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Review

Water chemistry poses health risks as reliance on groundwater increases: A systematic review of hydrogeochemistry research from Ethiopia and Kenya

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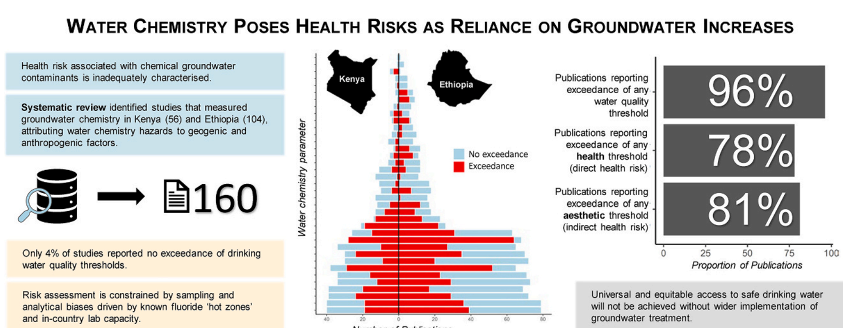
HIGHLIGHTS

- Only 4 % of 160 studies reported no drinking water quality threshold exceedance.
- 78 % reported exceedance of chemical parameters that present direct health risks.
- 81 % reported exceedance of chemical parameters that present indirect health risks.
- Spatiotemporal gaps and bias for fluoride and major ions limits risk assessment.
- SDG 6.1 will not be achieved without management of groundwater chemistry risks.

GRAPHICAL ABSTRACT



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ABSTRACT

Reliance on groundwater is increasing in Sub-Saharan Africa as development programmes work towards improving water access and strengthening resilience to climate change. In lower-income areas, groundwater supplies are typically installed without water quality treatment infrastructure or services. This practice is underpinned by an assumption that untreated groundwater is typically suitable for drinking due to the relative microbiological safety of groundwater compared to surface water; however, chemistry risks are largely disregarded. This article systematically reviews groundwater chemistry results from 160 studies to evaluate potential health risk in two case countries: Ethiopia and Kenya. Most studies evaluated drinking water suitability, focusing on priority parameters (fluoride, arsenic, nitrate, or salinity; 18 %), pollution impacts (10 %), or overall suitability (45 %). The remainder characterised general hydrogeochemistry (13 %), flow dynamics (10 %), or water quality suitability for irrigation (3 %). Only six studies (4 %) reported no exceedance of drinking water quality thresholds. Thus, chemical contaminants occur widely in groundwaters that are used for drinking but are not regularly monitored: 78 % of studies reported exceedance of contaminants that have direct health consequences ranging from hypertension to disrupted cognitive development and degenerative disease, and 81 %

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reported exceedance of aesthetic parameters that have indirect health impacts by influencing perception and use of groundwater versus surface water. Nevertheless, the spatiotemporal coverage of sampling has substantial gaps and data availability bias is driven by a) the tendency for research to concentrate in areas with known water quality problems, and b) analytical capacity limitations. Improved in-country analytical capacity could bolster more efficient assessment and prioritisation of water chemistry risks. Overall, this review demonstrates that universal and equitable access to safe drinking water (Sustainable Development Goal target 6.1) will not be achieved without wider implementation of groundwater treatment, thus a shift is required in how water systems are designed and managed.

1. Introduction

Aquifers are recognised as critical resources that support the majority of drinking-water supply and key socio-economic and ecological functions throughout Africa (Gaye and Tindimugaya, 2019). Groundwater use is also a core part of strategic planning for climate resilient water supply, particularly in drought-prone regions (Howard et al., 2016; Pavelic et al., 2012). Development agencies and governments respond to growing population and economic pressures by installing groundwater supplies to increase access to water (AMCOW, 2008). Research across Africa has focused on groundwater quantity and accessibility, encouragingly reporting high potential for groundwater resource development (Gaye and Tindimugaya, 2019; MacDonald et al., 2012). Nevertheless, researchers and governments state that the hydrogeology and potential productive use of aquifers in Sub-Saharan Africa (SSA) remains poorly understood (Walker et al., 2019). In particular, risks associated with groundwater quality have been understudied in much of SSA compared to other regions (Lapworth et al., 2020).

Key gaps remain for characterising and managing health risks from groundwater chemistry, which is determined by complex interactions of natural processes and anthropogenic activities: Water-rock interactions, evapotranspiration, surface water interconnectivity (e.g. lateral flow around rivers), and seawater intrusion are key processes controlling major ion and trace element concentrations in groundwater (Merkel and Planer-Friedrich, 2017). Agriculture, industry and other anthropogenic waste streams and interventions in natural systems further increase the complexity of groundwater quality conditions (Anderson and Cumming, 2019). Water infrastructure itself can also contribute chemical contaminants to water supply: for example, brass components in handpumps and public taps have been associated with lead contamination in rural water supply in Ghana, Mali and Niger (Fisher et al., 2021). There have been calls for research on African groundwater chemistry for decades (Edmunds, 1996), but work to-date has concentrated on a few prioritised parameters – most notably, nitrate (Ouedraogo et al., 2016), fluoride (Podgorski and Berg, 2022), and arsenic (Ahoulé et al., 2015). However, international water quality guidance and emerging research has directly linked 23 chemical elements to health concerns that range from hypertension to cancers, disrupted cognitive development, nephropathy and more (see an overview of this guidance in Supplementary Table 1).

Groundwater quality risks are important from a human health perspective because, particularly in resource-constrained settings, groundwater supplies are usually installed without water treatment infrastructure or support services (Amrose et al., 2020; JMP, 2023). This modus operandi avoids the operation and maintenance costs of water treatment processes, and it is premised on the generalisation that groundwater has better microbial water quality than surface water: notably, the 2006 World Health Organisation (WHO) report on groundwater states that "Groundwaters often require little or no treatment to be suitable for drinking" (Schmoll et al., 2006: p4). However, data from global tracking of progress on SDG target 6.1 (universal access to safe and affordable drinking water) shows that groundwater supplies are often contaminated (JMP, 2023; Bain et al., 2014). It is estimated that 2.1 billion people relied on contaminated drinking water in 2022, and contaminated sources were most prevalent in Sub-Saharan Africa, with only 36 % of the population having access to water that is free from *E. coli* and priority chemical contamination (JMP, 2023).

These global estimates provide an important but limited view. 'Priority chemical contamination' is restricted to fluoride and arsenic, with data collection focused on a sub-set of countries and known areas of contamination (JMP, 2020). In many settings in SSA, particularly in rural areas, the chemistry of groundwater that is used for drinking is not monitored (Lapworth et al., 2020; Peletz et al., 2016), leaving potential health risks unknown to water users and the water managers and authorities who are responsible for safe water delivery. Groundwater chemistry monitoring is limited partly because, at a strategic level, the chronic non-communicable diseases (NCDs) associated with chemical pollution and geogenic contamination are considered lower priority than the acute impacts of microbial pathogens (WHO, 2022). However, managing microbial risks (alone) is not sufficient to ensure water safety. Chemical contaminants in water must be evaluated to understand the contribution of unsafe drinking water to prevalence of NCDs, such as chronic kidney disease for example (George et al., 2019). This will become increasingly important as the relative contribution of NCDs to overall disease burden continues to rise throughout SSA (GBD Collaborators, 2020).

Beyond the lower prioritisation of chronic health risks, chemistry monitoring is also disincentivised because it raises politically challenging questions about the roles and responsibilities of water sector stakeholders (Nowicki et al., 2020). When groundwater contamination is identified, a common response across the water sector is to encourage household water treatment (HHWT) practices; but uptake and adherence issues challenge the effectiveness of this approach particularly in contexts of poverty (Anthonj et al., 2022; Nowicki et al., 2022). Chemical water quality problems, in particular, are more difficult to treat than microbial contamination and there are few HHWT technologies that can reasonably be promoted to manage water chemistry risks at household-level (Amrose et al., 2020). Thus, in systems-thinking terms, the lack of both water chemistry monitoring and treatment capacity for groundwater supplies creates a problematic reinforcing feedback loop: chemistry monitoring is not justifiable because there is no capacity to act on identified hazards, but lack of monitoring reinforces the lack of capacity because information about health risk is not available to justify the additional cost of including treatment in water supply projects (Nowicki, 2021). Ignoring the impacts of groundwater chemistry on health leaves chronic health risks misunderstood and unmanaged. This can lead to unjustly blaming marginalised communities for their poor health (Rajapakse et al., 2019) and allowing pollution hazards to remain insufficiently characterised and unchallenged (Mengistu et al., 2021).

