org/10.1016/j.envdev.2025.101193
65. Salza A. Drought and floods at Lake Turkana: an anomaly for pastoralists?. Nomadic Peoples. 2023;27(1):95–9.
66. Nyaberi D, et al. Groundwater resource mapping through the integration of geology, remote sensing, geographical information systems and borehole data in arid-subarid lands at Turkana south sub-county, Kenya. 2019.
67. Olago DH. Protecting groundwater for climate resilience and water security in Turkana. FCDO; 2022.
68. Makokha M, et al. Situational analysis of groundwater resources in Kenyan drylands, case study of Turkana County. International Journal of Environment and Geoinformatics. 2024;11(3):1–10.
69. Bauman P, Ernst E, Woods L. Surface geophysical exploration for groundwater at the Kakuma refugee camp in Turkana County, Kenya. CSEG Recorder. 2017;42:36–43.
70. Tanui FJ. Characterization of the hydrogeology of the Lodwar alluvial aquifer system, Turkana County, Kenya. University of Nairobi; 2021.

71. Rusiniak P, Sekuła K, Sracek O, Stopa P. Fluoride ions in groundwater of the Turkana County, Kenya, East Africa. Acta Geochim. 2021;40(6):945–60. https://doi.org/10.1007/s11631-021-00481-3
72. Avery S, Eng C. Lake Turkana & the Lower Omo: Hydrological Impacts of Major Dam and Irrigation Developments. African Studies Centre, the University of Oxford; 2012.
73. Avery S. What future for lake Turkana. Oxford: University of Oxford; 2013.
74. Saslaw M, Yang D, Lee D, Poulsen CJ, Henkes GA. An isotope mass balance analysis of evaporative loss from Lake Turkana, Kenya Using δ18O and δD of Natural Waters. Water Resources Research. 2024;60(6). https://doi.org/10.1029/2023wr036076
75. Shisanya CA. Farming systems characteristics in semi-arid southeast Kenya: resource base, production dynamics and the way forward. Chemchemi. 1999;1:56–74.
76. Kenya National Bureau of Statistics, M o, The DHS Program ICF. Kenya Demographic and Health Survey (KDHS) County-Level KDHS Data. 2022.
77. Sandhu G, Weber O, Wood MO, Rus HA, Thistlethwaite J. An Interdisciplinary Water Risk Assessment Framework for Sustainable Water Management in Ontario, Canada. Water Resources Research. 2023;59(5). https://doi.org/10.1029/2022wr032959
78. Guo D, Shan M, Owusu E. Resilience assessment frameworks of critical infrastructures: state-of-the-art review. Buildings. 2021;11(10):464. https://doi.org/10.3390/buildings11100464
79. Marttunen M, Mustajoki J, Sojamo S, Ahopelto L, Keskinen M. A Framework for Assessing Water Security and the Water–Energy–Food Nexus—The Case of Finland. Sustainability. 2019;11(10):2900. https://doi.org/10.3390/su11102900
80. Everlyne E, Roxventa O, Jackline K, Samson O, Patrick M, Jesse O. Plant species and their importance to housing in the Turkana community, Kenya. J Hortic For. 2020;12(3):101–8. https://doi.org/10.5897/jhf2020.0634
81. Turkana County. https://www.turkana.go.ke
82. Oula Muok B, Dennis Onyango O. Impacts of conflicting, institutional mandates on water security: pathways for water sector development in Turkana County, Kenya. STPP. 2020;4(2):44. https://doi.org/10.11648/j.stpp.20200402.11
83. United Nations. United Nations Development Assistance (UNDAP), Turkana County. 2015-2018. United Nations Joint Programme; 2015.
84. Ojwang W, et al. Lake Turkana: World's largest permanent desert lake (Kenya). In: Finlayson CM, et al., editors. The Wetland Book: II: Distribution, description, and conservation. Dordrecht: Springer Netherlands; 2018. p. 1361–80.
85. Cohen AS, Manobianco J, Dettman DL, Black BA, Beck C, Feibel CS, et al. Seasonality and lake water temperature inferred from the geochemistry and sclerochronology of quaternary freshwater bivalves from the Turkana Basin, Ethiopia and Kenya. Quaternary Science Reviews. 2023;317:108284. https://doi.org/10.1016/j.quascirev.2023.108284
86. Kaguara PW. An assessment of the effects of climate variability and change on sustainable livelihoods in Turkana County, Kenya. University of Nairobi; 2023.
87. Kenya National Bureau of Statistics. Population and Housing Census of Kenya. 2019.
88. Stauber C, Miller C, Cantrell B, Kroell K. Evaluation of the compartment bag test for the detection of Escherichia coli in water. J Microbiol Methods. 2014;99:66–70. https://doi.org/10.1016/j.mimet.2014.02.008 PMID: 24566129
89. Katsi L, Siwadi J, Guzha E, Makoni FS, Smits S. Assessment of factors which affect multiple uses of water sources at household level in rural Zimbabwe – A case study of Marondera, Murehwa and Uzumba Maramba Pfungwe districts. Physics and Chemistry of the Earth, Parts A/B/C. 2007;32(15–18):1157–66. https://doi.org/10.1016/j.pce.2007.07.010
90. Kelly E, Shields KF, Cronk R, Lee K, Behnke N, Klug T, et al. Seasonality, water use and community management of water systems in rural settings: Qualitative evidence from Ghana, Kenya, and Zambia. Sci Total Environ. 2018;628–629:715–21. https://doi.org/10.1016/j.scitotenv.2018.02.045 PMID: 29454211
91. Oyerinde AO, Jacobs HE. The complex nature of household water supply: an evidence-based assessment of urban water access in Southwest Nigeria. Journal of Water, Sanitation and Hygiene for Development. 2022;12(3):237–47. https://doi.org/10.2166/washdev.2022.176
92. Joint monitoring programme (JMP) for water supply and sanitation. UNICEF/WHO. 2011. http://www.wssinfo.org/definitions-methods/introduction
93. Afullo AO, Danga BO, Odhiambo F. Implications of time to water source on water use in the arid and semi-arid land counties of Kenya. IJW. 2014;8(4):381. https://doi.org/10.1504/ijw.2014.065794
94. Tucker J, MacDonald A, Coulter L, Calow RC. Household water use, poverty and seasonality: Wealth effects, labour constraints, and minimal consumption in Ethiopia. Water Resources and Rural Development. 2014;3:27–47. https://doi.org/10.1016/j.wrr.2014.04.001
95. Improved sanitation facilities and drinking-water sources. World Health Organization; 2022.
96. Kolding J. A summary of Lake Turkana: an ever-changing mixed environment. Mitteilungen. 1992;23(1):25–35.
97. Obiero K, et al. Lake Turkana: Status, challenges, and opportunities for collaborative research. Journal of Great Lakes Research. 2022;:102120.
98. Behailu BM, Hukka JJ, Katko TS. Service failures of rural water supply systems in Ethiopia and Their Policy Implications. Public Works Management & Policy. 2016;22(2):179–96. https://doi.org/10.1177/1087724x16656190
99. Ngigi S, Busolo DN. Devolution in Kenya: the good, the bad and the ugly. Public Policy and Administration Research. 2019;9(6):9–21.
100. Impact: A performance report of Kenya's water services sector–2023/24. Water Services Regulatory Board; 2025.

