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Seifu Kebede

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Features, Numbers and Opportunities

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Preface

In the context of regional geodynamics, the Geology of Ethiopia is the result of complex orogenic evolution that involves: terrain accression and collision in Precambrian; peneplanaton, glaciations, and Gondowana breakup in Paleozoic; cyclic marine transgression and regression events leading to accumulation of multilayered sedimentary rocks in Mesozoic; huge continental flood basalt eruption and formation of rift valley in Cenozoic and sedimentation, and deep incision of river valleys and pluvial-interpluvial sediment accumulation in Quaternary. These mega events have left distinct imprints on landscape, hydrology, and groundwater occurence in Ethiopia.

Why this book?

(a) *Evolution in geological knowledge provides new hydrogeological knowledge* How much we know about hydrogeology and groundwater resources potential depend as much on the knowledge of geology. The unique and extensive flood basalts of Ethiopia, the closed basin lakes and associated sediments, and the unique setting of the Great East African Rift attracted several international and national geo-scientific researches in disciplines ranging from global geodynamics, rift evolution, paleo-climate re-construction, and so on. Knowledge in the geosciences of Ethiopia has evolved so much, so that it necessitates a commensurate updating of hydrogeological framework of Ethiopia. Over the last five decade alone over 3,500 scientific papers have been published regarding the geology, geodynamics, tectonics, geomorphology, magmatism, hydrology, hydrogeology, and environment.[1] A rapid look at the scientific literature shows how the knowledge and insight on geology of Ethiopia have

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[1] The number of the published scientific literature is estimated from searching for published works on Ethiopia via 'ScienceDirect'. ScienceDirect is one of the largest online collections of published scientific research in the world. The term 'Ethiopia' and 'Geology' has been entered and the search result gives 3,500 articles on the end of 2010. The total number of published works is estimated to double this size if other portals such as Springer Link, Tylor-Francis, Wiley etc., were included.

Table FM.1 Evolution in knowledge on Ethiopian Geology and its implication to hydrogeology

Domain	Old view	Prevailing view
Basement complex	The Precambrian basement of Ethiopia forms a transition zone among the low-grade volcano sedimentary succession and mafic ultramafic complexes of the Arabian Nubian Shield (ANS) and the high grade multiply metamorphosed and deformed schists and gneisses, migmatites, ophiolite fragments, and granulites of Mozambique Belt (MB).Based on field relation, structural style and metamorphic grade of the Precambrian rocks of Ethiopia has been classified into three groups: (1) the Lower complex (Archean cratonic basement), which is composed of the multiply deformed and metamorphosed high grade gneisses, migmatities, and associated granulites; (2) the Middle complex (Paleo to Meso proterozoic platform cover) which consists of psammitic and politic metasediments, and (3) the Upper Complex (Neoproterozoic mobile belt), which constitutes low-grade rocks of island arc-ophiolite association. The lower and middle complex belongs to the MB and the Upper complex to the ANS	The Precambrian basement of Ethiopia forms a transition zone among the low grade volcano sedimentary succession and mafic ultramafic complexes of the Arabian Nubian Shield (ANS) and the high grade multiply metamorphosed and deformed schists and gneisses, migmatites, ophiolite fragments, and granulites of Mozambique Belt (MB).Because of similarity in age between ANS and MB rocks of Ethiopia the classification into Upper Middle and Lower complex is replaced by a 2-fold classification as (1) the reworked pre Pan African Crust and (2) the Pan African juvenile crust.
Mesozoic stratigraphy	The Adigrat Sandstone is a fluvital-deltaic sandstone forming a single unit from its base to top	The Adigrat sandstone is marine-deltaic sandstone with two distinct formations separated by paleosol. The base of the Adigrat sandstone is highly cemented by iron, hard, and indurate, the upper Adigrat formation is porous, reddish, and the upper most layer is highly lateratized and hardened
Rift margin Architecture	Progressive doming, volcanism, and rifting took place at the axial zone of the Rift until present hence including the young volcanics and associated sedimentary rocks are inclined outwards of the Rift axis. This domal structure is believed to be formed contemporaneous with Rifting and flexuring associated with rift formation.	The uplifting of eth Ethiopian Terrain predates the outpouring of the flood basalts and formation of the rift. The dipping of strata at the margin of the rift has complex setting with dipping direction of lithologies varying with time and space.

(continued)

Table FM.1 (continued)

Domain	Old view	Prevailing view
The Volcanic plateau stratigraphy	Traditionally, the Oligocene volcanism of the northwestern Ethiopia has been divided into three formations (Zanettin and Justin-Visentin 1974); the Ashangie and Aiba basaltic units, separated by an angular unconformity and the upper Ignimbritic Alaji unit. This chronostratigraphic subdivision, although only based on a few sections from the eastern and southern part of north western Ethiopian plateau, was assumed to be valid for the entire plateau.	The Oligocene volcanism represents a continuous lava sequence from the base to the top of the plateau rather than the pilling of three or more successive and stratigraphicaly distinct units. Most of the Ethiopian flood basalts erupts 30 Myr ago during a short 1 Myr period to form a vast volcanic plateau. Immediately after this peak activity, a number of large shield volcanoes developed on the surface of the volcanic plateau, after which subsequent volcanism was largely confined to regions of rifting.
Geomorphology, karstification, planation surfaces, drainage history, paleo hydrology	In Ethiopian hydrogeology, the linkages between groundwater occurrences and geologic processes such as geomorphology, karstification, planation surfaces, regolith development, and stripping and drainage history are little known. These are the principal factors that affect groundwater occurrences, usability and vulnerability to climate change, and human forcings. Significant knowledge has been created over the last decade on these processes through geological research. In existing hydrogeological maps of Ethiopia and classification of aquifers were basically based on lithology, recharge conditions, and lateral extent of lithologies with little due emphasis on other controls such as karstification degree, geomorphology, landscape, hydrography, tectonics, diagenetic history, or rocks, environmental functions of groundwater, recharge mechanism and so on. For example, a clear linkage exists between the geomorphology of the Ethiopian flood basalts and their permeability structure. The basal units (traditionally called Ashangie basalts) form gentler topography while the top part (traditionally called the Aiba basalts) is cliff forming. Field evidence shows that none of the parameters such as flow thickness, types of volcanic structures, modal mineralogy, percentage of phenocrysts, and the degree of alteration could be able to explain the geomorphic variations. However, the geomorphic variations are related to presence of zone of soft, nonoutcropping material such as flow top breccias and highly fractured horizons. The geomorphic characteristics of the flood basalts are indicative of the difference in permeability. A high concentration of clay rich paleosols in units at the top of the Ashangie formation may account for reduced resistance of these units and gentler slope. A process called sapping a term that describes the formation of plateaus and escarpments through preferential erosion of nonresistant and nonpermeable horizons by outflow of groundwater that infiltrates the overlying resistant and permeable rocks. Geomorphic evidence shows the Aiba basalts are more permeable than the Ashangie.	

evolved and widened. Table FM.1 provides some of the evolution in knowledge of geology. This evolution provides an opportunity to update the knowledge on groundwater resources of Ethiopia. *The book aims to provide updated and detailed scientific context to the hydrogeology of Ethiopia.*

(b) *Evolution in paradigm of hydrogeology* Groundwater resources assessment which started in the 1960 and continued to recent time evolved under the *paradigm of steady state*. Ground water occurrence mapping and potential assessment sufficed for the purpose. Currently, the prevailing paradigm is that of quantifying aquifer response to changes in climate and human-induced forcing (pumping, land use changes) and maximizing the resources use sustainably. 'Water-centered development' is explicitly seen as the entry point for growth and poverty eradication in Ethiopia. Increasingly, water resource development is integrated with economic development and land use planning. Groundwater is of paramount importance for Ethiopia to supplement the available surface water resources in providing drinking water to its population and for socio economic development (agriculture, livestock, industry, tourism). The usability of groundwater resource in addition to its intrinsic properties such as water quality and vulnerabilities can be affected by the suitability of the system which intends to use it. For example, in Afro Alpine agro-climatic zone the usability of the available groundwater is limited by availability of soil, topography, climate, and so on. Therefore, groundwater resources availability alone cannot lead to its intensive use unless the availability is linked to other external factors such as land use planning, agroecology/climate, and accessibility by existing technology. In this book, attempt has been made to increase the scope of groundwater resources assessment beyond the mere description of aquifers to viewing the role of groundwater in other cross cutting issues such as climate change adaptation, poverty reduction, investment opportunities, urban planning, groundwater dependent ecosystem, and so on.

(c) *Groundwater as strategic resource* Over the last decade groundwater development has become a new phenomenon. It has become source of domestic water for growing urban population. It has become of paramount importance in rural areas. There are several reasons why groundwater is of paramount importance in rural areas: Groundwater is generally cheaper to develop relative to alternatives; aquifers are able to offer natural protection from contamination; and groundwater offer reliability of supply and a buffer against drought. For irrigation the benefits of controllability are also significant, allowing efficient and flexible in field application on demand. This is a key reason why yields from groundwater irrigated areas are typically much higher than under surface water schemes. Groundwater is the only practical means of meeting rural community in arid and semi-arid regions of Ethiopia, and note that groundwater also supplies many urban centers including the capital city Addis Ababa. In this regard, future development of settlements and urban centers in Ethiopia are highly dependent on the potential of nearby aquifers to meet ever increasing demand from population growth and industries. In rural poverty reduction, groundwater is an important credit. There is an increasing shift of paradigm: hydrogeological mapping for specific project site (e.g. water supply of a village, a city) loaded with science jargons (transmissivity, storativity, extent of aquifer, water quality, recharge rate, etc) to a new paradigm: groundwater use for development and economic growth, groundwater as strategic resource, groundwater in poverty reduction, and groundwater has environmental function. This necessitates the need of value chaining hydrogeological knowledge, i.e., provision of policy, practice, and management relevant information on groundwater resources. Such policy relevant information include maps such as: drought proof maps, recharge mechanism maps, aquifer vulnerability maps, water poverty indicators for regions, water availability maps, and so on. This book aims to provide such management relevant information on groundwater resources of Ethiopia.

(d) *Groundwater as environmental water* Groundwater is ecologically important. The importance of groundwater to ecosystems is often overlooked, even by freshwater biologists, and ecologists. Groundwater sustains rivers, wetlands and lakes, as well as subterranean ecosystems within karst or alluvial aquifers. While there are other terrestrial ecosystems in more hospitable environments where groundwater plays no central role, groundwater is, in fact, fundamental to many of the world's major ecosystems. Water flows between groundwater and surface waters. Most rivers, lakes, and wetlands are fed by, and (at other places or times) feed groundwater, to varying degrees. Groundwater feeds soil moisture through percolation, and many terrestrial vegetation communities depend directly on either groundwater or the percolated soil moisture above the aquifer for at least part of each year. Hyporheic zones (the mixing zone of stream water and groundwater) and riparian zones are examples of ecotones largely or totally dependent on groundwater. This book provided comprehensive account on groundwater dependent ecosystems including their origin, groundwater surface water relation, and specific roles of groundwater.

Seifu Kebede

Contents

Chapter 1
Introduction

1.1 Definitions of Groundwater and Aquifer

There is variable definition for groundwater. Agronomists define groundwater as any water below the ground. For engineers groundwater is often termed as subsurface water and occurs below the ground. For hydrogeologists groundwater is water in the saturated zone. A number of other names are attributed to groundwater. This include: sub surface water, under groundwater and groundwater. Rocks in which groundwater occur are also named differently. Aquifer is a rock that holds and transmits water at an economical rate. Aquiclude is a rock that doesn't hold or transmit water at economical rate. Aquitard is a rock that holds water but doesn't transmit the water to wells at economical rates. Groundwater exists inside fractures of rocks or inside open spaces called porosities of rocks. Open spaces are formed either after or during the formation of the rocks themselves.

How much groundwater exists in the subsurface is therefore the function of the amount of the open spaces in rocks and the spatial extent of these rocks. Difference in groundwater potential between regions, countries, and continents is intrinsically linked to the rock type, extent of the rocks and the recharge rates and conditions. Recharge here refers to the amount of water that joins the groundwater from external sources such as rivers, rainfall, lakes, or from any other adjacent aquifer. Three principal categories of rocks are known to geologists: Igneous rocks, sediment and sedimentary rocks, and metamorphic rocks. These can further be classified into hundreds of different class or sub class of rocks. Basically two categories of igneous rocks are known. These are volcanic rocks-which form from cooling of magma on the surface, and intrusive volcanic rocks which cool from magma inside the earth. Table 1.1 shows examples under the three major categories of rocks.

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Table 1.1 Major category of rocks and their examples from Ethiopia

Rock type	Examples in Ethiopia
Volcanic	Basalts, ignimbrites, volcanic ash, rhyolites, scoria
Sedimentary	Sandstones, limestones, shales, gypsums, alluvio lacustrine sediments, sands, gravels, alluvial fans, alluvial valleys etc.
Metamorphic	Granites, schists, granulites, slates, marbles, gneisses

1.2 History of Groundwater Development in Ethiopia

Water occurrences and access to water resources have contributed to the shaping of Ethiopian history and culture. Ancient and modern civilization in Ethiopia has been founded on areas where groundwater has been available mainly as springs (Table 1.2). Many place names (e.g. names of settlements and settlements that have grown to township) are named after the water source that supplies them. In northern Ethiopia for instance Mai means water. There are a number of town now in Tigray with prefix ‘Mai’ including Maishum (ancient name for Axum meaning-the chieftain water cistern), Maichew, Mainebri etc. In Southern Oromia and Somali regions of Ethiopia the term ‘ella’ stands for traditional wide diameter dug wells or water point. Several place names retain their names after the water sources, for example El-kere, El-bana, El-gof.

There is well documented evidence that the very well being of the traditional Borena community in Southern Ethiopia is strongly linked to groundwater resources management. An eloquent summary and investigation (Tiki et al. 2010) shows groundwater wells play a pivotal role in Borena pastoral production, cultural identity, and the institutional organization of water management (Cossins and Upton 1987; Dahl and Megersa 1990).

Indigenous well-water system of the ancient Tula wells has had a critical function in the sustainable management of savanna grazing lands in southern Ethiopia. The indispensable role of the wells is expressed by their connection to human and livestock fertility, continuity of lineages, clan solidarity, and the peace of Borena (nagaa Borena) (Dahl and Megersa 1990). In this ancient water system, water changes the meaning of landscape by transforming the land into a cultural landscape (Burmil et al. 1999) and it conserves useful indigenous environmental knowledge for managing the water system. The combination of hydrological and engineering systems, social institutions, and regulatory customary laws (aadaa seeraa) that evolved around water created strong environmental–human systems that have been exploited by Borena pastoralists on a sustainable basis for several centuries (Helland 1998).

As to when exactly, development of the groundwaters through artificial intervention (digging, drilling etc.) has started is not apparently documented. There is historical evidence that the ancient (2000 years ago) Axum Township used cisterns to supply the settlement (Phillipson 1995). The cistern called Maishum was a constructed structure that collects surface water runoff and (probably low

Table 1.2 History of water sourcing for old towns of Ethiopia (from Pankhurst)

Water sourcing of old Ethiopian settlements at the time of their establishment (Pankhurst, 1985)	
Gondar	The city suffered, as throughout history, from an acute shortage of water. Many inhabitants complained of this, as there were no wells, and water had to be obtained from the rivers to the east and west. Drinking water was taken from the higher and for cattle from the lower reaches of these streams.
Gafat	Gafat was conveniently situated only an hour walk from Gondar, and enjoyed good supply of water throughout the year from numerous springs which joined Zufil stream. The area soon developed as a center of missionary activity.
Maqdala:	Maqdala and its environs were moderately well supplied with water. There were several springs at Eslamge and one south of Sellase. Tewodros orders the digging of numerous wells and the construction of 'several large tanks' at Maqdala and at least one at Fahla. Water in the fort was, however, sometimes scarce, and had on occasion to be obtained from the foot of the mountain. The hill of Sellase was furthermore virtually devoid of water, and apparently for that reason uninhabited.
Harar	In 1887 there were nine wells containing water which the Egyptians liken to that of the Nile. Water was scarce and the scarcity continued to date. The principal water source was just beyond the walls, to the west of the city, a site frequented by many of the womenfolk. A public water fountain was, however, installed in the Farasmagala in 1907.
Addis Ababa	Menilek's principal capital, Entoto, proved unsatisfactory as a capital. Through well situated for defense on account of the steep sites of the mountain on which it was situated, as strategically convenient in being perched between the Blue Nile and Awash River systems, it was by no means suitable as a settlement in peaceful times. It lacked any good source of water, and, because of its distance from agricultural land, could not easily be supplied with provisions. Moreover, it suffered, during the rains, from a particularly intemperate climate. The plains of Filwuha, or Finfine immediately to the south of Entoto, on the other hand enjoyed a mild climate, as was the site of hot thermal springs-traditionally a great attraction to Ethiopian Rulers. Menilek and his court accordingly rode down to camp by these springs, for the first time apparently in 1885.
Diredawa	The town was also unusual in having piped water. This was installed, like the roads, by the railway authorities. The supply came from two natural springs, over one of which, had been 'erected a small masonry pyramid with four troughs for cattle and mules'. The other spring filled two concrete reservoirs, each measuring about 17 m by 5 and 8 m deep, covered by a wooden roof. The overflow was used for domestic purposes.
Debretabor	The first well was dug in 1901.
Gore	The town like most of Menilek's camps was in a good strategic position. It stood in the mountains dominating the Baro river and was virtually impenetrable, being surrounded by sharp escarpments on all sites except the south. No less conveniently it had numerous springs which yielded water throughout the year.

discharge springs) in the ancient Axum. The traditionally Borena wells are thought to have been existed as much as the community themselves and dates back several centuries (Helland 1998).

Addis Ababa (also called Finfine), the capital of Ethiopia, is founded in 1870s thanks to the presence of thermal springs which attracted the rulers interest to use the springs as natural spas.

There is a clear document as to when modern groundwater drilling started in Ethiopia. The first machine drilling of wells dates back to 1867–1868. The wells have been drilled by the British Military led by Napier while they entered into war with emperor Tewodros of Abyssinia. The drilling facility or the wells are called *Norton Tube wells* or Abyssinian Wells. While these wells mark the first machine drilled wells in Ethiopia, the British War of 1867–1868 is associated with significant innovation through the widespread use of the Norton Tube Wells. This was a perforated pipe with a pointed bottom end which was driven into the ground by rising and dropping a cylindrical weight on to its upper surface and the system is proven to be effective in alluvial and other unconsolidated sediments (Robins and Rose 2009).

The installation of the first modern water facility in capital city Addis Ababa dates back to 1884 and the water supply system taps springs in the hills north of the National Palace. The installation of the palace water supply that year was engineered by Alfred Ilg (Swiss technician and engineer) and this has created much excitement as the poem below shows (Pankhurst 1985). The water brought to the palace compound by the pipe is then used to irrigate gardens, for washing, laundry etc. From that time onwards people were no longer seen going to the river to wash their clothes.

> We have seen wonders in Addis Ababa,
>   Water worships Emperor Menilek,
>   O Dagnew [Menilek] what more wisdom will you bring?
>   You already make water soar in the air!
>   “Kind Abba Dagnew, how great is he becoming!
>   He makes the water rise into the air through a window,
>   While the dirty can be washed and the thirsty drink.
>   See what wonders have already come in our times.
>   No wonder that some day he will even outdo the faranje.
> (Pankhurst 1985)

Much of drilling history is lacking for the period between 1900 and 1930. However reports show a number of wells have been supplying water for the city of Addis and Harar. Richard Pankhurst writes for instance:

> There was also at times a dearth of water, particularly during the dry months of April, May and June. In 1910, for example, two thirds of the wells were dry, and the half dozen canals by then dug to draw water from the springs of Entoto had dried up the rivers for half the year. It was therefore considered necessary to construct reservoirs in the hilly area of Gullale to North West of the city. Water, however, remained scarce, a British resident Charles Rey reporting that in 1922 all the wells in the neighborhood of the Etege Hotel were empty, and that this was a common occurrence in the dry season. During 1920s and the Regency of Hailesilassie a greater part of the town nevertheless continued to rely on wells. Water was usually carried in 4 gallons tins.

Reports show (EGS 1974) that the Italian military occupiers of Southern Ethiopian and the Somali region of Ethiopia, have drilled several wells in the region between 1936 and 1941.

Drilling activities between mid 1930s and 1974 has been documented (Hadwen 1975). According to this report, total of 1,000 boreholes have been drilled in Ethiopia (including Eritrea) between mid 1930s and 1974. Government agencies, private companies and Aid organizations have been involved in drilling activities. National Water Resources Commission, a government agency has been the largest operator up to 1970s with its 20 rigs. The Ministry of Mines also conducts drilling activities mainly for mineral exploration, hydrogeological mapping, and road construction water sourcing since 1973. Ministry of Interior has been engaged in contracting the private sector in drilling and water supply for townships. A number of other foreign and national private companies have also conducted drilling work during this time.

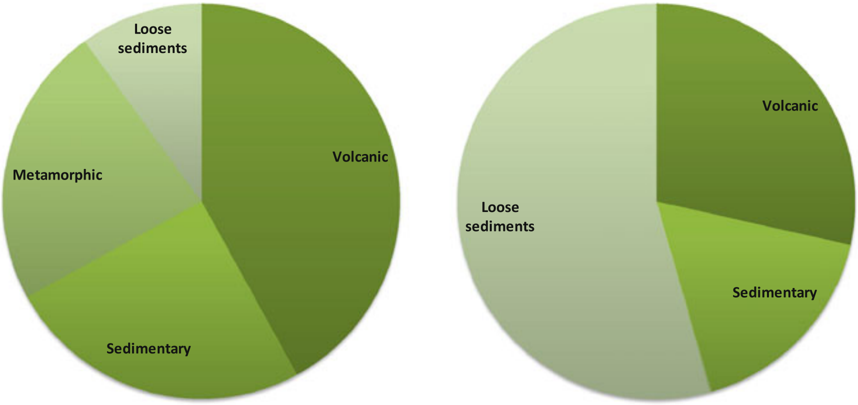
A remarkable increase in number of drilling rigs and drilling activities follows the response to the drought of early 1970s. Since 1974 a number of missionaries and bilateral aid agencies have brought out drilling rigs to the drought stricken areas. Notable among them are Sudan International Mission (SIM), World Vision Incorporated, and Lutheran World Federation (Hadwen 1975).

The Swedish International Development Agency (SIDA) drilled more than 70 boreholes in Chilalo Awraja (South Eastern Highland) up to the end of 1974. The British aid program have brought out to Mekelle through Hunting/MacDonalds a large drilling rig, the Chinese in association with National Water Resources Commission (NWRC) have commenced a drilling program in Urban and Rural areas throughout the country. Japanese aid agency has started drilling for farmers in various sector of Ethiopia during the same period. There are also records that show UNICEF and International Bank for Reconstruction and Development (IBRD) imported drilling rigs into Ethiopia in order to able to alleviate the drought impacts of 1974. Hadwen (1975) also records the history of drilling related to mineral exploration, dewatering and petroleum exploration in Ethiopia. Since the early 1990 a significant expansion of water well drilling activity is taking place. The drilling is being conducted by government agencies, faith based organizations, bilateral cooperation programs, United Nation agencies etc.

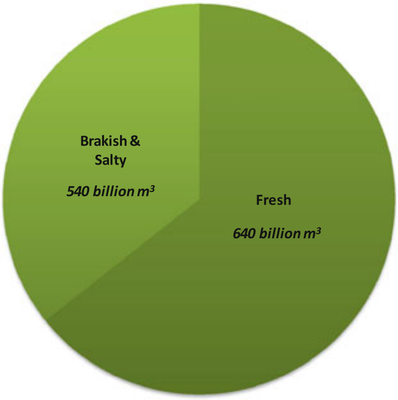
1.3 Groundwater Storage: General

There are four major categories of aquifers in the country, the formation of which relate to geological processes. The spatial extent and the groundwater storage in these aquifers is given in Fig. 1.1 and the description of the aquifers is given in Table 1.3.

Estimation of stored subsurface water is essential in groundwater studies as it gives a clear indication of the storage capacity of the aquifers. Great amounts of stored groundwater provide a better chance of obtaining water of good quality and high productivity. The calculation of the groundwater storage in each zone of the aquifer was performed by the following relationship shown in box 1.