To contribute to a more comprehensive understanding of the consequences of relying on untreated groundwater in current and future drinking water supply planning, this article systematically reviews evidence on groundwater chemistry from research and monitoring in two case study countries: Kenya and Ethiopia. These countries were selected because, as detailed in Section 2.1, groundwater is already a significant proportion of their national water supply, and there are plans to further expand groundwater use. Additionally, Kenya and Ethiopia were chosen because they enable comparison between areas where geogenic contamination risk has received high-profile attention (both countries have regions that are part of the Rift Valley) versus areas that have received less international and political attention, but which nevertheless have varied environmental conditions and anthropogenic influences that represent a range of potential chemistry risks. On the basis of this review, parameters of concern are highlighted and gaps in the spatial and temporal coverage of sampling for different parameters are identified. The direct and indirect health consequences that are associated with groundwater chemistry as it is represented by the reviewed data are discussed. Finally, recommendations for research and policy to advance groundwater quality risk assessment and management are put forward.

2. Methods

For this study, English-language publications containing groundwater quality data from Ethiopia and Kenya were reviewed using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) approach (Liberati et al., 2009). Database searches were run through Web of Science, Scopus, and PubMed with key search terms including: [groundwater OR hydrogeolog*, OR geolog*] AND [quality OR chem* OR hydrochem* OR geochem* OR hydrogeochem* OR ion* OR saline OR salinity] AND [Kenya OR Ethiopia] as specified in Fig. 1. The year of document publication was not constrained, it ranged from 1989 to 2022. Reference lists of included studies and reports were manually searched for additional potentially relevant publications. A further 29 records were identified through the University of Nairobi online thesis repository, the Ethiopian Water Works Design and Supervision Enterprise records, and the British Geological Survey digital publication channel, EARTHWISE. Further searches of the WHO Global Health Library, African Index Medicus, and SciELO did not return additional records.

The search was updated through September 2022. After eliminating duplicates, 1541 records were screened by title and abstract and 1341 were excluded on the basis of not reporting original groundwater sampling data; not reporting groundwater quality results from study sites in Kenya or Ethiopia; reporting only samples from geothermal wells or hot springs; reporting only microbial, isotope, radioactivity, or rare earth element results; or not having accessible full-text reports (Fig. 1). The full-texts of the remaining 200 records were further assessed for eligibility. Eligible studies reported original groundwater quality data for chemical parameters of interest from an identified study site in Kenya or Ethiopia such that the maximum concentration and/or percent of sites exceeding water quality guidelines could be extracted. Data were extracted from 160 studies including 138 peer-reviewed papers and 22 books, thesis or reports. In total 104 datasets from Ethiopia and 56 from Kenya were accessed.

The parameters of interest for which data were extracted are physicochemical attributes of water that have standards and/or guidelines specified by the Ethiopian Standards Agency (ESA) as used by the Ethiopian Water Works Design and Supervision Enterprise (WWDSE), the Kenyan Bureau of Standards (KEBS) as used by the Kenyan Water Services Regulatory Board (WASREB), the East Africa Standards Committee (EASC), the World Health Organisation (WHO), or the United States Geological Survey (USGS) and Environmental Protection Agency (EPA). For each parameter, a reference threshold was selected (Table 1). In the first instance, the threshold was chosen to adhere to the Kenyan and Ethiopian national standards, which are based on international guidance with adaptation for country context (ESA, 2013; WASREB, n. d.). Where the national standards differ, the tie-breaker was the recently updated WHO guidance (WHO, 2022) in the first instance, or the EASC (EAC, 2014) guidance. Parameters for which neither country has a specified standard were assessed against the WHO health-based drinking-water guideline, the WHO aesthetic guideline, or the East Africa Standard (EAS) for natural potable water. Cobalt, lithium, silver, strontium, and thallium were assessed against the non-regulatory health-based screening levels (HBSLs) published by the USGS and US EPA (Norman et al., 2018). Organic chemistry pollutants are not included in Table 1. These were not purposefully excluded from the outset, but the broad search did not identify sufficient data to justify including them in the data synthesis and thresholds comparison.

Electrical conductivity (EC), total dissolved solids (TDS), and pH are not linked to particular health outcomes, but guideline thresholds exist for these parameters and they are included in Table 1 because they provide a useful overview of chemical water quality. When EC and TDS thresholds are exceeded it means water has high concentrations of dissolved elements, which indicates that the water is likely to be unpalatable and potentially unsafe. pH is a more context-dependent parameter. The importance of pH for health is largely related to implications for mobility of other elements. Beryllium for example, will not be found in excess dissolved concentrations in water unless pH is lower than 5 or higher than 8 because of solubility effects (WHO, 2022).

For each major ion and trace element listed in Table 1, the aesthetic and health factors associated with consuming water containing concentrations in excess of the threshold values are summarised in Supplementary Table 1. The summary information was drawn primarily from the WHO Guidelines for drinking-water quality, 4th edition (WHO, 2022) and associated official background documents. Where appropriate, additional information was included from recent peer-reviewed studies identified using Web of Science with search terms: 'water', 'health', and the element in question, for example 'calcium'. Arsenic, fluoride, and nitrate/nitrite are the best-known chemical contaminants in drinking-water. The latest edition of the WHO drinking-water guidance also highlights lead, manganese, selenium, and uranium as contaminants of concern (WHO, 2022).

For all parameters with a selected threshold (Table 1), data were extracted from the 160 reviewed publications to represent maximum concentrations and the proportion of water sampling points exceeding the health or aesthetic threshold. For publications that reported individual sample results, the proportion of exceedances is calculated as a percentage. For publications that only provided summary statistics, the proportion of exceedance is represented categorically as either high (mean is above the threshold) or low (mean is below the threshold). Where data were reported separately for dry versus wet seasons, this separation was retained to allow seasonal comparison in the summary of the results.

In addition to the water quality data, for each publication the location of the water sampling points was captured – coordinates were recorded when available, otherwise the name of the nearest town or city. ArcGIS version 10.4.1 was used to produce maps showing the groundwater sampling locations. The distributed points in the groundwater sampling location maps represent the studies for which geographic coordinate information was available. For the studies that did not report coordinates, the basins from which the groundwater sampling was done are indicated on the maps with grey rectangles or, when studies reported only that samples were taken in or nearby a city or town, the cities or towns are shown on the maps.

The location of the water chemistry analysis was recorded by laboratory type (commercial, university, government) and country. Sampling and analysis methods were tracked, including whether the sample collection protocol was reported in sufficient detail to be reproduced, which analytical methods were used, and whether quality assurance and control (QAQC) measures were reported (duplicate and blank samples). Further, the stated purpose of sampling; the types of contamination that were discussed as potential risks; the types of waterpoints that were sampled; and whether or not links were drawn between groundwater use and climate change were captured from the Introduction and Discussion sections.

2.1. Country contexts

The Republic of Kenya, with a total land area of 580,370 km^2, is in East Africa. The altitude ranges from sea level to 5199 m above sea level at the peak of Mount Kenya. Coastal Kenya experiences a tropical

