Hydrogeology Journal (2019) 27:1051–1065
https://doi.org/10.1007/s10040-019-01928-x

PAPER

Review: Groundwater resource potential and status of groundwater resource development in Ethiopia

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Received: 21 June 2018 / Accepted: 9 January 2019 / Published online: 19 March 2019

Abstract

The groundwater resources potential of Ethiopia is estimated to be about 40 billion cubic meters. Groundwater has been used as the main source of water supply since the 1970s for the main cities, towns and dispersed rural communities across the country, where provision of reticulated surface-water schemes is often expensive because of initial project construction costs and poor water quality. The exponential growth of the urban population and agriculture-led industrial development have resulted in greater attention to groundwater as the potentially cost-effective water supply source. As part of the growing focus on the use of groundwater, the Ethiopian government is currently implementing irrigation projects. One plan involves nine irrigation projects covering an estimated area of 8,000 ha, being developed on a pilot scale, with 9,000 test wells, 28,000 monitoring wells and 14,657 spring improvements. If this unprecedented Ethiopian groundwater-centred development plan is implemented successfully at such a scale, it is highly likely that its success will persuade other Sub-Saharan developing nations to put in place the necessary policies, regulations and investment for infrastructure and capacity development for exploring, exploiting and managing their groundwater resources.

Keywords Groundwater resource potential · Irrigation · Groundwater management · Ethiopia · Sub-Saharan Africa

Background

A 2004 UNESCO report stated that groundwater supplies potable water to roughly 70% of the world's population, with 51% of countries reportedly withdrawing over 100 m^3 per capita annually (Zektser and Everett 2004). Accelerated agricultural production in rural economies of South Asia, North Africa and the Middle East drive the need for enhanced initiatives for groundwater exploration, drilling and investment (MacDonald et al. 2012). However, Sub-Saharan Africa, which includes Ethiopia, has yet to undertake intensive exploration and development of groundwater resources for agricultural use.

The accessibility of groundwater throughout Sub-Saharan Africa has traditionally been through use of hand dug wells and springs including seepage areas, which has controlled the extent of human settlement beyond the major river valleys and riparian tracts (Calow et al. 2010). Currently, it is the presence of successful water wells equipped with reliable pumps that allows the functioning of settlements, clinics, schools, market places and livestock posts over very large areas of rural Africa. Failure to construct and/or sustain such water wells directly impacts, in a number of ways, on the prospects of achieving the sustainable development goals (SDGs) which have superseded the UN-Millennium Development Goals (MDGs).

Ethiopia has seen unprecedented economic growth averaging 10% in the years from 1998 to 2016, prompting rapid urbanization from 6 to 20% (ADB Report 2014; Knoema 2016). This development has prompted uncontrolled migration of the rural population to the major urban centres in search of jobs, which has put immense strain on the existing infrastructure, especially water supplies, among other issues. Water supply authorities are scrambling to address the impending water supply crises by moving away from the traditional surface-water reservoirs/dams as the accepted source of water supply, which usually take a long time to complete and require huge amounts of initial financing (Macdonald et al. 2001). External financing of Ethiopia's water

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supply schemes has usually been hindered by the reluctance of funding organization because of the fact that most of the tributaries are part of the contentious transboundary river systems where external financial institutions require the consent of downstream countries. The situation has compelled the country's decision makers to focus on exploiting groundwater resources around the main population centres. The introduction of deep drilling and pumping technology in the country since the 1970s has enabled groundwater exploitation and human settlement to be extended in response to increasing population. The situation created a new era of awareness by the authorities and they commenced multi-million dollar groundwater projects in year 2012 to develop five well fields with a supply capacity of 105 million litres per day (ML/day) of groundwater to augment the 195 ML/day supplied from surface water sources (MoWE Report 2013). This paper aims to present a review of the state of groundwater resources in Ethiopia including its occurrence, potential, quality, development and management.

Overview of climate, geology and hydrogeology

Ethiopia is located in the northeastern part of Africa (Fig. 1). It is the second populous nation in the continent with over 100 million people, and it is well known for its diverse ethnic groups as well as more than 200 dialects (DHS Report 2016). The country has one of the most spectacular landscapes in the region mainly because of the fact that the East African Rift system divides it into two distinct highlands, namely, the Western and the Eastern Ethiopian highlands. The country is well known for its mountain ranges made up of relics of extinct volcanoes towering as high as 4,550 m above mean sea level (amsl). Additionally, the country has one of the lowest and hottest places of the earth, the Danakil Depression, which is characterized by an elevation of 150 m below mean sea level (bmsl). The western and eastern Ethiopian highlands are separated by the low-lying rolling-to-flat rift valley, where the vegetation, temperature and landforms dramatically change to a real semi-desert steppe, ending up as one of the driest places on earth, i.e. the Afar Triangle. This contrasting landscape not only creates unique scenic beauty but also an equally distinct population settlement pattern, culture, soil type, extreme climate and vegetation disparities, among other things (Fig. 2).

Ethiopia is characterized by subtropical cool highlands with mainly orographic rainfall that occurs from June to September (rainy summer months), with the western part of the country receiving up to 2,500 mm/year rainfall (Cheung et al. 2008; Fig. 2). The sparsely populated semi-desert north-eastern, eastern and south-eastern parts of the country are

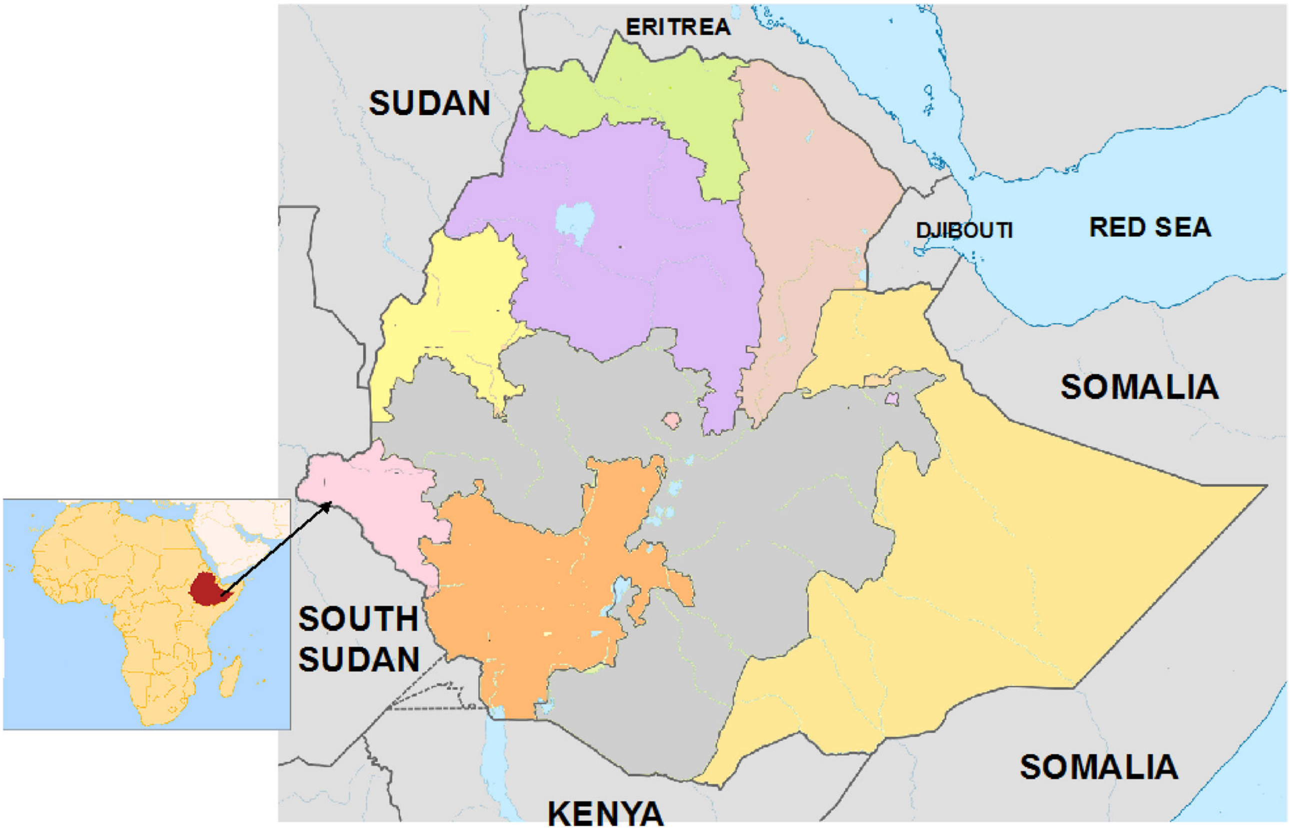

Fig. 1 Location of Ethiopia in Africa. Inset map adapted from FAO (2016)

drought prone and generally receive less than 200 mm/year rainfall. Severe shortage of water supply for livestock and access to grasslands are the main causes of nomadic tribal conflicts in the semi-desert regions. On the other hand, the highlands are densely populated, where fertile volcanic soil has allowed sedentary farming-type communities, which have caused considerable soil degradation due to overgrazing and poor farming practices (UNDP 2006).