(a) *area proportion* **(b)** *storage proportion*



(c) *proportion of fresh and saline groundwaters number in billion meter cube*

Fig. 1.1 An illustration showing the spatial coverage in Ethiopia of the four major categories of aquifers (**a**—by surface area, **b**—by storage, **c**—by proportion of fresh/saline groundwaters out of the total storage volume)

Box 1: Estimating permanent groundwater storage in Ethiopia

To calculate the saturated volume for the aquifer, four types of maps namely, lateral extension of the aquifer isopach map, water level map, and depth to the top of the aquifer were used. Reliance has been made on preexisting hydrogeological map and wealth of information that exists from literature.

$$S = \sum_{i=0}^{n} AiTi\eta i$$

S the total stored subsurface water in the aquifer in m^3;

Ai the differential horizontal area in km^2;
Ti the average saturated aquifer thickness in m;
Hi the effective porosity corresponding to the differential area i in fraction

Assumption for storage estimation is a follows: Basement rocks ($\eta = 0.001$, T = 10 m); Loose sediments ($\eta = 0.2$, T = 20 m); Volcanic aquifers ($\eta = 0.01$, T = 50 m) and Mesozoic sedimentary rocks ($\eta = 0.01$, T = 50 m). The total groundwater storage taking into consideration the total surface area of Ethiopia is estimated at 1000 billion meter cube.[1]

The Ethiopian terrain is imprinted by volcanism, uplifting, and rifting. 80 % of highest mountains with height exceeding 3,000 m are located in Ethiopia. Sedimentation and formation of marine and continental sedimentary rocks predates these activities. Sedimentation took place on basement peneplain composed of metamorphic rocks. The uplifting accelerates erosion rates. The uplifted terrain of Ethiopia has been undergoing erosion at a rate of between 0.029 and 0.185 mm/yr for nearly 30 million years (Pik et al. 2003). The erosion over this long geologic time produced highly rugged terrain, fragmented plateau, deep gorges and canyons, mountain peaks, buttes and mesas. These prominent topographic features of Ethiopia in turn affect the water resources distribution, the rainfall pattern, and groundwater occurrence and movement.

In the global maps of groundwaters or groundwater aquifers, the Ethiopian aquifers are classified as the most complex, compartmentalized, and relatively low storage aquifers (WHYMAP 2005). Two third of Ethiopia is covered by volcanic rocks. The rest of Ethiopia is covered by Sedimentary and metamorphic aquifers. Figure 1.2 shows the spatial coverage of different aquifers. Table 1.3 shows salient properties of these aquifers.

1.4 Groundwater Occurrences in Ethiopia: General

All the four major categories of rocks (Fig. 1.2) hold groundwater at different specific capacities.[2] Owing to their stratigraphic position volcanic rocks form the most accessible aquifers in central Ethiopia. Sedimentary rock forms aquifers in areas where they are exhumed by erosion of the volcanic caps (such as in the Blue Nile basin, the Mekelle Outlier) or where the volcanic rocks didn't exist initially (such as the Ogaden lowlands). In localities such as the Ambo-Guder valley, the escarpment facing Afar from Diredawa, and the Didessa valley, sedimentary rocks

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[1] *It should be noted that the saturated thickness and therefore the total storage is conservative estimate.*

[2] Specific capacity refers to the amount of water that can be stored per unit volume of an aquifer-or water holding rock.

Table 1.3 Major aquifer rock categories and their salient characteristics (depth classification adapted from Ethiopian Groundwater Management Framework document (MWR 2010)

Aquifer type	Rock type and color code	Salient characteristics
Volcanic	Shallow (30–100 m) Deep (100–250 m) Very deep (> 250 m)	Groundwater occurs in fractures and joints formed during formation or after the formation of the rocks. These fractures come mostly in unpredictable pattern in spacing, aperture opening, and length. These make volcanic aquifers very complex, anisotropic and heterogeneous. Degree of fracturing in these rocks is the determinant of storage potential of the rocks. These rocks occupy highlands forming isolated volcanoes, volcanic shields, plateaus, volcanic cones etc. The geomorphology that is formed by the volcanic rocks is favorable for the emergence of groundwater as springs along the foothills of the volcanic shields. Volcanic rocks generally cover central Ethiopia.
Sedimentary	Deep (100–250 m) Very deep (> 250 m)	Groundwater occurs in pore spaces, fractures or cavities, as the result sedimentary rocks are considered as dual porosity aquifers. In Ethiopia Sedimentary rocks occur in Blue Nile gorge, in the Mekelle outlier and in the south eastern highlands extending down to Ogaden. In the other parts of the world (e.g. The Northern Africa, Australia, and Western Africa) sedimentary rocks are known for highest storage and transmission properties.
Metamorphic	Very shallow (0–30 m) Shallow (30–100 m)	While no outright comparison is possible between the Sedimentary rocks and volcanic rocks of Ethiopia in terms of their storage potential, Metamorphic rocks in Ethiopia are known for their low storage and transmission properties. In Ethiopia metamorphic rocks occupy the peripheral lowlands where rainfall is often low. This leads to limited development of regoliths and seprolites weathering products. These are secondary materials known to enhance storage of groundwater in metamorphic terrains, for example in Uganda and central Africa.
Alluvio lacustrine sediments and volcaniclastics	Very shallow (0–30 m) Shallow (30–100 m)	Alluvio-lacustrine sediments occupy vast regions of the rift valley, and filling intermountain grabens and local depressions, river valleys and lake margins. They occur as alluvial fans, deltas, alluvial plains, marginal graben filling sediments etc. Typical feature of alluvio lacustrine sediments is that groundwaters occur in primary porosity, water table is mostly shallow, water quality is extremely variable, etc.

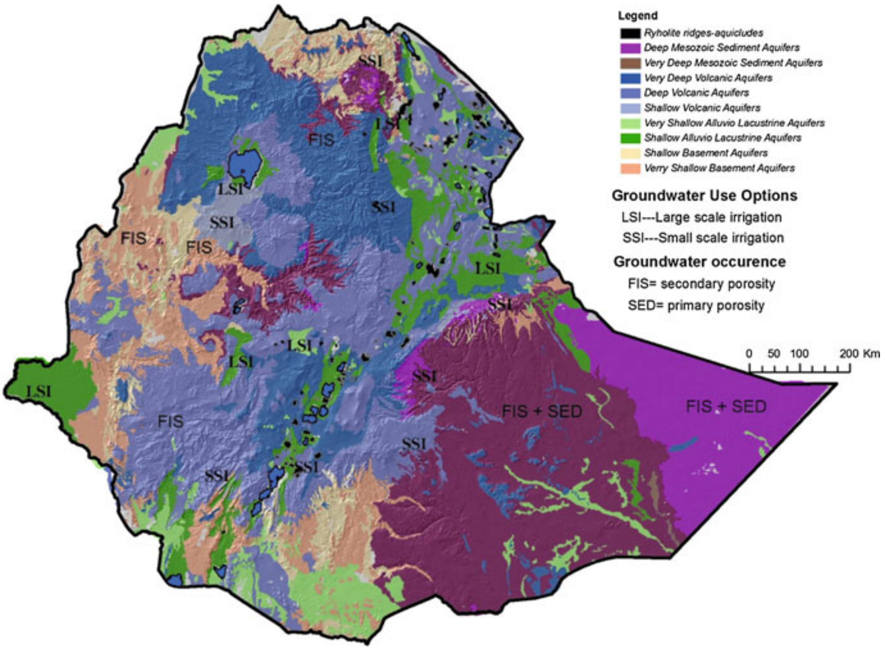

Fig. 1.2 Map showing aquifer type distribution, depth to water table, type of permeability, and potential uses of the aquifers (Modified from Geological Map of Ethiopia, EGS 1996)

are exposed to surface owing to regional tectonic down cutting. Basement rocks form most of the western peripheral lowlands and northern Ethiopia. They also occur in the Hammer Koke block in southern Ethiopia, the Borena lowlands in southern Ethiopia and in some localities around the South Eastern Highlands. The loose Miocene-Quaternary sediments occupy the vast plains of the Rift valley, the Afar depression and along river valleys in the lower Wabisheble basin (south Eastern Ethiopia).

As shown in Fig. 1.2, volcanic rocks are the most extensive by surface area while by groundwater storage the loose sediments are the most important aquifers (Fig. 1.1).

1.5 Hydrostratigraphy: General

In the context of regional geodynamics the Geology of Ethiopia is the result of a complex orogenic evolution (see Table 1.4 for sequence of geologic events) that involves: terrain accression and collision in Precambrian; peneplanaton, glaciations and Gondowana breakup in Paleozoic; cyclic marine transgression and regression events leading to accumulation of multilayered sedimentary rocks in

Table 1.4 Sequence of mega geologic events and hydrostratigraphy of Ethiopia

Unconformity	Peneplanation	Epoch	Volcanism	Peneplanation	Glaciation+	Lateritisation	West Ethiopia	South Ethiopia	North Ethiopia
	Quaternary	Holocene	🟦	■		🟧	Exhumation of underlying Basement rocks and old regolith mantle and continued lateratization, by removal of Cenozoic volcanics, Widespread Lateratization, formation of ferricrete since Late Miocene	Striping of Cambrian , Permian and Cretaceous regolith, with minor formation of regolith in the higher grounds, widespread duricrust in low laying areas	Exhumation of underlying Basement rocks and old regolith mantle with limited late quaternary lateratization
		Pleistocene	🟦	■	▒	🟧			
≈	Tertiary	Pliocene	🟦	■		🟧			
≈		Miocene	🟦	■		🟧			
		Oligocene	🟦	■					
		Eocene							
		Paleocene							
≈	Mesozoic	Cretaceous		■		🟧	Wide spread Lateratization	Widespread Lateratization	Wide spread Lateratization
		Jurassic							
≈ ~		Triassic		■		🟧			
	Paleozoic	Permian		■	■	🟧			Edagaarbi glacials
		Carboniferous		■	■				
		Devonian		■					
		Silurian		■	■				Enticho Sst
		Ordovician		■	■	🟧			
		Cambrian		■		🟧			
~		Proterozoic				🟧	High grade Mozambique belt rocks and Low grade Arabian Nubian shield Metavolcanics and Metasediments with Ultrabasic rocks with some break in geologic history and formation of Kejmiti beds	High grade Mozambique belt rocks and Low grade Arabian Nubian shield Metavolcanics and Metasediments with Ultrabasic rocks	Low grade Arabian Nubian rocks post tectonic with granitic intrusions

Mesozoic; huge continental flood basalt eruption and formation of rift valley in Cenozoic and sedimentation, deep incision of river valleys and pluvial-interpluvial sediment accumulation in Quaternary. These mega events have left distinct

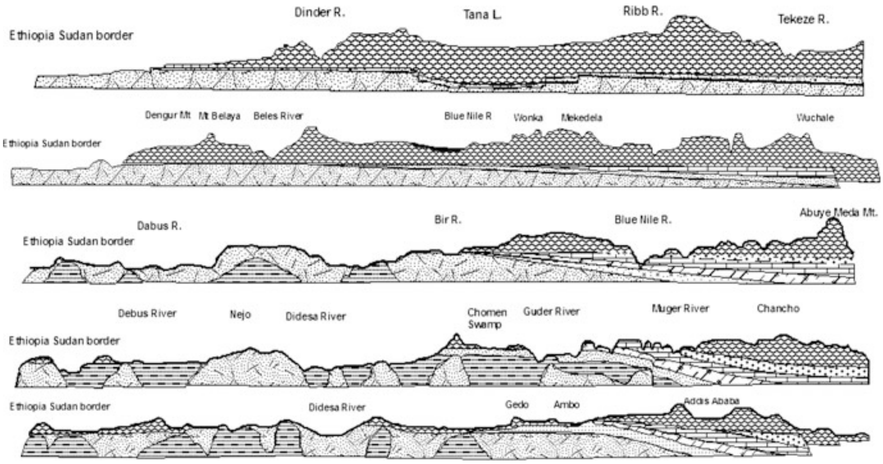

Fig. 1.3 Stratigraphy of Ethiopia as show in the cross section rock layers from the North Western Ethiopian plateau (modified from USBR 1964)

imprints on stratigraphy, landscape, hydrology, and hydrogeology of Ethiopia. Figure 1.3 shows the stratigrphy and West to East profile of the Blue Nile plateau (western half of Ethiopia). The cross section shows undulating erosion surface of the Precambrian, the low-angle slightly-diping tabular plateau forming Mesozoic sediments, and the thick monotonous but locally deformed (e.g. in Lake Tana basin) Cenozoic volcanic pile.

Water bearing formations (Fig. 1.3) come in the following order. The oldest aquifers are the Basement aquifers and associated regoliths and wadi bed sediments; this is overlain by Mesozoic sediments composed of multilayered continental and marine sediments. The vast majority of the basement rocks and the sedimentary rocks are mantled by thick Cenozoic volcanic rocks this in turn is draped by Quaternary sediments.

The Precambrian basement of Ethiopia forms a transition zone between the low grade volcano sedimentary succession and mafic ultramafic complexes of the Arabian Nubian Shield (ANS) and the high grade multiply metamorphosed and deformed schists and gneisses, migmatites, ophiolite fragments, and granulites of Mozambique Belt (MB). In Northern Ethiopia the basement rocks are low grade metavolcanics and metasediments intruded by granites. The proportion of high grade belts is higher in southern, Western and East Ethiopian basements. Groundwaters occur in fractures, regoliths and recent alluvial sediments associated with the basements.

The Mesozoic sediments come in cyclic sequence marine and continental sediments. Unlike most of the world where folding and basin subsidence lead to formation of folds, and structural traps, the Ethiopian Mesozoic sediments form uplifted tabular plateau dissected by deep river gorges and river valleys and dipping slightly forming a regional low angle monocline. This structural feature results in steep slopes which in turn lead to rapid outflow of recharging waters to the river valleys. Another prominent feature of the Ethiopian Mesozoic sediments unlike the same rocks in other part of the world is the low degree of karstification and rarity of karst landscapes. The proportion of karstified rocks compared to karstifiable rocks is in the order of 5 %. The dominantly muddy Adigrat sandstone is marine-deltaic sandstone with two distinct formations separated by paleosol. The base of the Adigrat sandstone is highly cemented by iron, hard and indurate, the upper Adigrat formation is porous, reddish and the upper most layer is highly lateratized and hardened. The whole package of the Mesozoic sediments forms multilayered aquifers with dual porosity (fracture + minor karst and primary porosity). The Cenozoic volcanic cover comes in monotonous but locally deformed (e.g. In the Yerer Tullu Wellel Volcanic Lineament Zone, the Lake Tana Basin and along the Margin of the rift) and intruded by dykes. Groundwater occurs in fractures and flow contacts. Aerially less extensive unit is the Miocene to Quaternary sediments. This forms loose sediments of higher primary porosity leading to the largest groundwater storage in Ethiopia (Fig. 1.1).

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Chapter 2
Groundwater Occurrence in Regions and Basins

2.1 The Broad (Oligo-Miocene) Volcanic Plateau and Associated Shields

Geology and Stratigraphy

The broad volcanic plateau (Fig. 1.2) accounts for about 25 % of Ethiopian landmass. The Ethiopian volcanic plateau is a thick monotonous, rapidly erupted pile of locally deformed, flat lying basalts consisting of a number of volcanic centers with different magmatic character and with a large range of ages. The trap volcanics including the associated shield volcanoes cover an area at least 6×10^5 km^2 (around two-third surface of the country), and a total volume estimated to be at least 3.5×10^5 km^3 (Mohr 1983) and probably higher than 1.2×10^6 km^3 according to Rochette et al. (1998). Flat-topped hills and nearly horizontal lava flows is a common scene in the broad volcanic plateau. Topographic features of the basaltic plateau are vertical cliffs, waterfalls, V-shaped valleys, vertical and mushroom-like outcrops of columnar basalts, and step-like hill terraces. Interlayered with the flood basalts, particularly at upper stratigraphic levels, are felsic lavas and pyroclastic rocks of rhyolitic, or less commonly, trachytic compositions (Ayalew et al. 1999).

The traps are traversed by dykes. The width of dykes ranges from a few centimeters to about 6 m. The dykes act either as barriers or as conduits for flow of groundwater depending upon their nature as resistant to weathering or highly weathered and fractured. The densest network of dykes is noted in the Lake Tana Basin and the upper Tekeze watershed. The basal formation of the trap basalts is the most frequently cut by dykes.

According to the traditional classification of the Ethiopian flood basalts there are four different stratigraphic units all diachronous: from bottom to top, Ashangie (Eocene), Aiba (32-25), Alaji (32-15 Ma) and Termaber (30-13) (Mohr 1983; Mohr and Zanettin 1988). A more recent classification of the stratigraphy of the broad volcanic plateau put forwards four stratigraphic units (Fig. 2.1). These are (a) the basal basalt sequence forming gentle and rugged terrain corresponding to

S. Kebede, *Groundwater in Ethiopia*, Springer Hydrogeology,
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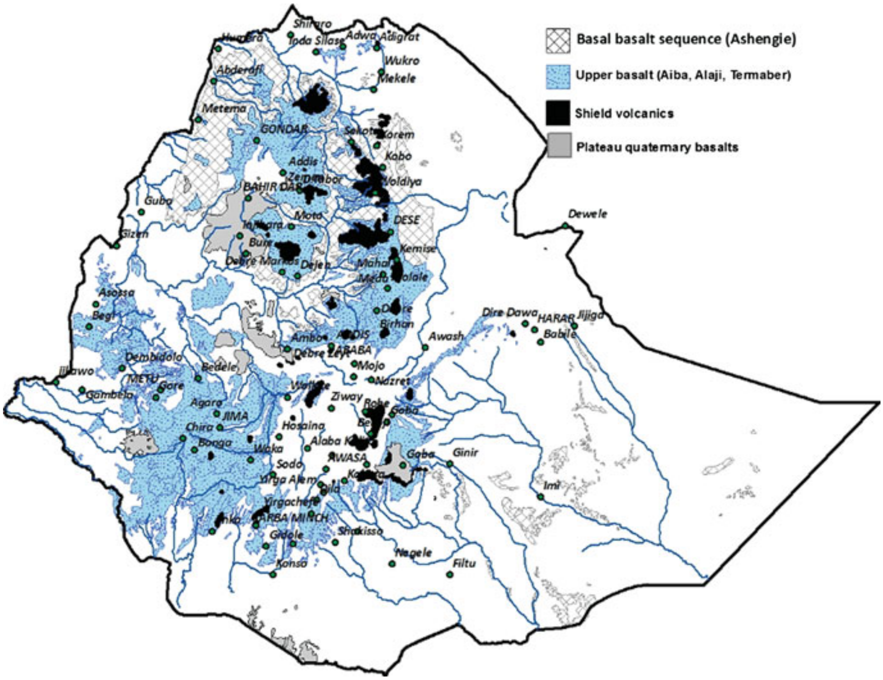

Fig. 2.1 Map showing the distribution of plateau flood basalts, prominent shield volcanics and associated central volcano related quaternary basalts

the Ashengie, (b) the upper basalt sequence forming the plateau proper corresponding to the Aiba-Alaji-Termaber sequences, (c) broad based shield volcanics caping the plateau and d) quaternary scorea basalts associated with the shields (Kieffer et al. 2004). Unlike the former classification which put the plateau basalt into four groups the new classification put the plateau basalt only into two categories. The whole volcanic sequence has been emplaced with no apparent development of paleosol and erosional surfaces (Rochette et al. 1998).[1]

The *Ashangie* is basaltic formation marked by its deep weathering, thin layering (<10 m), smooth topography and cross cutting sets of dykes. There are minor acid products (such as volcanic ash, rhyolites, and ignimbrites) in the Ashangie formation. Individual flows are discontinuous laterally and have irregular thicknesses. Intrusions of diabse and dykes are common in the Ashangie formation. In the north central sector extensive quartz and opal mineralization owing to paleothermal groundwater circulation has been noted. In most parts brecciated materials has been noted. The most extensive breccia has been observed in the Weleh valley south of Sekota (*see* Fig. 2.1 *for location*) area at the foot hill of the Amdework ridge. Acidic rocks are minor in the Ashangie formation (Fig. 2.2).

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[1] For the upper part of the flood basalt volcanism a number of other names have been given in the literature including: Jima volcanics, Mekonnen basalts, Wolega basalts etc.

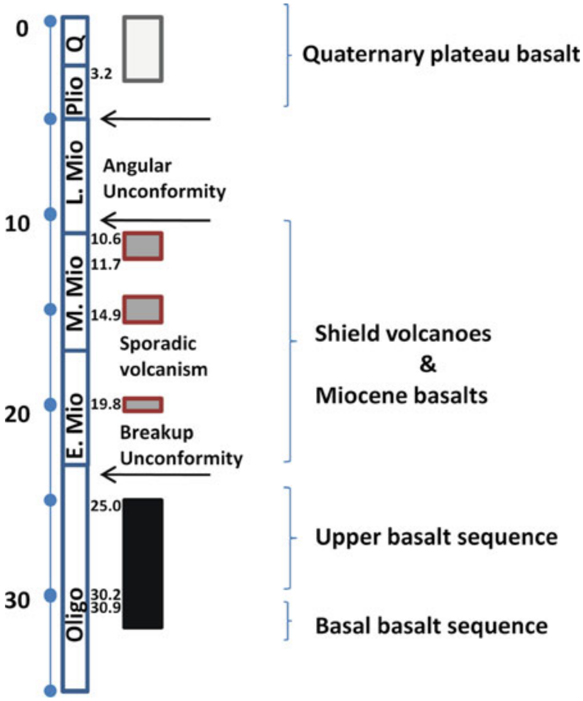

Fig. 2.2 Stratigraphy of the Trap basalts numbers are age in Ma

By contrast, the Aiba formation is a succession of massive cliffs corresponding to thick (10–50 m) basaltic flows (Rochette et al. 1998). The Aiba and Alaji formations are marked by their low degree of weathering, thick layering, and cliff forming topography.

Frequent lacustrine deposits have been marked in the Aiba formation as evidenced by lenses of diatomites and porcelain lithologies particularly surrounding the Sekota area. The Termaber formation is marked by its jointing, thick layering, cliff forming topography with flat tops.

Geomorphology

The volcanic terrain of Ethiopia comes in variety of landforms that is of significant importance to groundwater occurrence and movement. Table 2.1 shows list of landform features that can be observed in the volcanic provinces. The distinct landforms particularly the composite stratigraphy manifested by the flood basalt pile provides a rapid field based evidence to distinguish different stratigraphic/hydrostratigraphic units.

Table 2.1 Landform features associated with the broad Cenozoic basalts

Name	Volcanic landform
Monogenic landforms and fields	Continental flood basalts, Cinder or scoria cones, tuff cones and tuff rings Maars and diatremes, domes, lava flows and fields, ash flows and ignimbrite sheets, plains and plateaus
Polygenic volcanoes and calderas	Stratovolcanoes. Intermediate silicic multivent centers, calderas, volcano tectonic depression
Erosional landforms	Composite stratigraphy, flat topped plateau, volcanic plugs etc
Other landforms	Dykes, plugs, dolerite intrusions, faults, shield

Dykes are prominent landform features that play a role in concentrating groundwater flow and storing groundwaters. A detailed account of the role of Dykes in groundwater dynamics can be found from (Mege and Rango 2010).

Hydrogeology and Groundwater Occurrence

Four broad hydrogeologic units can be recognized for the entire volcanic province of the of Ethiopian Plateau. The recognition of the four hydrostratigraphic units is based on geomorphic manifestations (which in turn are the result of permeability of the lithologies and resistance to weathering), aquifer properties and mode of groundwater occurrence, groundwater flow and discharge. The contrast in geomorphic appearance of the various stratigraphic sequences of the plateau flood basalt is the manifestation of differences in erosion resistance which in turn is partly related to permeability structure of the formations (Fig. 2.1, Table 2.2). The four hydrostratigraphic units are:

1. **Basal sequence**: The gently undulating, rugged thinly bedded, brecciated, deeply weathered and low permeability[2] base of the flood basalts (traditionally called Ashangie basalts)
2. **Upper sequence**: The flat topped, cliff forming, thickly bedded scoriacious, slightly weathered, permeable and relatively higher productivity aquifers with some intercalations of acid rocks, capping the entire Ethiopian volcanic plateau. Traditionally this hydrostratigraphic unit is made of the Aiba, Termaber and Alaji formations. Other names have also been previously used including Jima volcanics, Wellega basalts, Mekonnnen basalts etc.
3. **Shields**: The morphologically prominent, shield volcanics made up of composite stratigraphy of volcanic materials (ashes, rhyolites, trachytes, basalts) occupying broad area. Typical hydrogeologic features are emergence of springs (some prolific) at various locations of shield volcanoes.

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[2] In previous hydrogeological classification of Ethiopia (Chernet 1993) the Ashengie formation is considered as high productivity aquifers although evidence now show that the Ashengie basalts are the least productive aquifers compared to younger flood basalts and rift volcanics.

