Groundwater resources in the East African Rift Valley: Understanding the geogenic contamination and water quality challenges in Tanzania

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ABSTRACT

Over the years, groundwater has been used as a means of adaptation to the seasonal and perennial scarcity of surface water. Groundwater provides water for households, livestock, and irrigation in semi-arid areas of Tanzania. It is acknowledged that groundwater is susceptible to chemical and other mineral contamination which not only poses a threat to the health of human beings and livestock but also agriculture. However, the potential of groundwater in terms of its viability and quality has not received adequate scrutiny from scholars. This paper provides a review of water quality and highlights the geogenic contamination of groundwater resources in Tanzania. The literature reviewed focused on the water resource sector in the major drainage basins of Tanzania, the information about drinking water quality with respect to geogenic contamination were sought. This paper has established that fluoride is the main and well-known groundwater contaminant. This is attributed to the existence of fluoride-rich minerals such as fluorite (CaF₂), fluorapatite (Ca₅(PO₄)₃F), cryolite (Na₃AlF₆), sellaite (MgF₂), villiaumite (NaF), and topaz ((Al₂(SiO₄)F₂), bastnaesite ((Ca, La, Nd)CO₃F), and their ash deposits peeling from the granite and alkaline volcanic rocks, dominant in the region. The presence of fluoride in water sources in northern Tanzania, part of the EARV contributes to the serious health effects on humans such as dental, skeletal, and crippling fluorosis. In addition, some literature indicated arsenic as a serious drinking water geogenic pollutant in the north-west parts of Tanzania. They pointed out that oxidation of arsenopyrite minerals is responsible for the dissolution and release of arsenic into groundwater. From this review we conclude that information...
Introduction

There is a global concern about the increased demand for freshwater. This increased demand is attributed to the increased domestic water usage and other developmental activities such as agricultural crop farming, livestock farming, and industrialization. Tanzania, which is among the the East African Rift Valley (EARV) countries is not exceptional [1,2]. Because of its ubiquitous nature, drought resistance, and availability on-demand [3], groundwater serves as a supplement and/or alternative to surface water supplies in Tanzania [4]. Even though only about 1% of cultivated land in Africa is irrigated using groundwater, compared to about 14% in Asia [5], the emphasis for exploration of groundwater for agricultural activities will go hand in hand with other uses particularly drinking and other domestic purposes. About 25% of the Tanzanian population depends entirely on groundwater for drinking [6]. Increasing demand for groundwater has already been noted in other African countries particularly in East Africa. Just like in most African countries, groundwater is one of the important sources of drinking water and other household uses in Tanzania, especially for people living along the EARV [5,7]. Thus, the use and quality of groundwater will remain crucial for most of the human development activities on the region and African continent at large.

The quality of groundwater in Africa is questionable. It is estimated that about 300 million people in Africa have no access to safe drinking water [8,9]. This is attributed to contamination from both geogenic [10] and anthropogenic sources which increasingly threatens the quantity and quality of potable water [6]. Elevated concentrations of fluoride in the volcanic rocks of the EA-RV are reported [11-16]. Elevated concentration of arsenic and other potentially toxic elements (PTE) including mercury, copper, iron, manganese, phosphate, and nitrate have also been reported in the north-west part of Tanzania [10,17-24], the Ethiopian rift valley aquifers [25-29], and other regions of Africa [19,30-37]. This level of contamination should be a major concern for Tanzania and other African countries that rely on groundwater.

The presence of geogenic contaminants especially fluoride and arsenic has been assessed as a great concern in the EARV system of Tanzania. Some studies have been conducted to establishing the quality of groundwater in some aquifer systems in northern Tanzania. For instance, Kitalika [15] reported the variation of fluoride around Mount Meru in Arusha Tanzania. However, did not include other geogenic pollutants of significant health concern. Comte et al [38] conducted a study about challenges in groundwater resource management on the East African coast by focusing on the groundwater accessibility based on physical and societal drivers but did not elaborate on the level of geogenic contamination. Recently, Ijumulana et al [137,138] have studied extensively the spatial distribution of fluoride and health risks due to consumption of water with fluoride concentration below 0.5 mg/L and above 1.5 mg/L in the three regions; Kilimanjaro, Arusha and Manyara.

Although the evaluation of water quality is supposed to be part of any groundwater development project in the region, it is acknowledged that information about the quality of groundwater in Sub Saharan Africa is scarce [1,10,39-45]. This scarcity hinders the establishment of a comprehensive understanding of the quality of groundwater in the EA-RV region. The aim of this paper is therefore to provide a review of the quality of drinking water from groundwater sources in Tanzania. Information gathered in this review will serve as the basis for further research on potential and sustainable exploitation and remediation of groundwater resources in the country.