The complex geodynamic evolution of the Horn of Africa is evident from the observable tectonic and magmatic processes. Much of the western and eastern highlands of the country are comprised of Tertiary volcanic rocks generated by two episodes (45–35 Ma and 19–12 Ma) of massive magma outpouring of dominantly basaltic composition, predating the opening up of the rift valley (George et al. 1998; MacDougall 1988; Pik et al. 1998; Kebede et al. 1999). The volume of lava was estimated to be 350,000 km^3 and covering a 600,000–750,000-km^2 area (George et al. 1998; MacDougall 1988; Mege and Korme 2003). The volume of post-rifting volcanic lava is estimated at 60,000 km^3 and is accompanied by associated sediments covering approximately 17% of the surface area within the rift valley (Fig. 3).

The eastern part of the country is composed mainly of Mesozoic carbonates and Tertiary sediments covering roughly a quarter of the country's surface area (Wolela 1997, 2007, 2008). The remaining areas are covered by Precambrian basement rocks. These Precambrian basement areas are important to the mining industry, where much of the country's gold and other mineral reserves occur. Quaternary volcanic rocks occur mainly within the Ethiopian Rift Valley including the active Erta-Ale volcano in the Danakil Depression. The following are area percentages of the Ethiopian land mass covered by the main geological formations estimated by Abiye (2006), which were reproduced from Mengesha et al. (1996): (1) basement cover (18%) (2) Paleozoic and Mesozoic cover (25%) (3) Tertiary volcanics (40%) and (4) Quaternary sediments and volcanics (17%).

Groundwater occurrence

The natural geological environment plays an important role in controlling the occurrence and circulation of groundwater and governs the aquifer productivity (Fetter 2001). Ethiopia is characterized by complex hydrogeology