Table 2.2 Summary of geological and hydrogeologic framework of the volcanic aquifers associated with the board plateau of North western and eastern Ethiopia

Hydrostratigraphic unit	Geologic frameworks	Hydrogeologic framework
Basal Basalt sequence (Ashangie basalts)	Rugged topography, thinly bedded, with cross cutting dykes, deeply weathered, low permeability, dissected and irregular morphology, brecciated, reddish when deeply weathered, closer look at Ashangie formation may reveal presence of three zones-the lower gentle slope forming part, the middle more resistance layer and the upper gentle slope forming unit. The middle part when exposed by erosion may form locally extensive plateau which is normally rare in Ashangie formation (e.g. around Upper Tekeze plains around Lalibela and Belesa plain). More resistant layers are thin, the less resistance layers are mostly scoracious, several thin beds of clay soils are common in the Ashangie basalts, deformed and dipping in northern section up to 40°	Recharge takes place vertically from the overlying upper basalt, springs are rare, discharge takes as diffuse discharge to slopes and leading mostly to land sliding, cliff forming sub layers are more productive, contact between Lower basalt and upper basalt is characterized by discharge of springs, primary porosity and secondary porosity are highly sealed by secondary mineralization (calcite, zeolite, silica). Dykes crosscutting through the lower basalt are sites of groundwater convergence and discharge, Rugged topography does not allow extensive lateral size of the lower basalt, depressions within the rugged terrain are site of scree slope and groundwater discharge. At its base it is affected by mineralization filling the fractures, dykes and gabro-diabase intrusion. In several sectors the Ashangie basalts are brecciated. Field evidence show that the brecciate parts are characterized by lower permeability
Upper basalt sequence (Aiba, Alaji, Termaber)	Dual porosity, permeable, plateau and cliff forming, artesian, confined, Aiba formation contains intercalations of rhyolitic formations, Termaber forms or are associated with shield volcanics, uniform topography and flat topped, shows columnar jointing, mostly massif basalt but columnar jointed layers are common, Laterally the most extensive, layers of acidic rocks rhyolites and tuffs are common, paleosol layers may be visible between the contact of Ashangie and Aiba, flat laying	Recharge vertically through soil zone and fractures, discharge to wetlands, and spring at the margin of cliffs, water table varies between 0 and 250 m, yield generally up to 20 l/s, transmissivity in the order of, groundwater occurs in joints, fractures and scoracious layers, Pumping test analysis and well logs of Termaber formation show that, the aquifer system can be categorized as fractured aquifer where the dominant aquifer types are, confined-double porosity and single plane vertical aquifer. The double porosity aquifers are related to deeply drilled wells reflecting presence of large and narrow fracture systems with high permeability but lower storage capacity. Transmissivity varies between 0.5 and 1,400 m^2/day. The Ashangie formation has transmissivity ranging between 0.5 and 85 m^2/day

(continued)

Table 2.2 (continued)

Hydrostratigraphic unit	Geologic frameworks	Hydrogeologic framework
Shield volcanics	The basal diameters of the shields range from 50 to 100 km, radiate from peak and dip at an angle of 5°, compared to the flood basalts rhyolites and trachytes are more common	Recharge through fractures at highlands, discharge in form of springs. Prolific springs are common at the foot of the shields. The intercalation of volcanic ash along with basaltic flows allow a dual groundwater system whereby the ash act as storage medium and the fractured part act as flow conduits. Shields dominated by acid volcanic rocks show lower groundwater potential (e.g. in the Bale Massif)
Quaternary basalts	Related to volcanic centers, are mostly vesicular and scoracious, limited lateral extent, associated with shield volcanoes, The most extensive is found in the Lake Tana Basin	Highly productive, yield of wells reach 20 l/s, discharge takes place to rivers and fracture springs, Elsewhere in Ethiopia the quaternary volcanics are highly productive with dual porosity nature

4. **Quaternary basalt sequence**: Scoraceous basalt thinly bedded, central volcano related, highly productive quaternary basalt (occurring in head waters of Ghibe, Tepi, Lake Tana, Borena, Bale massif etc).

Vast area of the broad volcanic plateau is mainly covered by the *upper sequence*. It forms gently undulating plain that receives adequate rainfall and has moderate run-off resulting in good direct rainfall infiltration and formation of extensive and moderately productive or locally developed and highly productive *fissured* aquifers.

According to earliest investigation by USBR (1964) the *upper sequence* is fairly tight basaltic cap covered with slowly permeable clays, and scarcity of groundwater outcrop in the deep eroded canyons don not suggest the presence of large quantities of groundwater. The streams reflect only a very slow yield from groundwater, since their flow is almost entirely depleted soon after rains cease. However, the wells that have been dug and other observations indicate that generally an adequate water supply for groundwater sources for domestic use could be obtained in most locations within the basin.

Some of the older, more massive lavas, *the lower sequence*, can be practically impermeable (such as the Ashangie basalts in the Upper Tekeze Valley) as are the dykes, sills and plugs which intrude them, and the thick beds of younger air-fall ashes that may also be extensive in some volcanic areas. However, younger lavas (the Quaternary basalts and the Shield volcanoes) provide some of the most prolific springs (see Table 2.3).

Groundwater occurrence in the broad Ethiopian volcanic plateau is in phreatic condition in the weathered zone above the hard rock and in semi-confined to confided condition in the fissures, fractures, joints, cooling cracks, lava flow junctions and in the inter-trappean beds between successive lava flows, within the hard rock.

Table 2.3 Location and discharge of major springs associated with shied volcanoes

Springs associated with shields	Discharge (l/s)	Volcanic shield	E	N
Lomi Springs	120	Choke		
Jiga	400	Choke	372269	1040679
Sanka	70	Abune Yoseph	546289	1320128
Bure Baguna	30	Choke	288084	1184475
Bahir Timket	1,045	Debretabor	354299	1304392
Tankua Gebriel	28	Debretabor	355074	1309388
Debark	20	Simen	379314	1459196

A feature of volcanic areas is the prevalence of springs which develop at the basal contact of the *shield sequence* and the *upper basalt* cap. Volcanic spring discharge rates are generally <0.1 l/s but may be adequate for a village water supply. Exceptionally high spring discharge from volcanic highlands exceeds 100 l/s. These happens when discharge is taking place from lava tubes or when regional groundwater flow emerge to the surface along the foot hill of vast volcanic shields (Table 2.3). The *quaternary basalt sequence* provides some of the highest yielding shallow aquifers in Lake Tana basin (Fig. 2.1). Springs flowing from volcanic rocks (e.g. Lomi Wuha spring Fig. 2.4) are the source of water supply in Bahrdar-Capital of Amhara regional state (Fig. 2.1 for location of Bahrdar). Most of the springs emerging from tertiary volcanic rocks are topographically controlled and others emerge along structures indicating that the groundwater flow is controlled by both factors.

Infiltration is particularly good in areas where the plateau is covered by thick elluvial sediments. Aquifers outcropping in the plateau area also feed deeper fissured aquifers developed in underlying volcanic and sedimentary rocks.

The groundwater flow direction in the whole basin coincides with the topography following the surface water flow direction. The flow is partly controlled by the structure and partly by the geomorphology of the area. Local groundwater flow directions vary from place to place according to the local topography.

The altitudinal zonality in groundwater discharge distribution is observed in volcanic rock areas. Generally the basal (Ashangie) unit (lower basalt) shows the least groundwater potential owing to closure of the porosities by deep weathering and isolation of the unit from recharge by overlying cap. The upper sequence of the basalt which forms the ‘plateau proper’ has highest groundwater storage and recharge owing to well developed fractures and connection to modern day recharge. The broad shield overlying the plateau is highly rugged hindering any meaningful accumulation of groundwaters, nevertheless ash beds intercalated within the shield volcanics act as storage medium while the fractured rocks as a permeable medium through with groundwater move. These properties when combined locally results in emergence of sustained and high discharge springs (Table 2.3 and Fig. 2.4).

Rainfall is also highest in the areas covered by upper sequence of the basalt (top units of flood basalts) and increases towards top of shield volcanoes. The *basal unit* (Ashangie) is mostly found in the rain shadowed northern Ethiopia (e.g. The

Tekeze valley) leading to lower recharge rates. Thus, the altitudinal climatic zonality determines the potential possibility of replenishment of groundwater resources. The upper basalt units exposed in the south western Ethiopia (Fig. 2.1) are also located under highest rainfall condition leading to well developed regoliths which allow shallow groundwater circulation and storage and enhanced recharge. This general picture of the zonal distribution of groundwater potential in the volcanic plateau may be disrupted in some areas by the azonal manifestation of individual factors of conditions such as alluvial deposits, regional structural disturbances (e.g. In the YTVL, Lake Tana basin, Belesa plain, Lalibela plain, Sekota plains groundwater potential is much higher than the surrounding owing to tectonic structures and presence of alluvial materials).

Analysis of extensive pumping test data shows that the top part of the *upper basalt sequence* (traditionally called the Termaber formation) has been categorized as consolidated fractured aquifer system where the dominant aquifer types are 'confined double porosity' and 'confined single plane vertical fractured' aquifers. The observed double porosity aquifers are mainly related presence of two fracture systems; the first are large and wide fractures of high permeability and low storage capacity and the second is; the matrix blocks of low permeability and high storage capacity. Depth wise and age wise transmissivity variation analysis shows that the younger trap basalts have higher aquifer productivity than the older and both the older and younger volcanic products shows decreasing aquifer productivity trend with increased well depth (Gebresilassie 2010). A closer look at the structure of upper basalt sequence reveals the presence of heterogeneity. The more massive flows are generally impermeable, although the junctions of many flows can be highly productive, as they may contain shrinkage cracks and rubbly zones caused by the covering over of the rough surfaces of the lava by the chilled bottoms of the next flows.

Little work exists on the hydrogeology of the broad volcanic plateau of the South Eastern Ethiopia. However it is observed that the behavior of the aquifers in that sector is similar to those in the North Western Plateau. The Shield volcanics of Bale Massif manifests emergence of several high discharge springs. The Quaternary basalts occupying the vast plain around Robe, Goba and Goro are highly fractured and productive. The acid volcanic products forming the shield are however of low productivity aquifers.

2.2 The Shield Volcanics (Choke, Guguftu, Simen, Guna and Batu etc.)

Geology

The Ethiopian Plateau is made up of several distinct centers of different ages (Figs. 2.3 and 2.4). The Choke Mountain is one such shield. A number of large shield volcanoes developed on the surface of the volcanic plateau cap the flood

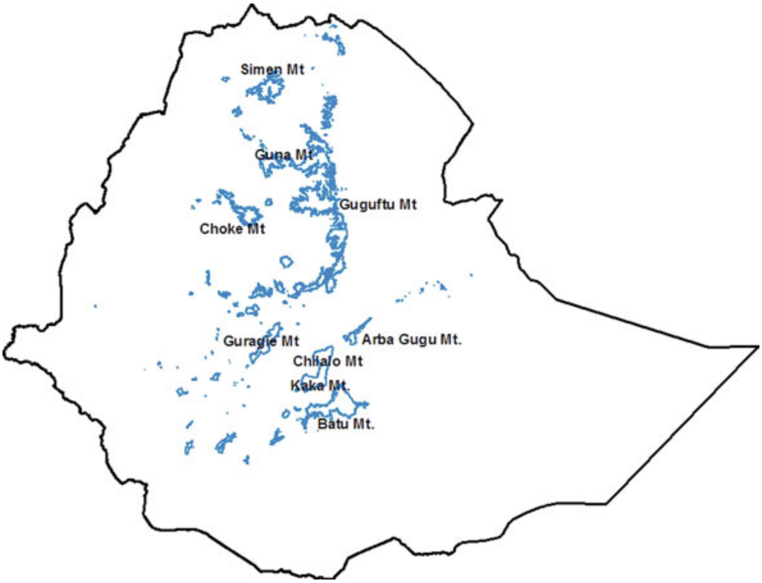

Fig. 2.3 Distribution of shield volcanoes

basalt province of northern Ethiopia. These volcanic shields are a conspicuous feature of the Ethiopian Plateau and distinguish it from other well known, but less preserved, flood basalt provinces such as the Deccan and Karoo (Kieffer et al. 2004). The basal diameters of the shields range from 50 to 100 km and the highest point in Ethiopia, the 4,533 m high peak of Ras Dashen (Simen Shield, Fig. 2.4), is the present summit of the eroded Simen Shield. Although smaller in diameter, the summits of many of the other shield volcanoes also exceed 4,000 m. Mt Choke has a basalt diameter of over 100 km and rises to 4,052 m, some 1,200 m above the surrounding flood volcanics. Guguftu is more highly eroded and its original form is difficult to discern (Kieffer et al. 2004).

Type examples of continental flood basalts, such as those of the Deccan and Karoo provinces, are described as thick, monotonous sequences of thick, continuous, near horizontal flows of tholeiitic basalt. In contrast, the Ethiopian province reveals a series of flood basalts overlain by large and conspicuous shield volcanoes. Owing to the young age of the flood basalt volcanism of the Ethiopian plateau, the upper most section of the flood basalts including the shields are well preserved while in other flood basalt provinces (e.g. Deccan trap), are higly eroded and lateralized.

The Choke shield is one of the three major shield volcanoes enclosed within a large meander of the Blue Nile. It is a broad flat symmetrical shield made up dominantly of lava flows and extends radially out from the central conduit with dips less than 5°. The contacts between different lava flow units leads to enhancing permeability and storage properties of the shields.

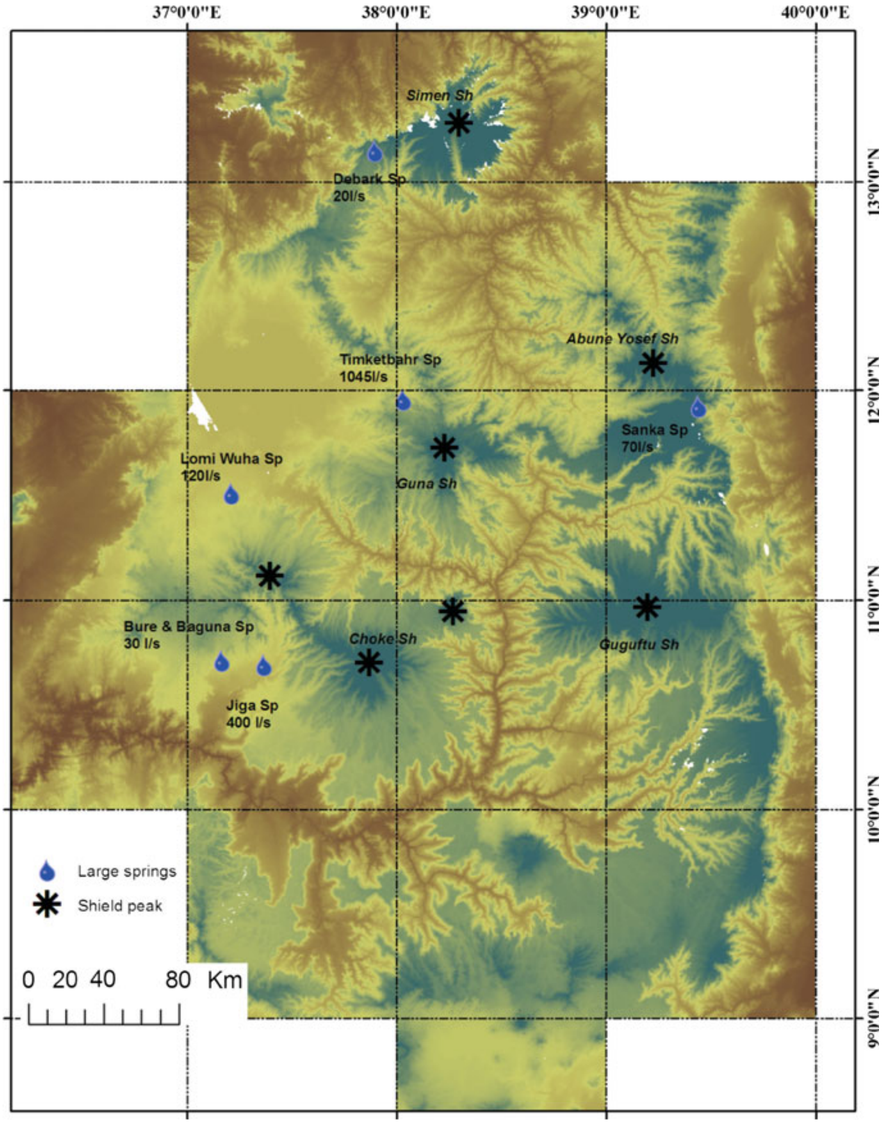

Fig. 2.4 Location of some prolific springs associated with the shield volcanoes

Hydrogeology and Groundwater Occurrence

In the shield volcanoes, the interlayer of acidic lava and ash components with fractured basaltic layers create a unique feature for groundwater storage in movement. In the shields where lavas alternate with air-fall ash, productive two-part aquifer systems has been encountered as revealed by discharge of high yield springs

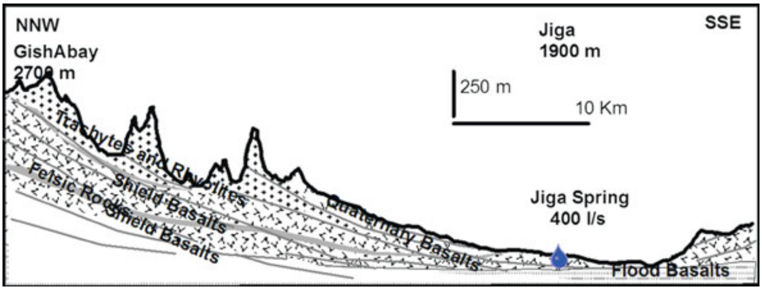

Fig. 2.5 Hydrogeolgic section showing the origin of the Jiga spring (cross section after Kieffer et al. 2004)

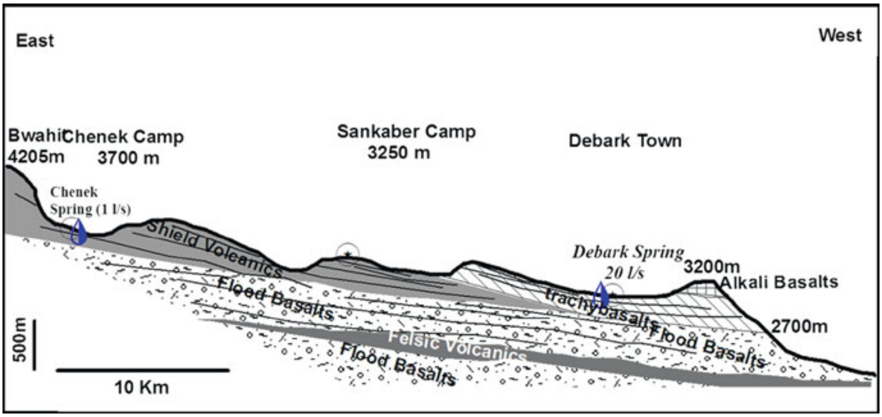

Fig. 2.6 Hydrogeologic cross section showing the origin of the Debark springs (cross section modified from Kieffer et al. 2004)

(Table 2.3). Highly permeable but rubbly or fractured lavas act as excellent conduits but have themselves only limited storage. Leakage from overlying, porous but poorly permeable, volcanic ash compensates for this by acting as aquitards, and is the storage medium for the system. Figures 2.5 and 2.6 show schematic model of emergence of prolific springs associated with shield volcanoes.

Apart from the significance of these prominent geomorphic characteristics of the shield volcanoes in the groundwater recharge and circulation, the structure of the lava flow units make the shield volcanoes a distinct hydrogeologic units as compared to the underlying horizontally lain flood basalt plateau. The lava flows the shield volcanoes are thinner and less continuous than the underlying flood basalts. This leads to the close association of spring emergence at frequencies with the shield volcanoes. One of the largest discharge spring recorded in Ethiopia (Jiga Springs) emerges at the foot hill of the Choke shield volcano (Figs. 2.4 and 2.5). Assasa spring at discharge of 500 l/s emerges at the foot hill of Arsi-Bale mountains (east of Mt Kaka, Fig. 2.4) in South Eastern Ethiopia.

The Jiga spring is located within the area occupied by geographically young lava flows, originating from recent volcanic craters higher on the mountain slope north of the spring eye (Fig. 2.5). This late phase of volcanism spread a veneer of basaltic lava along the previously eroded slopes and valleys forming wide or broad, gently sloping land area. The Jiga springs are believed to emerge to the surface being forced by subsurface water flowing over impervious bedrock (upper basalt sequence) materials. The same emergence model has been proposed for other springs associated with the shield volcanoes (e.g. The Bure Baguna springs emerge to the surface being forced by permeability difference between the upper basalt aquifer and underlying Mesozoic sandstones). A number of other springs are noted along the foothill of such volcanoes. These include the Sanka spring in the foothill of Abune Yoseph shield, the Debark Springs at the foothill of the Simen (Fig. 2.6), the Wanzaye and Gurambaye springs at the foothill of the Guna shield in the Lake Tana basin.

Particular limitation of groundwater use associated with high rising shield volcanoes is that frost and rime are frequent during the dry season excluding the plantation of most tropical crops.

2.3 The Lake Tana Basin

Geology

Unlike most part of the head water system of the Blue Nile basin (dominantly covered by upper basalt sequence) the Lake Tana basin is characterized by complex lithologic and tectonic features. The main geologic features of the basin are subsidence and block fault formation, accumulation of Miocene organic rich sedimentary rocks, Plio Pleistocene basin volcanism and late quaternary volcanic activity and recent lacustrine and alluvial deposition along the margin of the lake. Geothermal system also exists in an otherwise tectonically stable part of Ethiopia.

According to Chorowicz et al. 1998, Lake Tana basin is situated at the junction of three grabens (Fig. 2.7): the Dengel Ber (buried), Gondar (exposed by erosion) and Debre Tabor (reactivated). This structural complex was notably active during the build-up of the mid-Tertiary flood basalt pile, into which the Tana basin is impressed. Fault reactivation occurred in the Late Miocene–Quaternary, accompanied locally by predominantly basaltic volcanism. Fault-slip indicators are consistent with crustal subsidence centered on the present morphologic basin. Concentric and radial dike patterns common features in the Tana region.

The northwestern Plateau of Ethiopia is almost entirely covered with extensive Tertiary continental flood basalts that mask the underlying formations. Mesozoic and Tertiary sediments are exposed in a few locations surrounding the Lake Tana area suggesting that the Tana depression is an extensional basin buried by the 1–2 km thick basalt sequences. However a most recent study by Hautot et al. 2006

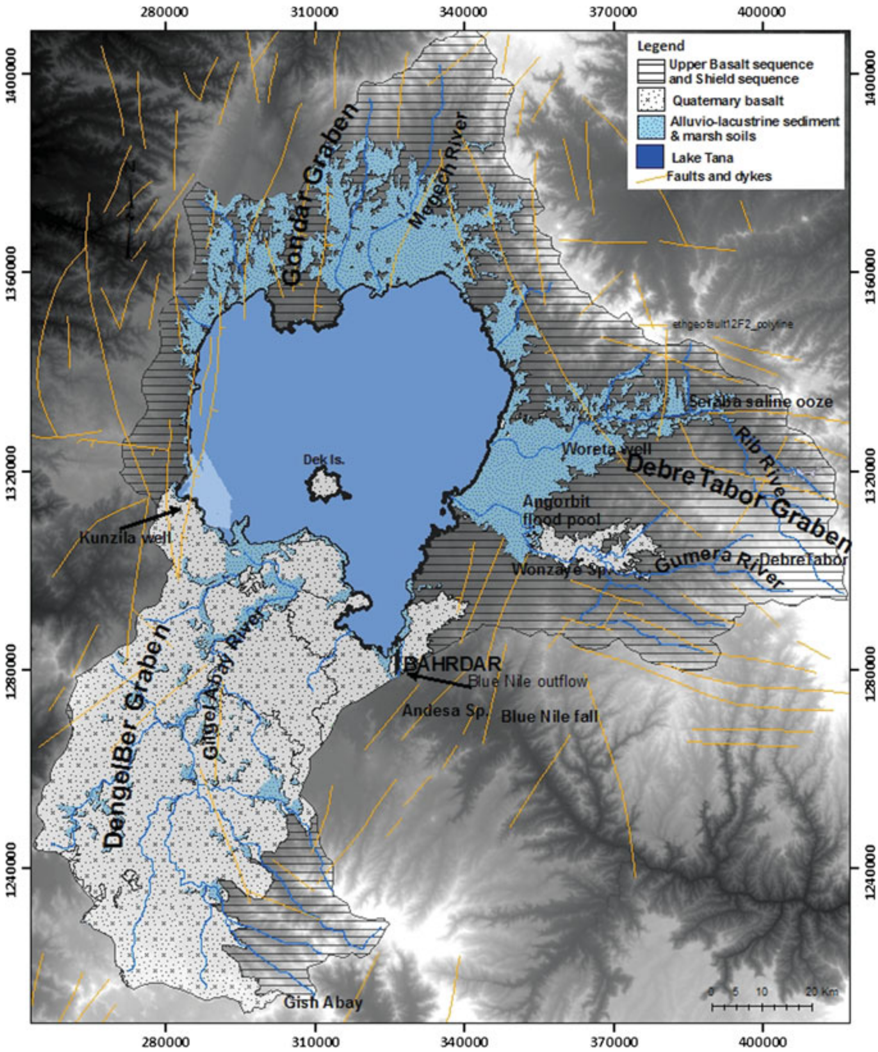

Fig. 2.7 **a** Simplified geologic map of the Lake Tana Basin

using magneto telluric imaging that carried out south and east of Lake Tana revealed that there is a consistent NW–SE trending sedimentary basin beneath the lava flow (Hautot et al. 2006). And the lave flow in the Tana plains is merely 250 m think (Fig. 2.8). The thickness of the sediments has been estimated at 1.5–2 km, which is comparable to the Blue Nile stratigraphic section, south of the area. The thickness of sediments overlying the Precambrian basement and underlain 0–250 m thick continental flood basalts averages 1.5–2 km, which is comparable to the Blue Nile stratigraphic section, south of the area. A km thickening of sediments (middle of Fig. 2.8) over 30–40 km wide section suggests

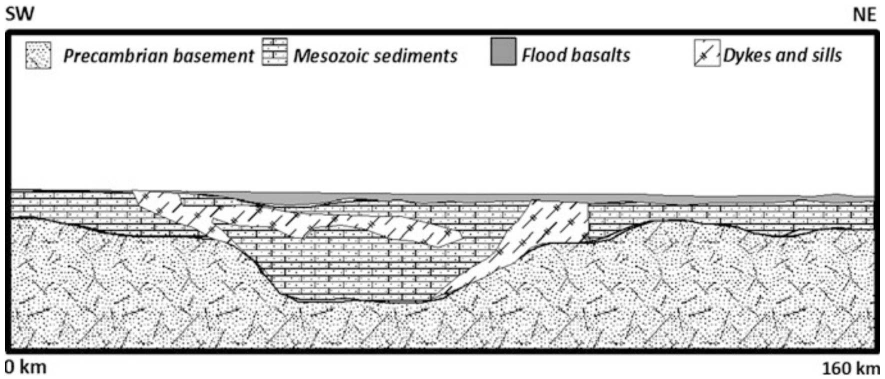

Fig. 2.8 Schematic geological cross-section interpreted from the resistivity model (adopted from Houtot et al. 2006)

that the form of the basin is a half graben (Hautot et al. 2006). The presence of Mesozoic sediments beneath the volcanic cover has been previously postulated from groundwater geochemistry and isotopic investigation in the Lake Tana basin (Kebede et al. 2005). Particularly the carbon isotope data of a spring (Andesa near Tis Abay fall) reveal signature of marine carbonate testifying the presence of these sediments underneath the volcanic cover.