Methodology

The review methodology employed in this paper was through reading literature searched by using different keywords such as water quality, drinking water quality, the East African Rift Valley, aquifers, groundwater, transboundary water basin, geogenic contaminants, fluoride removal, and arsenic remediation. The literature search was done on relevant search engines, databases, and websites which include; Web of Science, Google Scholar, PubMed, Scopus, Science-Direct, JSTOR, Springer, Elsevier, different journal sites, thesis and dissertations, websites of institutions in the Tanzanian Water Sector (Ministry of water, water basins, water institutes, and private organizations). Under certain circumstances, grey literature (library catalog, world health organization (WHO), United Nations Educational, Science and Cultural Organization (UNESCO), United Nations (UN), ERIC, Research4Life, NTIS, open grey, OpenDOAR and personal communications) were consulted. The review was mainly focused on Tanzania (Fig. 1).
Water resources in the major drainage basins of Tanzania

Tanzania is broadly divided into five major drainage basin systems; (i) the Indian Ocean drainage system, (ii) the internal drainage system of Lake Natron and Eyasi, (iii) Bubu depression complex, (iv) the internal drainage of Lake Rukwa, (v) the Atlantic Ocean and the Mediterranean Sea drainage system. The drainage systems are further subdivided into nine (9) major river or lake basins (Fig. 1), namely; Lake Victoria, Internal, Pangani, Lake Tanganyika, Lake Rukwa, Rufiji, Wami-Ruvu, Ruvuma/Southern Coast, and Lake Nyasa. The following subsections present an overview of the major Lake and river basins in Tanzania.

An overview of the Tanzanian River/Lake Basins

The Lake Victoria basin (LVB): Is one of the significant transboundary water resources in Tanzania, Kenya, and Uganda with a total area of 238900 km². The Tanzanian part of the basin lies in the north-west with a surface area of about 115400 km² [46] (Fig. 1). It consists of the following major rivers; Kagera, Ngono, Simiyu, Magogo, Mara, Mbarageti, Mori, and Grumeti, which pours water into Lake Victoria. Lake Victoria is shared between Kenya, Tanzania, and Uganda and is the source of the White Nile which pours its water into the Mediterranean Sea in Egypt. The LVB is characterized by variations in climate. It has a mean annual rainfall of 1300, 950, and up to 2000 mm per year in the east, south, and west of the Lake Victoria, respectively.

The Internal Drainage Basin (IDB): Is one of the biggest basins where most rivers are found. The basin system is mainly comprised of troughs and faults that run southward from Lake Natron at the border with Kenya to central Tanzania in the Bahi depression and varies in width from 30-90 km. The total basin area on the Tanzanian side is about 143,099 km² and lies within the semi-arid region. The main drainage systems within Tanzania in this basin include; Lake Eyasi system, which drains areas in North Tabora Region, and East Shinyanga by the Wembere and Manonga river systems, Lake Manyara System, and Bubu complex where important features are the Bubu swamps. Other small independent lakes and swamps with no outlets in this basin are Lake Basuto and Lake Natron. With a tropical savanna climatic condition, the average annual rainfall ranges from 600 to 900 mm.

The Pangani River Basin (PRB): Is another groundwater transboundary resource. Pangani basin (Table 1) is shared by Tanzania and Kenya. The basin covers an area of 43650 km² where 95% of it lies in Tanzania [47]. The major river in this basin is Pangani, which is a collection of small rivers originating from the catchments of Mount Kilimanjaro, Mount Meru, Pare, and the Usambara Mountain ranges. The river extends from the northern part of Tanzania to the south-east where it discharges its water in the Indian Ocean. The basin receives a wide range of average annual rainfall from 650 to 2800 mm with both dry hot and cool wet climatic conditions [47].
Table 1: Major transboundary aquifers in Tanzania [42,60-62]