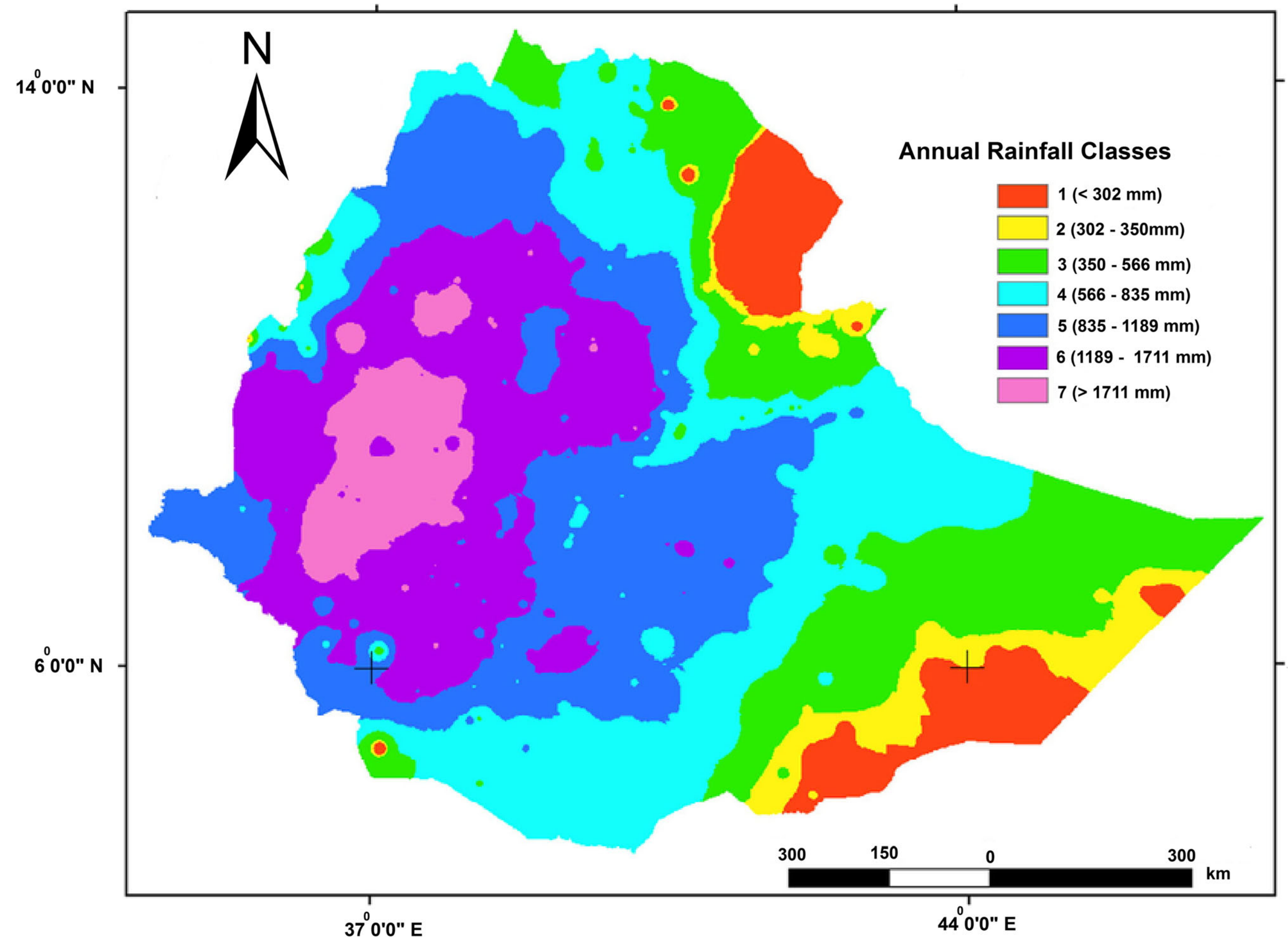

Fig. 2 Distribution of average annual precipitation in Ethiopia

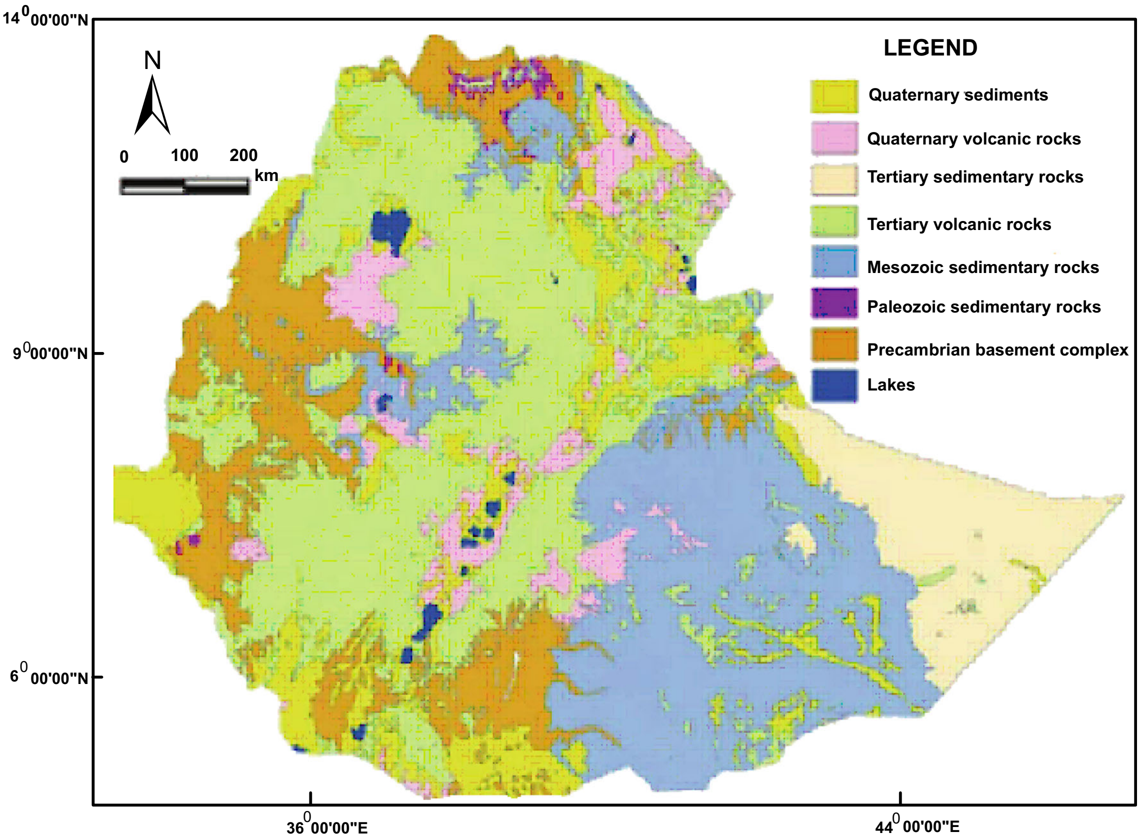

Fig. 3 Simplified geological map of Ethiopia on the basis of lithology as well as hydrological properties of major rock units (adapted from Berhanu et al. 2014)

with high spatial variability due to various complex geological evolutionary processes including tectonic movement and climatic variability. As a result, the occurrence of groundwater across the country is not uniform and depends on various geological and environmental factors (Abiye 2006). The most important factors controlling the occurrence of groundwater in the context of Ethiopian aquifers are:

- High mountainous areas, highlands, lowlands, wide depressions, and piedmont areas that are characterized by a climate ranging from very wet to extremely arid conditions.
- Outcrops of pervious or impervious hard rocks, buried or actual riverbeds consisting of thick horizons of alluvial deposits, sandy or clayey soil layers derived from weathering of country rocks, and alluvial fans along the escarpment.
- These physiographic and geological conditions result in a wide variation among the main factors of the water budget, i.e. rainfall, runoff, actual and potential evapotranspiration and infiltration rate.
- There are large differences among the various hydraulic parameters of the aquifers, including porosity, permeability, transmissivity, and storativity and/or specific yield.

Assessment and analysis of data from 8,000 boreholes, from the federal and regional water departments, indicate that more than 80% of groundwater use is for domestic water supply derived from shallow wells that yield less than 10 L/s (Ayenew et al. 2008). Low-productivity hard-rock basement aquifers, Tertiary volcanic aquifers and Mesozoic sediment are the most common aquifers as the rock units cover the majority of the country. However, the high yielding alluvial and Quaternary volcanic aquifers, especially in the rift valley, are known to have limited areal extent (Fig. 4).

Additionally, it is also important to highlight the fact that based on current knowledge, between 25 and 30% of the mapped aquifers are categorized as high yielding and feasible for exploitation (Fig. 5). Although the distribution of aquifers is now reasonably mapped over large areas of Ethiopia, quantitative information on aquifer characteristics and recharge rates, groundwater flow regimes, abstraction rates is uneven and water quality information is generally incomplete (Demlie et al. 2007, 2008).

The presence of widely distributed shallow wells in the crystalline basement aquifer is a characteristic feature of aquifers located in the humid part of the country. The depths of most of these shallow dug wells range between 12 and 35 m. The widespread distribution of shallow wells within the basement aquifers is not an indication of a major aquifer that supplies water through reticulated schemes. Rather, it is an

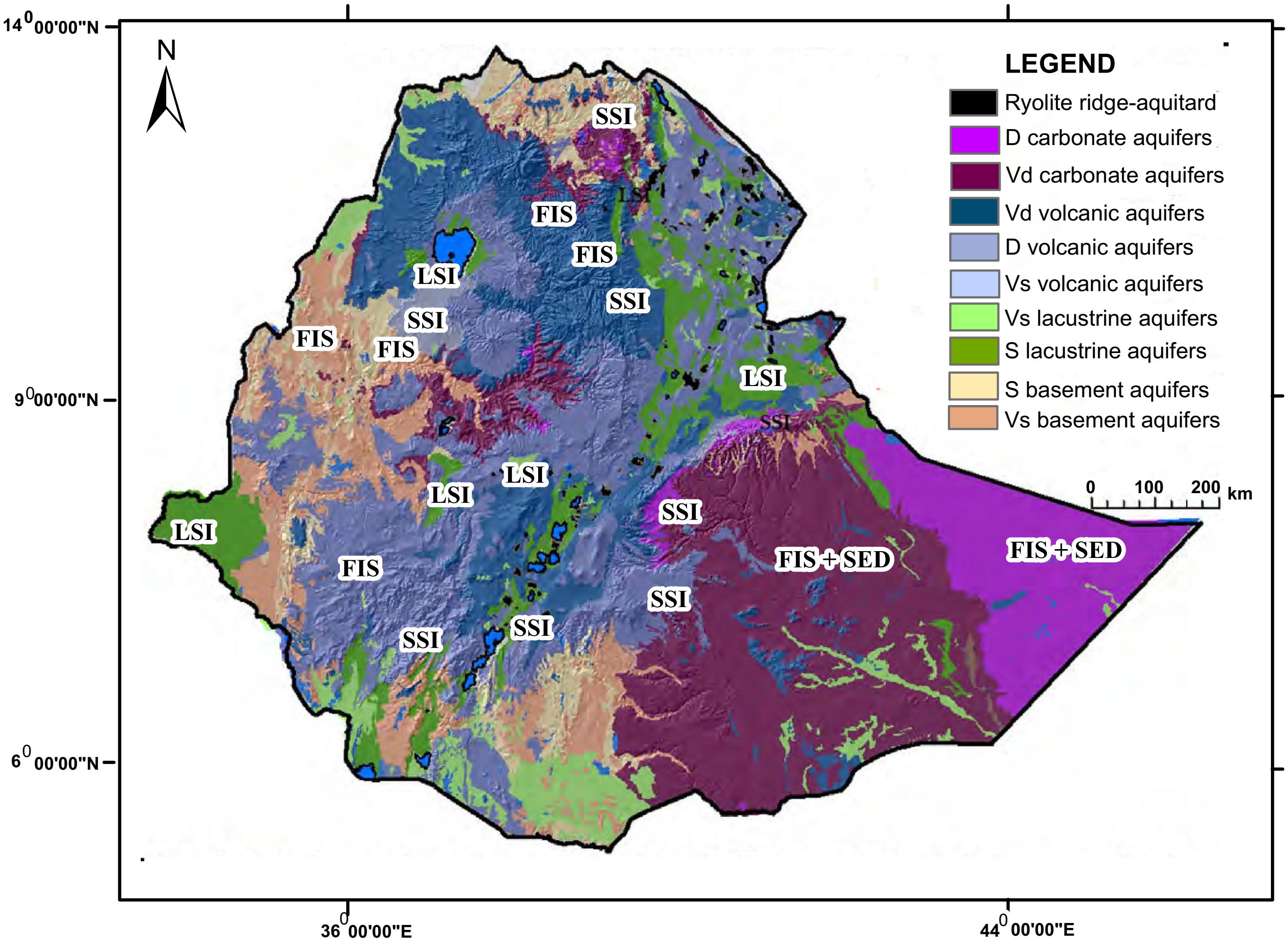

Fig. 4 Distribution of major aquifers in Ethiopia (modified from Ethiopian Geological Survey (EGS), 1996). D – Deep, Vd – Very deep, S- Shallow, Vs – Very Shallow; Groundwater Occurrence: DSED - Primary porosity, FIS - Secondary porosity, Groundwater use options: SSI - Small scale irrigation, LSI - Large scale irrigation

indication of the occurrence of groundwater within the shallow fractured and weathered regolith in otherwise impermeable crystalline hard rocks. However, it may satisfy the water supply needs of scattered rural communities with the limited abstraction rate, while on the other hand, boreholes targeting the more productive aquifers reach to depths greater than 250 m.