Hydrogeology and Groundwater Occurrence

There are at least four major categories of aquifers in the Lake Tana basin these are the Tertiary volcanics (upper basalt sequence and shield volcanics), Quaternary volcanics, Miocene sediments, and the alluvio lacustrine sediments. Groundwater flow is mainly controlled by regional tectonics associated with the formation of the Lake Tana graben itself.

- The alluvial aquifer is recharged from lateral groundwater inflows from the volcanic aquifers from the upper catchments. The aquifer is discharges to Lake Tana during low Lake level and to evapotranspiration from the wetlands.
- The volcanic aquifer of quaternary vesicular basalt is recharged from rainfall and most of its recharge water later discharges to springs, wetlands, streams and directly to the southern sector of Lake Tana.
- The Tertiary scoraceous basalt is recharged from rainfall within the Lake sub-basin principally discharges to springs and streams.

Groundwater occurrence and yield: According to the Hydrogeological study of Abay River Basin Integrated Development Master Plan Project (BCEOM 1999), the Tertiary basalts and recent lava flows which are widely distributed in the Tana sub basin are grouped as extensive aquifer with fracture permeability.

The maximum average depth drilled in this formation is about 120 m. The water point inventory data (BCEOM 1999) shows that the average depth of boreholes drilled in this rock unit is in the order of 70–80 m. Yield from the Tertiary basalts is estimated at 13 l/s.

The Miocene Lacustrine deposit extensively lies in the northern part of Lake Tana and occupies the localities known as Chilga-Gondar graben. These sediments are composed of clay, silty claystone, silty sandstones volcanic ashes, and lignite beds. Bore hole drilling result shows that the thickness of Lacustrine deposit reaches 90 m and it is underlain by volcanic rocks. Wells drilled in these sediments turns out to be dry.

The dominantly scoraceous and fractured quaternary basalts underlying most part of the Gilgel Abay sub catchment (Fig. 2.7) show the highest groundwater potential as measured by its high infiltration capacity (20 %) and hydraulic properties. Many high discharging springs emerged from this rock unit act as base flow for Gilgel Abay River, which drains to Lake Tana. Areke and Lomi Wuha springs are high yielding springs, which currently serve as water supply for Bahrdar town, have a discharge rate of 120 and 50 l/s respectively.

Alluvial sediments are commonly distributed along the mouth of the Megech, Rib and Gilgel Abay Rivers. Alluvial sediments have limited distribution within Lake Tana sub-basin dominantly at the eastern and northern side of the Lake. The thickness reaches more than 50 m. There is a progressive fining of the sediments as one go from the foot of the mountains towards the lake shore. Bore hole drilled (depth 53 m) for Woreta town (Fig. 2.7) showed significant discharge with relatively low drawdown ($Q = 7$ l/s, drawdown $= 4$ m).

According to SMEC (2007), the aquifer transmissivity and yields of the sediments are relatively low and the aquifer properties are highly variable laterally. It is considered that even with a combination of wells, the yields required to meet the demands of a large scale irrigation development are unlikely to be achieved from the aquifers in most areas. The general conclusion is that there would be inadequate resources available for large scale, sustainable groundwater based irrigation development. However there shallow groundwater can be economically extracted and used for household and small scale commercial farming activities.

Geothermal waters are also noted in the Lake Tana graben. The most prominent ones are the Wanzaye thermal waters and the Andesa springs on the Bahrdar to Tis Isat Fall. The thermal waters are associated with heating related dykes penetrating through the basin aquifers (see Figs. 2.7 and 2.8).

Aquifer property: The upper basalt sequence and the shield volcanic aquifer system is scoraceous in nature in most parts. Transmissivity values from pumping test results are with the interval of 6–40 m^2/day. SMEC (2007) report shows transmissivity of the Tertiary basalts varies from 0.1 to 32 m^2/day. The productivity of this aquifer is highly controlled with intensity of the fracture and the presence of the major structure affecting the area. It is aquifer with a relatively moderate productivity. The Yields of Tertiary volcanic aquifers are in the order of 0.7–17 l/sec. Specific capacity ranges are generally low, with average values of 0.25 and 0.27 l/sec/m (SMEC 2007).

Quaternary basalts are the most productive aquifers system which is characterized with plenty of vesicles and highly weathering. The relative occurrence of high discharge springs and wells implies its potential for bearing of high ground water. The major springs of Areke and Lomi emerge from this aquifer unit with 140 and 50 l/s respectively.

The productivity of alluvial aquifer is associated with the pores of unconsolidated gravels and sand. The available data on this aquifer indicate high productivity with boreholes yielding more than 6 l/s with from shallow depth.

Groundwater flow: Groundwater level data (SMEC 2007) show convergence of groundwater into the lake from all directions. Groundwater surface elevation contour shows that groundwater elevation generally follows the ground surface contours with the groundwater flow directions largely consistent with the surface water catchment boundaries (Fig. 2.9). High groundwater heads occur in the south and east around the two shield volcanoes of Mt Choke and Mt Guna with the hydraulic gradient radiating from these points. Elsewhere around the eastern and western basin margins, there is a steep hydraulic gradient towards Lake Tana flattening on the plains adjacent to the lake. The hydraulic gradient in the Ribb and Gumera catchements is relatively steep at around 0.02 although it appears to be a relatively even grade in the direction of the Lake. In low lying areas, particularly the plain east of Lake Tana there is a sharp reduction in head and lower hydraulic gradient (approximately 0.01) beneath the plain. A similar situation occurs in the Megech valley where the hydraulic gradient flattens out in the low laying areas from 0.02 around Gondar to 0.006 beneath the plains. In the Gilgel Abbay, the groundwater gradient reduces from around 0.02 in the south to around 0.005 in lower laying areas approaching Lake Tana. East of the Gilgel Abay, as the topography drops sharply into the Abay River, the hydraulic gradient steepens. As noted previously, it is expected that groundwater is close to the ground surface in the downstream parts of Gilgel Abbay, with discharges to high volume springs and also to low lying swampy areas. The groundwater elevation flattens in the lowland areas around the Lake and it is considered that groundwater level in these areas is likely to be controlled by the discharge to streams. There is a potential for water logging in low lying areas away from the drainage lines as the piezometric level approaches the ground surface. It is expected that this level will be controlled by evapo-transpiration. Areas prone to flooding largely coincide with areas in which the groundwater gradient decreases.

Groundwater lake water interaction shows that groundwater contributes less than 7 percent of lake water budget (Kebede et al. 2006). The low contribution of groundwater to the lake may be due to the thick exceeding 80 m stiff clay underlying the Lake Tana bed. Isotopic evidence (Kebede et al. 2006; 2011) precludes the presence of appreciable amount of groundwater leakage from the Lake to adjacent aquifers.

Base flow as index of recharge: Stream hydrograph analysis results in the upper Blue Nile basin shows that about 15 % of annual flow is derived from shallow groundwater. However, for some catchment it reaches 44 %. Kebede et al. (2011) and references therein) indicated that about 45 % of the total surface water inflow

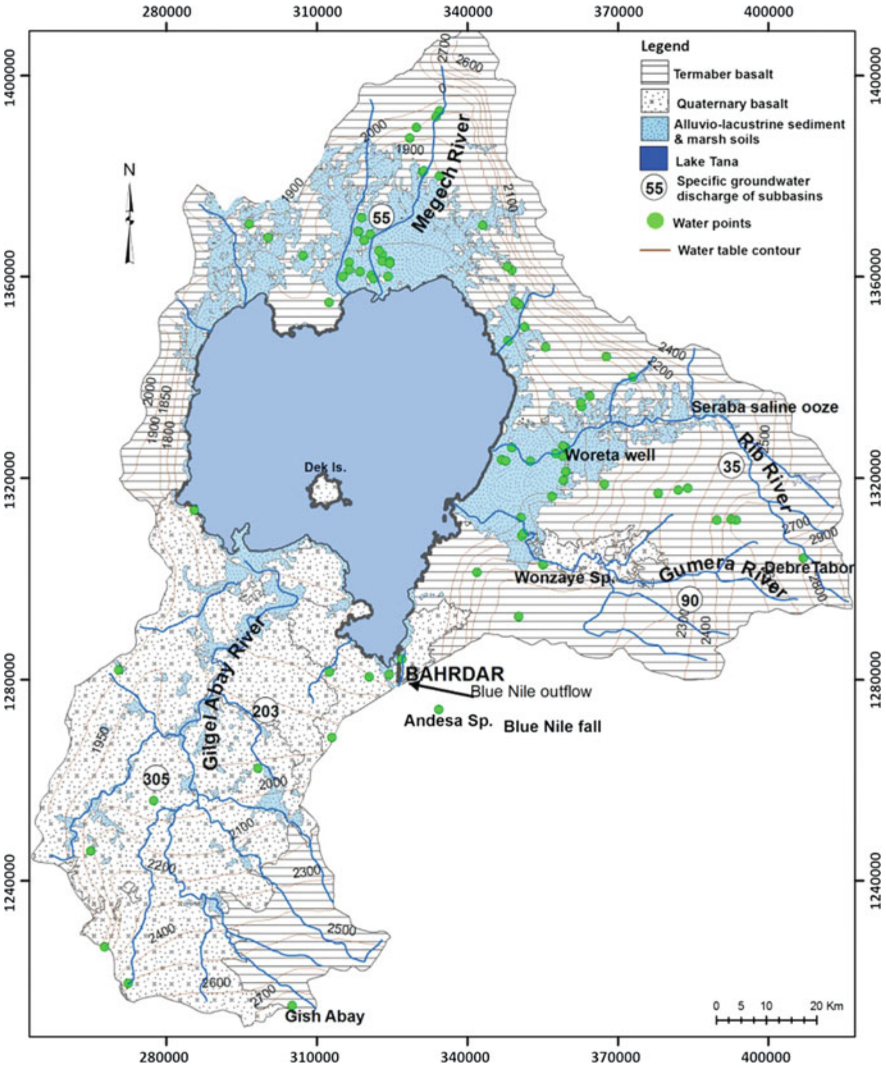

Fig. 2.9 Some hydrogeological features of the Lake Tana basin (water table map in meters above sea level) numbers inside circles are specific discharge of the sub basins

to Lake Tana (about 500 mm/year) is derived from ungauged basins. The annual recharge into the basin, which is obtained from integrated methods (chloride mass balance, base model, base flow separation, etc.) varies between 70 and 120 mm/year. Hence, the annually renewable groundwater recharge is estimated to vary between 1.2 and 2 billion m^3. Table 2.4 and Fig. 2.9 shows the highest groundwater contribution to surface waters (or indirectly high recharge) takes place in the Gilgel Abay sub catchment while the lowest is in Rib. The Gilgel Abay drains the high rainfall highlands in the south and is underlain by porous quaternary basalts—

Table 2.4 Summary of base flow index for the sub catchments of the Lake Tana basin (BCEOM 1999)

Sub basin	Station	Latitude		Longitude		Catchment Area (Km^2)	Groundwater specific discharge (mm/year)
Gilgel Abay	Bahir Dar	11	22	37	02	1,664	305
Koga	Merawi	11	22	37	03	244	203
Rib	Addis Zemen	12	00	37	43	1,592	35
Gumara	Bahir Dar	11	50	37	38	1,394	90
Megech	Azezo	12	29	37	27	462	55

reasons for high groundwater contribution to surface waters while the Eastern sub catchment, Rib drains the Debretabor shield which has lower hydraulic conductivity.

Groundwater Surface Water Interaction and Wetlands

There are a number of wetlands and groundwater dependent ecosystem in the Lake Tana catchment. Most of these wetlands remain green even in the dry seasons. The wetlands are depressions formed by volcanic topography or by tectonic depressions. The plains surrounding the lake (Fig. 2.9) form extensive wetlands during the rainy season. As a result of the high heterogeneity in habitats, the lake and surrounding riparian areas support high biodiversity and are listed in the top 250 lake regions of global importance for biodiversity (SMEC 2007). In some places, close to the lake shore there is extensive growth of papyrus (*Cyprus papyrus*). The littoral zone (depth 0–4 m) of the lake, which comprises water logged swamps, the shallow lake margins and the mouths of rivers feeding the lake, is relatively small, covering about 10 % of the total surface area.

Lake Groundwater Interaction

An earlier investigation of Lake and ground water interaction is predicted by isotope geochemical studies of groundwater in the vicinity of the Lake which show little evidence of mixing lake water with the adjacent aquifers (Kebede et al. 2005 and Kebede et al. 2011). The same study predicted less than 7 % Lake Inflow is from ground water. The study also shows possible but unverified inflow of groundwater inflow to the Lake in the southern part from the quaternary sediments into the rocky lake bottom around the town of Bahrdar. The linkage of groundwater outflow or inflow from the Lake is probably limited by the thick and stiff clay sediments occupying the Lake bed. Drilling the middle of the Lake shows that the thickness of sediments in the Lake Tana floor exceeds 80 m and is composed of stiff clay and silt.

The analysis of the SMEC (2007) with assumption of an average lake level of 1,785 m and even with an underlying head of say 1,800 m, the vertical leakage through the 80 m thick clay, with a vertical hydraulic conductivity of 0.0001 m/day would suggest a leakage rate of 7 mm/year (58,397 m^3/day).The assumption take a head in the aquifer beneath the lake with a relative high magnitude, but vertical leakage to and from the lake into the underlying aquifer is considered negligible. The prevailing low hydraulic gradient in areas surrounding the Lake does not likely lead to significant lateral leakage into or out of the lake. Applying the regional gradients from the groundwater elevation contour ranging from 0.02 to 0.005 towards the lake, assuming discharge into the lake from a 50 m thick aquifer with hydraulic conductivity of 1 m/day, the discharge into the lake will be less than 1 mm/year (8,342 m^3/day) SMEC (2007). In summary the inflow to the lake from vertical leakage through the clay materials and lateral inflow from the aquifers is estimated at 66,739 m^3/day, which is inconsiderable compared with direct rainfall on the Lake and surface water flow to the Lake.

2.4 The Upper Tekeze River Basin and Associated Massifs

Geology

The Upper Tekeze area is marked by prominent uplifting, massif volcanoes, deep dissection and erosional fragmentation. The basin has undergone several changes in base level of erosion and stream geometry. The boundaries of the basin are defined by prominent regional structures (the rift margin from east, the Lake Tana graben from south and west, and the basement foliation from north) and prominent shield volcanoes (e.g. Simen, Guna, Debre Trbor, Abune Yosef etc.).

The basin is underlain be the basement complex at the base (composed of low grade meta-sediments and metavolcanics), the Mesozoic sediments mainly composed of sand stones and marine sequences, and extensive think Cenozoic volcanic cover (Fig. 2.10). Quaternary Climate change has also left its imprints as lacustrine sediments and glacial moraines. The marine sequences are localized to the north eastern sector of the upper Tekeze basin. The extension under the volcanic cover of the Mesozoic sediments, in the south though indirectly indicated, is yet to be proved-thought the regional E-W geologic cross section by USBR (1964) shows the presence of the Mesozoic sedimentary rocks under the volcanic cover (Fig. 1.3). However a deep well drilled recently to a depth of 500 m around Guhala town (Fig. 2.10) does not encounter the Mesozoic sediments.

Most of the outcrop in the Upper Tekeze basin is underlain by volcanic pile accounting for 80 % of the landscape. The volcanic eruptions come in four major formations, all diachronous: from bottom to top, Ashangie (Eocene), Aiba

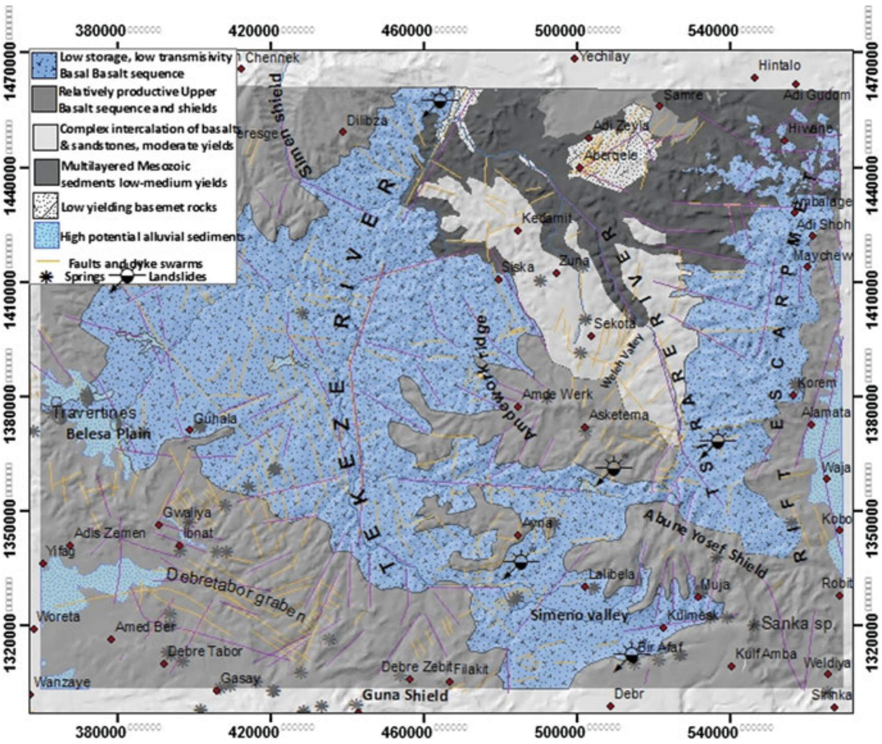

Fig. 2.10 Geologic map and some water resources feature of the of the upper Tekeze upper river basin

(32-25 Ma), Alaji (32-15 Ma) and Termaber (30-13 Ma) (Mohr 1983; Mohr and Zanettin 1988). According to the new stratigraphic classification the four units are classified in two folds as the basal unit (Ashangie) and upper unit (containing the remaining three formations). The whole volcanic sequence has been emplaced with no apparent development of paleosol and erosional surfaces (Rochette et al. 1998).[3]

The basal sequence (*Ashangie*) is basaltic formation marked by its deep weathering, thin layering (<10 m), rugged and gentler topography and cross cutting sets of dykes. There are minor acid products (such as volcanic ash, rhyolites, and ignimbrites) in the Ashangie formation. Individual flows are discontinuous laterally and have irregular thicknesses. Intrusions of diabase and dykes are common in the Ashangie formation. In the north central sector extensive quartz and opal mineralization owing to paleo thermal groundwater circulation has been noted. In most parts brecciated materials has been noted in the Ashangie

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[3] It should be noted that in the new classification and modified hydrogeological map of Ethiopia the trap basalts are classified as Lower basalt (traditionally called Ashengie) and the Upper basalt (Aiba, Alaji, Termaber).

formation. The most extensive breccia has been observed in the Weleh valley south of Sekota town at the foot hill of the Amdework ridge. Evolved acidic product is minor in the Ashangie formation.

By contrast, the Aiba formation is a succession of massive cliffs corresponding to thick (10–50 m) basaltic flows (Rochette et al. 1998). The *Aiba and Alaji* formations are marked by their relative freshness, thick layering, and cliff forming topography. Frequent lacustrine deposits have been marked in the Aiba formation as evidenced by lenses of diatomites and porcelain lithologies particularly surrounding the Sekota complex. The *Termaber* formation is marked by its jointing, thick layering, cliff forming topography with flat tops.

Among the Mesozoic sediments the Adigrat Sandstones are the most predominant formations in the Upper Tekeze. Exposure of the Marine Antalo sequence is limited to the North Eastern part. In a few pocket areas in the Weleh Valley metamorphosed limestone of a few meters thick has also been noted. The contact between the Adigrat sandstone and the underlying basement is characterised by white reddish coarse breccia with abundant clastic materials coming from the weathering of the schistose basement and characterized by a dimension of tens of centimetres. In places between the Adigrat sandstone and the basement the Palaeozoic sandstones (Enticho sandstones) have also been observed. When cut by rivers the Adigrat sandstone form vertical cliffs often of several hundred meters thick.

The Adigrat Sandstones represent the basal horizon of the Mesozoic sedimentary sequence of the Central and Northern Ethiopian Plateau. The Adigrat sandstones are generally reddish in colour and very compact near its top part. Generally the sandstone is characterized by a prevailing quartz component, often also silicate with abundant feldspars content, but not as much clay. In some localities highly weathered phyroclastic layers constituted by white grey ash fall tuffs, settled within an environment characterized by the occurrence of a free water surface have been noted.

The Adigrat Sandstones are mainly constituted by clasts of quartz, feldspars, micas, tourmaline, etc., typical components of the granite and diorite rocks and crystalline schists, but also by fragments of the same rocks. The most abundant mineral occurring in these rocks is undoubtedly the quartz, with associated micas and heavy minerals, while the feldspars are quite subordinated. The quartz grains are mainly sharp cornered, but rarely are they also round shaped.

The *Undifferentiated volcanic and associated dolerites*. These are formations occupy the areas between Sekota and Tsirare River on the road between Sekota and Samre. The dolerites often come as intrusions and in places they form isolated circular domes and cones. The Dolerite volcanics are highly jointed and the columnar joints are narrowly spaced. This makes them highly fragmented-fragments of fresh and hard dolerites. In this formation there are several lacustrine diatomites and porcelinaites of different sizes.

Tectonic Structures

Regardless of its location in the center of the Ethiopian plateau, which is otherwise known as tectonically stable, the upper Tekeze is cut by prominent regional faults. For example the NW–SE running Tsirare River follow a regional fault that cut the Abune Yoseph Mountain and intersect with the Afar rift margin around Woldia area. Dyking and dyke swarms are also common features. Complex tectonic and stratigraphic features are also noted in the north central part of the area surrounding the Sekota district. The complexity in stratigraphy is the direct impression of the tectonics processes.

The boundaries of the Upper Tekeze drainage basin are formed by prominent regional tectonic. From the East Tekeze drainage is bounded by rift margin faults; to the west by the Chilga-Gondar sub rift of the Lake Tana structure; to the south by the Debretabor sub-graben of the Lake Tana rift. In its central part it is cut by a prominent NNW-SSE running Tsirare fault system. Within its bounds the Upper Tekeze is characterized by presence several dyke swarms, fractures, faults and regional slumps which are the manifestations of the basin boundary tectonics. The Tekeze River also runs N–S following a regional tectonic feature originating as far north from the Mekelle Outlier. The major curved shape valley dissecting the Simen massif also taught to be the result of regional slump.