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Total aquifer area (km$^2$)</th>
<th>Aquifer type</th>
<th>Sharing Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal sedimentary basin 1</td>
<td>16801</td>
<td>Quaternary and consolidated sedimentary rocks.</td>
<td>United Republic of Tanzania and Kenya</td>
</tr>
<tr>
<td>Coastal sedimentary basin 3</td>
<td>23075</td>
<td>Quaternary and consolidated sedimentary rocks.</td>
<td>United Republic of Tanzania and Mozambique</td>
</tr>
<tr>
<td>Karoo Sandstone</td>
<td>40007</td>
<td>Consolidated sedimentary rocks</td>
<td>United Republic of Tanzania and Mozambique</td>
</tr>
<tr>
<td>Tanganyika</td>
<td>222297</td>
<td>Fractured, basalt and granite.</td>
<td>The United Republic of Tanzania, Democratic Republic of Congo, Rwanda, Burundi</td>
</tr>
<tr>
<td>Kilimanjaro aquifer</td>
<td>14579</td>
<td>Volcanic alluvium.</td>
<td>United Republic of Tanzania and Kenya</td>
</tr>
<tr>
<td>Kagera aquifer</td>
<td>5779</td>
<td>Alluvial unconsolidated sand and gravel.</td>
<td>United Republic of Tanzania, Uganda and Rwanda</td>
</tr>
<tr>
<td>Weathered basement</td>
<td>25842</td>
<td></td>
<td>United Republic of Tanzania, Malawi, and Zambia</td>
</tr>
</tbody>
</table>

The Lake Tanganyika Basin (LTB): Located in the western part of Tanzania, the LTB is also transboundary (Table 1). It covers an area of about 250000 km$^2$ and has a total surface area of 33000 km$^2$ shared between the Democratic Republic of Congo (45%), Tanzania (41%), Burundi (8%), and Zambia (6%) [40]. The main water body within the basin is Lake Tanganyika, which is within the western branch of EARV. Malagarasi and Luzizi are the major rivers that discharge their waters into the lake and the Lukoga River is a major outflow that empties into the Congo River drainage system [48]. The Tanzania part of the basin covers an area of about 151900 km$^2$ and is comprised of the following major sub-catchments, Malagarasi, Ugalla, Ruchugi, Luiche Lugufu, and Lugele all contributing 60% of the total runoff to Lake Tanganyika [48,49]. The basin is characterized by a sub arid climate condition with an average annual rainfall of 1000 mm.

Lake Rukwa Basin (LRB): This is a lake drainage basin that is part of the EARV, located in the south-western part of Tanzania with an area of about 88000 km$^2$ (Fig. 1). The mean annual temperature and rainfall are about 23°C and 1095 mm respectively. The major water body in the area is Lake Rukwa, which is an inland lake with no outlet. Rivers discharging water into the lake are both perennial and seasonal. The major perennial rivers are Lupa, Chambua, Songwe, Momba, Luiche, and Katuma.

The Rufiji River Basin (RRB): This is the largest basin in Tanzania consisting of four major rivers; the Great Ruaha, Kilombero, Luwegu, and the main Rufiji river systems. It covers an area of about 175,000 km$^2$ [29]. The named rivers experience variable climatic conditions ranging from wet to dry seasons [50,51]. Geologically the basin is characterized by crustaceous, jurassic, limestone, shales, alluvial deposits, precambrian gneiss, and schists [4]. The average rainfall in the basin ranges from 400 mm to 2000 mm.

The Wami/Ruvu River basin (W/RRB): is located in the east of Tanzania having an area of about 66,294 km$^2$ (Fig. 1). It comprises the Wami and Ruvu rivers as major rivers and the coastal drainages. While the Wami River originates from the northern part of the country, the Ruvu River originates within the eastern part of the country but both rivers discharges their waters into the Indian Ocean [52]. Ruvu River is the main source of freshwater for Dar es Salaam city [53]. The basin is rich in groundwater aquifers of the following forms; precambrian, quaternary, cretaceous jurassic, and tertiary aquifers [54,55]. The basin also receives a wide range of annual rainfall from 500 mm in the semi-arid region to more than 2000 mm in the eastern arc mountains [56]

Ruvuma and the Southern Coast River Basin (RSCRB): This basin covers a large part of the Ruvuma and Mtwara regions towards the south-east coast of the Indian Ocean (Fig. 1). The basin is a transboundary with approximately 81% of its length being shared between Tanzania and Mozambique. The predominant rocks in this basin are the Usagaran and Karoo crystalline limestone. Ruvuma River is the main river that originates in the highlands of Makonde plateau and discharges its water into the Indian Ocean. (Fig. 2), [57]. The annual rainfall ranges from 395 mm to 1780 mm with an average of 965 mm in the Tanzanian part of the basin [58]

Lake Nyasa Basin (LNB): This is a transboundary basin in the southwest of Tanzania bordering Malawi and Mozambique (Fig. 1). The main rivers in this basin are Ruhuulu, Songwe, Kiwira, Rufirio, and Lumbira, they all discharge their waters into the Lake Nyasa. The basin covers an area of about 165,109 km$^2$. Apart from the rift valley features, the basin is characterized by uplifted and warped plateaus, covering about 90% of the total basin. Approximately 32% of the basin is covered by sedimentary rocks of the Karoo formation, which can be easily eroded resulting in permeable strata and higher aquifer recharge. On the other hand, about 68% of the basin is covered by the Precambrian complex that is dominated by crystalline rocks [59].