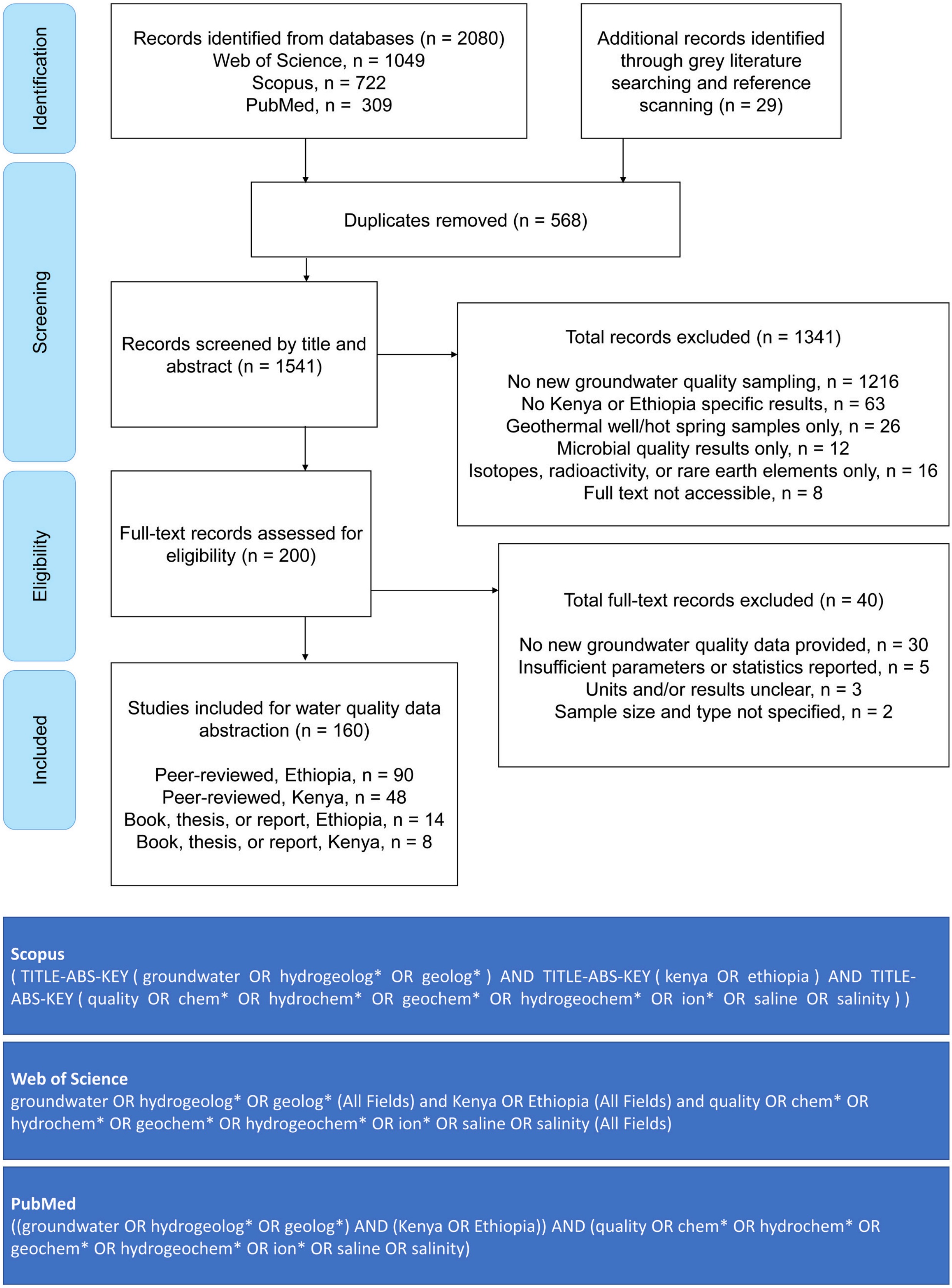

Fig. 1. Flow diagram of the screening process for systematic review of chemical groundwater quality in Kenya and Ethiopia.

Table 1
Selected water quality thresholds based on comparison of drinking water quality standards and guidelines. Note: thresholds related to health are indicated by 'H', aesthetic acceptability thresholds are indicated by 'A'.

Group	Parameter	Units	Kenyan standard	Ethiopian standard	WHO health guideline	WHO Aesthetic guideline	EAS for natural potable	US EPA MCL	USGS HBSL	Selected threshold
General	EC	µS/cm					2500			2500
	pH		6.5–8.5	6.5–8.5			5.5–9.5			6.5–8.5
	TDS	ppm	1500	1000			1500			1500
Major ions	Ca	ppm	250	75			150			150 (A)
	Cl	ppm	250	250		200	250			250 (A)
	F	ppm	1.5	1.5	1.5		1.5	4		1.5 (H)
	K	ppm		1.5						1.5 (A)
	Mg	ppm	100	50			100			100 (A)
	Na	ppm	200	200			200			200 (A)
	NH_3	ppm	0.5	1.5		1.5	0.5			1.5 (A)
	NO_2	ppm		3	3		3	1		3 (H)
	NO_3	ppm	10	50	50		45	10		50 (H)
	SO_4	ppm	400	250		250	400			250 (A)
Trace elements	Ag	ppm			0.1[b]				0.1	0.1 (H)
	Al	ppm	0.1	0.2	0.9[d]	0.1	0.2		6	0.9 (H)
	As	ppm	0.05	0.01	0.01[a,c]		0.01	0.01		0.01 (H)
	B	ppm		0.3	2.4		2.4		5	0.3 (H)
	Ba	ppm			1.3			2		1.3 (H)
	Be	ppm			0.012[e]			0.004		0.012 (H)
	Cd	ppm	0.005	0.003	0.003		0.003	0.005		0.003 (H)
	Co	ppm							0.002	0.002 (H)
	Cr (total)	ppm	0.05	0.05	0.05		0.05	0.1		0.05 (H)
	Cu	ppm	0.1	2	2	1	1	1.3		1(A); 2(H)
	Fe	ppm	0.3	0.3		0.3	0.3		4	0.3 (A)
	Hg	ppm	0.001	0.001	0.006		0.001	0.002		0.001 (H)
	Li	ppm							0.01	0.01 (H)
	Mn	ppm	0.1	0.5	0.08[b]	0.1	0.1		0.3	0.08 (H)
	Mo	ppm					0.07		0.03	0.07 (H)
	Ni	ppm			0.07		0.02		0.1	0.07 (H)
	Pb	ppm	0.05	0.01	0.01[a,c]		0.01	0.015		0.01 (H)
	Sb	ppm			0.02			0.006		0.02 (H)
	Se	ppm	0.01	0.01	0.04[b]		0.01	0.05		0.01 (H)
	Sr	ppm							4	4 (H)
	Tl	ppm							0.002	0.002 (H)
	U	ppm			0.03[b]				0.03	0.03 (H)
	Zn	ppm	5	5		3	5		2	5 (A)

[a] Provisional guideline based on testing capabilities (analytical achievability).
[b] Provisional guideline because available data are considered inadequate to derive a well-supported health-based value.
[c] Provisional guideline based on practicalities of treatment.
[d] Indicative value, derived from the Joint FAO/WHO Expert Committee on Food Additives (JECFA) provisional tolerable weekly intake (PTWI) calculations.
[e] Indicative value, derived from a study conducted with dogs, expected to be conservative.

climate, with temperatures ranging from 22 °C to 34 °C. Inland and in the highland areas, the climate is more temperate with temperatures ranging from 10 °C to 28 °C depending on the altitude (World Bank, 2021a). The rainfall pattern is generally bimodal, with the long rains occurring from March to May and the short rains from October to December (Opiyo, 2014), although rainfall is highly variable across the country – ranging from less than 200 mm per year in the northern region to 1800 mm in the Mount Kenya region, with an annual average rainfall of 630 mm (Hassan and Tularam, 2018). Over 80 % of the county is classified as arid or semi-arid and surface water resources are limited (Tabu et al., 2013).

The majority of surface water, around 75 %, originates as precipitation runoff from five "water towers" located in central and western Kenya (USAID, 2020). The country has a number of important rivers including the Tana, Athi-Galana-Sabaki, Ewaso Ng'iro, and Turkwel. Due to unavailability of surface water sources in dryland areas, groundwater is a major resource for water supply in most of the country. Important aquifers exist in volcanic terrain (Coetsiers et al., 2008; Kuria, 2011; Olaka et al., 2022) and associated quaternary sediments (Kairigo et al., 2016; Tanui et al., 2020; WRMA, 2016), and in sedimentary terrain underlain by metamorphic rocks in northern and coastal Kenya (Gevera et al., 2020; Karegi et al., 2018; Ng'anga et al., 2018). Pavelic et al. (2012) estimated that 57.21 million cubic metres of groundwater was abstracted in Kenya in 2012. Kenya is currently facing a water scarcity crisis, with only 718.1 m^3/yr renewable freshwater per capita (Hassan and Tularam, 2018). It is predicted that the renewable freshwater per capita in Kenya will decrease to 235 m^3/yr per capita by 2025 (Hassan and Tularam, 2018). The Nairobi (Tana Basin) and Merti (Ewaso Ng'iro Basin) aquifers are being over-abstracted due to poor regulation and concentrated demand for domestic and public water supply, which has led to lowered water tables (USAID and SWP, 2021).