101. Njiru B. Challenged livelihoods as a result of water scarcity among Maasai women pastoralists in Kajiado County, Kenya. Impacts of climate change and variability on pastoralist women in Sub-Saharan Africa. 2013. p. 45.

102. Agholor AI. Gender gap in Sub-Saharan Africa, reminiscence of rural extension and advisory services: delineation, challenges and strategies. S Afr Jnl Agric Ext. 2019;47(3). https://doi.org/10.17159/2413-3221/2019/v47n3a514

103. Allen N. Gender Disparity and Climate Change–Addressing the Disproportionate Effects of Climate Change on Women. Global Energy Law and Sustainability. 2022;3(2):206–26. https://doi.org/10.3366/gels.2022.0080

104. Lautze J, Gibson J, McCartney M. The Omo-Turkana Basin. Routledge; 2021.

105. Marks SJ, Onda K, Davis J. Does sense of ownership matter for rural water system sustainability? Evidence from Kenya. Journal of Water, Sanitation and Hygiene for Development. 2013;3(2):122–33. https://doi.org/10.2166/washdev.2013.098

106. Strengthening Transparency, Accountability and Participation in and through WRUAs. 2023.

107. Wangombe SW. Influence of water resources users' associations (WRUAs) in water conflict resolution among the communities of sub-catchment 5BE in Meru-Laikipia counties, Kenya. University of Nairobi; 2013.

108. Vincent Casey VC, Lawrence Brown LB, Jacob D. Carpenter JDC, Jacinta Nekesa JN, Bonny Etti BE. The role of handpump corrosion in the contamination and failure of rural water supplies. Waterlines. 2016;35(1):59–77. https://doi.org/10.3362/1756-3488.2016.006

109. Karamunya TW. Assessment of the contribution of community participation to sustainability of donor-funded boreholes in arid and semi-arid lands of Pokot South Sub-County, Kenya. Kisii University; 2018.