The Quaternary volcanic aquifers occur around Lake Tana in the northwest, in the central and northeastern Main Ethiopian Rift (MER) and to a smaller extent in the southwest of the country (Fig. 5). These Quaternary volcanic aquifers are known to have basaltic composition, and are vesicular and highly fractured (Jepson and Athearn 1961; Abate et al. 1996; Pik et al. 2003; Mishra et al. 2004; Hautot et al. 2006). Of particular interest are the Quaternary aquifers located around Lake Tana and Addis Ababa (rift margin), which are crucial for supplying significant amounts of groundwater for the two major cities, namely Bahir Dar and Addis Ababa.

The Quaternary volcanic aquifer around Lake Tana (Bahir Dar City; Fig. 6) is considered as one of the highly productive aquifers with transmissivity ranging from 100 to 200 m^2/day (BCEOM 1999; Asmerom 2008). The areal extent of the Quaternary volcanic aquifer is approximately 9,000 km^2 and it receives a high amount of precipitation (up to 2,500 mm/year) with estimated recharge between 70 and 120 mm/year (Asmerom 2008). The recharge mechanisms are both (1) direct and (2) preferential pathways through recent faulting and associated fractures (Alemayehu 2003). The region is known to have several high yielding springs (discharge ranging from 65 to 158 L/s), mainly emerging at the intersection of fractures (Chorowiz et al. 1998; Gani and Abdelsalam 2006; Gadisso 2007; Gani et al. 2009). Some springs are mineralized springs, indicating groundwater that has circulated deeply and they have attracted mineral-water bottling companies such as Bure Bagunna (Alemayehu 2003). The majority of the springs around this region have a Ca-HCO$_3$ hydrochemical composition and low total dissolved solids (TDS) of less than 1,000 mg/L, except the mineralized springs which are characterized by a Na-HCO$_3$ type water and higher salinity (Abiye and Kebede 2011).

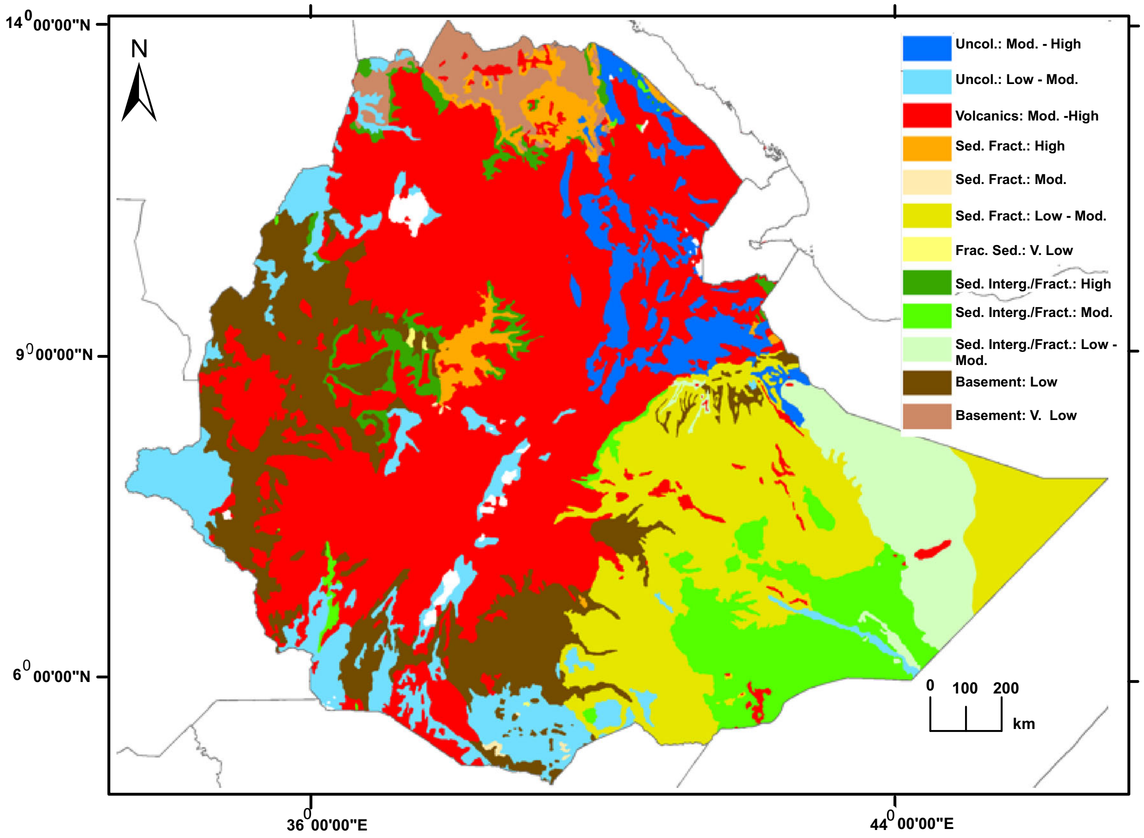

Fig. 5 Distribution of aquifers based on yield in Ethiopia (reproduced from MacDonald et al. 2010, 2012). Note the following abbreviations: Uncol. - unconsolidated, Sed. - sedimentary, Fract. - fractured, Interg. - intergranular, Mod. - moderate, V - very

The Quaternary volcanic aquifer around Addis Ababa is composed of Scoria deposits, vesicular and scoriaceous basalt, and fractured basalt (Fig. 7) and receives recharge at an average rate of about 10% of the mean annual precipitation (Kebede et al. 2005, 2006; Demlie et al. 2007, 2008; Demlie 2007). The aquifer is characteristically multilayered with intercalation of scoriaceous basalt, fractured basalt and, in places, highly fractured ignimbrites. The thickness of the aquifer is variable but can reach up to 250 m in some places. The younger volcanics are more permeable compared to the older ones. The Bishoftu volcanic unit, which has both primary and secondary porosity, has a yield range from 3 to 87 L/s. The weathered and fractured Addis Ababa Basalt is characterized by intervolcanic coarse sediments and has a yield range from 0.5 to 20 L/s. The Miocene–Pliocene Nazareth Group composed of predominantly fractured ignimbrites has a yield range from 1 to 8 L/s.

As part of the Addis Ababa City water supply project, wellfields located south of the city center (Fig. 7) have been developed (MoWR-GMATE 2011). The Strategic Framework for Managed Groundwater Development Task Force Report (MoWE 2013) states that the total volume of groundwater pumping from the wellfields through 26 deep boreholes in 2013 was about 73,000 m^3/day. It was planned to increase the pumping rate to a total groundwater supply of 105,000 m^3/day. Recently, wells as deep as 500 m have been drilled targeting the lower Tertiary Tarmaber and Amba-Aiba basalts that are dominantly scoriaceous in composition (Yitbarek 2009). These boreholes have average yields of 65 L/s, with some of the wells yielding more than 100 L/s. Since the recharge area of the wellfields is highly urbanized, one of the most challenging issues, at least to the Akaki wellfields in the long term, is the risk of groundwater pollution coming from the Addis Ababa City. The city of Addis Ababa lies between the recharge area and the Akaki wellfields which are located downstream of the city (Demlie 2007).