Ethiopia, with a total area of 1.1 million km^2, is in the northeast of the Horn of Africa. Elevations range from 125 m below sea level in the Danakil Depression to 4533 m above sea level in the Siemien Mountains. There are two predominant patterns of rainfall in Ethiopia (World Bank, 2021b): the primary rainy season, Kiremt, occurs from mid-June to mid-September and accounts for 50–80 % of annual rainfall. Parts of central and northern Ethiopia also experience a sporadic secondary wet season, Belg, which occurs from February to May. The mean annual rainfall distribution is approximately 2000 mm over the southwestern highlands and less than 300 mm over the south-eastern and north-eastern lowlands (World Bank, 2021b). Temperatures across Ethiopia can range from −15 °C in the highlands to above 25 °C in the lowlands (World Bank, 2021b).

Combining surface water and groundwater resources, the total internal (generated from endogenous precipitation) renewable water resource of the country has been estimated at 122 billion m^3 per year (Kebede, 2012). Surface water resources are substantial in only 4 of the

12 major Ethiopian watersheds, these 4 are located in the west and north-west of the country. 70 % of domestic water use in rural Ethiopia is supplied by groundwater, and large cities like Addis Ababa get up to 40 % of water supply and industrial water use from groundwater (Kebede, 2012). Volcanic rocks are the most extensive and accessible aquifers in central Ethiopia. In terms of groundwater storage, loose sediments are the most important aquifers (Kebede, 2012).

3. Results

Groundwater quality studies have been increasing in both Kenya and Ethiopia since the early 2000s, with 30 % of the studies published in the last 3 years. The majority of publications reported data for boreholes (83 %). Data for dug wells and springs was reported in 54 % and 39 % of cases, respectively. Fewer than 10 water points were sampled in 25 % of the studies; many studies (46 %) sampled between 11 and 50 water points, and 11 % sampled more than 100 water points. Summary information for the reviewed publications is reported in Supplementary Table 2. A full list of the publications including references and extracted results can be found in Supplementary Table 3. The following sections report the review results with focus on spatial and temporal coverage of sampling, sampling purpose and focal threats, synthesis of sampling results, and analytical capacities.

3.1. Spatial and temporal coverage of sampling

There are gaps in the spatial coverage of groundwater chemistry sampling (Figs. 2a and 3a). Studies have concentrated around the capital cities of Addis Ababa and Nairobi, in the Ethiopian Rift Valley and highlands, and in western and coastal Kenya; data are sparse in other areas – particularly where population density is low (Figs. 2b and 3b). The geology across both countries is complex and variable, making spatial extrapolation of groundwater chemistry difficult. Figs. 2c and 3c are simplified geological maps showing five major categories, namely: (i) acidic volcanic rocks in the central Rift Valley; (ii) mafic volcanic flows in western Kenya; (iii) metamorphic rocks of northern Ethiopia and south-eastern Kenya; (iv) Quaternary sediments in central Ethiopia and northern, eastern and coastal Kenya; and (v) multi-layered sedimentary rocks underlying the Quaternary sediments in eastern Kenya.

Sampling was conducted once or twice per water point in 71 % and 11 % of cases, respectively. Only 4 publications, all from Kenya, reported more than 12 sampling events per water point. The season during

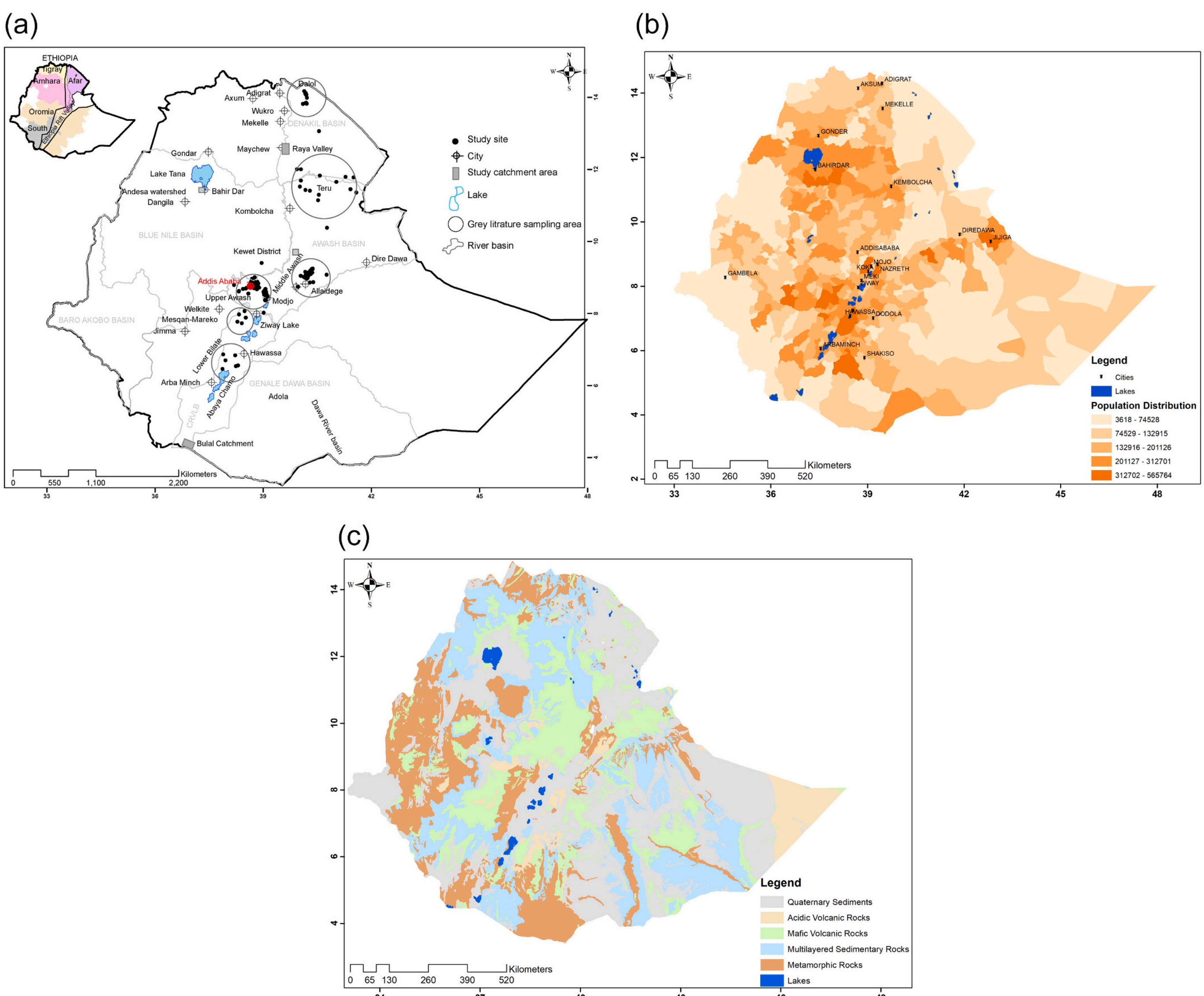

Fig. 2. Maps of Ethiopia showing (a) groundwater sampling locations, (b) population density, and (c) major geological categorisation. The maps are represented using the World Geodetic System 1984 Geographic Coordinate System (GCS_WGS_1984) with grid marks corresponding to degree increments.