Cross-cutting concerns of groundwater quality in the river basins

Groundwater is mainly used for domestic, agriculture, livestock, and small scale industries in the 9 major drainage basins of Tanzania. Groundwater quality status in terms of geogenic contamination does not vary significantly in the 9 basins. Aquifers in the basins with similar geological characteristics have more or less similar composition of water. For example, fluoride is the main geogenic contaminant in basins within the EARV [8,15,20].

Recent studies have expressed concern about the pollution of groundwater sources in some of the basins. For example, in the LVGR groundwater contamination is associated with mining activities. The reported geogenic contaminants which are
of public health concern include heavy metals and trace elements such as arsenic, mercury, and fluoride [17,19,29,39,63-66]. The IDB, part of PRB, and LVB are characterized by fluoride pollution, mainly associated with granitic and volcanic rocks, which are predominant in these drainage basins [13,67-69]. The high salinity, up to about 23280 μS/cm, and 21370 μS/cm is reported in Lake Singidani and Kindai respectively, with pH ranging from 7.3 to 8.3 [13,70,71]. Also, there is a high variability of fluoride concentration in the IDB ranging from zero to as high as 38 mg/L [14,72].

In the PRVB and W/RRB, there has been a notable increase in demand for water for domestic, agriculture, and industrial activities. The increasing population within the catchment areas and along the river basins has caused a decrease in the water quality and quantity [12]. Groundwater potential is sufficiently high within the basins whereby some boreholes can yield more than 100000 liters/hour, and about 88% is used for irrigation [47] (Fig. 1). Poor land-use practices, elevated concentration of fluoride [73], and saltwater intrusion are the major threat to groundwater quality especially in the W/RRB [74].

The Global Water Sustainability (GLOWS) [56] reported the water quality in the W/RRB to be good for human consumption based on the following parameters: total phosphorus, ortho-phosphorus, total nitrogen, nitrate, ammonia, total suspended solids, total dissolved solids, calcium, magnesium, lead, and chromium [55,56]. The mentioned parameters were within the minimum allowable limit based on the World Health Organization (WHO) and Tanzania Bureau of Standards (TBS), although saltwater intrusion and water hardness are common in some parts of the basin along the coast of the Indian Ocean [38,75]. Pollution from anthropogenic sources such as wastewater from domestic, industries, and agriculture also threatens the overall groundwater quality in the basin [38,54,56,76].

Groundwater resources within the LTB are subjected to environmental pollution from both natural and anthropogenic sources such as erosion, deforestation, pesticide residues from agricultural activities, and uncontrolled municipal wastes [48,77]. Climate change and anthropogenic stresses are the main threat to LTB groundwater quality [78]. A water quality monitoring study report published in 2015 showed that, overall the basin is less polluted with geogenic contaminants, water quality is characterized by high alkalinity and pH values, low nutrient (phosphorus and nitrogen) values, and very low concentration of inorganic pollutants such chloride (3.6 to 15.8 mg/L), fluoride (up to 0.17 mg/L), sulphate (3.8 to 19.5 mg/L) aluminium (0.12 to 0.22 μg/L), copper, mercury (0.04 to 0.1 μg/L), cadmium (0.015 to 0.025 μg/L), lead (0.01 to 0.3 μg/L), arsenic (0.24 to 0.27 μg/L), chromium (0.02 to 0.36 μg/L) [79]. However, lack of adequate environmental monitoring programs have lead to the sparse data on groundwater quality [78].

In the RRB there is scant data on groundwater quality concerning arsenic, fluoride, and other geogenic contaminants. During the 1999-2006 period, the Rufiji Water Board (RWB) analyzed several water samples (mostly surface water) for fluoride and other trace elements except for arsenic. The analyzed water quality parameters were below WHO and TBS
allowable limits. A recent report from Kilombero Valley shows significant impairment of water quality whereby ammonium, nitrate, and turbidity are high in irrigation waters [80,81].