The current water use database, which records only 500 boreholes, lacks uniformity in its content in that some boreholes have complete location, log, well-construction, aquifer-test and analytical data; however, for the majority of the boreholes, one or more items of information were not properly captured. Therefore, much needs to be done on standardization of borehole information captured through standard templates for all new boreholes, and the existing borehole information should be transferred to the standardized templates. Moreover, water quality data for the Quaternary volcanic aquifers, which are projected to supply 30% of the city's water supply, are very limited. Therefore,

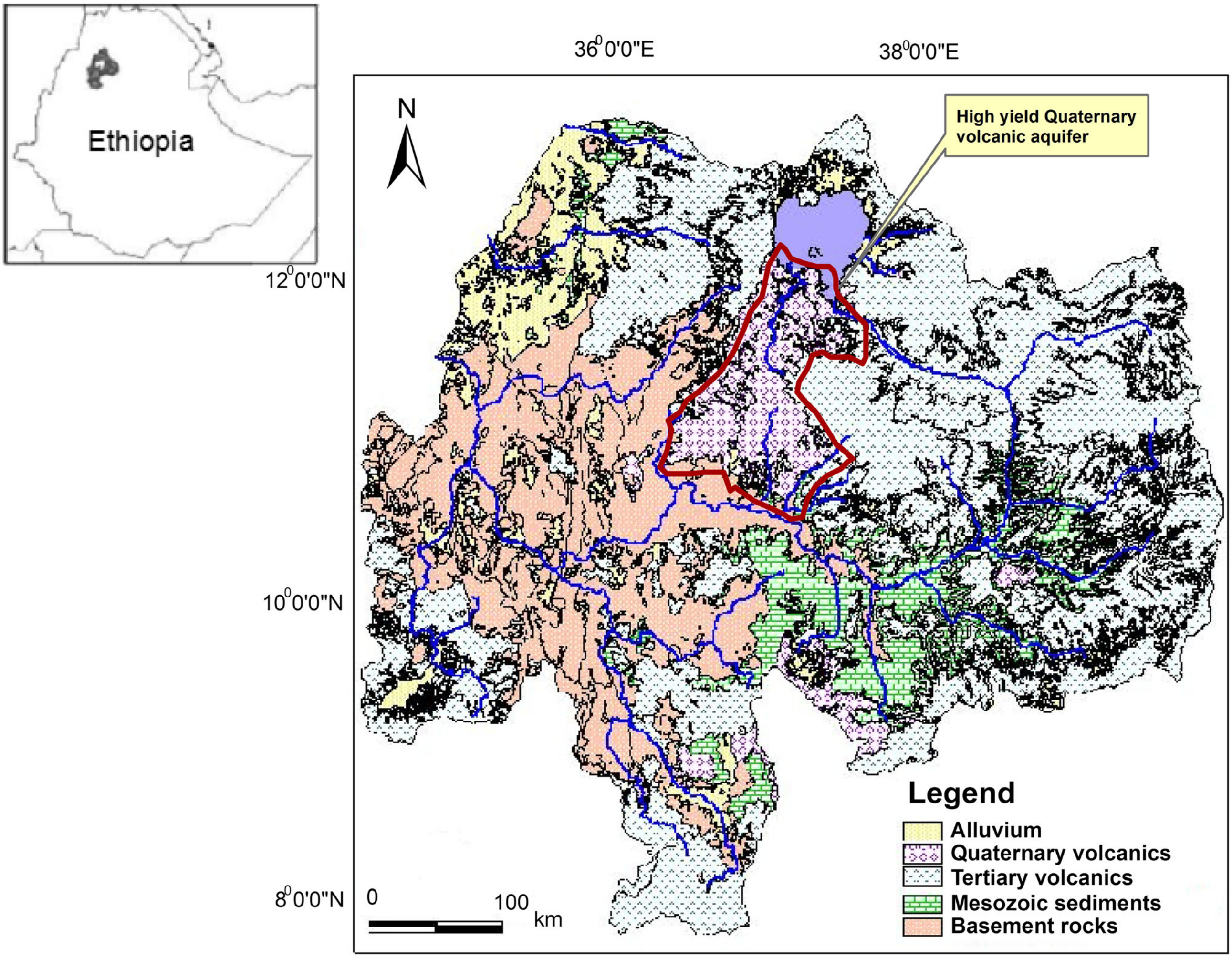

Fig. 6 Quaternary volcanic aquifers south of Lake Tana, in the vicinity of Bahir Dar City

there is an urgent need to gather and properly document groundwater physico-chemical properties, and major and minor ion and trace metal data.

Mesozoic carbonate rocks (mainly karstic limestone and subordinate dolomite) dominate the geology of southern and southeastern Ethiopia including the Sof-Omar Cave System. The limestone is locally subdivided into the Hammanlei Formation (well jointed), Uarandab series (shale and marl) and Gabredare series, which is known to have the most dissolution channels and most developed karst system (Assefa 1991; Russo et al. 1994; Asrat et al. 2008). On the basis of a few reports, the Gabredare Aquifer is known to have been fed by the eastern plateau (Bale Mountain Range), where the headwaters of major rivers Shebele and Juba are located. Despite the aquifer having huge groundwater storage potential owing to karstification of the area, detailed characterization is yet to be conducted, as the area is considerably far from major population centers. The Gabredare and Hammanlei aquifers in southeast Ethiopia are estimated to be between 200 and 1,000 m thick with typical water table depth ranging between 200 and 400 m bgl (Earthwise-BGS 2018). The other carbonate aquifer is named Antalo Limestone Aquifer and it outcrops in northeast Ethiopia. Antalo Limestone Aquifer has an average thickness of 150 m, but it lacks prominent dissolution caves, and the boreholes show low yield; therefore, the aquifer has mainly limited productivity with the use of hand-dug wells (< 1.5 L/s yield).

State of groundwater resources development in Ethiopia

Groundwater in Ethiopia, with an estimated reserve potential of 40 billion cubic meters, is shaped by complex geological formations and diverse topography and soil, and its population lacks skills to explore, develop and manage the groundwater resource; thus, there is inadequate knowledge of groundwater as a viable and strategic resource (Awulachew 2010; Melesse et al. 2014; SINF 2015). There has been a dramatic rise in

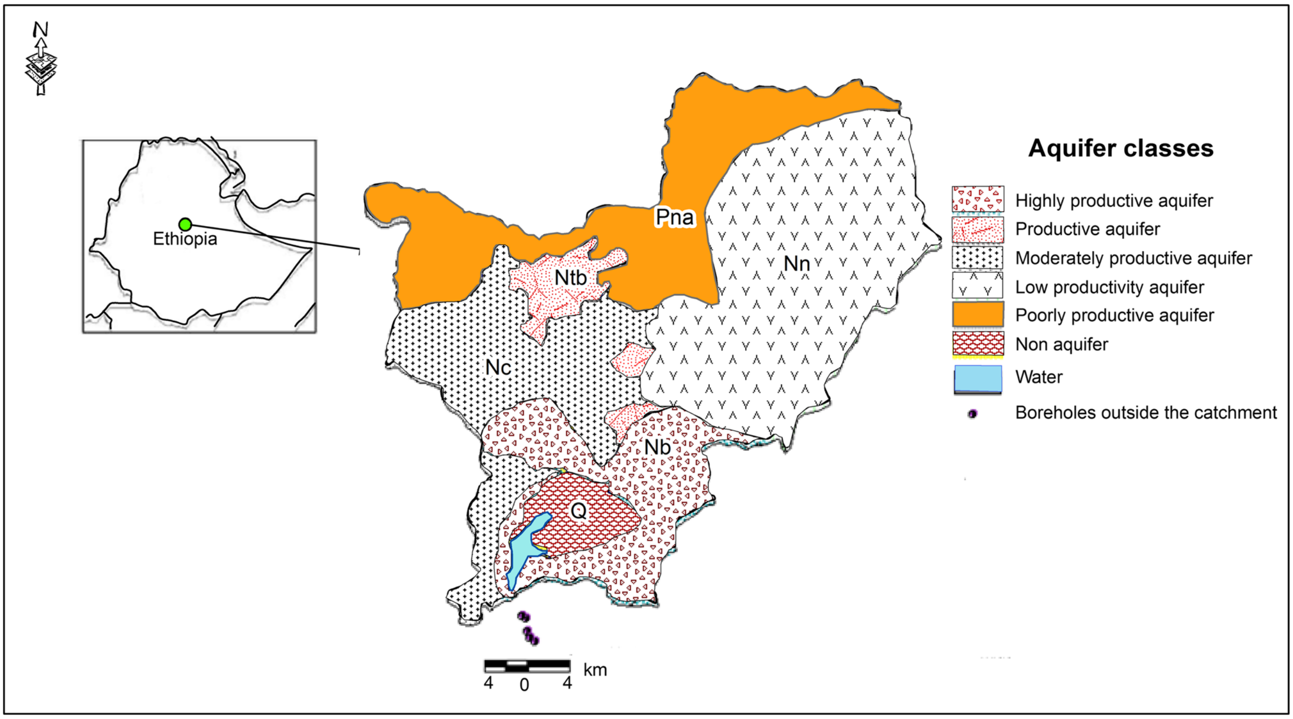

Fig. 7 Simplified hydrogeological map of the Akaki catchment, around Addis Ababa, central Ethiopia, indicating the highly productive Quaternary volcanic aquifers (modified from Demlie et al. 2007)