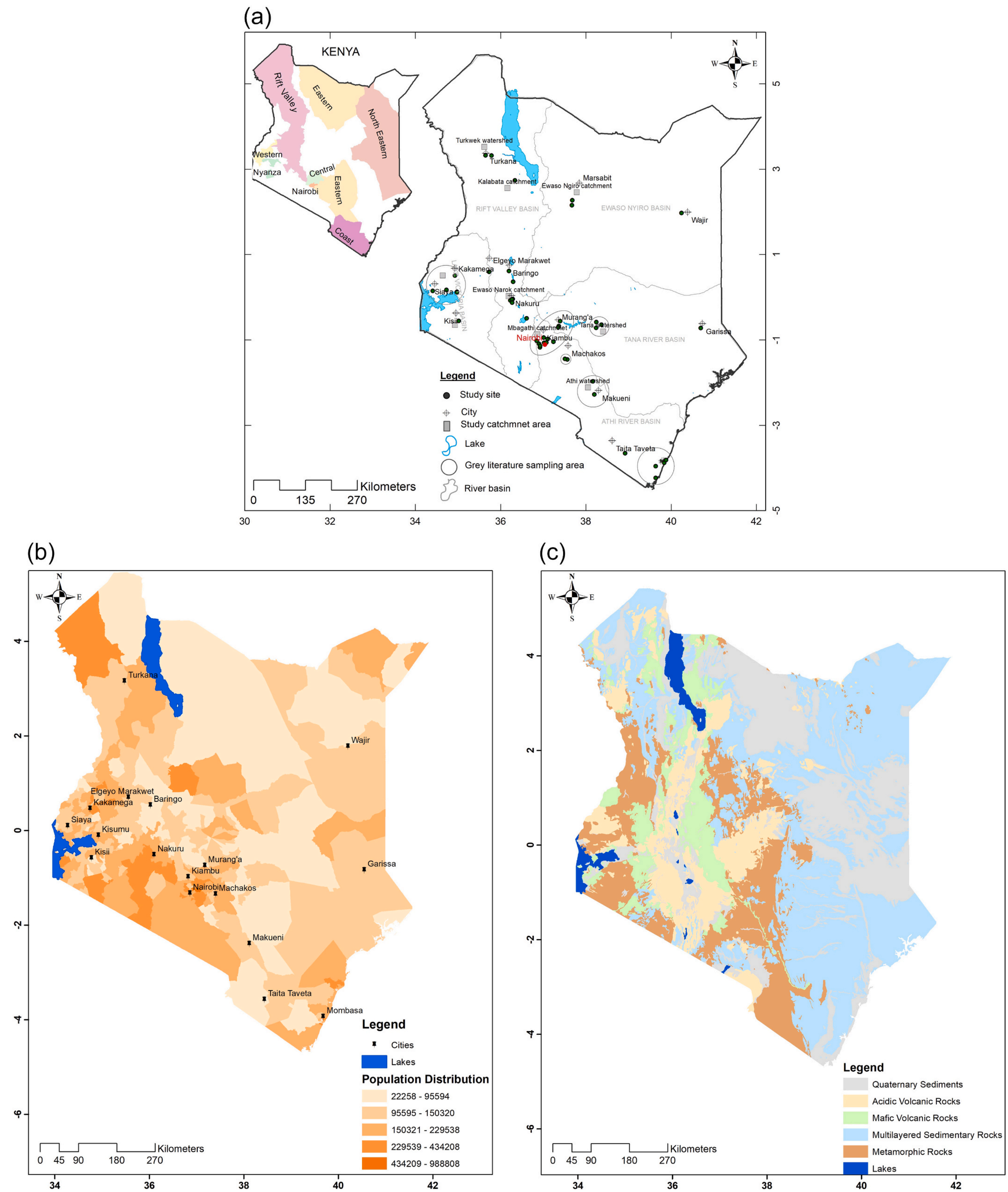

Fig. 3. Maps of Kenya showing (a) groundwater sampling locations, (b) population density, and (c) major geological categorisation. The maps are represented using the World Geodetic System 1984 Geographic Coordinate System (GCS_WGS_1984) with grid marks corresponding to degree increments.

which the groundwater sampling was conducted was not reported in half of the reviewed publications (Supplementary Table 2). Of those that did report the season of sampling, 27 % reported data from dry season sampling only, 27 % reported data from mixed season sampling (this means that some water points were sampled in the dry season and others in the wet), 14 % reported data from wet season sampling only, and 4 % reported data from sampling during a season transition. The remaining 28 % (23 studies) reported data for each water point from dry season and wet season sampling.

3.2. Sampling purpose and focal threats

Many of the reviewed studies set out to assess the suitability of water quality for drinking (35 %), drinking & irrigation (10 %), or only irrigation (3 %). Some studies focused on a particular parameter – fluoride, arsenic, nitrate, or salinity (18 %) or particular source of pollution (10 %). Other studies evaluated general aquifer hydrogeochemistry (13 %) and flow dynamics (11 %). Potential threats to the suitability of water quality were identified in the framing of 89 % of the publications, and 41 % highlighted multiple threats (Fig. 4). The threats related to natural hazards including geogenic contamination or saline intrusion or they were categorised as anthropogenic. When specified, anthropogenic threats were related to economic activities including agriculture, urban industry (tanneries, manufacturing), and geoindustry (oil and gas, mining, and geothermal); and to waste management challenges including inadequate sanitation, leachate from landfills, and municipal or urban runoff. Only two studies analysed for contaminants of emerging concern (CECs): Murigi (2004) tested but was not able to detect 14 pesticides and K'oreje et al. (2022) tested for 28 pesticides, personal care products, and pharmaceutically active compounds.

Comparing the two countries, a higher proportion of the Ethiopia publications highlighted geogenic concerns (59 % of Ethiopia publications compared to 46 % of Kenya publications). On the other hand, a higher proportion of the Kenya publications highlighted potential threats related to sanitation (21 % of Kenya publications compared to 3 % of Ethiopia publications), saline intrusion (11 % compared to 1 %), and industry (29 % compared to 21 %). The proportions were within 5 % for the other threat categories. No studies focused on assessing the impact of climate change on water quality, although 28 of the reviewed publications highlighted the link between groundwater reliance and climate change (half of these were published in the last 3 years).

3.3. Synthesis of sampling results

No studies reported results for all 36 parameters for which selected thresholds are listed in Table 1. Total dissolved solids, conductivity, pH, and major ions were most frequently analysed, whereas the proportion of publications reporting each trace element ranged from only 1 % for thallium to 29 % for iron (Fig. 5). The median number of parameters per publication was 10 (maximum = 35, 75th percentile = 12, 25th percentile = 4, minimum = 1). These results indicate a data availability bias, towards major ions and general physicochemical parameters, which is largely driven by in-country analytical capacity (see Section 3.4).

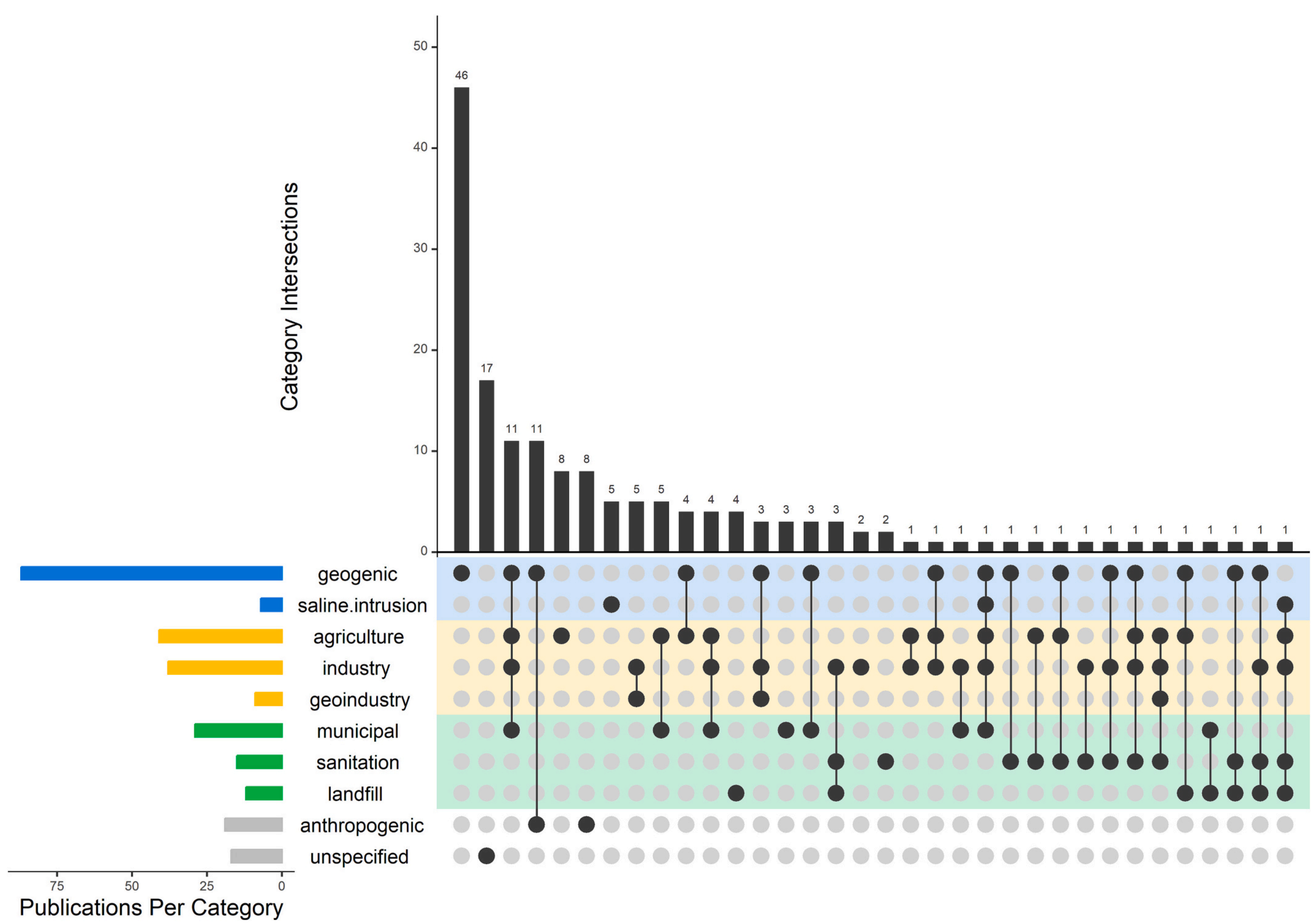

Fig. 4. Upset chart showing combinations of the categories of water quality threats identified in each publication. The threat combinations are shown by the black dots across each threat category. The columns display the count of publications that identified each combination of threats. Blue signifies natural hazards, yellow signifies economic activities, green signifies waste management, and grey signifies that threats were unspecified or broadly categorised as anthropogenic.