In some water basins, there are limited up-to-date databases with regard to groundwater pollution emanating from geogenic contamination. For example, according to the latest hydrological reports of the LRB and LNB, there was no groundwater monitoring program and adequate information regarding groundwater pollution by geogenic contaminants [82,83]. While no comprehensive water quality data have been reported in the RSCRB, salinity is expected to be very high in this basin due to the geological setting and saltwater intrusion. With only 8 groundwater monitoring stations, the RSCRB has high salinity as the most threat to groundwater quality [84], with some cases of high turbidity and total hardness [58].

Albeit the huge paucity of groundwater resources information, the dominant economic activities in the basins can reflect the exploitation and possible pollution threats to groundwater resources. Studies are sought to establish the status of groundwater resources in terms of quantity and quality in the entire basins due to its potential for agriculture and livestock production in the country [50,85].

**Groundwater quality in Tanzania**

_A glimpse of Groundwater Resources in Tanzania's pre-independence, 1930-1960_

The history of groundwater resources and water supplies in Tanzania dates back to the colonial era, which targeted the development of water supplies to major townships such as Shinyanga, Tabora, and Kondoa [49]. Activities related to the development of water supplies were conducted mainly by the Geological Survey of the then Tanganyika (Tanzania Mainland). In his report, Gillman [49], provided detailed information about the hydrology of Lake Tanganyika. Lake Tanganyika is the major freshwater reservoir within the western branch of the EARV in Tanzania. Groundwater status in the central part of Tanzania (Dodoma) was reported by Fawley [86]. Another study reported on hot springs in various parts of Tanganyika such as Shinyanga, Morogoro, and Singida [87]. From 1960, the Geological Survey of Tanganyika passed the responsibility of the development of groundwater to the Department of Water of Tanganyika [67]. As might be expected, such limited information about the overall quality of groundwater in Tanzania was caused by several reasons including limited instruments for exploration of groundwater availability and shortage of analytical instruments for analysis of groundwater quality.

**Geological influence on groundwater quality and availability**

The availability, quantity, and quality of groundwater are determined by geological conditions. Notably, the geological conditions of the aquifer determine the occurrence and composition of groundwater [88]. In Tanzania, the geological condition has been documented in previously published works; it is largely characterized by Precambrian and Phanerozoic formations [7,8,39,79,89]. The Crystalline rocks are dominated by the Precambrian basement complex of varying composition and age [8,55,88,90,91]. The heterogeneous nature of the geological formations leads into groundwater with varying characteristics and composition. Under favourable conditions such as low/high pH, toxic inorganic contaminants are dissolved into groundwater.

Groundwater recharge and flow vary with geological settings. For instance, within the EARV in Tanzania groundwater flows laterally from the rift escarpment to the rift floor and the axial movement of groundwater is usually away from the rift floor culmination [91,92]. The volcanic rocks underlying the rift valley are generally less permeable and aquifers are normally found in the confined fractured volcanic rocks [59,60,88,93,94]. Aquifers that are found in the weathered crystalline basement rocks are considered to have less water storage as compared to thick porous sedimentary aquifers [95]. In weathered crystalline aquifers, groundwater occurs only in the uppermost weathered mantle or in fractures. However, such aquifers can provide enough water in the dry season [88,96] (Table 2).

The quality of some of the groundwater sources in the EARV region of Tanzania may not be fit for human consumption. This is because the general chemistry of the Tanzanian rift valley is mostly alkaline and silica undersaturated [89,93,98]. Most aquifers are volcanic and their composition is heterogeneous in parameters such as pH, total dissolved solids (TDS),
Table 3
The principal aquifers in Tanzania

<table>
<thead>
<tr>
<th>Type of aquifer</th>
<th>Recharge type</th>
<th>Groundwater quality and quantity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconsolidated aquifers consisting mainly of alluvial deposits (normally unconfined) e.g. the volcano-pyroclastic and alluvium deposits of the Kate basin and Sanya basin in Kilimanjaro</td>
<td>Rainfall and infiltration from lakes and rivers</td>
<td>Water quality is generally good with exception of aquifers in the coastal plains which are subjected to saline intrusion. Over abstraction can lead to saline intrusion from the ocean, this is a common case in the coastal regions such as Dar es Salaam. Decreasing bore the whole yield has been observed in Sanawari area, Arusha.</td>
<td>[53,55,136]</td>
</tr>
<tr>
<td>Consolidated aquifers (The coastal sedimentary and Karroo sandstone aquifer)</td>
<td>Rainfall and infiltration from lakes and rivers</td>
<td>Good water quality with the challenges saline and nitrate intrusion from the ocean and municipal wastes respectively, intrusion of manure and fertilizers from urban agriculture, household wastes from pit latrines, septic tanks, household drainage</td>
<td>[53,55,99,100,136]</td>
</tr>
<tr>
<td>Basement complex aquifers (usually discontinuous and confined) e.g. the Fractured aquifers of the Makutupora basin in Dodoma</td>
<td>Recharged occurs through weathered and fractured zones, joints and faults</td>
<td>Groundwater quantity may vary depending on the rate of abstraction, for example parts of the water level in Makutupora basin is declining. Groundwater quality also may vary subject to intrusion of contaminants from both natural and anthropogenic sources such as nitrates from domestic sewages.</td>
<td>[90,96]</td>
</tr>
</tbody>
</table>