110. Omanwa EB, Muchai SK. Effects of post-implementation community participation on sustainability of borehole water projects in embu County, Kenya. IJEPM. 2021;5(2):27–51. https://doi.org/10.47604/ijepm.1188

111. Dulo S, et al. Draft Turkana Water Audit Report. REACH Kenya; 2017.

112. Tiwari C, Water services delivery as a business: an approach to sustaining water services in rural areas. 2013.

113. Kieni M, Wilson D. Market-based operation and maintenance for rural water projects: Bundled water schemes in Turkana County, Kenya. 2024.

114. Drinking Water Quality and Effluent Monitoring Guideline, W.S.R. Board, Editor. National Environment Management Authority (NEMA); 2018.

115. Busienei PJ, Ogendi GM, Mokua MA. Open Defecation Practices in Lodwar, Kenya: A Mixed-Methods Research. Environ Health Insights. 2019;13:1178630219828370. https://doi.org/10.1177/1178630219828370 PMID: 30814843

116. Whitley L. Targeting water, sanitation and hygiene interventions in pastoralist populations in the Afar region of Ethiopia.

117. Gevera P, Mouri H. Natural occurrence of potentially harmful fluoride contamination in groundwater: an example from Nakuru County, the Kenyan Rift Valley. Environ Earth Sci. 2018;77(10). https://doi.org/10.1007/s12665-018-7466-7

118. Gevera PK. The occurrence of high fluoride in groundwater and its health implications in Nakuru County in the Kenyan Rift Valley. South Africa: University of Johannesburg; 2017.

119. Mwiathi NF, Gao X, Li C, Rashid A. The occurrence of geogenic fluoride in shallow aquifers of Kenya Rift Valley and its implications in groundwater management. Ecotoxicol Environ Saf. 2022;229:113046. https://doi.org/10.1016/j.ecoenv.2021.113046 PMID: 34875514

120. Ontumbi GM. Effects of geological variability and selected physical parameters of water quality on fluoride levels in river njoro catchment, Kenya. University of Eldoret; 2020.

121. Gaciri SJ, Davies TC. The occurrence and geochemistry of fluoride in some natural waters of Kenya. Journal of Hydrology. 1993;143(3–4):395–412. https://doi.org/10.1016/0022-1694(93)90201-j

122. Kulinkina AV, Sodipo MO, Schultes OL, Osei BG, Agyapong EA, Egorov AI, et al. Rural Ghanaian households are more likely to use alternative unimproved water sources when water from boreholes has undesirable organoleptic characteristics. Int J Hyg Environ Health. 2020;227:113514. https://doi.org/10.1016/j.ijheh.2020.113514 PMID: 32247226

123. Chew JF, Corlin L, Ona F, Pinto S, Fenyi-Baah E, Osei BG, et al. Water Source Preferences and Water Quality Perceptions among Women in the Eastern Region, Ghana: A Grounded Theory Study. Int J Environ Res Public Health. 2019;16(20):3835. https://doi.org/10.3390/ijerph16203835 PMID: 31614511

124. Wagner J, Cook J, Kimuyu P. Household Demand for Water in Rural Kenya. Environ Resource Econ. 2019;74(4):1563–84. https://doi.org/10.1007/s10640-019-00380-5

125. Eze JN, Dauda SN, Ocheni BA, Ayanniyi NN, Opaluwa D, Ekaette JE. Exploring Water Source Preferences and Agricultural Water Use in Rural Communities in the Changing Climate in Yobe State. BJARE. 2024;6(2):133–43. https://doi.org/10.35849/bjare202402/193/013

126. Thompson J. Drawers of water II: 30 years of change in domestic water use & environmental health in east Africa. Summary. Iied; 2001.

127. Vedachalam S, MacDonald LH, Shiferaw S, Seme A, Schwab KJ, PMA2020 investigators. Underreporting of high-risk water and sanitation practices undermines progress on global targets. PLoS One. 2017;12(5):e0176272. https://doi.org/10.1371/journal.pone.0176272 PMID: 28489904

128. Rodrigues Peres M, Ebdon J, Purnell S, Taylor H. Potential microbial transmission pathways in rural communities using multiple alternative water sources in semi-arid Brazil. Int J Hyg Environ Health. 2020;224:113431. https://doi.org/10.1016/j.ijheh.2019.113431 PMID: 31978728

129. Stoler J, Brewis A, Harris LM, Wutich A, Pearson AL, Rosinger AY, et al. Household water sharing: a missing link in international health. Int Health. 2019;11(3):163–5. https://doi.org/10.1093/inthealth/ihy094 PMID: 30576501

130. Cholera epidemics infects thousands in Kenya. The New York Times. 2009.

PLOS Water

131. Water shortages lead to cholera outbreak. The New Humanitarian. 2009.

132. et al. Factors associated with cholera in Kenya, 2008-2013. Pan African Medical Journal. 2017;28(1):156.