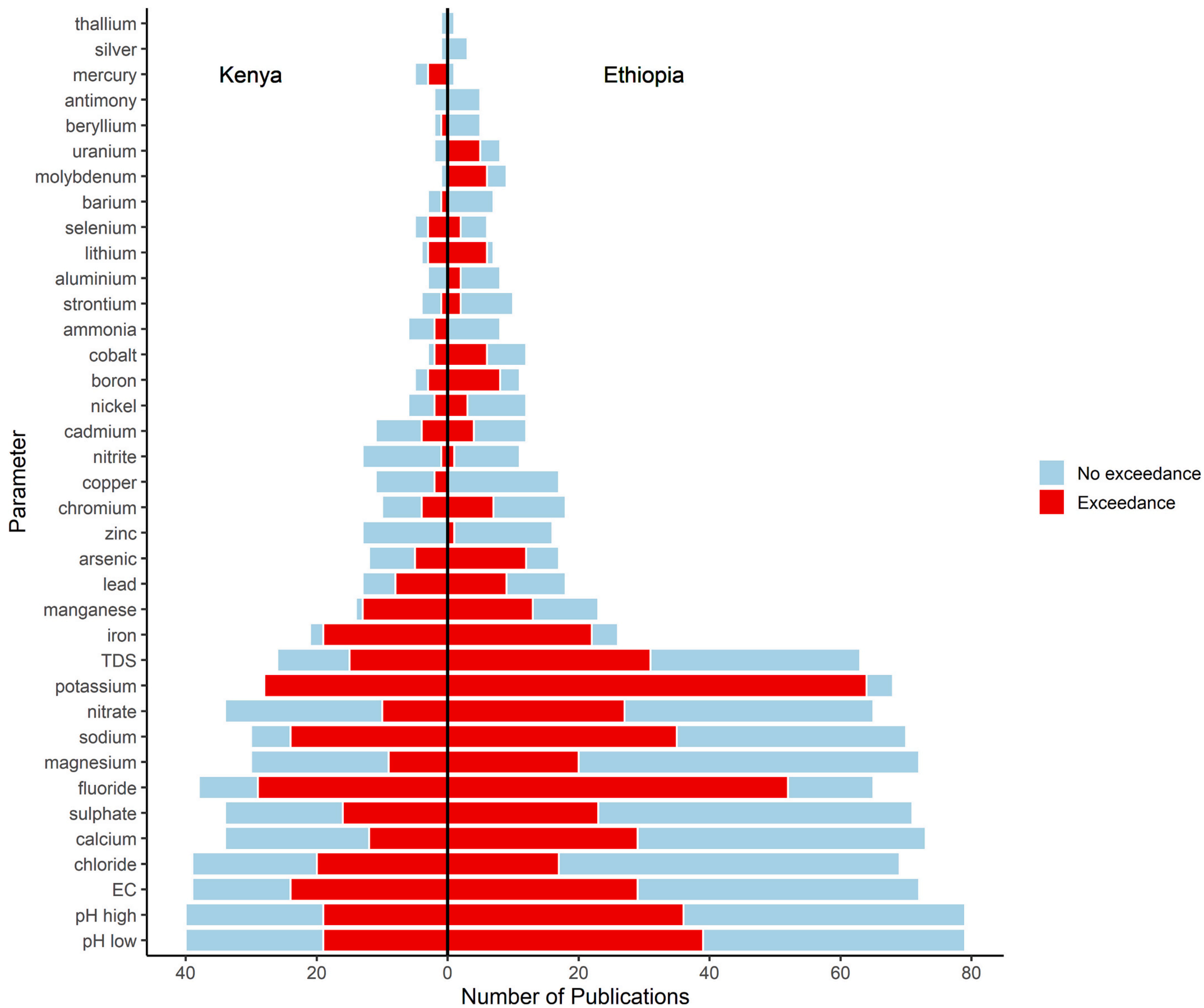

Fig. 5. Stacked bar chart of the number of publications reporting data for each parameter, with publications grouped as reporting no water points exceeding guideline threshold or reporting at least one water point exceeding threshold.

Of the 160 reviewed publications, only 6 reported no exceedance of drinking water quality thresholds. At least one health-based parameter threshold was exceeded in 78 % of the publications, and at least one aesthetic parameter or general physiochemical parameter (total dissolved solids, conductivity, pH) threshold was exceeded in 81 % of the publications. Guideline threshold exceedance was reported for 30 parameters (Fig. 5). The parameter with the most exceedances was potassium due to the low Ethiopian standard value of 1.5 ppm. A maximum sample concentration of more than 25 times the guideline threshold was reported for 20 parameters – most commonly for potassium (33 cases), pH (16 cases), fluoride (11 cases), lead (9 cases), and manganese (6 cases) (Supplementary Fig. 1). These parameters were also most likely to be reported as having the highest proportion of sampled sites exceeding the guideline threshold – more than two-thirds of sampled sites exceeded the guidelines for potassium in 50 cases, for fluoride in 21 cases, pH in 10 cases, lead and iron in 9 cases each, and manganese in 8 cases (Fig. 6).

For the 23 studies that reported both dry season and wet season sampling results, it was possible to compare the results for 35 parameters by season. For each parameter, the number of seasonal comparison cases ranged from 1 to 21. For each seasonal comparison case, the relative percent difference (RPD) in maximum concentrations from the dry season versus the wet season was calculated as: RPD = $[X_{dry} - X_{wet}] / [(X_{dry} + X_{wet})/2]$. These RPD calculations show that the seasonal signal is noisy (Table 2) but some parameters tended to be higher in the dry season (e.g. copper, zinc, lead, nitrate) while others were more often higher in the wet season (chromium, lithium, nickel).

3.4. Analytical capacities

In two-thirds of the reviewed studies, all of the water quality analysis was conducted in-country. Where studies used in-country laboratories fewer trace element analyses were undertaken, with results reported for an average of 1.9 trace elements per in-country study. Laboratories outside of Kenya or Ethiopia were used in a quarter of the studies, which reported results for 8.2 trace elements on average. In 15 cases (9 %) the country of the analysis was not reported. The analysis was done at academic institutions (43 %); at government facilities (23 %); using field measurement only (6 %); at industry, commercial, or non-governmental organisation facilities (3 %); or not reported (24 %).