demand for groundwater resource exploitation, mainly for domestic water supply and to a smaller extent for agricultural use (MoWE 2013). In addition to the rehabilitation of non-functional wells, the Ethiopian Government developed nine irrigation projects with an estimated total area of 8,000 ha between 2006 and 2012, on a pilot scale, with 9,000 test wells, 28,000 monitoring wells and 14,657 spring developments (MoWR-GWMATE 2011; MoWE 2013). The ambitious plan required massive human capacity development, considerable technology transfer and institutional capacity development. Moreover, the Ethiopian Strategic Framework for Managed Groundwater Development (MoWR-GWMATE 2011) reported that domestic water supply during the implementation of the Millennium Development Goal (MDG) for the country was to reach 70% of the population by 2015. According to the National Planning Commission and UNDP (2015), Ethiopia has achieved the MDG Target 7C of reducing by half the number of people without sustainable access to safe drinking water, where at a national level, about 55% of Ethiopian households had access to an improved source of drinking water in 2014.

Major groundwater quality issues in Ethiopia

In most developing countries and specifically in Sub-Saharan Africa, more attention is given to water resource assessment than water resource management and protection. It is not always right to make the excuse of financial constraint as the major reason for not doing enough and thereby falling far behind on aspects of proper water resources management and protection (Zektser and Everett 2004; UNDP 2006). Further, most water resources projects do not last long. The main reasons are lack of understanding on the need to pay attention to maintenance and to conduct follow-up of operational water supply infrastructure once the water resource is developed, whereas lack of active local community participation is another reason.

However, in recent years there has been strong interest in addressing the issue of deteriorating water quality due to industrialization, population growth and other rapidly growing economic activities. A recent compilation of water quality data from 1,488 hand dug wells, 1,366 boreholes and 216 springs in 21 Sub-Saharan countries shows the extent of domestic waste contamination of shallow wells especially in high-density cities (Lapworth et al. 2017). The major groundwater quality issues in Ethiopia are summarized as (Fig. 8):

- High fluoride concentrations in groundwater mainly in Central Rift Valley areas
- High groundwater salinity in the arid areas of southeastern Ethiopia
- High microbiological and nitrate concentrations in shallow unconfined aquifers around major metropolitan cities

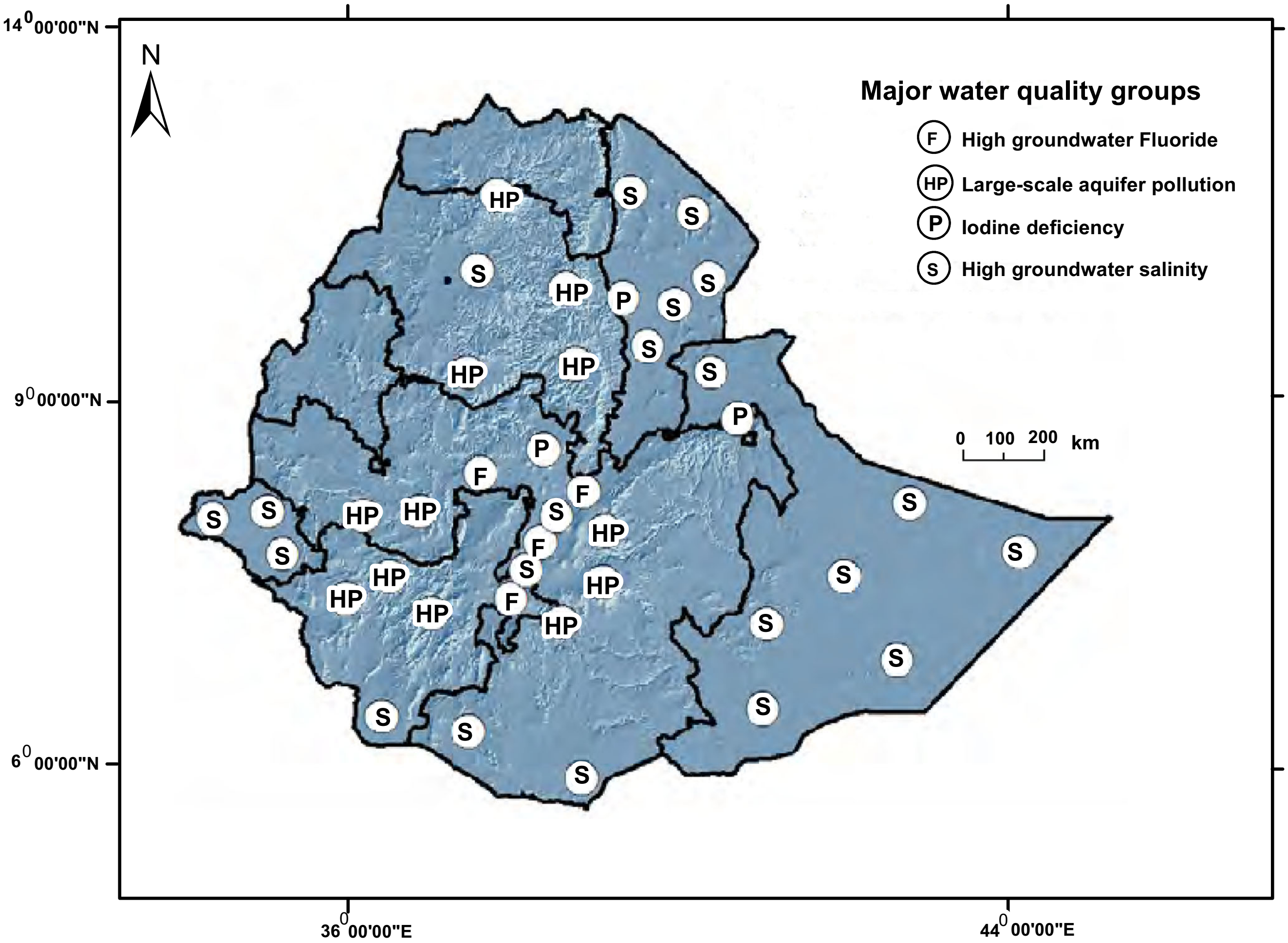

Fig. 8 Generalized groundwater quality groups showing extensive coverage of high-salinity water in the eastern portion of the country and high fluoride in the central Rift Valley. Note that groundwater pollution areas coincide with the locations of major cities (adapted from Rango et al. 2012; Kebede 2013; Akale et al. 2017)

High concentrations of fluoride

The average annual rainfall in the Ethiopian rift valley ranges from 600 to 1,100 mm/year, while the potential evapotranspiration ranges from 1,000 to 2,500 mm/year. The annual rainfall distribution is typical of the Ethiopian Rift Valley which is bimodal, where the main rainy season is from July to August and minor rainy months occur from March to May. Groundwater in this region occurs in volcanic rock aquifers essentially located on the plateau and rift escarpments, while there are lacustrine sediment aquifers in the centre of the rift. The volcanic rock aquifers, which cover 60% of the Ethiopian Rift Valley, are largely ignimbrites, but alkaline basalts and trachybasalts, recent basalts and acidic complexes (rhyolites, tuffs, pumice and obsidian) occur as well. These aquifers have moderate to high permeability with borehole yield ranging from 0 to 6 L/s (Abiye 2010; Berhanu et al. 2014). The second extensive unit is lacustrine sediment aquifers covering 16% of the area and consist of alternating fine and coarse beds and they are predominantly fine to medium grain, showing low to moderate borehole yield ranging from 1 to 5 L/s (Abiye 2010; Berhanu et al. 2014).