redox potential (Eh), trace elements, and major ions [91]. In addition, substantial amount of groundwater for human consumption is not accessible as it is usually locked up in consolidated clay formations (aquicludes), while the other amount is lost in the natural weathering processes. Sometimes, in some areas, substantial amount of water may be deeply percolated beyond economic extraction zones. In the aforementioned scenarios, the groundwater quality in different areas may be contaminated at varying levels.

Types and characteristics of aquifers

Groundwater emanates from different types of aquifers having diverse characteristics and composition. This is because groundwater is abstracted from both confined and unconfined aquifers (Table 3). The most common types of aquifers include: confined aquifer, unconfined aquifers, and aquicludes. Confined aquifers are characterized by less permeability, a feature that leads to a slower rate of groundwater flow and depleted oxygen levels. Layers that are made up of clay materials restrict the interaction of the aquifer from the surface processes such as water runoff from rainfall and land use activities such as irrigation. Confined aquifers are less prone to contamination from surface pollutants. However, due to the slow rate of groundwater flow, the interaction of groundwater with the underlying rocks is high which causes groundwater to be mineralized with chemicals such as iron, fluoride, manganese, and arsenic [99,100]. On the other hand, unconfined aquifers are relatively more permeable and are usually open to the land surface and natural processes such as glaciation and rainfall. Due to their openness, unconfined aquifers recharge more rapidly from surface runoffs but are easily polluted from land-use activities taking place on the surface. Usually, the pollution is associated with contaminants such as nitrates, phosphates, sulfates, and microbes. The extent of confinement leads to the control of aquifers recharge and can further be used to predict the quality and quantity of groundwater of the wells abstracting water from them [53]. Aquicludes are normally completely impermeable hence they are in most cases not regarded as sources of groundwater.

Nevertheless, the sought literature indicates that, in Tanzania, little is known about the characteristics and recharge of many aquifers as well as groundwater exploitation and governance for large scale agriculture and industrial uses and the associated challenges [38,77]. Due to the population growth, environmental degradation trends, and climate change the the currently available surface water will continue to diminish. The shortage of surface water with required quality for human consumption has been evidenced by occasional periods of drought in semi-arid regions of the country [101]. Hence groundwater will continue to be a potential resource for the survival not only of the human and animal population but also the preservation of the ecosystem and biodiversity at large.

Hydrogeochemical characteristics of groundwater in Tanzania

The hydrogeochemistry of groundwater is dependent upon the source rocks of the aquifers and through which water passes from the aquifers to the abstraction point. As it is the case with any part of the world, the constituent of groundwater are derived from the geochemical reactions within the aquifers which in turn are mainly affected by rock type, residence
time and the extent of water-rock interaction [102]. The dissolution of minerals from the parent rocks during recharge and flow of groundwater determine the composition and hence the quality of groundwater. Tanzanian aquifers are characterized by basement aquifers with granitic and basaltic rock types where water flows through joints and fractures [103]. The weathering of these rocks is usually poor hence the longer residence time of groundwater the higher the dissolution of minerals from the source rocks. A typical example is the oxidative dissolution of sulphide rich minerals in basement aquifers and reductive dissolution of iron-rich minerals, which lead to arsenic pollution in groundwater [104-106]. On the other hand, the longer residence time of groundwater in the basement aquifers that are characterized by high pH and alkalinity leads to the dissolution of fluoride-rich minerals such as (CaF₂, fluorapatite (Ca₅(PO₄)₃F), cryolite (Na₃AlF₆), sellaite (MgF₂), villiaumite (NaF), topaz ((Al₉(SiO₄)F₂)₃), and, bastnaesite ((Ca, La, Nd)CO₃F), and their ash deposits peeling from the granite and alkaline volcanic rocks [8,16,107-109,137].