In addition to limitations in parameters analysed, further analytical limitations were observed with respect to detection limits: there were 41

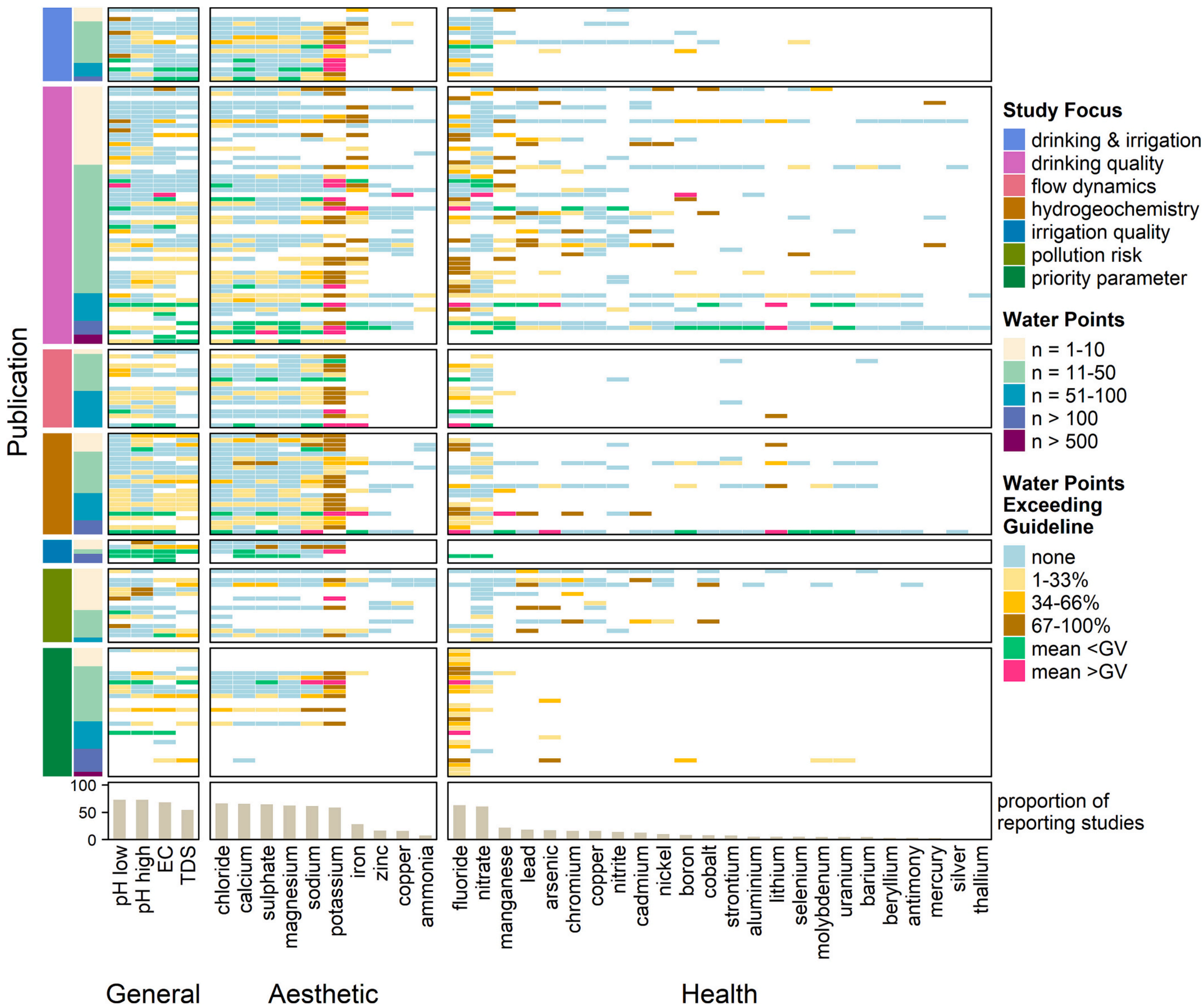

Fig. 6. Heatmap of the proportion of water points exceeding the guideline threshold concentration for each water quality parameter for each reviewed publication. Note: 21 % of the publications reported only summary statistics. In these cases, the proportion is expressed as either 'mean < GV' (the mean is below the guideline value) or 'mean > GV' (the mean exceeds the guideline value). The first annotation bar on the left shows the study focus, indicating the intended purpose of the water quality sampling. The second annotation bar shows the number of water points sampled for each publication. The column chart on the bottom of the figure shows the proportion of publications reporting data for each parameter. The heatmap was created with R package 'ComplexHeatmap' (Gu et al., 2016).

instances across 19 parameters where no samples had concentrations above the analytical detection limit (DL). This was most frequent for cadmium (7 studies) and lead and manganese (4 studies each). In preparing Fig. 6 and Supplementary Fig. 1, results that were reported as below DL were coded as measured and not exceeding the guideline threshold. This is not entirely accurate, however, because in 7 instances, the DL was higher than the guideline threshold value. In these cases, the below DL result does not conclusively confirm that the parameter meets the guideline. For example, the guideline for cadmium is 0.003 ppm but in two cases cadmium was reported as below DL where the DLs were 0.1 ppm or 0.01 ppm. In 5 cases, the DL was specified as being lower than the guideline threshold value, but in the majority of cases it was not specified.

Reporting of methods and quality assurance and quality control (QAQC) measures was inconsistent. A quarter of the publications did not report full sampling procedures and half did not report QAQC measures for the water quality analysis.

4. Discussion

Groundwater is an important resource in Kenya and Ethiopia, as it is for much of the African continent, where aquifers support the majority of drinking-water supply and serve key socio-economic and ecological functions (Gaye and Tindimugaya, 2019). Climate change is driving yet more reliance on groundwater, as countries plan for and respond to increasing weather volatility and drought (Howard et al., 2016). This review identified that research in Kenya and Ethiopia is increasingly a) highlighting links between groundwater reliance and climate change, and b) aiming to assess the suitability of groundwater chemistry for drinking and/or irrigation purposes. The results show that groundwater chemistry is an area of concern for research and water management throughout these countries due to geogenic hazards, saline intrusion, and pressures from waste streams and other activities associated with agriculture, industry, and urbanization. The data synthesised for this review showed that 96 % of the study areas had groundwater that exceeded at least one inorganic chemistry drinking water threshold. This

Table 2
Median, 10th and 90th percentile relative percent difference of maximum concentrations by season for parameters with at least 2 water points sampled seasonally.

	Parameter	P10 RPD	P50 RPD	P90 RPD	n[$]
Higher in dry season	Cu	−187%	−92%	83%	6
	Zn	−149%	−46%	62%	5
	Pb	−95%	−26%	111%	6
	NO3	−145%	−26%	19%	16
	NO2	−66%	−6%	87%	8
	K	−82%	−4%	58%	13
	Cl	−95%	−2%	60%	14
	Ca	−20%	−2%	50%	14
Weak seasonal signal	pH low	−99%	0%	104%	21
	NH3	−25%	0%	17%	6
	Cd	0%	0%	152%	3
	Al	−12%	1%	15%	2
	TDS	−38%	2%	53%	14
	As	−33%	2%	37%	4
	F	−154%	2%	80%	14
	pH high	−159%	7%	133%	21
	Mg	−78%	8%	75%	14
Higher in wet season	SO4	−43%	11%	45%	14
	Na	−7%	11%	44%	14
	EC	−30%	13%	87%	20
	Mn	−152%	16%	131%	6
	B	−155%	27%	103%	3
	Fe	−71%	29%	168%	7
	Cr	−6%	63%	157%	6
	Li	27%	96%	165%	2
	Ni	49%	97%	146%	2

[$]For the parameters with only a single seasonal comparison case ($n = 1$), the RDPs of maximum concentrations were −77 % for Tl, −44 % for Se, 0 % for Sb, 3 % for U and Hg, 6 % for Sr, 26 % for Mo, 63 % for Ba, and 137 % for Co.

shows that health hazards from groundwater chemistry are wide-spread, although data resolution was not sufficient to disaggregate results to water point level to fully understand distribution of risk. The lack of data on organic chemistry pollutants is notable, organic contaminants are expected to further increase the extent of health risk from groundwater chemistry. Despite these water quality concerns, groundwater supplies, especially in rural areas, are commonly installed without infrastructure or service arrangements to monitor and manage chemistry issues (Amrose et al., 2020; JMP, 2023).

4.1. Health risks related to groundwater chemistry

Chronic health conditions associated with long-term consumption of excess chemical elements may become increasingly important as life expectancy rises and reliance on untreated groundwater increases. These chronic health conditions include cancers, heart disease, congenital anomalies, blood diseases, musculoskeletal disorders, and neurological damage (Prüss-Ustün et al., 2011; Supplementary Table 1). For example, arsenic in drinking water is linked to skin lesions, peripheral neuropathy, peripheral vascular disease, cardiovascular disease, kidney disease, and cancers of the skin, bladder, and lung (Supplementary Table 1). Environmental health researchers estimate that 1 in 5 deaths among the 18 million people who drink arsenic contaminated water in Bangladesh may be caused by the consequences of arsenic poisoning (Loewenberg, 2016).