133. Okinyi S, Karomo JN, Mbinya ND, Thoya MK. Multiple Linear Regression Analysis of Factors Contributing to the Spread of Cholera in Kenya from 2000 to 2022. IJDSA. 2024;10(2):33–40. https://doi.org/10.11648/j.ijdsa.20241002.12

134. Wanjiru, A.M., Caregiver's knowledge, perceptions and practices on diarrheoal diseases among children under five years in Turkana County, Kenya. Kenyatta University. 2018.

135. Mwangi B, et al. Prevalence and Risk Factors of Diarrhea Among Children Under Five Years in Northern Kenya's Drylands: A Longitudinal Study. medRxiv. 2024:11.13.24317266.

136. Kariuki JG. Effectiveness of sanitation and hygiene interventions in changing mothers' behaviour and improving child health in Turkana District, Kenya. 2013.

137. Gikunju JK. Fluoride in water and fish from Kenyan rift valley lakes. University of Nairobi; 1990.

138. IGRAC. Turkana's silent struggle. 2023.

139. Chandrajith R, Nanayakkara S, Itai K, Aturaliya TNC, Dissanayake CB, Abeysekera T, et al. Chronic kidney diseases of uncertain etiology (CKDue) in Sri Lanka: geographic distribution and environmental implications. Environ Geochem Health. 2011;33(3):267–78. https://doi.org/10.1007/s10653-010-9339-1 PMID: 20853020

140. Sasikaran S, et al. Physical, chemical and microbial analysis of bottled drinking water. 2012.

141. Rosinger AY, Bethancourt H, Swanson ZS, Nzunza R, Saunders J, Dhanasekar S, et al. Drinking water salinity is associated with hypertension and hyperdilute urine among Daasanach pastoralists in Northern Kenya. Sci Total Environ. 2021;770:144667. https://doi.org/10.1016/j.scitotenv.2020.144667 PMID: 33515884

142. Okesanya OJ, Eshun G, Ukoaka BM, Manirambona E, Olabode ON, Adesola RO, et al. Water, sanitation, and hygiene (WASH) practices in Africa: exploring the effects on public health and sustainable development plans. Trop Med Health. 2024;52(1):68. https://doi.org/10.1186/s41182-024-00614-3 PMID: 39385262

143. Rheingans R, Kukla M, Adegbola RA, Saha D, Omore R, Breiman RF, et al. Exploring household economic impacts of childhood diarrheal illnesses in 3 African settings. Clin Infect Dis. 2012;55 Suppl 4(Suppl 4):S317-26. https://doi.org/10.1093/cid/cis763 PMID: 23169944

144. Fuente D, Allaire M, Jeuland M, Whittington D. Forecasts of mortality and economic losses from poor water and sanitation in sub-Saharan Africa. PLoS One. 2020;15(3):e0227611. https://doi.org/10.1371/journal.pone.0227611 PMID: 32196493

145. United Nations Educational S, C. Global education monitoring report 2020: Inclusion and education: All means all. 92310038. 2020.

146. Water security & the global water agenda: A UN-water analytical brief. United Nations University (UNU). 2013.

147. Umukiza E, Ntole R, Chikavumbwa SR, Bwambale E, Sibale D, Jeremaih Z, et al. Rainwater harvesting in arid and semi-arid lands of africa: challenges and opportunities. ASPFC. 2023;22(2):41–52. https://doi.org/10.15576/asp.fc/2023.22.2.03

148. Mwenge Kahinda J, Taigbenu AE. Rainwater harvesting in South Africa: Challenges and opportunities. Physics and Chemistry of the Earth, Parts A/B/C. 2011;36(14–15):968–76. https://doi.org/10.1016/j.pce.2011.08.011

149. Che-Ani A, et al. Rainwater harvesting as an alternative water supply in the future. European Journal of Scientific Research. 2009;34(1):132–40.

150. Lockwood H, Smits S. Supporting rural water supply: moving towards a service delivery approach. 2011.

151. Water U. Status report on integrated water resources management and water efficiency plans. Prepared for the 16th session of the commission on sustainable development (New York). 2008.

152. Tac G. Integrated water resources management. 4. Stockholm: Global Water Partnership Technical Advisory Committee; 2000.