**Groundwater quality with a focus on arsenic and fluoride**

There is a lack of consensus on the yardsticks for the determinants of water quality and safety between the technical and the common man’s perspective. It should be noted that the term “quality of groundwater” is dependent upon its specific uses, such that the standard requirement for drinking water, irrigation water, and industrial water may differ significantly. The WHO guidelines for drinking water quality [110], defines safe drinking water based on three broad categories of water quality; microbial (bacteria, viruses, protozoa, and helminths), chemical (organic/inorganic naturally occurring and anthropogenic) (Table 4), and physical/aesthetic (turbidity, odor, taste, smell, appearance/color). Most of the groundwater users report the quality of water, based on physical/aesthetic water quality indicators (Fig. 2). While this is a common practice especially in rural communities, it sometimes misleads the groundwater users, for example some users usually confuse salty and hard water with fluoride polluted water (dissolved fluoride being colorless and tasteless).

The quality of groundwater is largely determined by the geological and hydrogeological features. Lithological variations determine the chemical composition and quality of groundwater as is the case with arsenic and fluoride content in the groundwater in the EARV of Tanzania [6,8,59]. Rock types influence the composition of water percolating through them and the release of chemical ions to groundwater. An example is the fluoride contamination from the fluoride-bearing minerals in rocks and sediments [111,112]. When volcanic rocks containing fluoride bearing minerals mix with groundwater through water-rock interactions in the aquifers, it subsequently causes high fluoride concentration in the groundwater [8,113]. On the other hand, most of the anthropogenic pollutants are becoming serious threats partly due to the increase in the global population, which subsequently leads to the increase in demand of water for energy (combustion of fuels), food and mineral resources exploitation [114].

The major source of groundwater fluoride in Tanzania is particularly attributed to the dissolution of fluorite and anion exchange with micaceous minerals and their clay products [6]. In crystalline volcanic and basement rocks such as those commonly found in the EARV in Tanzania, hydrolysis is the major type of chemical reaction that releases Na⁺, K⁺, Ca²⁺, Mg²⁺, and HCO₃⁻. Evaporative enrichment is common in arid and semi-arid regions where evaporation is the dominant hydrologic process that releases ions such as Ca²⁺ and SO₄²⁻ to the groundwater. The release of ions is accompanied by the dissolution of of salts that give ions such as Na⁺, Ca²⁺, SO₄²⁻ and Cl⁻ [115]. Thermodynamic control also plays a great role in determining the groundwater composition, because it controls which reaction is possible under given conditions of rock type, temperature, saturation indices and ions activity [115,116].

The common naturally dissolved ions impairing groundwater sources in Tanzania are fluoride (most common in rocks of the Rift Valley) and arsenic (in rock exposed to oxidation by mining activities). Kebede [22,115,118] reported that one of the key factors for the composition and availability of groundwater in the rift valley aquifers is their connection with the high rainfall plateau and the residence time of groundwater before reaching the rift floor. In most aquifers associated with volcanicity, conditions such as high temperature and strong acidity enhance water-rock interactions and often lead to the high concentration of toxic elements. For example, as a result of interaction with deep–rising fluids or leaching of ore deposits, groundwater circulating in active volcanic areas may contain a high amount of arsenic [119]. On the other hand, some literature based on the Rift Valley has associated the occurrence of fluoride in elevated concentration to the hyper alkaline volcanic rocks such as nepheline and carbonatite and their ash deposits [11,13,113,120]. Therefore, fluoride can enter groundwater directly from weathering of the named rocks and high-fluoride geothermal solutions [1,121].
Fig. 3. The typical cases of (a) dental and (b) skeletal fluorosis due to consumption of elevated levels of geogenic fluoride in groundwater [129].

Table 5
Guideline values for naturally occurring chemical pollutants with health significance in drinking water [117].

<table>
<thead>
<tr>
<th>Chemical Constituent</th>
<th>Significance and health effects</th>
<th>Guideline value(mg/L)</th>
<th>TBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic (As)</td>
<td>Toxic, carcinogenic</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Barium (Ba)</td>
<td>0.7</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Boron (B)</td>
<td>toxic</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>Essential as Cr(III), toxic as Cr(VI)</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>*Fluoride (F)</td>
<td>Prevent tooth decay at around 1 mg/L, toxic at high concentration</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>Essential at the lower level, toxic at higher levels</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>Toxic, carcinogenic</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>Microcystin-LR</td>
<td>toxic</td>
<td>0.001</td>
<td>-</td>
</tr>
</tbody>
</table>

*Consumption from other sources and volume of water intake should be considered when national standards are set.