Several prominent faults belonging to the Lake Tana graben (the northern extension of the Chilga-Gondar sub rift), the rift domain and the E–W structures dissect area. The intensive erosion however has masked most of this geologic structure therefore evidence for faulting mostly comes from interruption in lateral discontinuity of lithologies. The NNW–SSE running major tectonic feature (Tsirare fault) dissect the upper Tekeze into two and pass just east of the Abune Yoseph massive pile. The spring with the highest discharge (Sanka spring—see Fig. 2.4) recorded in the area emerge on the southern extension of the Tsirare fault. In the Eastern part of the Upper Tekeze river, the drainage which should have been oriented E-W because of the flexuring of the rift margin is now draining NW owing to the Tsirare fault system. Dolerites cones and domes also crop out at the NW end of the Tsirare fault. A number of NW–SE running faults are also observed in the Sekota area. The faults are responsible for block rotation, lateral disruption of lithologies, and emergence of springs in the area. The tectonic features are described as follows:

The North Lake Tana graben bounding from west: North South running fault system which makes part of the Lake Tana basin, responsible for the conveyance of groundwater from the RasDashen massive towards the Debark Debat plain. These are the north ward extension of the Chilga and north Tana sub-grabens. Faults belonging to this regional tectonics mark the western boundary of the Tekeze drainage.

The Debre Tabor graben bounding from south west: East–west running parallel faults affecting the drainage divides between the Lake Tana and the upper Tekeze. The DebreTabor sub graben runs E–W for nearly a 100 km. Several faults belonging to this regional tectonics are noted in the south western part of the Tekeze. The prominent fault bounding the Debretabor graben from north is also responsible for the formation of the half graben around Ibnat town. The Ibnat half graben is locally filled by 5–10 m thick alluvial sediments. The mountains bounding the Belesa plain from south form the northern margin of DebreTabor Subgraben.

The Tsirare fault dissecting the North Eastern part: Deep regional fault running NNW-SSE and responsible for the emergence of the Sanka springs (50–60 l/s) near Woldia.

The Sekota complex structures: These are *m*ainly NNW-SSE running fault systems pre-dating Cenozoic volcanic activity or contemporaneous with them. Responsible of permeability contrast between lithologies, juxtaposition of rocks of contrasting ages, rotated fault blocks. The Sekota complex is probably an old failed rift of 'basin and range' characteristics the original topography of which is masked by young volcanics and recent tectonism. The prominent fault among the Sekota complex structures is the regional fault that run SSE ward from around Sekota and run towards Hamusit town. IN this region complex stratigraphy including juxtaposition of metamorphosed limestones and sandstones with the Cenozoic volcanics is probably related to these structures. The orientation of the May Lomi River north of Sekota also follows this regional structure. This *sub*-region is characterized by complex stratigraphy variously tilted sedimentary formations overlying and underlying igneous rock units. Horizontal stratigraphic lithologic interfaces, tilted beds and tectonic contacts which are also affected by faulting and dyking, doleritic intrusions, engulfing and pushing up older sequences are very distinctive.

Dyke Swarms and other lineaments: Commonly observed in southern part of the upper Tekeze area particularly in the Simeno valley near Lalibela and in the foot hill of the DebreTabor and Guna shields. The dyke swarms are the manifestations of the boundary faults and are related to tectonic events.

The Basement structures: These are mainly a N–S running regional faults and associated E–W striations developed on the Basement outcrops in the northern sector of the region. Folds, foliations, faulting have been noted in the basement complex; all associated with continental scale deformation.

In most part of the Upper Tekeze area where the Adigrat sandstone is exposed, it is overlain by the Cenozoic volcanics or by upper sandstone (sometimes also called Tekeze sandstones). The absence of the Antalo sequence is not surely due to full erosion of the calcareous and clayey layers, but more properly to their lack of deposition by means of the notable palaeogeographic and environmental continuity which has characterized the whole area not allowing any other sedimentation if not that of the sandy materials.

Drainage and Hydrography

The upper Tekeze basin is generally water stressed dissected highland. The present day water stress in the Tekeze basin is the outcome of general drying and erosion fragmentation of the plateau and lack of suitable drainage and geomorphologic

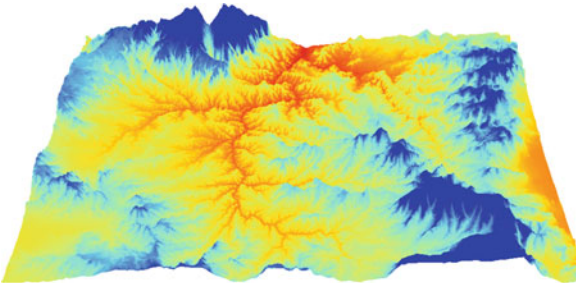

Fig. 2.11 Geomorphic features of the Upper Tekeze river basin. Note that the highland in the Southeastern part of the area is the most water stressed owing to its geomorphology and rain shadow effects. The twin summits in the north western sector is the Simen (Ras Dashen) massif

features for storage of surface and groundwaters (Fig. 2.11). Regardless of this generally a number of potential areas exist to store and transmit groundwaters particularly at deeper levels. The basin is occupied by several denuded shield volcanoes (Rasdashen, Abune Yoseph, Guna, and DebreTabor). These volcanoes play prominent role in controlling the drainage pattern. The Simen, DebreTabor and Guna diverts the surface water to converge in the Main Tekeze river which runs S to N. Separate from this is the Tsirare water shed which runs NW starting from the Abune Yoseph mountain. The pattern of the Tsirare River itself is controlled by a NW–SE running regional fault. The southern western margin of the Upper Tekeze is bounded by the Northern boundary of the DebreTabor Graben which runs towards Lake Tana. North of DebreTabor for instance E–W striking faults with a morphologic expression indicating southerly down throw can be traced further east, where they turn to ESE–WNW before termination against the Guna Shield volcano. The faulting then reappears on the southeastern flanks of the shield.

Mean long term denudation rate for the Tekeze basin since the emplacement of the volcanics and onset of erosion is estimated at 0.03 mm/year (Pik et al. 2003). More than 85 % of the project area has slope greater than 60° indicating the major part of the area is dissected, cliffs with minor small often less than 1 ha inter-mountain valleys available for agriculture. Out of the less than 15 % area with slope less than 60; the Belesa plain (Fig. 2.10) and plains in the Lalibela (e.g. Simeno valley) area account for the major part. The rest are small patches of land such as landslide or talus slopes, riverine terraces, and tops of dissected plateaus, tectonic depressions or intermountain valleys.

Tectonic features also affect the drainage pattern in the region. The prominent example is the trend in Tsirare River which follows NNW–SSE structure, probably reactivated Mesozoic rift. Likewise, uplifting owing to fault plane movement affecting river channel depth observed on the Siska drainage system whereby deep erosional river morphology is observed upstream of a fault scarp while the downthrown part shows slightly dissected river channel.

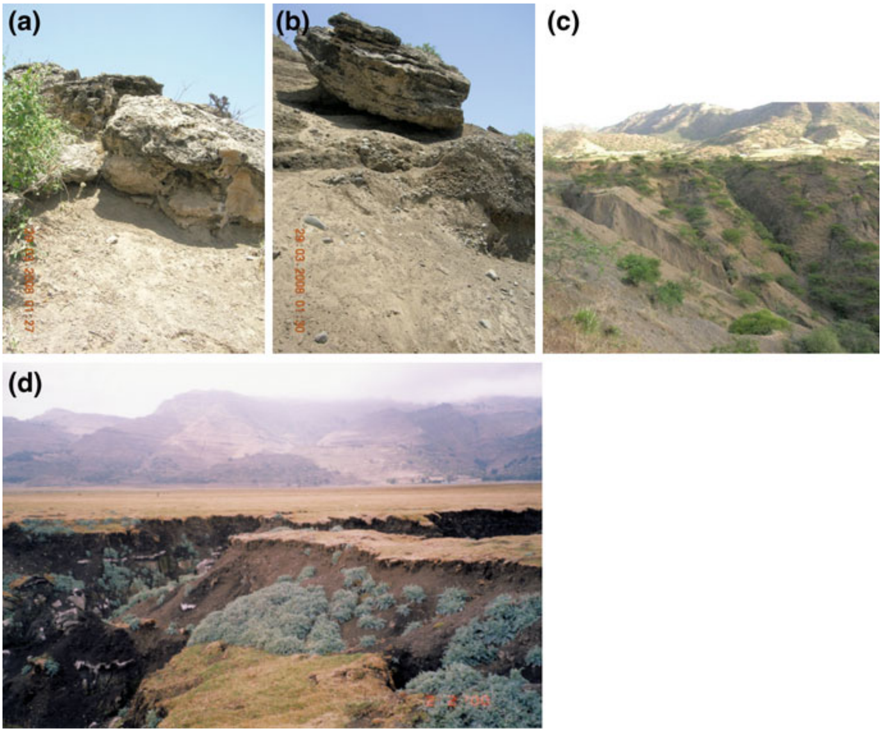

Fig. 2.12 Plate showing alluvio-lacustrine sediment and associated spring travertines in the Belesa Plain (**a** and **b**) and thick alluvio lacustrine sediments in the Taba village East Central Tekeze (**c**) and gully erosion in the Ashangie plain probably indicating lowering of water table probably staring 17th century owing to the lake Holocene drying

Geomorphology and Environmental Change

The regional geomorphology is dominated by the massif volcanoes which are also responsible for the drainage patterns (Fig. 2.11). The Simen Massif, the Abune Yosef Massif and the Guna Shield are prominent Volcanoes. In addition to their role as major controls on drainage control the volcanoes also are responsible for rainfall redistribution in the Upper Tekeze area.

Regions adjacent to the Upper Tekeze undergo remarkable Holocene climate changes as documented in valley fill sediments in the Tigray region (Nayssen et al. 2003; Mechado et al. 1998) lake level data in from sediment proxies in the rift (Gasse 1977) and in sediment beneath the lake Tana sediments (Lamb et al. 2007) Although evidence lack from dated sedimentary records in the Tekeze there are a number of imprints and indicators of climate and base level changes in the Upper Tekeze (Fig. 2.12). Notable among these are the 30 m thick alluvial-lacustrine sequence in the South Western corner of the Tekeze basin (namely the Belesa plain); the pockets of spring travertine deposits dotting the region; and the alluvial sediments in several sectors (e.g. around Taba village in the central highland). That most of these paleosediments lack major incisions could be indicative of their formation in the recent epoch probably belonging to the climate changes in the Holocene. Dates on the travertine occurrences in the Upper Tekeze basin is lacking but their geomorphic characteristics and stratigarphic position suggest similar genesis as that of other travertine sequences elsewhere in northern Ethiopia. For the past 1,000 year, and in particular since the early 17th century, stratigraphic records together with historic chronicles suggest increasing aridity. Pediments dissected by gullies common in many areas in upper Tekeze (Fig. 2.12d) are indicative of these general drying.

Hydrogeology and Groundwater Occurrence

The major reason for lower groundwater storage in the Upper Tekeze is the erosional fragmentation of the plateau and fragmentation of the aquifers into small sizes with no meaningful storage volume. Suitable locations where extensive aquifers could exist include the Lalibela area, the Belesa and Sekota areas (Fig. 2.12).

The volcanic rocks particularly the Upper basalt sequence are important aquifers in the Upper Tekeze area. These rocks, which, form the western and eastern highlands, bear considerable amount of secondary porosities resulting from the effects of extensive weathering, jointing, faulting and fracturing. Emergence of springs of significant discharge from these basalt sequences suggests the productivity of the Aquifer systems.

Field evidences on recharge and discharge zonation, description of topographic and geological and structural features, conventional evidences such as springs, tree lines, wet grounds etc. allow the identification of the groundwater occurrence zones in the Upper Tekeze catchment as depicted in Table 2.5 and hydrogeologic description of stratigraphic units in the basin is given in Table 2.6.

Groundwater Recharge and Discharge

Springs and streams are the major discharge path ways. In limited localities discharge to talus slope and diffuse discharge on slopes have been noted. Spring discharge data shows that most of the springs from the volcanic highlands range in their discharge between 0 and 0.5 l/s. The prominent springs with large discharge are associated with major volcanic massifs or with regional tectonic features. The spring with largest discharge (Sanka discharge (>70 l/s) on the way from Woldia to Lalibela, emerging at the escarpment of the Wolo highland) for examples emerge as the result of the intersection between the Tsirare regional fault cutting the study area and the N–S oriented rift margin faults (Figs. 2.12 and 2.4). Most of

Table 2.5 Groundwater occurence in the Upper Tekeze basin

Groundwater occurrences	Characteristics of the occurrence
Mesozoic sediments underneath the volcanic pile when exhumed by erosion or when the volcanics are thinned	May form regional aquifers of several thousand kilometer square, mostly regional flows of good water quality, groundwater occur mainly in fractures as primary porosity is low
Mountain bounded alluvial valleys	Shallow or deep groundwaters in extensive alluvial plains such as Belesa, Lalibela etc. Groundwater mainly occur in alluvial sediments and volcanic piles underneath the alluvium
Tectonically formed depression	Several such depression of a few tens of km 2 are observed around the villages of Weleh, Taymen and Ibnat; because of the depressions formed by faulting and graben structures groundwater converges to these low points and may result in shallow groundwater occurrence
Pockets of alluvial valleys	Several such valley but of a few hundred meters sq in extent occur in depressions formed by erosion of the volcanic pile, this may form local shallow groundwaters
Extensive fractured basalts particularly the Ashangie formation	The flood basalt which cover nearly 80 % of the project site form in some localities extensive aquifers over several thousands of sq km. Groundwater mainly occurs in contact zones, along dyke swarms and in weathered volcanic materials
Talus slope and paleo or modern landslide bodies	In several localities (e.g. Just on the road from Gashena to Lalibela on the slope of the escarpment several landslide bodies exist). The lose bodies of landslide allow groundwater inflow from the mountain body and springs emerge in most of these landslides. Locally the landslide body and associated loose fragment of soil allow development of groundwater for household irrigation

major discharge springs emerge at the contact between the Ashangie sequences and the underlying Adigrat sandstone (e.g. a spring near Siska village on Sekota Siska road). The Adigrat sandstone is in places highly indurated and thermally compacted in its top part.

The most water stressed area is the N–S running ridge resting in the middle of the Tekeze river basin bounded from the east by the Tsirare River and the west by the main Tekeze River (Fig. 2.11). Both surface water and groundwater flows away from this ridge and very limited suitable condition for storage of groundwater exist in this sector of Tekeze. Mostly perched groundwaters can be exploited from the region.

Table 2.6 Hydrogeogic characterization of aquifers in the Upper Tekeze area

Aquifer type	Transmissivity m^2/day	Yield (l/s)	Characteristics
Basement		<0.1 l/s	These are low grade metamorphic rocks mostly metasediments (phylites), groundwaters mostly occurs in shallow part. In places N S running basement faults and foliations coupled with EW shears enhance permeability of the rocks
Dolerite sills and intrusions		<2	These are highly fragmented and jointed, the joints are narrowly spaced, and the dolerites form intrusions and remain within the Adigrat sandstones, in many places particularly associated with the Tsirare fault system they make it to the surface forming isolated hills and domes. Because of their limited lateral extent
Adigrat sandstone		<2	Highly indurated, massive, and cemented sandstone with low primary porosity, the top part of which is encrusted by heating from Cenozoic volcanism, groundwater springs emerging at the contact of the Adigrat sandstone and the volcanic formation indicate low permeability of the sandstone, Fracture sets are common on the sandstone
Basal Basalt sequence	0.5–80	0.7–5.6	Deeply weathered, flows are laterally discontinuous; several springs emerge at the contact between this lithology and the underlying Adigrat sandstone, at its base it is affected by mineralization filling the fractures, dykes and gabro-diabase intrusion. In several sectors the Ashangie basalts are brecciated. Field evidence show that the brecciate parts are characterized by lower permeability
Upper Basalt sequence	1–100	1–20	Thickly bedded, columnar jointed product covering extensive area. The columnar joints are very closer to each other, Several lacusterine sediments sandwiched between the sequence can be noted. Individual flows are laterally extensive. In some places vesicular texture is common. Intercalation of rhyolites and ignmbrites capping the Cenozoic volcanic products are noted in highlands bounding the Tekezer river from West. Yield of wells can be very low in case of sites on shields. Dry wells are common example around the Guna Shield volcano. The rhyolitc and ignimbritic components are poor aquifers. Owing to their topographic location the shield volcanoes do not allow storage of apreiacble amount of groundwater although in some case prolific springs are associated with them

(continued)

Table 2.6 (continued)

Aquifer type	Transmissivity m^2/day	Yield (l/s)	Characteristics
Alluvial sediments	1–500	20	These are alluvial materials probably developed during accompanying the Holocene climate fluctuations, the alluvial materials are composed of diatomites, red beds, fluvial materials and paleosols. The most extensive deposit occurs mantling the Belesa plain while several such pockets are also common in the Lalibela area, in the Taba village, and filling paleo channels in sekota area
Talus slope, landslide bodies, alluvial terraces		1–2	These are small pockets of 0.5–2 km^2 slope material. The loose texture of the material enhance permeability in some places and groundwater from the mountain body often diffuse towards the talus slope and landslide bodies, cold springs are common in this materials. The slope material also supports several villages in the basin because of their gentler slope, soil development and groundwater discharge foci

The groundwaters of upper Tekeze are characters by low total dissolved solids and mostly satisfy the drinking and irrigation water quality standards. Incipient pollution of the groundwaters around the well heads has been noted. Groundwaters mainly occur in the volcanic cover. Tectonic depressions also play a major role in localizing groundwaters.

Recharge to the aquifers mainly occurs from rainfall and losing streams. Total annual recharge rate within the Tekeze basin is estimated at 50–100 mm/year from global estimates. WAPCOS (1990) estimated recharge in the basin at 100 mm/year. WATBAL estimate using the soil water balance book keeping method yields a deep recharge of 19 mm/year the majority of this recharge takes place in August and September (WWDSE 2009). According to previous isotope hydrological study (Kebede et al. 2005) groundwater recharge to aquifer in the regions surrounding the Tekeze basin basically takes from summer rainfall.

WATBAL soil water balance method The WATBAL (an Integrated Water Balance Model) model is used to estimate recharge over upper Tekeze valley from which rainfall and runoff data are available. A total of 178 million m^3 recharge for shallow aquifers which ultimately become base flow above the gauging station and a total of 565 million m^3 of deep aquifer recharge which leave the basin elsewhere has been estimated. Therefore the total groundwater recharge is estimated at 743 million m^3 of recharge goes to shallow and deep groundwaters.

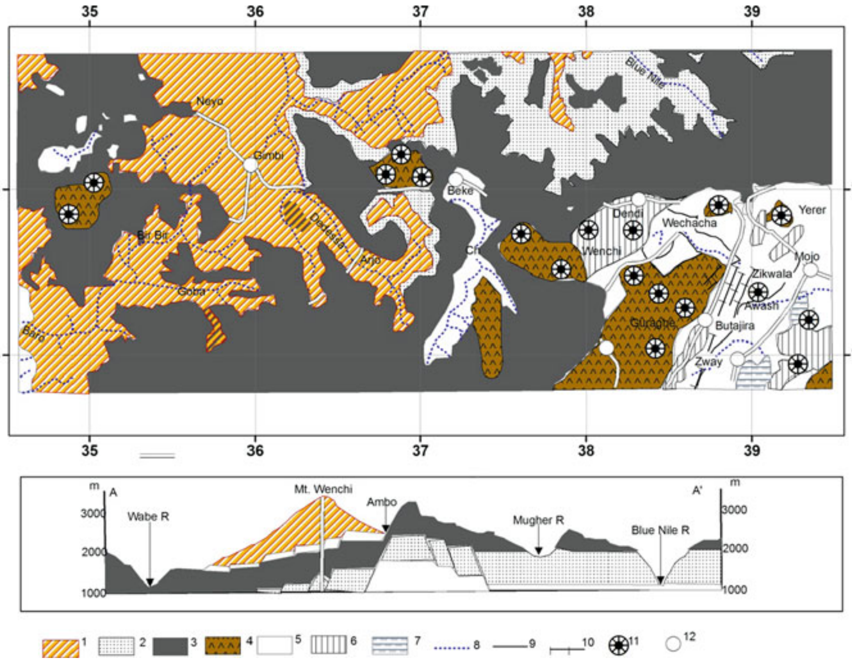

Fig. 2.13 Geology of the Yerer Tullu Wellel Volcanic Lineament zone where coordinates in the map is given in degrees. *1* Precambrian basement, *2* Mesozoic cover, *3* Oligocene volcanics (Ethiopian plateau volcanics), *4* Late Miocene volcanics, *5* Quaternary volcanics, *6* Alluvial cover, *7* Lakes, *8* Rivers, *9* Main escarpment, *10* Faults, *11* Central volcanoes, *12* Hot springs (modified from Abebe et al. 1998)

2.5 The Yerer Tulu Welel Volcanic Lineament Zone and the Wonchi Volcano

Geology

The YTVL is an east–west trending regional structure that partly crosses the Blue Nile basin (Fig. 2.13). It has a length of 800 km and a diameter of 80 km. The YTVL is a kind of half graben bounded by the Ambo fault from the north (Abebe et al. 1998). The Ambo fault has a throw of about 500 m. The major lineaments in the YTVL zone are the Dedessa Lineament (DL) and the Ambo-Butajira Lineament (ABL). These lineaments are deep faults and lineaments that cut across the YTVL. The lineaments are fed by dykes and aligned volcanic plugs.

Along the YTVL, three main rock successions crop out: the Precambrian basement, the Mesozoic sedimentary rocks, and the Cenozoic volcanics. The volcanics are predominant whereas the basement and the sedimentary rocks are locally exposed. The sedimentary rocks (sandstones and limestones) thin out towards the southern part of YTVL. The Quaternary volcanics which cover the YTVL are mainly rhyolites and trachytes with abundant alkali-feldspars, alkali-amphiboles and quartz. Faulting in the YTVL (the Ambo fault and associated lineaments) for instance juxtaposes the Mesozoic sediments and the volcanic cover favoring the formation of high discharge, hypothermal springs in the region. These hypothermal springs have unique geochemistry. They are low pH, high $p\mathrm{CO}_2$, *and* Na–Ca-Mg–HCO_3 springs containing naturally sparkling gas. They are oligo-mineral waters rich both desirable and undesirable trace elements.

Geochemistry and Origin of Naturally Sparkling (High pCO₂) Groundwaters

The majority of the low temperature thermal groundwater springs from the YTVL have high TDS (generally greater than 1,000 mg/L). Sodium (Na) and potassium (K) dominate their cation species and bicarbonate (HCO_3^-) is the dominant anion. These groundwaters fall in the Na–Ca–HCO_3 type groundwaters in the Piper plot. This is because with further hydrolysis of silicate minerals by the Ca–Mg–HCO_3 type waters, the concentration of sodium, potassium, magnesium and bicarbonate increase but Ca and Mg enrichment is limited by an earlier saturation and precipitation of carbonates. The high TDS and the enrichment of sodium therefore testify that the thermal and the high TDS groundwaters have undergone a relatively pronounced degree of groundwater chemical evolution. High fluoride (F) is observed in few water points issuing from acid volcanic rocks of the Quaternary acid volcanics in YTVL and in the groundwaters associated with thermal systems. The high fluoride in the groundwaters associated with acid volcanism has its source from leaching of fluoride bearing accessory minerals. Some rock forming minerals of acid volcanic rocks such as alkali amphiboles, alkali mica or accessory minerals such as apatite often contain F^- associated with OH^- groups of the minerals releasing F^- up on rock water interaction.

Naturally sparkling springs associated with the Wonchi volcano: Figure 2.14 depicts a schematic model characterizing the origin of the low pH high CO_2 springs associated with YTVL. Major hydrologic processes responsible for the origin of the thermal springs are (a) Recharge at high altitude by Ca–HCO_3 type waters, (b) major residence in acid volcanic rocks, open system hydrolysis of silicate minerals, lowering of pH by addition of CO_2 from metamorphic de-carbonation of the underlying Mesozoic sediments or from direct CO_2 input from deeper sources along the fault zone, (c) release of CO_2 on emergence or before emergence and deposition of travertine and silica sinter leading to waters with Na–HCO_3 characteristics as final composition.