The region is a large closed basin characterized by rift valley lakes which are hydrologically interconnected (Ayenew and Robert 2007). Each lake has a different level of being closed and of being replenished, and with different amounts of discharge and evaporation, which largely control the level of salinity. Surface-water and groundwater flows concentrate towards Lake Shalla, filling up a large caldera in the rift floor at the lowest elevation. The Lakes Region is characterized by geothermal features especially in the central portion of the Ethiopian Rift Valley, which is part of the East African Rift system. Several thermal springs and fumaroles are also found in the vicinity of the central Rift Valley lakes (Fig. 9).

An estimated 8 million people are exposed to high levels of naturally occurring fluoride in the Ethiopian Central Rift Valley (ECRV), which is about 16,000 km^2 in area (Tekle-Haimanot 2005**;** Abiye 2010; Rango et al. 2012, 2013; Datturi et al. 2017). Daily intake of fluoride (primarily through

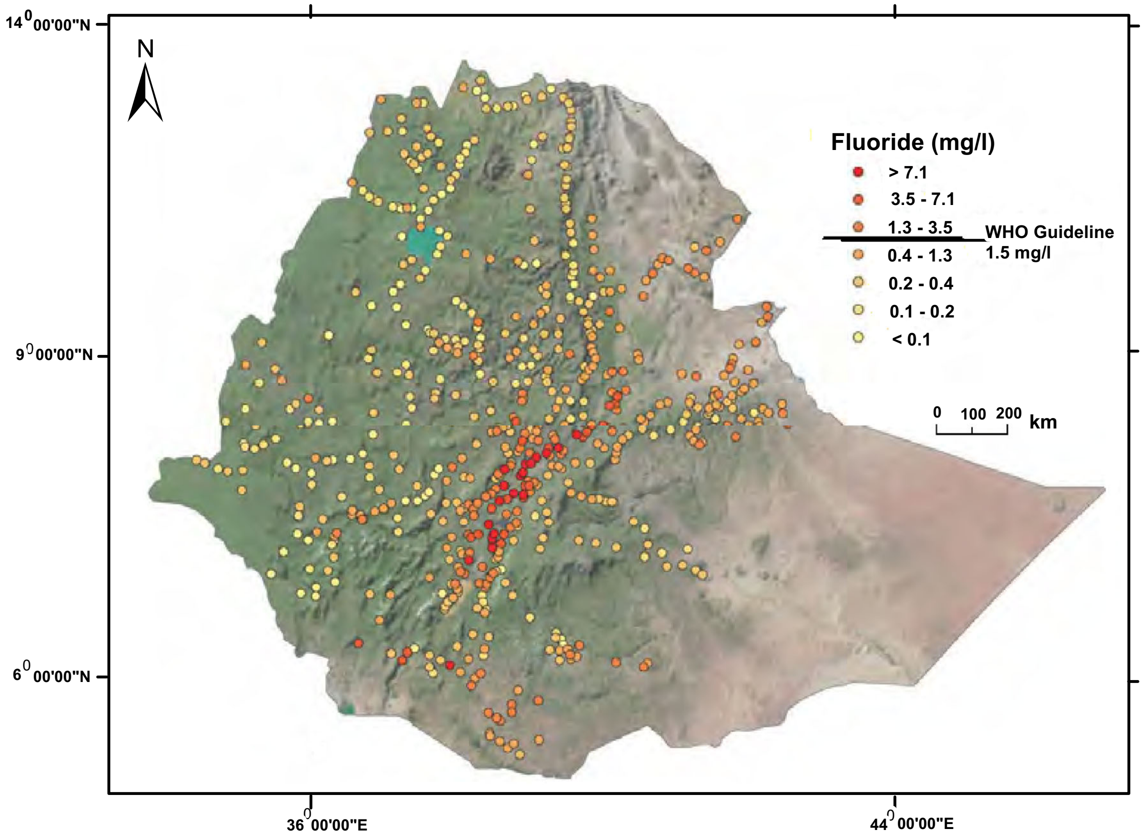

Fig. 9 Country-wide average fluoride concentrations in mg/L (adapted from MacDonald et al. 2009). Note the cluster of high groundwater fluoride concentrations within the central Rift Valley

drinking water and beverages but also via food) puts a large part of the rural population in the Ethiopian Central Rift Valley at risk of dental and skeletal fluorosis (Rango et al. 2013). Fluorosis does not only affect people's health, but also has serious economic and social consequences—for instance, appearance-related and psychological problems caused by the aesthetic value of dental fluorosis, particularly among the young, should not be underestimated. The prevalence of fluorosis and the related widespread health problems may stigmatize entire villages where some of the world's highest concentrations of fluoride are found (Tekle-Haimanot 2005; Rango et al. 2012, 2013).

On the escarpment sides of the rift, fluoride contents reach no more than 3 mg/L, with most of the cold springs found in the highlands having a fluoride concentration of less than 0.6 mg/L compared to 2.6 mg/L in the lowlands with some thermal waters reaching up to 7 mg/L (Chernet and Travi 1993). Groundwater in the lacustrine sediments have fluoride concentrations in the range from 5 to 10 times greater than groundwaters in the ignimbrite units; thus, there is evidence of thermal spring contribution and hydrological influence for the high concentration of fluoride due to proximity to the lakes. The main source of fluoride is the acid volcanic rocks, which have both high fluoride and low calcium concentrations. Over 40% of deep and shallow wells are contaminated with fluoride concentrations up to 26 mg/L (Tekle-Haimanot 2005; Demlie 2007; Demlie et al. 2008; Abiye 2010; Furi et al. 2011); however, the distribution of fluoride in the deep wells is largely variable, even among wells that are closely spaced. There are three causes of high fluoride concentration in the Ethiopian Rift valley groundwater:

1. Addition of fluoride by active volcanic and fumarole activities in the area
2. High water–rock interaction in the area, particularly interaction of water with volcanic ash and volcano sedimentary rocks
3. Low calcium concentration in the area, which restricts the precipitation of fluoride as fluorite (CaF_2)

Detailed analysis on the origin of high fluoride in the local groundwater shows that the water samples are saturated with respect to calcite and equilibrium with fluorite is often attained for medium or very concentrated waters (Bonetto et al. 2015; Ayenew 2008). With respect to most very-high fluoride lake waters, it was found that a high concentration of sodium fluoride precipitates during localized drying-up of the sediments generates high fluoride concentrations in water (Chernet and

Travi 1993). According to Tekle-Haimanot (2005), the key issues and challenges of fluoride mitigation in Ethiopia include:

- Poor knowledge on the vertical variation of fluoride within different aquifer systems
- Limited fresh surface-water resources in the affected areas and high treatment costs
- Low rainfall and high evapotranspiration in the affected areas
- High cost and less effectiveness of defluoridation methods
- Challenges of meeting the globally acceptable limit (WHO) of fluoride (1.5 mg/L)

It has been reported that small-scale community defluoridation plants in three pilot sites use the Nalgonda method (aluminum sulphate and lime) and reduce fluoride from 7.5–9 mg/L to <3 mg/L (Datturi et al. 2017). The defluoridation plants appear to show encouraging results of benefitting an average 1,000 beneficiaries/unit with capital cost of roughly 2,300 USD and maintenance and operation cost of 1,040 USD/month (Datturi et al. 2017).