In Tanzania and other East African Countries through which the EARV extends (notably Uganda, Ethiopia, and Kenya), the most alarming and frequently reported cases of geogenic groundwater health problems are associated with fluoride contamination-fluorosis (Fig. 3), particularly in the Northern part of Tanzania; Arusha, Manyara, Kilimanjaro, part of Singida and Dodoma [8,14,15,113,122-124], the Kenyan Rift Valley region [4,95,112] and the Ethiopian rift valley [25-28,120,125]. Recently, elevated concentration of arsenic has also been reported in the north-west part of Tanzania [17,63,126,127]. High concentrations of other chemical parameters of significant health concern such as copper, iron, manganese, phosphate, nitrate, are also problematic in the region [19,90,128]. Despite the struggles by different stakeholders to combat the problem through designing treatment technologies, most of the population especially in the rural settings (Table 5), are still under the risk of exposure to inorganic pollutants and saltwater intrusion for groundwater which are in the proximity to saltwater bodies [38,75,96,116].

Impact of climate change on groundwater resources and sustainability

Groundwater resources are increasingly becoming an important agenda in both the global and Tanzanian context. The agenda encompasses different approaches to meet the rapidly growing demand for water for domestic, agriculture, and industrial uses. Sustainable development of groundwater resources in Tanzania is characterized by several key issues, including climate change, pollution (from natural and anthropogenic sources), catchment degradation, limited knowledge on groundwater resources potential, and shortage of groundwater resources monitoring practices. The highlighted issues can be resolved by increasing emphasis on National Water Policy, Groundwater Resources Management Strategy, Institutional Framework for Water Resources Management, Legal and Regulatory Framework Demand Management, Assessment of Groundwater Resources Potential, Conjunctive use of Surface and Groundwater, Conservation and Protection of Catchment Areas, Protection of Groundwater Sources and, Prevention, control of pollution, and groundwater resources monitoring [3].

In all the above-mentioned aspects, both the public and private sectors must be involved and work in collaboration preferably through Public-Private Partnership (PPP). According to Tsitsili and Kanakoudis [131], the PPP success factors in most parts of Africa are political commitment, public acceptance, stakeholder involvement, and decentralization of authority. However, PPP initiatives could raise some challenges related to accountability in either public or private sector, political risks, lack of project completion which may result in poor service delivery. Thus, for any PPP to be successful the aforementioned obstacles should be observed.
To ensure the future sustainability of groundwater resources in Tanzania, an adequate regional groundwater database containing all-important water quality parameters should be established and updated regularly. Studies on the resilience of groundwater resources to the consequences of climate change should also be emphasized in the national water policy frameworks. Furthermore, there should be proper allocation, management, and control of water resources for domestic, agriculture, and industries through the integration of national economic development with groundwater supply and demand and integrated benefit of water resources development [77,132], with a focus on both social and environmental benefits.

Due to the possible uncertainties on the currently available projections based on hydrological modeling, the management of groundwater in Tanzania requires monitoring systems that consider adaptation and information from both groundwater and meteorological monitoring systems which show the response of groundwater systems to climate change [133,134] and increased exploitation. Unfortunately, so far, little emphasis has been given to groundwater resources in most of the climate change impact studies as mentioned by Taylor [135].

Conclusions

In this review, a substantial shortage of published literature about the geochemical characterization and mechanisms of mobilization of arsenic, fluoride, heavy metals, and trace elements of health significance has been realized in Tanzania. This paper revealed that global and regional availability and quality of potable and drinkable water from groundwater sources is expected to decrease from time to time due to climate change and the increase in pollution from both natural and anthropogenic contaminants. It was noted that the management and development of water resources at the national level is partly associated with the inefficiency in terms of control, monitoring, and management of groundwater resources. This makes it more worrying because the communities that rely on this water resource may be vulnerable to health risks. It is thus recommended that in addition to programs implemented at the national level, members of the community should be more encouraged to participate in the water resources management using community-based groups such as the recently introduced Water User Associations (WUAs), Water User Groups (WUGs), and District Facilitation Systems (DFTs) through capacity building programs involving Integrated Water Resource Management (IWRM) approaches. Since many chemicals may occur in drinking water and only a few are of immediate health concern, it is recommended that priorities, especially in the situation where resources for monitoring and remedial actions are scarce, should be targeted to those contaminants of greater health concern. Detailed understanding of the geochemical characteristics and mobilization of the geogenic contaminants is important for the selection of mitigation measures and the provision of safe drinking water to the communities at greater risks.

Declaration of Competing Interest

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

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