Naturally sparkling water in Didessa valley: Here naturally sparkling thermal springs occur in association with dykes. The most notable are those in Wama river valley NE of the confluence with Didessa River, many hot springs are observed emerging along NE–SW trending alkaline basaltic dykes in the flat lowlands of

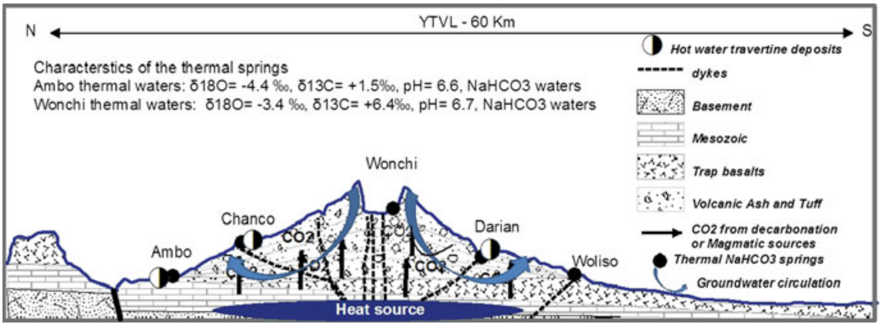

Fig. 2.14 Schematic model showing the mechanism of origin of the naturally sparkling groundwaters around Wonchi Volcano

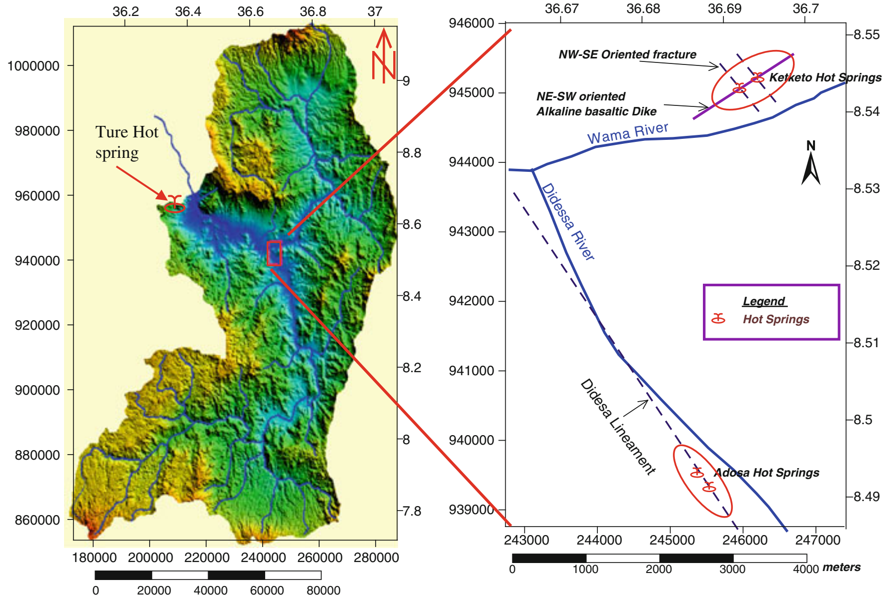

Fig. 2.15 Relation between thermal springs and lineament features in the Didessa valley

Didessa and Wama river valleys. The dykes are 4–5 m wide, composed mainly of K-feldspars, and are vertical, and fractured in the NW–SE direction which is in the major Didessa Lineament direction (Fig. 2.15). In Adosa area, in Didessa river valley, SE of the confluence of Didessa with Wama river, the springs emerge along the main Didessa Lineament. All the springs are related to regional tectonic structure and are aligned along the faulting direction of the area. Deep rooted NE-SW oriented dike, probably to the depth of heat convicting layer cut by younger NW–SE oriented vertical fractures may be responsible for the emergence of the hot springs from regional groundwater flow system. The hot springs may also be indicative of the presence of magmatic anomaly in the area. There are many hot springs at distance of 5–250 m along Ketketo hot springs, and these springs have similar pH, Temperature and EC values and are categorized together under Ketketo springs.

The springs in Didessa valley have relatively higher temperature than those reported in YTVL. The maximum temperature recorded is at Katkato hot spring (maximum 48 °C) as compared with the temperature reported in YTVL hot springs, 25–40 °C (Kebede et al. 2005). The springs are characterized by high Na^+, lower Ca^{2+} and Mg^{2+}, high HCO_3^-, SO_4^{2-} (115–140 mg/l), F^-(5.6–9.6 mg/l) and Cl^- (32–58 mg/l) than ordinary groundwaters in the region. This shows intense rock water interaction that produces the geochemistry of thermal springs because of heating and mantle CO_2. The lateral extension of this sandstone under the volcanic succession and its relation with the hot spring of the study area is not well mapped but like in the Wonchi volcano plays an important role in releasing CO_2 for rock water interaction. This is evidenced by low pH and high HCO_3 type water.

2.6 The Volcanic Aquifers Bounding Addis Ababa

Geology

The Addis Ababa area is located at the junction of the Ethiopian plateau and the Northern section of the Main Ethiopian Rift. As the result the geology is marked by the presence of both the Plateau volcanic cover and the rift related volcanic sequences. The area is covered by the Oliogo-Miocene plateau unit, Miocene rift shoulder basalts, ignimbrites, rhyolites and quaternary basalts and alluvio-lacustrine sediments. The region is also dotted by several central volcanoes such as Furi, Yerer, Wachacha, Menagesha, Bedegababe, etc. (Fig. 2.16).

Oligo-Miocene Plateau Unit (*Termaber and Alaji units-basalts*, *rhyolites and trachytes*): At the base of the rift margin volcanic rocks, the trap basalt (22.8 Ma) of the Plateau unit is in fault contact with the overlying Entoto unit (22.2-22.0 Ma) (Morton et al. 1979; Chernet et al. 1998). The Entoto unit consists of trachyte-rhyolite flows and associated ignimbrites at its base (22.2 Ma) and plagioclase phyric basalt (22.0 Ma) in its upper part. Because of their close relationship, the Plateau and Entoto units are here collectively referred to as the plateau unit (specifically the Upper basalt sequence of the Plateau volcanic). In traditional stratigraphic nomenclature the top part of plateau basalt sequence is composed of the Termaber Basalt and the Alaji Rhyolites. The Alaji Rhyolites unit is exposed in the northern central part of the study area. It is consisting of rhyolites, ignimbrites and subordinate trachytes. Obsidian bearing rhyolites are common. The Termaber Basalt is the dominant unit exposed in the western and northern plateau parts and watershed divide of the Awash and Abay river basins. In the rift valley part of the

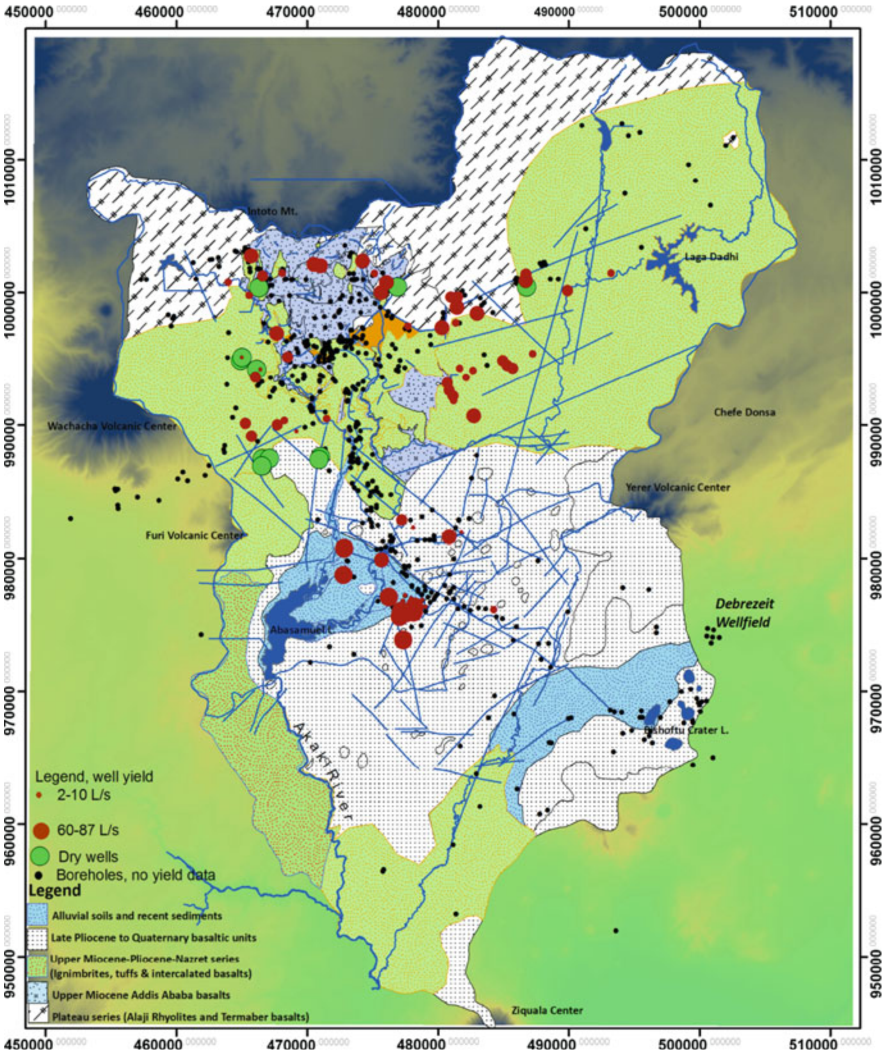

Fig. 2.16 Geological Map of the Addis Ababa area (Akaki river catchment). *Green circles* show sites of dry wells (modifed from AAWSA 2002)

study area this unit is downthrown by the regional east west running Ambo fault (which marks the northern boundary of the YTVL-see Sect. 2.5) and is covered by thick (300 m) younger ignimbrite (Lega Dadi and Melka Kunture area mapping boreholes data) or Middle to Upper Miocene Addis Ababa Basalts. It is consisting of mainly scoraceous lava flows and at places it is columnar olivine bearing basalt as pockets within the scoraceous components. It is highly weathered and fractured.

Upper Miocene Addis Ababa basalts: This unit is composed of principally of coarse grained olivine-plagioclase phyric basalts. The vertical extent of these basalts in less than 130 m and overlies the ignimbrites associated with the earlier trap basalts. The eruption of the Addis Ababa basalts took place at 7–9 Ma after considerable hiatus between 22 and 10 Ma.

Upper Miocene-Pliocene rift series (*Nathret group*) *volcanic*: This unit comes in complex pattern and is composed of unwelded tuff, welded tuffs, ignimbrites, rhyolites and trachytes. They are associated with or derived from prominent trachytic volcanic centres such as Ziquala, Furi, Yerer, Wachacha, Menagesha etc. The thickness of the units may rich 300 m or more. The unit comes in complex inter-fingering of volcanic products coming from different volcanic centres. The base of the Nazret group unit is made up of the Upper Miocene Addis Ababa basalts. The Nazret group rocks crop out in most part of Eastern part of Addis Ababa. Here is composed of welded tuff (ignimbrite) and non welded pyroclastics fall (ash and tuff). It is greyish to white colour and when welded it exhibits fiamme textures, elongated rock fragments of various colour. Around the Lega Dadi plain and Melka Kunture (northwest of Ziqala) area the thickness of this unit reaches up to 200 m. In the Becho plain area (west of Furi volcano in Fig. 2.16) it is covered by thin 5–7 m thick residual soil developed from the same rock. In the Southern part of the Akaki catchment (Fig. 2.16), this unit is represented by sequence of welded per alkaline rhyolitic ignimbrite. The unit comprises numerous rhyolitic and trachytic domes. Rock fragments and crystals, generally broken, are abundant; alkali feldspars, quartz, aegirine and amphiboles are the most common crystals. In Chefe Donsa are the unit consist of fall deposits (ash, tuff and pumice) and poorly welded ignimbrites of rhyolitic composition. Central volcanic units of tracytic composition in this unit include the Wachacha, Furi and Yerer Trachytes. These are mainly trachytic lavas exposed at Wechecha, Furi, Yerer, Western and South western ridges forming an elevated ridges or mountain picks. The Yerer trachyte is elevated about 1,000 m from the surrounding plain. Basalt formation is also associated with this unit though it has been argued that these basalts within the Nazareth series are equivalent to the Upper Miocene Addis Ababa basalt.

Late Pliocene to Quaternary basaltic units: This unit represents basalt flows associated with numerous scoria cones found on the subdued escarpments of southern part of Addis Ababa and around Debrezeyit. These basalts typically range in age between 2.8 and 2 Ma and are often referred to as the Bishoftu Basalt. Bishoftu basalts are characteristically alkaline. Volcanism of quaternary in this unit is represented by various spatter cones and maar lakes and fissural basalts around Debrezeyit. In Akaki area the basalt units are highly vesicular basalt and in places the vesicles are filled by secondary minerals. It is dotted by scoria and spatter cones. Thickness of the entire units exceeds 200 m.

Tectonics

The geology of **Addis Ababa** is the result of the intersection of two major tectonic features and Cenozoic to quaternary volcanism. The two tectonic features are the

Yerer Tullu Welele Volcanic Lineament (YTVL) and the western margin of the Main Ethiopian Rift (MER). The YTVL is an East–West running fault and volcanic zone (Sect. 2.5). Abebe et al. (1998) elaborately described the origin of the structures in YTVL, their evolution and their importance in controlling the origin of quaternary volcanics in the region. The intersection between YTVL and MER created the Addis Ababa embayment, where the rift become wider and the step faults defining the rift are subdued. Kebede et al. (2005) described this zone as 'the YTVL hydrogeologic switch' whereby the groundwaters are drained from central part of the Plateau and flows down the rift following regional topography. The E–W faults act as a barrier to the N–S groundwater flow around Addis Ababa resulting in the emergence of productive thermal springs in the central Addis Ababa.

Groundwater Occurrence and Flow

The hydrogeology of this region is of critical importance because the Addis Ababa City (population >3,000,000) gets 40 % of its water supply from groundwater (Akaki well field in southern suburb of Addis Ababa) which is part of the intersection zone. Recharge rate estimation in the region have been the subject of many previous studies (Gizaw 2002 and references therein). Many previous studies assume groundwater flow path follow the topography (AAWSA 2002) and it is generally from north to south.

Mirroring the four geologic units four hydrostratigraphic units can be recognised in Addis Ababa area (Fig. 2.16, Table 2.7). The *Plateau series* composed of Alaji rhyolites and the Termaber formation are exposed mainly in the higher grounds in a high rainfall area in the north. When exposed these units are characterised by the presence of shallow circulating groundwaters and discharges to low discharge springs as evidenced by numerous springs emerging in the Entoto ridge and regions in the north. Groundwater occurs in scoraceous layers and in flow contact zones. The southward extension of the plateau series is intercepted by the prominent E-W running Ambo fault of the YTVL (the fault defines the contact between the plateau series and the rift series rocks-Fig. 2.16). The throw of this fault is around 500 m (see elevation contrast between the highland and the lowland from the background coloured topo-map in Fig. 2.16). MWR (2007) reports that, the Termaber basalts extend underneath the Rift series and the Quaternary volcanic of the region forming important regional aquifers. This aquifer is characterised by artesian and confined condition. The confinement is locally assisted by the presence of low permeability ignimbrites and tuffs belonging to the Nazareth series volcanic.

The upper *Pliocene-quaternary basalts* form an important shallow to deep aquifers and is currently the most widely exploited for water supply in Addis Ababa region. Because of its scoraceous structure this unit holds important volume of groundwater. Prominent well fields such as the Akaki and the Debrezeyit well fields tap this aquifer. The aquifer is mostly unconfined while locally the intercalated ash units and paleosols favour semi confined or confined conditions.

Table 2.7 Hydrogeologic properties of major aquifers around Addis Ababa

Aquifer unit		Average yield of water well (l/s)	Transmissivity (m^2/day)	Storativity	Remark
Late Pliocene to Quaternary basaltic units (Scoria, scoraceous basalts, vesicular and fractured basalts including the Akaki and Debrezeyit well fields		3–87	1,833–100,000	0.0065–0.016	Highly productive
Upper Miocene Addis Ababa basalts-fractured and weathered basalt aquifer with inter volcanic coarse sediment		0.5–20	2–6,000		Moderately productive
Upper Miocene to Pliocene-ignimbrites, welded tuffs, ashes and unweldded tuff and associated basalt intercalations		0.4–15	15–110	0.0001–0.003	Least productive
Oligo-Miocene plateau unit (Upper Basalt Sequence)	Termaber basalts	5–200 l/s	??	??	Semi confined to artesian condition
	Alaji rhyolites	Very low	Non aquifer, fractured and weathered zones in this region are important recharge zones and shallow circulating groundwater could be tapped through hand-dug wells and from springs		

The thickness of the unit reaches more than 300 m in places. The lateral continuity of this unit is often interrupted by the Nazareth series units and volcanic centres. The transmissivity of this aquifer is highly variable as a function of faulting and fracturing and the type of basalts. It varies from 50 to 27,000 m^2/day. The yield of boreholes varies accordingly. Geochemically the groundwaters are characterized by fresh groundwater with electrical conductivity value less than 700 μS/cm and TDS less than 400 mg/l. Most of the groundwater of this aquifer forms the baseflow of the streams in upper Awash and part of it is discharged into Debrezeyit lakes, where most of the outflow from these lakes is through evaporation and also recharges the lower basaltic aquifers.

The *Nazareth series* volcanics because of their low permeability and storage properties act as local aquifers of low yields or act as regional confining layer for the Plateau series units. The phyroclasitc units and welded ignimbrites act as low productivity aquifer along the weathered and fractured zones. In central, eastern and south western corner of Akaki River catchment (Fig. 2.16) the unit act as a confining layer for underlying plateau basalts and leads to a number of artesian wells (e.g. Well at Melka Kunture, CMC, and Legadadi etc.). Most of wells which turn dry on drilling are mostly located on this unit (Fig. 2.16). The Upper Miocene Addis Ababa basalts also form locally important aquifer.

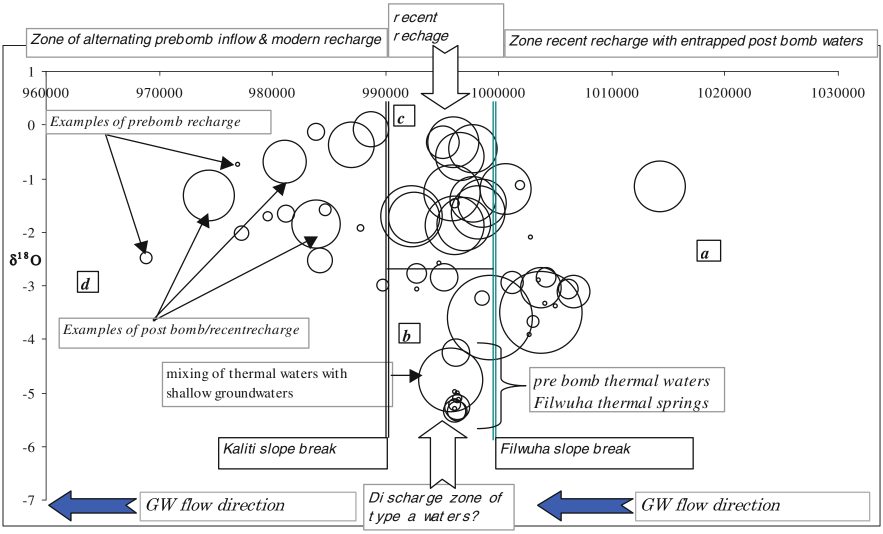

Fig. 2.17 Spatial tritium and oxygen 18 variation in groundwaters of Addis Ababa. The figure show latitudinal variation (along a transect taken parallel to longitude 470500 UTM coordinate) in δ^{18}O and tritium content of groundwaters around Addis Ababa along Entoto-Akaki transect. Tritium concentration varies between 0.1TU (the *smallest circle*) and 20TU (the *largest circle*)

Groundwater flow is generally from north to south following the topography. Direct recharge from rainfall through soils is the principal source of groundwater recharge. Discharge takes place to springs and streams and in central part of Addis Ababa discharge also takes place to thermal springs.

Isotopic and Geochemical Evidence of Groundwater Occurrence and Flow

Geochemical and isotopic evidence show there are at least four recognizable groundwater compartments between Entoto and Akaki. The four compartments of groundwaters are identified based on tritium (^{3}H) content, δ^{18}O and the geographic distribution of the samples as shown in Fig. 2.17. The following major observations can listed from the examination of the figure.

1. Around the Entoto ridge (type *a*) both very high tritium and very low tritium (pre-bomb[4]) waters are observed (North of 10,000,000 UTM north)

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[4] Exclusively pre bomb recharge refers tritium content less than 0.6 TU if measured in 2003 in Addis Ababa.

2. In the central transect (between 9,850,000 and 10,000,000 UTM north) of the town two types of groundwater exist. These are (1) the ^{18}O enriched but tritium rich waters (type c) and (2) the ^{18}O depleted but low tritium waters (type b). The Filwuha thermal springs the most depleted of the ^{18}O depleted low tritium waters of type b.
3. The Filwuha thermal springs (type b) are depleted in $\delta^{18}O$ than the modern day or the pre-bomb waters of Entoto
4. Some of the Filwuha springs although they are the most depleted they contains some tritium ($\sim$3TU)
5. Excluding the Filwuha thermal springs which are the most depleted, the low tritium containing waters in central transect (type b) of the town have similar $\delta^{18}O$ composition to the Entoto groundwaters
6. The low tritium and ^{18}O depleted waters of the central transect of the region (type b) are rarely observed in the low lying plain (south of 9,800,000 UTM north) beyond Kaliti (type d). Likewise the ^{18}O depleted water of Entoto type is rarely observed in the southern sector of Addis Ababa. Generally water around the Akaki well field (type d) has similar $\delta^{18}O$ composition to that of c type waters. But the low tritium waters of type d are more similar in $\delta^{18}O$ to the zone c waters. Most high tritium containing waters of zone d waters generally contain also enriched $\delta^{18}O$

Origin of Groundwaters Around Addis Ababa

1. Groundwaters of the region occur in compartments. At least four compartments vertical/horizontal can be identified from isotopic evidence
2. The presence of pre-bomb type groundwaters in Entoto indicates entrapment or slow flow of groundwaters in rhyolitic Entoto ridge. This shows the low transmissivity of the ridge. This is consistent with the aquifer transmissivity distribution of Addis Ababa (AAWSA 2002) determined from physical approaches
3. Entoto type meteoric waters (low $\delta^{18}O$) are not observed in groundwater wells or springs beyond the Kaliti slope break, therefore the Entoto ridge is not the major recharge source to shallow groundwater wells beyond Kaliti including the Akaki well field. The flow of Entoto type water underneath the well field at greater depth (exceeding 250 m) cannot be ruled. However, low tritium waters in the central sector (type b) which have similar $\delta^{18}O$ as that of the Entoto waters are most likely recharged by infiltration at Entoto.
4. The similarity in their ^{18}O content shows that the groundwaters of type b in central sector of Addis Ababa seems to be the main recharge water/zone for the low tritium groundwaters south of 980,000 UTM north. The difference in tritium is related to radioactive decay (ageing of the water) as it moves from the central sector of the transect to the lowland.
5. The high tritium and ^{18}O enriched groundwaters beyond south of 980,000 UTM north are most likely recharged locally by vertical infiltration. The enrichment in ^{18}O and the high tritium indicate local vertical recharge.

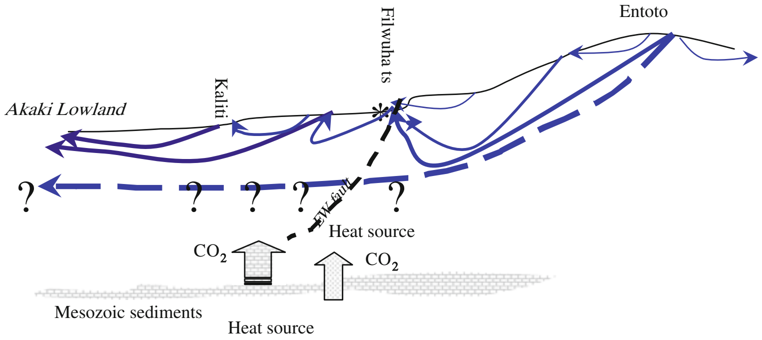


Fig. 2.18 Schematic diagram of groundwater flow patterns along N–S transect. The E–W fault in the central sector of the region acts as a major barrier to the N–S flowing groundwaters. Carbon dioxide from de-carbonation of the Mesozoic sediments is the principal catalyst for the hydrolysis reaction that produced the Filwuha high TDS high HCO_3 waters. Along the east west Filwuha fault barrier the groundwater inflow from west parallel to the fault can not be ruled out

6. The source of tritium in tritium containing thermal waters of Addis Ababa is local mixing with shallow tritium containing waters of the sector (c) upon ascent.

The Recharge Role of Entoto Ridge

The role of mountains in recharging adjacent groundwater bodies (alluvial fills or mountain front aquifers) is not as simple as one can imagine as '*mountains are recharge sources and valleys or adjacent low lands are discharge areas*'. The role of mountains in recharging adjacent aquifers depends on the permeability of the mountain block, the rainfall condition on the mountains, the presence of favourable geologic structures, and the proximity of the mountains to the aquifers. Figure 2.18 shows schematic groundwater flow pattern across the Entoto (North) Akaki (South) transect.