It has also been reported that the preferred intervention is to identify the high-fluoride water sources to prohibit them from being used for drinking and food preparation, and to incorporate the use of rainwater harvesting for households and schools (Tekle-Haimanot 2005 and Tekle-Haimanot et al. 2005). Additional ways of managing high-fluoride water include multi village gravity schemes in rural villages and semi urban areas with a centralized treatment plant as well as defluoridation, in the absence of other options.

Groundwater salinity occurrences

Groundwater quality problems related to high salinity conditions are prevalent in deep groundwater resources in the eastern and western parts of the country, both of which are categorized as low-lying areas in an arid climate. The vast lowland areas of the Ogaden region are known to have abundant groundwater resources within the Mesozoic carbonate and fluvial deposits. However, the groundwater resource cannot be utilized because of quality problems (British Geological Survey 2001). As a result, the area occupied by ethnic Somalis which practice nomadic farming, is experiencing periodic droughts and water-related clan conflicts.

Microbiological and nitrate contamination issues

Based on analysis of 216 water points, Lapworth et al. (2017) reported that 17 shallow wells in the Addis Ababa and Bahir Dar regions (two major urban centers) have higher levels of microbial and fecal contamination than permissible limits. According to UNICEF (2017), Sub-Saharan Africa sanitation coverage stands at 46% (58% of urban and 30% of rural populations). In Ethiopia, a 2016 welfare monitoring survey by the Central Statistical Authority (CSA 2016) showed that more than 37% of rural households do not have access to any form of sanitary facilities. In contrast, the urban coverage stands roughly at 8% of households without proper sanitation facilities. It was found that not only are the toilet systems few, but they also lack a proper hygiene regime and are structurally unstable.

The Ethiopian Central Statistics Agency 2016 Report (CSA 2016) further emphasized that basic health education and awareness facilitated the installation of pit latrines from less than 35% in 2012 to 62.5% in 2016 in rural areas and over 80% in urban areas during the same time. The number of flushing toilets remains low (roughly 1%) in rural areas and close to 10% in urban population centers mainly due to affordability. Nevertheless, much needs to be done to improve access to sanitation for the over 37% of mainly rural population who did not have any form of sanitation facility in the year 2016 (CSA 2016).

There is widespread local contamination of shallow wells with domestic waste especially from pit latrines, from washing, and from contamination from watering and urination of animals (Mengistu 2003; UNDP 2006; Abay 2010). A study by Haylamicheal and Moges (2012) in Southern Ethiopia shows that 85% of functional shallow wells show total coliform bacteria of up to 68 cfu in excess of the WHO guideline value, whereas 25% show detectable (1–10 cfu) fecal coliform bacteria. One of the reasons for high microbiological contamination of the shallow groundwater is related to the inappropriate installation of pit latrines closer to existing water infrastructure than the WHO guideline distance of 30 m. Furthermore, it was reported that 14% of the water points were found to be too close (<30 m radius) to pit latrines, significantly increasing the risk of fecal contamination. People were observed bathing and washing clothes near or around 36% of the water points. Additionally, 64% of the water points were not fenced at all, which could have prevented animals from reaching the water points and might have reduced the possibility of contamination.

Water resources governance structure in Ethiopia

Water governance in Ethiopia is a three-tier system, i.e. federal, regional and at the *woreda* levels (woreda is the smallest administrative district in the country) within a federal administrative structure. The Ministry of Water Resources is responsible for formulating national water policy, strategy and action plans, and for establishing national standards pertaining to water quality, water infrastructure and other relevant standards. In addition to its regulatory function in supervising and following up on the implementation of policy and strategy instruments, as well as administering overall sector standards, the ministry provides technical support to regional water bureaus (Mosello et al. 2015). At regional level, water resource development responsibilities are devolved into regional water Bureaus, and zonal and woreda level water development offices. River basin agencies were established for the main river basins under the Ministry of Water Resources to conduct and manage master planning of resources (water being one) up to the level of feasibility. However, often, adequate financial, human and technical resources are lacking to fulfill their mandates (Mosello et al. 2015). The federal level of water governance encompasses national (steering and technical) committees, water and sanitation and hygiene (WASH) coordination offices, and federal ministries (ministries of federal affairs, finance, capacity development, women's affairs) with the intention of coordinating federal support for emerging regions, capacity development, securing and monitoring finances, and mainstreaming gender equality into government programs (Arsano et al. 2010). Other actors include state drilling companies, technical and vocational training centres, aid agencies, civil society organizations, and the private sector (environmental and engineering consultants as well as manufacturing companies and suppliers).

Sustainable development of groundwater can be achieved by overcoming major deficiencies in human resources and equipment, and improving regulatory and management tools, as well as increasing stakeholder participation. Key challenges include the lack of ability to establish who needs what, when and how; high staff turnover; capacity gaps and poor scenario planning. Furthermore, neither institutional roles nor coordination mechanisms for water resource management are sufficiently well articulated, especially at sub-national level (Woldemariam 2009). Borehole drilling registration, licensing and water permit activities are poorly implemented, and lack of finance and technical capacity, as well as weak enforcement of regulations related to groundwater development at various tiers of the organizations, are among the challenges facing groundwater development in Ethiopia.

Discussion

The groundwater situation in Ethiopia conforms to the general picture for Sub-Saharan Africa in that there is a consensus in adapting managed development of groundwater systems. Furthermore, the need to develop sustainable groundwater systems, including storage provisions to guarantee continuous supply of water, integrated groundwater management and introduction of regulation and pollution mitigation measures, has been highlighted (Awulachew 2010; Berhanu et al. 2013). On the management front, some promising developments are taking place to link groundwater management with land use planning, but more is possible in the long term by forging stronger links with the river basin management schemes, and in the short term by giving more attention to conjunctive management (Awulachew et al. 2007a, b; Awulachew 2007; Fekahmed 2012). Establishment of the Water and Land Resource Center in 2011, mandated to centralize and manage a geospatial database for water and land management in Ethiopia under the auspices of Addis Ababa University, is a step in the right direction. Baseline information is key for planning and managing investments in water infrastructure. It is imperative that government and aid/donor agencies cooperate more closely to establish and promote the use of a single source of data and information. Incentivizing companies involved in water resources development, through tax breaks and government-backed loans, will strengthen public institutions and training centers for capacity development and improve implementation of projects and plans.

Groundwater quality protection, addressing serious natural water quality issues, has to be implemented sooner rather than later—such challenges include high hardness, nitrate and salinity levels, iodine deficiency and high fluoride in groundwater. According to Berhanu et al. (2013), particular attention and prioritization needs to be given to groundwater fluoride problems, as 40% of deep wells and 20% of shallow wells of the Rift Valley are contaminated by fluoride levels between 2 and 7 mg/L.

Conclusions and recommendations

The years between 2005 and 2015 witnessed groundwater development as a valuable water resource taking center stage in Ethiopia. The 5-year (2015 - 2020) and 10-year (2015–2025) country-wide water resource development plans are based mainly on groundwater. Groundwater has been the foundation for the increase in water supply coverage from 23 to 56% country wide between 2005 and 2015, and it currently provides roughly 40% of water supply in the biggest urban centers, including Addis Ababa and Bahir Dar. Groundwater is still being developed at an accelerated pace, with mapping of new aquifers throughout the country especially in the remote and long-forgotten corners of Ethiopia.

A large portion of the Main Rift Valley region of the country experiences water quality issues with very high fluoride concentration, especially in the shallow productive lacustrine aquifers that cover an approximate area of about 16,000 km^2. Water quality problems, which have been long over-looked but are increasingly getting attention, are nitrate and microbiological contamination of shallow volcanic groundwater in the central highlands of small towns and rural areas due to poor sanitation practices including pit latrines, while heavy metals and organic contaminants in major metropolitan areas are also causes for concern.

Groundwater resource management and protection lag far behind resource assessment and development in most parts of Sub-Saharan Africa in general and in Ethiopia in particular. Therefore, much needs to be done to develop and implement water resource protection and a robust water-resource-management strategy. Local communities as well as other stakeholders have to be engaged in the planning as well as implementation of water resource development and protection.

Acknowledgements The authors would like to acknowledge Prof. Daniel Olago and an anonymous reviewer for their comments, which substantially improved the quality of the paper.

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