The health crisis linked to arsenic in groundwater in Bangladesh is a high-profile example of the importance of considering chronic impacts from groundwater chemistry, particularly when designing and installing new water services. The crisis highlights the difficulty of addressing chemical hazards in small water systems through either retrofitting infrastructure or promoting household-level treatment: more than two decades after the arsenic hazard in groundwater was first mapped in Bangladesh, at least 18 million people remain at risk of disability and death caused by arsenic in their drinking-water (Government of Bangladesh et al., 2021; Khan and Charles, 2022).

In this review, arsenic exceedance was identified in 17 studies (11 %). Exceedances of other parameters, including fluoride, sodium, and 37 others, were also frequently identified in water supplied from boreholes, dug wells and springs. Of the parameters that have health thresholds (Table 1), fluoride is both the most frequently tested and the most frequently exceeding parameter across the reviewed studies. Fluoride is a high-profile geogenic groundwater contaminant in the region of the East African Rift (Podgorski and Berg, 2022). Thus, the review results demonstrate a data availability bias driven by the tendency for research to concentrate in areas with known water quality problems. However, the wider results show that other parameters that are less frequently tested also warrant attention. The review identified exceedances for 20 other elements that have health-based guideline thresholds. Several of the exceeding parameters are associated with kidney damage to varying degrees including uranium, selenium, mercury, lead, fluoride, chromium, cadmium, barium, and arsenic (Supplementary Table 1). The occurrence of kidney damaging contaminants in groundwaters used for drinking adds weight to the recommendation from George et al. (2019) that epidemiological studies are needed to examine contaminated water supplies as a potential risk factor for chronic kidney disease (CKD) in SSA.

The review also identified frequent exceedance of elements such as iron and sulphate, which have guideline thresholds based on aesthetic considerations. Palatability and other aesthetic aspects of groundwater chemistry can have indirect impacts on health because they influence the perception, use, and sustainability of groundwater supplies. Poor aesthetic quality discourages groundwater use and disincentivises efforts to maintain groundwater supplies in good working-order (Foster et al., 2018). For example, in south-eastern Kenya, there are reports of boreholes being abandoned due to salinity and excess iron (Gevera et al., 2020; Ng'anga et al., 2018). Water users in this region associate the saline taste of groundwater with dental fluorosis and/or gastrointestinal problems (Gevera et al., 2020, 2022). When chemistry issues dissuade the use of groundwater, it increases the likelihood that water users will be exposed to microbiological contaminants from alternate, less-protected waterpoints that are supplied by surface or rainwater collection systems (Nowicki et al., 2022).

4.2. Strengthening groundwater chemistry risk assessment

While this review demonstrates the breadth of potential health risks from groundwater chemistry in Kenya and Ethiopia, it also draws attention to weaknesses in the evidence-base for understanding health implications of groundwater use in these countries. Although people rely on groundwater for drinking in much of Ethiopia and Kenya (Section 2.1), there are substantial gaps in the spatial and temporal coverage of sampling. This creates water resource planning challenges since current mapping of groundwater chemistry risks is limited and it is difficult to assess how water quality will change under future climate scenarios. Research from Ochungo et al. (2020) investigated the potential impact of prolonged drought on groundwater quality deterioration in Langata, Kenya, but such studies are uncommon and typically limited by low resolution datasets. It is also important to recognise that the literature focuses on groundwater supplies that are in use, and does not reflect the quality of supplies that have been capped or abandoned due to health concerns or palatability issues; thus, the extent of challenges posed by groundwater chemistry is underestimated.

Furthermore, when sampling is conducted, many parameters are analysed infrequently and/or with insufficient sensitivity. This is expected from studies that aim to assess groundwater flow dynamics or priority parameters, but for those that set out to assess the suitability of water quality for drinking and/or irrigation purposes, it means that there are gaps in the robustness of their assessment. Only 23 of the reviewed studies reported seasonal comparisons of water quality and the consolidated results showed that some parameters tended to be higher in the dry season while others were more likely to be higher in the wet season. This reflects the complexity of the difference processes that drive groundwater chemistry including seasonal changes in polluting activities, flow regimes, and other concentration/dilution mechanisms (Anderson and Cumming, 2019; Merkel and Planer-Friedrich, 2017). More frequent sampling coupled with open data practices that enable meta-analysis would be worthwhile to improve understanding of the seasonal dynamics of groundwater chemistry risks.

Studies that aim to broadly characterise groundwater quality (e.g. to assess suitability for drinking, vulnerability to pollution, or geochemical characterisation) are limited by lack of access to advanced testing instrumentation at in-country laboratory facilities. In this review, only one study reported detectable CECs: the water samples were transported from Kenya to a laboratory at Ghent University in Belgium for analysis (K'oreje et al., 2022). Studies that only used laboratories in Kenya or Ethiopia analysed fewer trace elements (1.9 on average) compared to the studies that used laboratories in other countries (8.2 trace elements on average). Trace elements analysed in Kenya and Ethiopia were also more likely to be limited by the sensitivity of the test method (high detection limits and older testing techniques). In the course of our own research activities in Kenya and Ethiopia, the authors have faced challenges related to the cost and availability of testing services and instrumentation – for example, at the time of writing we have not found a laboratory in either country that will analyse uranium in water samples (but by transporting samples abroad we have detected uranium exceedances in groundwater used for drinking). Capacity for water chemistry analysis needs to increase to enable monitoring and more comprehensive assessment of water chemistry risks during borehole commissioning. Particularly, the lack of data on organic pollutants and CECs more broadly is a significant gap in Kenya and Ethiopia, and in African aquifers more broadly (K'oreje et al., 2022).

In addition to the issue of analytical capacity, this review also highlights a need for greater attention to national water quality standard setting and the role that these standards have in directing priorities for water safety management. More than 95 % of the 96 studies that tested for potassium reported exceedance of the 1.5 ppm guidance threshold, usually for more than two-thirds of the tested sites in each study (Fig. 6). In all but one case, potassium exceedance coincided with exceedance of at least one other parameter, so the high rate of potassium exceedance does not strongly influence the overall review results. It does, however, draw attention to the suitability of the 1.5 ppm threshold, which corresponds to the Ethiopian standard for potassium in drinking water. The authors were not able to find justification for why the Ethiopian Standards Agency has set a maximum permissible limit for potassium at 1.5 ppm. International guidance and the academic literature do not provide a health or aesthetic basis to be concerned about potassium at this low concentration (WHO, 2022). Kenya does not have a ppm standard and the WHO, EASC, and US EPA do not provide guidance for setting standards for potassium. In contrast, uranium was infrequently tested in the reviewed studies and does not have a maximum permissible limit in Kenya or Ethiopia. The WHO and USGS, however, provide provisional guidance for a uranium threshold in drinking water based on links to kidney damage (nephritis) and a range of other organ toxicity impacts (Banning and Benfer, 2017; Chandrajith et al., 2010; Kurttio et al., 2002; WHO, 2005). Thus, the opposing examples of potassium and uranium, demonstrate a need for evidence-based revision of water quality standards to better guide water safety management and research.

4.3. Conclusion

This review has demonstrated the breadth of potential health risks from groundwater chemistry in Kenya and Ethiopia whilst highlighting data availability bias driven by a) tendency for research to focus on areas of high-profile contamination and b) in-country analytical capacity limitations. There is a need for more evidence-based standard setting and stronger in-country analytical capacity. In addition to advancements in equipment and training, laboratories in Kenya and Ethiopia would benefit from programmes that strengthen institutional commitment to water quality monitoring (Peletz et al., 2018). This review focused on studies from two countries, but groundwater chemistry risks are insufficiently recognised and largely unmanaged across much of Africa and further afield, especially in rural and lower-income settings (Amrose et al., 2020; Rajapakse et al., 2019). Conventional practice in many water supply contexts relies on a long-standing assumption that groundwater can normally be safely used without treatment. Groundwater quality and health research has an important role to fulfil in re-examining such practice. Without measures to address groundwater chemistry risks, the global development target of universal and equitable access to safe water (SDG target 6.1) will not be achieved. Better understanding of groundwater chemistry health risks can encourage and guide organisations that deliver groundwater infrastructure and water supply services to include chemistry management measures in their programmes. This is increasingly relevant as reliance on groundwater increases due to climate change.

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CRediT authorship contribution statement

Saskia Nowicki: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Behailu Birhanu:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Florence Tanui:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **May N. Sule:** Conceptualization, Methodology, Writing – review & editing. **Katrina Charles:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Daniel Olago:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. **Seifu Kebede:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

The data compiled in this review are shared in Supplementary Table 3 https://doi.org/10.1016/j.scitotenv.2023.166929.

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