Figure 2.17 shows that the majority of groundwater wells and springs at the foot of the Entoto Mountain have higher tritium content than the majority of springs emerging within the mountain. This testifies that the Entoto Mountain is not feeding these wells and springs at its foot. One would imagine that the infiltration at Entoto follows deeper flow paths and is not detectable in shallower aquifers at the foot of the mountain. However, deeper aquifers further south of the Entoto ridge contains ^{18}O enriched waters than the Entoto ridge springs or wells. The groundwaters in the southern sector of Addis Ababa have similar ^{18}O content to aquifers in the central part of the transect. Thus main recharge source for the aquifers at furthest distance (Akaki) from Entoto seems the central sector of the slope (foot of Entoto Mountain) or local vertical recharge for those ^{18}O enriched (shallow) aquifers.

Origin of the Filwuha Thermal Springs

Figure 2.18 shows schematically the origin of the Filwuha thermal springs. Chemically and isotopically ($\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C$) the Filwuha thermal springs (type b in Fig. 2.17) are distinct from adjacent cold temperature groundwaters. As already noted by Gizaw (2002) the springs are characterised by high TDS, high Na and bicarbonate. Furthermore the springs are enriched in carbon-13. They are the most depleted in oxygen 18 and deuterium. All these observations indicate that the waters are characterised by intensive degree of rock water interaction relative to the cold groundwaters. Moreover, on Entoto plateau the present day $\delta^{18}O$ content of groundwaters is 2 % more enriched than the Filwuha springs. These suggest:

1. The present day recharge on Entoto ridge is not the major source of recharge for the Filwuha springs
2. The Filwuha springs follow deeper circulation path and were recharged under a relatively colder climate than today but they were recharged at Entoto or elsewhere
3. The enrichment in carbon-13 is caused by CO_2 coming from mantle or from the metamorphic de-carbonation of the Mesozoic sediment buried at deeper levels.

Aquifer Vulnerability Map Versus Tritium Distribution

Tritium composition of groundwaters can indirectly tell the vulnerability of aquifers to pollution. The assumption is that tritium containing groundwaters are recently recharged and have a direct connection to the surface. Low tritium waters represent those flow lines which follow deeper circulation pathways or those with longer subsurface residence time. There is a likely hood of high vulnerability near recharge zones. The tritium distribution shows groundwater aquifers type b, which contains the highest tritium, is located in the central sector of Addis Ababa. These aquifers are the most vulnerable. The deeper aquifers of the Akaki plain and some region of the Entoto ridge are the least vulnerable. Although some slight differences are observed around the Entoto ridge, evidence from tritium is consistence with the GIS based aquifer vulnerability map (Alemayehu et al. 2005) of Addis Ababa.

2.7 Scoria Cones, Maars and Associated Groundwater Resources

Geology

A maar is a low relief volcanic crater that is created by an explosion caused by lava or magma coming into contact with groundwater. Typical feature of a maar is low relief of the surrounding terrain and maar are found below the general low relief surface. Maars are shallow, flat bottomed depression having formed as a result of violent expansion of magmatic gas or steam. Most maars have low rims composed of a mixture of loose fragments of volcanic rocks and rock torn from the walls of the diatreme. Maar depressions when filled with water form maar lakes.

Several maar lakes are found in Ethiopia many of which occur as clusters of maar lakes or dry depressions. Notable cluster of maar lakes are found in the following locations:

1. Central Ethiopia in western shoulder of Main Ethiopian rift. These are the five Bishoftu Crater Lakes (Hora, Babogaya, Bishoftu, Arenguade and Kilole and more than 4 other empty maars) (see Fig. 2.16 for location of Bishoftu Crater Lakes).
2. Southern Ethiopian lowland bordering Kenya. These vast volcanic plain of the western Borena (Fig. 1.2) lowland is dotted by numerous maar lakes often filled with salt deposits or brines (e.g. Mega Crater, Goray etc.).
3. The maar lakes occur in the central Ethiopian rift near the head waters of Bilate River. This cluster is located on the southern portion of the so called Siltie Debrezeyit ridge (a fault zone that runs parallel to the rift and defining the western margin of the central Ethiopian rift). This cluster includes the Budameda, and Ashenta maar lakes at the foot hill of Butajiara mountains.
4. The fourth cluster occurs in the central Gojam plateau on the flanks of the Choke mountain shield. These include the Zengena and Tirba maar lakes.

All these maars have several things in common. For example all are associated with quaternary basalt volcanics. They are fed by groundwater as dominant form of water inflows.

Groundwater Hydrology

Typical linkage of maar lakes with groundwater lies in the fact that the very genesis of maar is related to subterranean explosion of a land surface because of interaction between an intruding magma (dyke or sill) and shallow groundwaters. Secondly because of their isolation from surface water drainage owing to the low relief and narrow maar walls the major water and solute flux to maar lakes come from groundwaters.

Clustered maar lakes are therefore indicators of presence of shallow groundwater aquifer (at least at the time of their explosion). Maar lakes are also important reservoirs that maintain recharge to downstream groundwaters. For example water wells in Debrezeyit town obtain up to 50 % of their recharge from Bishoftu Crater Lakes (Kebede et al. 2002). Wetlands south of Lake Zengena are fed by groundwater outflow from the lake.

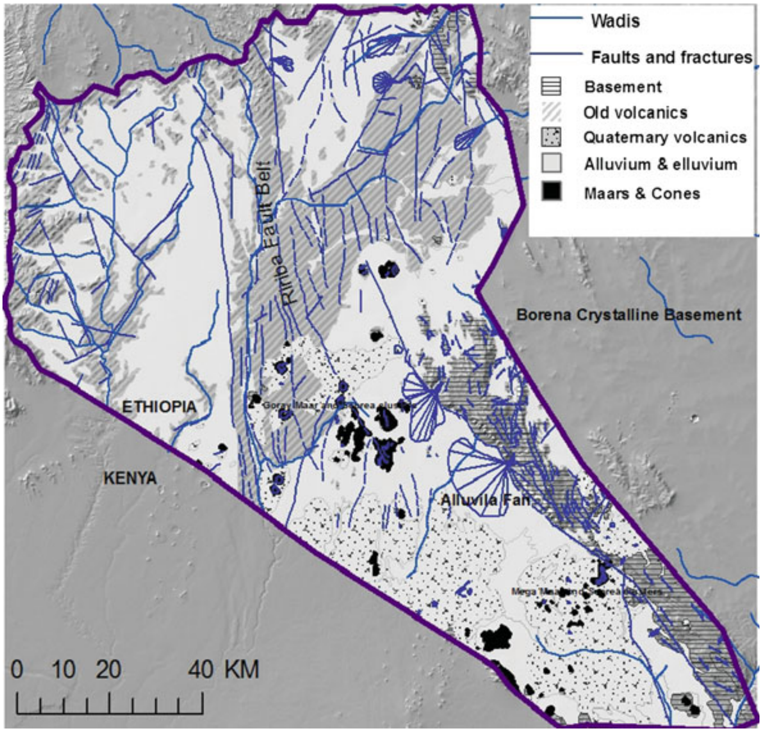


Fig. 2.19 Distribution of maar lakes and quaternary basalts in the western lowlands of Borena

Maar Lakes and Depression in Western Borena Lowlands

The scoria cones, maars and flows in the southern Ethiopia bordering Kenya are associated with volcanism related to current development of a new rift refered to as Ririba fault belt. The lithologies associated with these features are mostly vesicular basalts and scoraceous ejecta. The formation of maar signal explosive activity when magma interacts with groundwater. The scoria cones and maars are confined to the central and south eastern part of the Ririba basin. The cones and maars are often up to 2 km in diameter and protrude up to 200–400 m above the surrounding plain. The cones are well preserved except in places where they have been breached by subsequent eruption centers. The maar lakes contain extremely salty waters and in places salt deposits (e.g. Goray and Mega craters).

Hydrology of these maar lakes is poorly known. Nevertheless the maars in the south eastern tip of Fig. 2.19 are associated with productive and high potential aquifers. Groundwaters associated with the basaltic aquifers are characterized by relatively low EC and high HCO_3. The waters have low pH (high pCO_2) indicative of volcanic gas input from deeper sources. Ca, Mg and Na dominate the cations. The accumulation of salt in the crater lakes (Magado Crater and Goray) is indicative of groundwater inflow to the lakes but limited or no groundwater outflow, a situation that leads to accumulation of salt over time.

The Bishoftu Crater Lake in Central Ethiopia

The Bishoftu Crater Lakes are located on the western escarpment of the Main Ethiopian Rift, 45 km southeast of Addis Ababa, at 1800 to 2000 elevation (Fig. 2.20). The five permanent lakes are Hora (also known as Beite Mengist), Babogaya (Pawlo, Bishoftu Guda), Bishoftu, Kilol (Kilotes), and Arenguade. Artificial lakes and ponds in the area include Lake Kuriftu, a reservoir that fills an originally dry crater depression following the diversion of a tributary of the nearby Mojo River. Lake Cheleleka is a large, shallow swamp that has been present since the early 1970s. They are roughly circular in shape, with areas between 0.6 and 1 km^2. The lakes range in depth from 6.4 m (Lake Kilole) to 87 m (Lake Bishoftu). The lakes have no perennial surface inlets or outlets, and are fed by direct precipitation, surface runoff from the crater walls, and by groundwater.

The bedrock of the area is composed of 9 Ma old basalts and 1–4 Ma old acid volcanics (Gasparon et al. 1993). The maars, cinder cones, and lava flows represent more recent (10 Ka) volcanic activity.

The transmissivity of the older basaltic aquifers range from 400 to 21,600 m^2/day. The younger basic pyroclastic rocks interbedded with minor acidic products make up the largest part of the Ada'a plain and have transmissivities ranging from 1,100 to 18,000 m^2/day. The scoria cones and the acid volcanic domes are believed to be the major zones of groundwater recharge. Isotope hydrological and chloride mass balance studies have shown the water budget of the Lakes as indicated in Table 2.8 (Kebede et al. 2002). The lakes major water inflows are groundwaters. The low salinity of the Lakes is indicative of loss of significant portion of their water to groundwaters, though evaporation account for more than 75 % of water loss in all cases. Table 2.8 shows the water balance of the Bishoftu Crater Lakes and contribution of groundwater to the lakes.

Isotope evidence (Fig. 2.20) shows groundwater in the south western sector is more enriched than groundwaters in northern, western and north eastern sector the region. This implies that groundwater from all the region converges to the crater lakes and leaves the lakes towards the southwestern sector.

The Maar Lakes at the Foot Hill of the Butajira Mountain

Here there are cluster of three maar lakes filled by shallow saline waters. Of the three lakes better hydrogeologic data exists for Lake Tilo. Lake Tilo lies within a maar formed by explosive release of volcanically heated water below the Rift floor. It is one of three adjacent craters lying at an elevation of 1,545 m near the

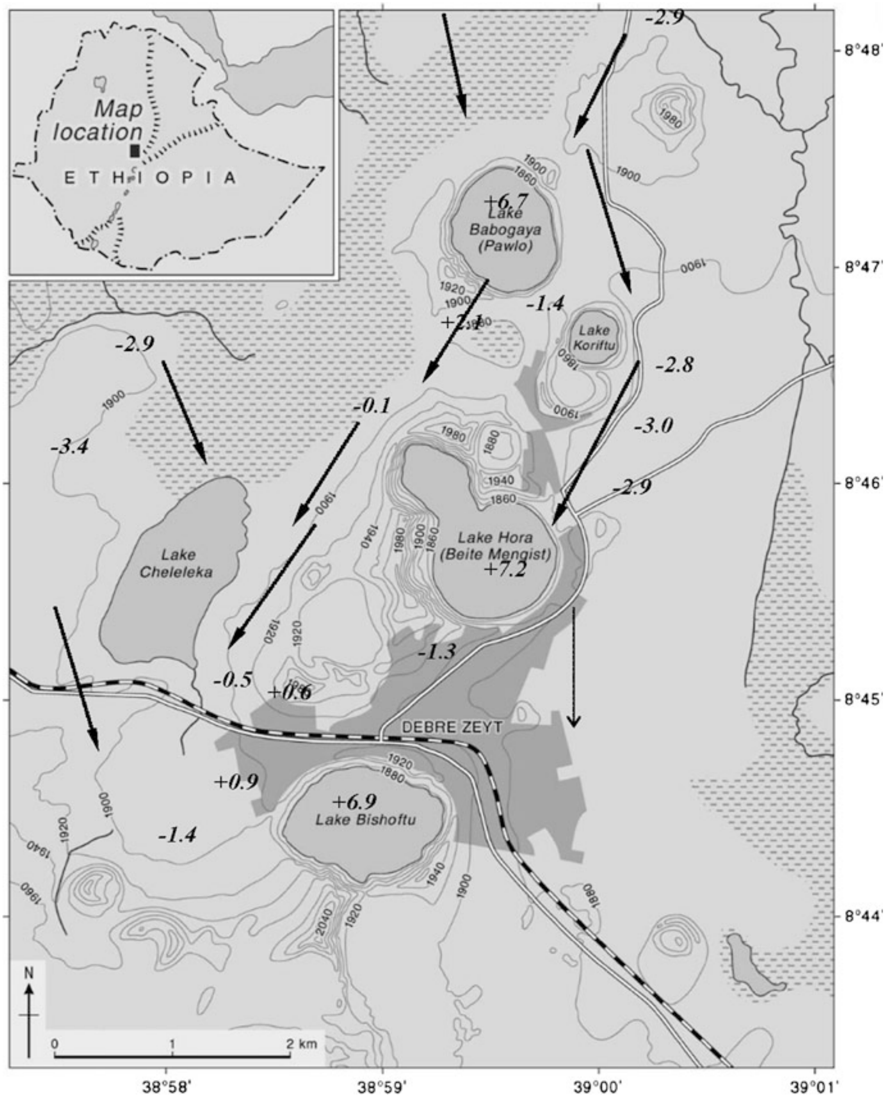


Fig. 2.20 Geomorphic features of the Bishoftu Crater Lakes, arrows indicated inferred groundwater flow direction around the Bishoftu Crater Lakes. Inset numbers are indicative of δ^{18}O content of groundwaters and Lakes

western edge of the Rift in south central Ethiopia (Fig. 2.21). Lacustrine marls with abundant freshwater mollusks and ostracods are evident on the crater walls, 40–60 m above the present lake surface indicating shallow groundwater discharge to this site in the past. The lake has a maximum depth of 10 m and is saline and dark brown in color; the hot springs are relatively dilute. Estimates of the

Table 2.8 Water balance of Bishoftu Crater Lakes and the role of groundwater in their hydrology

	Unit	P	Gi	R	E	Go
Hora	m^3/year	854070	552355	353165	1759590	~0
	%	49	31	20	~100	~0
Babogaya	m^3/year	4805570	587514	121595	990090	199590
	%	40	50	10	83	17
Bishoftu	m^3/year	771070	804586	160190	1588590	147256
	%	44	46	9	92	8

P Precipitation on Lake, *Gi* Groundwater inflow, *R* Runoff to the lake from crater wall, *E* Open water evaporation, and *Go* Groundwater outflow to adjacent aquifers

hydrological and salinity budgets for the lake (Telford and Lamb 1999) suggest that the springs account for only twelve per cent of water inflows to the lake (Fig. 2.21), but sixty-seven per cent of the solute inflows, the remaining thirty-three percent of the solute inflows being derived from the surface catchment via overland flow (Telford 1998).

The Maar Lakes of the Central Gojam Plateau

Here two prominent maar lakes are encountered namely Lake Zengena and Lake Tirba (in association with the quaternary basalts exposed around Injibara town). Both lakes have depth exceeding 150 m. They are flat bottomed. The principal source of water input is groundwater while evaporation accounts for 50 % of water loss and the rest is accounted by groundwater outflow. The lakes occupy high elevation plateau in the northwestern slope of the Choke mountain chain. They are surrounded by high aquifer productivity quaternary basalts. Salinity of both lakes is very low and is in the order of 100–200 mg/l.

2.8 The Alluvial Grabens Bordering the Rift

Geology

The junction between the highlands and the rift valley come in several types of architecture. A detailed account of the geometry of the plateau—rift interface can be referred from Bosellini (1989) and the hydrogeological significance from Kebede et al. (2007). Marginal grabens are one of such characteristics of the geometry of the plateau rift interface. Marginal grabens are smaller rifts bounding the principal rift. The can also be called 'rift within rift' structures. When these marginal grabens are filled by alluvio lacustrine sediments they offer sites of

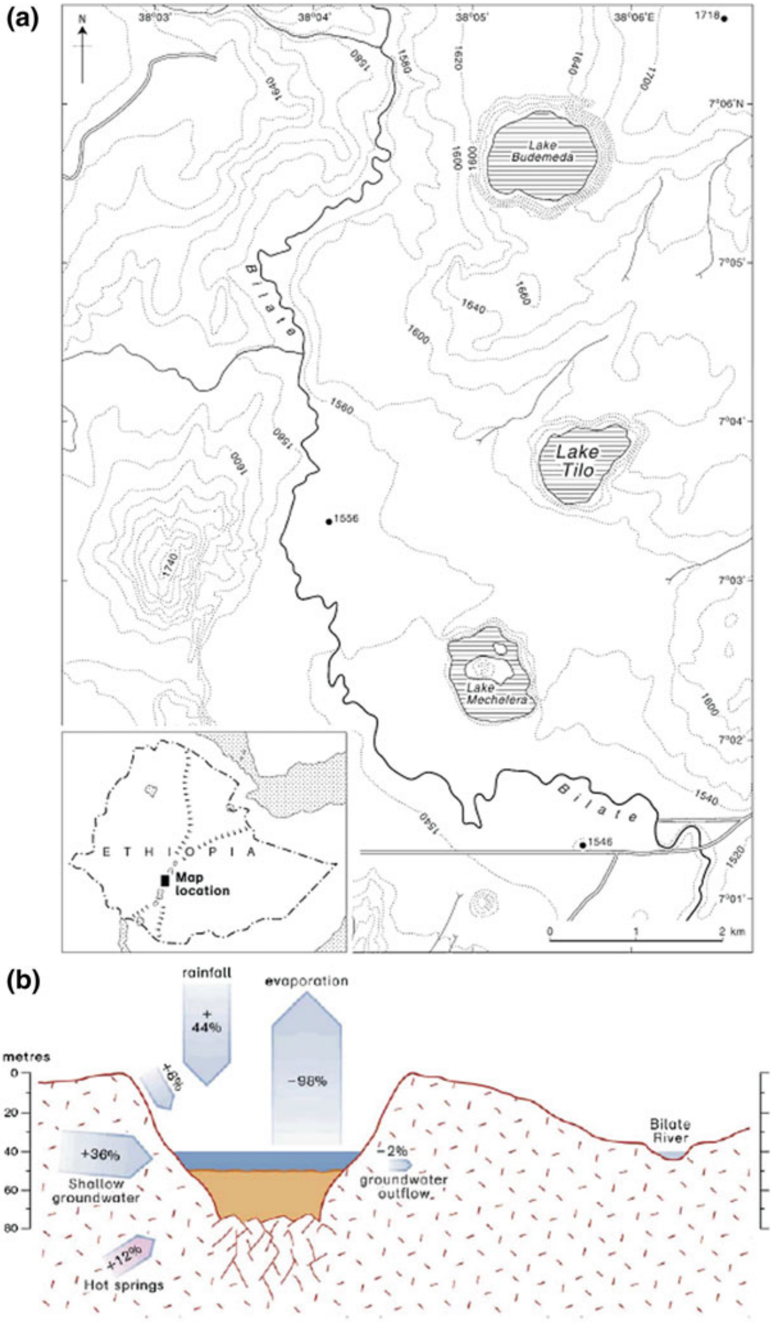


Fig. 2.21 Simplified hydrological characteristics of the Tilo maar lake (from Telford 1998)

highest potential of groundwater storage and availability. Several prominent alluvial sediment filled marginal grabens bound the Ethiopian Rift (e.g. Raya graben—Fig. 2.24; Boyo graben—Fig. 3.11; Shinile graben—Figs. 3.2 and 3.3; see also Sect. 3.13). The thickness of sediments and the sedimentary facies vary from one graben to another. The graben with the thickest and extensive sediment fill is the Shinile graben followed by the Raya graben.

Box 1: Communal features of alluvio-lacustrine sediments in the tectonic valleys

- Generally coarse grained near the escarpment front where they occur and fine grained away from the escarpment, property of aquifers mirror this changes in grain size and sorting. Higher transmissivity are usually noted near the foot slope and decreases away from the foot hill
- The geochemistry of groundwaters also mirrors changes in the grain size and groundwater flow direction. Generally at the foothills waters are of Ca–HCO_3 type with minor Cl and SO_4. Away from the foot hills TDS, Na, Cl and SO_4 increase and waters become mostly Na-HCO_3–SO_4–Cl type

The Borkena Kobo and Raya grabens share similarities in their geology and structure. Despite the significant distance in the N–S direction of this transect, the E–W progression in geology, tectonics and aquifer composition are similar. The plateau and the escarpments are covered by trap series volcanics, and the marginal grabens are filled by alluvial materials and thin lenses of lacustrine sediments. The transitional slope between the rift floor and the grabens is covered by basalts belonging to the Afar Stratoid, and the rift floor is covered by Quaternary basalts at depth and marine, lacustrine and alluvial sediments near the surface. The marine and lacustrine sediments contain thin lenses of evaporites (Battistelli et al. 2002). Detailed account of hydrogeology of each of the grabens is given in different sections in this book but Box 1 gives a common hydrogeologic features of the alluvial grabens.

2.9 The Bulal Basalt Aquifer and Associated Aquifers

Geology

The Bulal basalts underlay a half bowl shaped low laying areas between the Tertiary volcanic highlands from west and the Borena Precambrian basement rocks from east (Fig. 2.22). The volcanic highland in the west separates the Bulal Basalts from the Chew Bahr Rift. Separating the Bulal basalts and the Precambrian

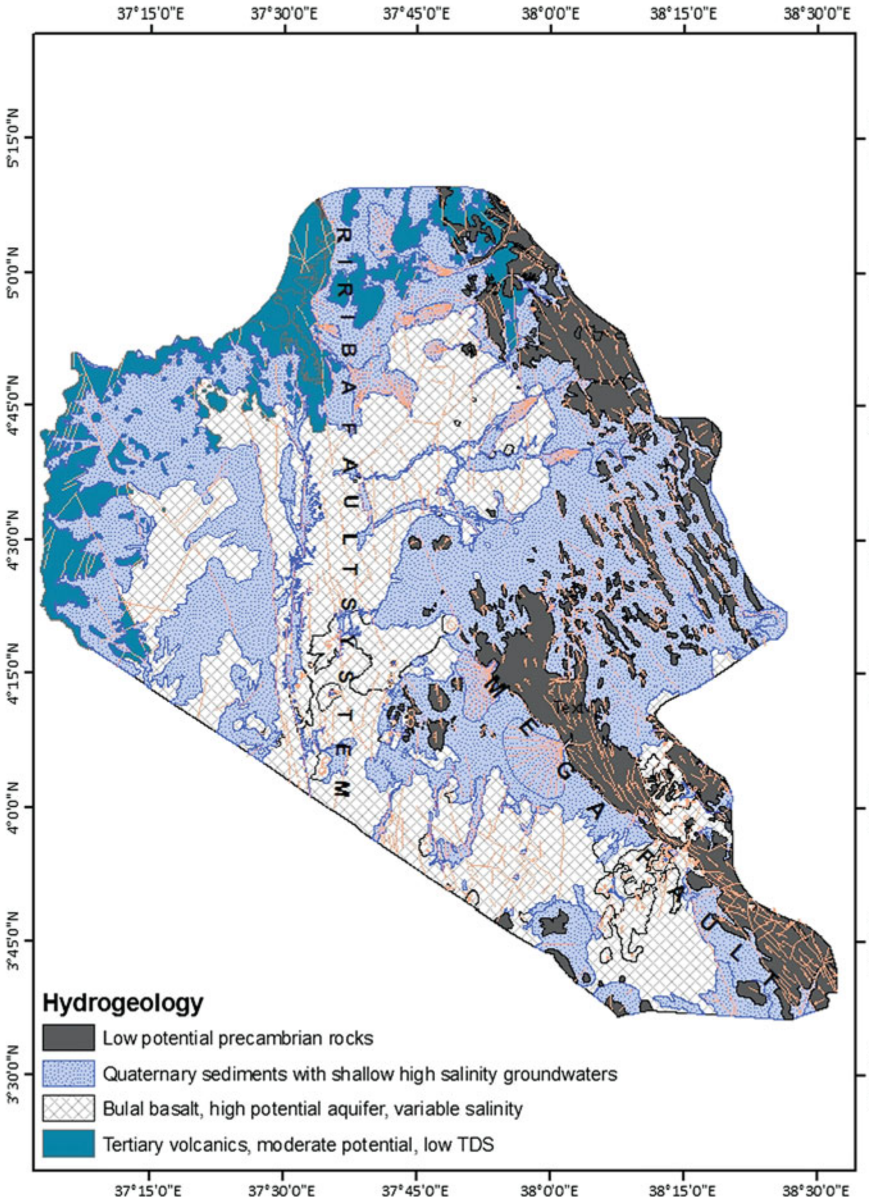


Fig. 2.22 Geologic map and cross section of the Bulal basalt aquifers and associated lithologies (from OWWDSE 2009)

basement in the east is the regional Mega fault belt running NW–SE. The basalts are made up of horizontally layered sheets of extensive flood basalt of late Tertiary age. The major fault/fracture systems in the area (Ririba fault system) run NS trend extends south into Kenya. Quaternary basalts also occur dotting the region as scoria cones, maar and craters. The major part of the volcanic formation is mantled by up to tens of meters thick alluvio-lacustrine sediments.

Hydrogeology and Groundwater Occurrence

Recharge to the Bulal aquifer mainly takes place at basin boundaries along the Mega fault belt and from floods confined to the Ririba fault system. Annual recharge rate is estimated to vary between 40 and 60 mm/year. Drainage is entirely intermittent. Flood water converges in the valley bottom and flow towards Kenya during flood periods. The mean annual aerial rainfall of the area is estimated to be about 593 mm and occurs between September and November and March and June. Mean annual potential evapo-transpiration reaches 1,700 mm/year. Maar lakes dotting the plain are indicative of groundwater circulating at deeper levels during the explosion of the Maar Lakes. The N–S oriented fault zones act as underground water conduits connecting recharge areas located in Ethiopia with discharge areas in Kenya.

The highest recharge takes place in the Ririba fault zone and it covers about 44 % of the area. The overall weighted average recharge estimated for the area is about 54 mm per year. Taking into consideration the low Cl groundwaters (0–50 mg/L) and the mean Cl content or rainwater from March–April rain at 2–3 mg/L (Kebede 2004) and mean annual rain in the highland regions at 700 mm, recharge has been estimated to vary between 30 and 45 mm/year.

Water table map in the Bulal basalts and adjoining highlands (Fig. 2.23) show that mostly groundwater converges towards the Ririba fault zone from the adjoining highlands and leave the volcanic plain of Borena to flow towards Kenya in the south.

Geophysical investigation (Vertical Electrical Sounding-VES) surveys indicate that the area is underlain by four main resistivity layers. These layers correspond, from bottom to top, the Precambrian basement rocks, highly weathered and/or fractured basalts, slightly fractured to massive basalt and the surficial loose and unconsolidated material. Geoelectric sections indicate that thick (50–90 m) deposits of unconsolidated materials (clay, silt, sand, gravel) cover the Ririba and Bulal River flood plains. Direct evidence from lithologic logs indicate the Bulal basalt is characterized by alternating layers of fractured basalt and scoraceous basalt with top part covered by silty clay soil of 2–6 m thickness.

Main groundwater strikes range from about 75–157 m below the ground. The water table is under confined and semi–confined condition with recorded pressure heads ranging from about 11–61 m above the water strike. The yield of the wells was found to be highly variable. The test wells located within the main Ririba rift area locality relatively higher yields.

The drilling result shows the main aquifer in the volcanics is situated between about 100 and 250 m depth. Below this depth lies the basement rock that acts as regional impermeable layer.

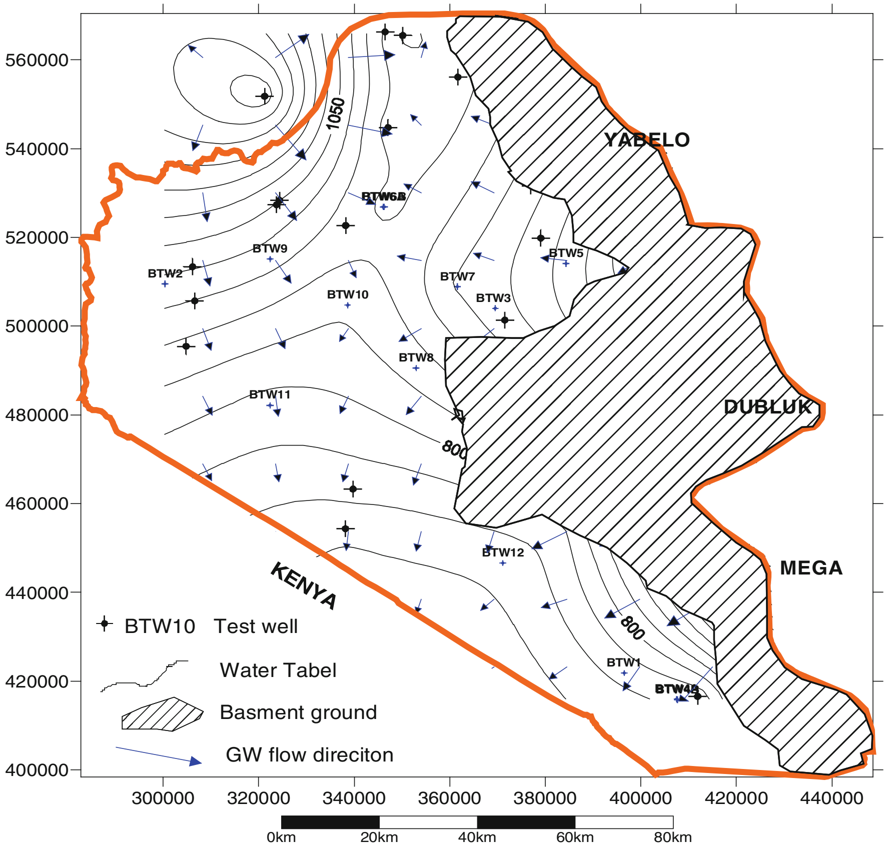


Fig. 2.23 Water table map of the Bulal basalt aquifer (from OWWDSE 2009)

From the drilling and testing results as well as related field hydrogeological evidences two other laterally less extensive aquifers of local importance has been recognized. These are (a) the alluvial deposits mantling the Bulal basalt and (b) the quaternary scoria and basaltic tuffs in the south eastern sector of the area bordering Kenya. Pumping test results indicate the transmissivity of the Bulal basalt aquifers is in the range of 10 m^2/day 100 m^2/day.

2.10 Groundwaters in the Main Ethiopian Rift and Flow Along Plateau-Rift Transects

The volcanic aquifers of Eastern Africa are placed as the least understood hydrogeologic system (UNESCO 2006). Compared to other aquifers in Africa, the volcanic aquifers of Eastern Africa are known for their lateral discontinuity, low storage capacity, and shallow groundwaters circulation following shallow flow paths.

The suitability of groundwater for water resource use in the rift is hampered by water quality limitations. In the center of East African rift, higher levels of salinity (Reimann et al. 2003) and fluoride (Kilham and Hecky 1973; Yirgu et al. 1999; Ayenew 2008) and elevated concentrations of trace elements such as uranium and arsenic (Reimann et al. 2003) are the most widely documented groundwater water quality degraders. In a recent survey in the Central Ethiopian Rift, Kassa (2007) documented that 80 % of groundwater well failures and abandonment after construction is related to discharge of poor quality (high salinity and high fluoride) waters.

In mountain bounded aquifers such as the Ethiopian rift aquifers because of the complexity of the stratigraphy and hydrography understanding the hydrogeology of the rift floor necessitates an understanding of the mechanism of groundwater flow and origin along the mountain—valley transect. Through this transect analysis important hydrogeological questions are sought to be addressed including (a) at what rate—fast, slow—groundwater recharged at high plateau reaches the valley aquifers, (b) what is the mechanism of the flow-diffuse, focused, (c) what is the contribution of each component of recharge—mountain block recharge, mountain front recharge (e.g. valley precipitation, flood water, lateral inflow from mountain etc.), (d) at what depth-shallow or deep—the groundwater from the highlands reach the valley bottom. Addressing this necessitates a closer look at the hydrogeology of mountain valley transects as given below.

The Western Afar Transect

The western side of the Afar depression is straddled by the Ethiopian plateau with elevation ranging between 3,600 and 4,000 masl. There is a sharp scarp transition zone over a distance of 70 km from 3,700 m at the edge of the plateau, to 500 m in the depression, which comprises an almost continuous Plio-quaternary rift following the 600 km stretch of the Afar western margin, only 10–15 km wide. This graben system is separated from the Afar low plains by an elongate continuous tilted block (600 km long, 30–60 km wide, 1,000–2,000 masl in elevation), dipping gently eastward towards Afar depression (Zanettin and Justin-Visentin 1974) (Fig. 2.24, also marked as 8 in Fig. 3.1).

This transect is characterized by the presence of marginal grabens bounding the principal rift floor. Three prominent marginal grabens (Kombolcha, Kobo and Raya) run N–S parallel to the principal rift axis. Despite the significant distance in the N–S direction of this transect, the E–W progression in geology, tectonics and aquifer composition are similar. The plateau and the escarpments are covered by trap series volcanics, and the marginal grabens are filled by alluvial materials and thin lenses of lacustrine sediments. The transitional slope between the rift floor and the grabens is covered by basalts belonging to the Afar Stratoid, and the rift floor is

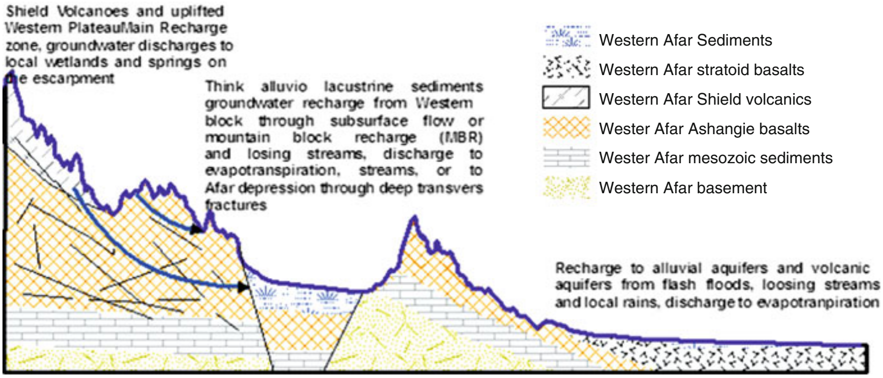
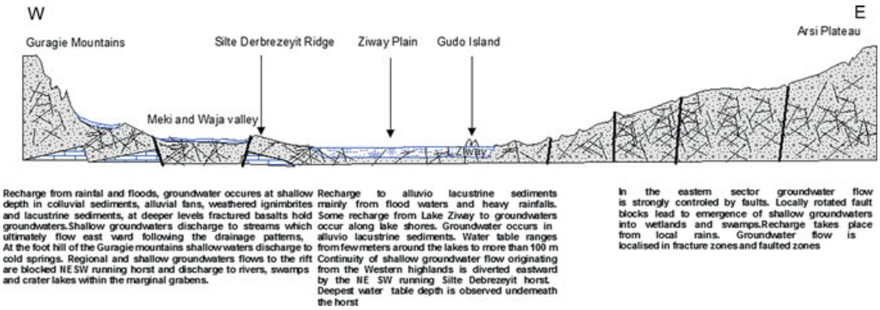


Fig. 2.24 Typical conceptual groundwater flow and recharge model along the Western Afar Transect, Modified after Kebede et al. 2007

covered by Quaternary basalts at depth and lacustrine and alluvial sediments near the surface. Thermal manifestations are localized in the axial part of the rift and around central volcanoes. These include the Tendaho and Allalobad springs located in the axial part of the rift and the Dobi springs near the Ethio-Djibouti border. The transmissivity of the alluvial aquifers in the marginal grabens vary from 0.5 to more than 500 m^2/day. The volcanic rocks making up the mountains are characterized by transmissivity ranging from 1 to 100 m^2/day. Rainfall decreases from 800 mm/year near the mountains to less than 200 mm/year in the rift floor.

The major ‘sinks’ for groundwaters coming from the mountains as mountain block recharge and runoff are the grabens. There is clear isotope hydrological evidence (Kebede et al. 2007) that the groundwaters from the mountains bounding the marginal grabens emerge first in the alluvial sediments as groundwater inflow. These groundwaters later join the streams and undergo evaporation. The evaporated waters later infiltrate through channel loss to recharge the groundwaters in the transitional slope and in the Afar rift floor.

In northern part of this transect, the region is drained mostly by intermittent streams which emerge from the highlands and disappear in the valley bottom to the alluvium or lacustrine sediments. The central part of Danakil depression is a flat salt encrusted plain, from which rises Dallol ‘Dome’, a notable topographic feature, composed of salt. The Teru depression (Sect. 3.13) is part of this transect and forms one of the regions receiving significant flows of rivers emerging from the highlands. Close to intermittent streams groundwater can be found at depth ranging from 80–120 m. In majority of the area alluvial sediments are the main source of groundwater for water supply uses. Fresh groundwater bodies can be found in association with alluvial materials and basalts and where evaporite sediments are minimum. Generally groundwaters are dominated by Na and Ca and Cl and SO_4 implying involvement of evaporation and salt dissolution in imparting salinity. The alluvial aquifers are found occupying grabens formed by tectonic activities.



Recharge from rainfal and floods, groundwater occures at shallow depth in colluvial sediments, alluvial fans, weathered ignimbrites and lacustrine sediments, at deeper levels fractured basalts hold groundwaters.Shallow groundwaters discharge to streams which ultimately flow east ward following the drainage patterns, At the foot hill of the Guragie mountains shallow waters discharge to cold springs. Regional and shallow groundwaters flows to the rift are blocked NE SW running horst and discharge to rivers, swamps and crater lakes within the marginal grabens.

Recharge to alluvio lacustrine sediments mainly from flood waters and heavy rainfalls. Some recharge from Lake Ziway to groundwaters occur along lake shores. Groundwater occurs in alluvio lacustrine sediments. Water table ranges from few meters around the lakes to more than 100 m Continuity of shallow groundwater flow originating from the Western highlands is diverted eastward by the NE SW running Silte Debrezeyit horst. Deepest water table depth is observed underneath the horst

In the eastern sector groundwater flow is strongly controled by faults. Locally rotated fault blocks lead to emergence of shallow groundwaters into wetlands and swamps.Recharge takes place from local rains. Groundwater flow is localised in fracture zones and faulted zones

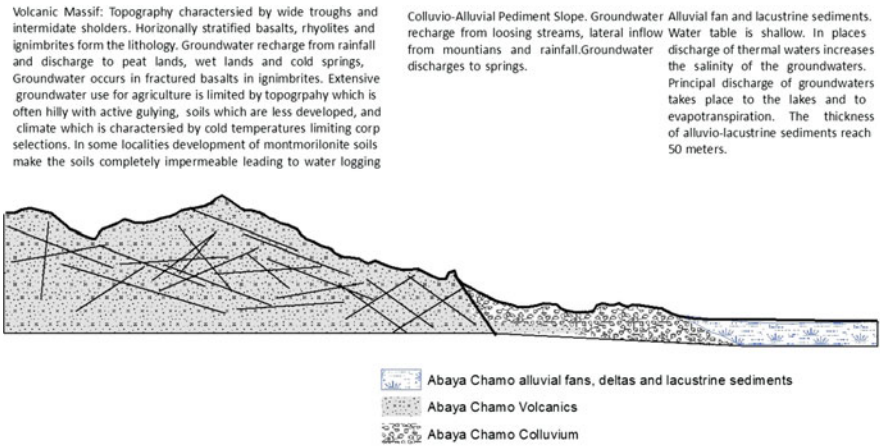
Fig. 2.25 Figure schematically showing features of groundwater recharge, flow and geochemistry along the two shields located in Guragie mountain—Arsi plateau transect (approximately between Welkite and Robe towns in Fig. 2.1)

The Butajira-Asela Transect

This transect extends from the Guragie mountains in the west to the Chilalo and Arsi massif in the East (Fig. 2.25). Typical feature of this transect is the abundance of acid volcanic rocks such as tuffs, ignimbrites and ash fall collectively known as the Dino formation. This formation is characterized by low aquifer productivity and yield. While the western margin is defined by a single prominent fault and minor marginal graben filled with sediments (e.g. Meki and Waja valley), the eastern margin is characterised by a series of step faults running parallel to the rift.

At the shoulder of the western escarpment, the geology is characterized by coarse grained (alluvial) deposits at the base of the scarp (pediment plain), and features shallow groundwater and springs. Well depths are in the order of approximately 90 m deep which penetrate mixed grain sized sediments, overlying ignimbrite formation. These aquifers have a yield of up to about 7 l/s. The transmissivity of the aquifer is indicated to be in the range of 16–137 m^2/day, values of 95–137 m^2/day are considered typical (Halcrow 2008). In the active western marginal graben also called Silti—Debrezeit fault zone contains lacustrine sediments and welded tuff on which are several interspersed coalescing nested scoria cones aligned parallel to the Guragie escarpment.

The groundwater around Siltie Debrezeyit ridge is deep within the fractured ignimbrite, groundwater being primarily found in large open joints. In a borehole drilled to a depth of 244 m at the Center of the Ridge (Koshe town), the main water strike was recorded between 234–244 m depth within the lithified pumaceous tuff (ignimbrite?) aquifer. Similarly, another well drilled in the area, to a depth of 229 m, has a recorded static water level of 174 m and yield of 5 l/s against draw down of 18 m from aquifers within water lain pyroclastics and rhyolite. Within the Woja River valley, groundwater occurs at relatively shallow depth in alluvial material (overlying ignimbrites) and offers some potential. One borehole in this area, 64 m deep, yielded 8.5 l/sec, with a static water level of 9.6 m, and a transmissivity of 232 m^2/day.


Volcanic Massif: Topography charactersied by wide troughs and intermidate sholders. Horizonally stratified basalts, rhyolites and ignimbrites form the lithology. Groundwater recharge from rainfall and discharge to peat lands, wet lands and cold springs, Groundwater occurs in fractured basalts in ignimbrites. Extensive groundwater use for agriculture is limited by topogrpahy which is often hilly with active gulying, soils which are less developed, and climate which is charactersied by cold temperatures limiting corp selections. In some localities development of montmorilonite soils make the soils completely impermeable leading to water logging

Colluvio-Alluvial Pediment Slope. Groundwater recharge from loosing streams, lateral inflow from mountians and rainfall.Groundwater discharges to springs.

Alluvial fan and lacustrine sediments. Water table is shallow. In places discharge of thermal waters increases the salinity of the groundwaters. Principal discharge of groundwaters takes place to the lakes and to evapotranspiration. The thickness of alluvio-lacustrine sediments reach 50 meters.

Fig. 2.26 Schematic hydrogeologic section of the Western Abaya Chamo Transect (transect running East wards from the town of Waka—see Fig. 2.1 for location of Waka)

At the valley floor (Ziway Plain), the depth to groundwater is shallow within the lacustrine deposits, particularly close to the lake, but declines (within the lacustrine deposits) away from the lake shore. The mixed sediments (sand, gravel, silt, clays, tuff, and diatomaceous materials) are in general anticipated to posses low to moderate permeability and but could provide moderate yields where coarser horizons are intercepted.

The eastern margin of the Ziway Shalla lake basin is marked by the dense Wonji fault belt which is dotted by several volcanoes. Faulting and fissural basalt flows are along the eastern margin are more intense than along the Siltii-Debrezeyit fault zone.

The Western Abaya Chamo: Lake Abya Chamo Transect

This transect is characterized by Tertiary volcanic cover making up the highlands in the west and alluvio-lacustrine sediments mantling the lowlands surrounding the Abaya-Chamo Lakes (Fig. 2.26). The center of the rift is only 30 km from mountain peak in the west (the transect in Fig. 2.26 runs between the town of Waka in Fig. 2.1 and the center of the rift in 20 km east of the mountain). The drainage basins are compact. This has led to the development of extensive colluviums deposits and associated alluvial fans extending down to the rift center and starting from the highlands. Unlike other Plateau-Rift transects in the whole Ethiopian Rift System, think alluvial-fan, colluviums deposits and lacustrine sediments directly extend to the center of the rift immediately mantling the plateau lithology. The western highlands stratoid basalts belonging to the Trap series form the dissected plateau on the top. Covering the trap series are Pliocene and early

Pleistocene ignimbrite sheets. Other prominent features are trachy-rhyolitic complex of Mount Damota (Located at Sodo in Fig. 2.1), a highly degraded shield-volcano. Fissurral basalt and associated scoria cones which date from Pleistocene cover a vast area to the north of Lake Abaya. Stratified lacustrine deposits of predominantly silty and clay texture cover the region west of Abaya. The alluvial cones lie on the piedoment slopes of the mountain ranges and stretch right down to the shores of Lake Abaya and Chamo. These sediments are chiefly alluvial and colluvial deposits which consists basaltic materials. Corse components pebbles mix with sand and silt. A recent strip of alluvial deposits is also found along the Bilate River and it opens into a wide delta in the Lake Abaya. Alluvial fans cover an area of 50,000 ha while the colluvio alluvial materials pediment surface covers an area of 41,000 ha. While the mountain bounding the rift from the West is characterized by low permeability rhyolites trachytes, the rift floor is mantled by alluvio-colluvial materials of hydrogeological importance. The hydrogeological features of this transect is shown in Fig. 2.26.

The Upper Awash: Middle Awash Transect

Geology and tectonics: This transect runs between the town of Addis Ababa in the West and and the Awash in the East (Fig. 2.1). The western margin of the northern MER[5] is displaced westward relative to Afar, forming what is commonly known as the Addis Ababa rift embayment (see unshaded area in Fig. 2.1 South of Addis Ababa stretching East–West). As a consequence, the rift is relatively broad here compared with other sectors of the Main Ethiopian Rift. The plateau–rift transition is gradual, because normal faults with displacements of up to tens of meters are generally confined to the region east of Debrezeyit (Damte et al. 1992; Mohr 1973). Within the rift valley are a series of asymmetric sedimentary basins, for example the Adama basin, bounded on one side by steep border faults (Ebinger and Casey 2001) and containing Pleistocene volcanic, volcaniclastic and lacustrine strata which overlie the Miocene—Pliocene felsic and mafic sequences of the Kesem and Balchi formations (Wolfenden et al. 2004).

Four principal geologic units (similar to the stratigraphy of Addis Ababa area-see Sect. 2.6, Fig. 2.27) crop out in this region. These are (a) the 30 Ma old flood basalts at the base of all the volcanic formation and resting unconformably on Mesozoic sediments; (b) a 10–11 Ma old second basalt sequence also called Addis Ababa basalt; (c) a 3.5 to 2.5 Ma old felsic volcanics containing ignimbrites, tuffs and rhyolites and (d) a 1.8 Ma old or younger intercalation of basalts and ashes. As a whole the basalts may constitute up to 60 % of the total volume at least in the northern MER (Wolfenden et al. 2004). Basalts are usually associated with monogenetic vents

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[5] MER—Main Ethiopian rift is a depression running from the Gidole area in the south west to the Awash town in the north East, see Fig. 2.1. Its width is around 80 km.

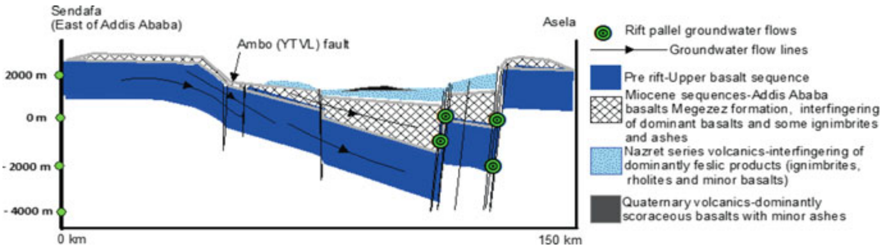
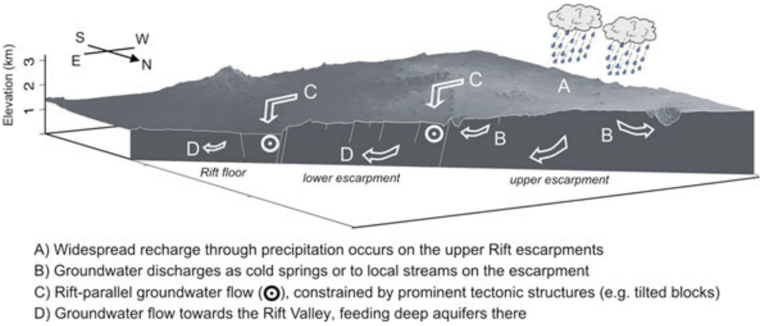


Fig. 2.27 Shematic figure showing major geologic features and hydrostratigraphic units central Ethiopian rift across the W–E transect from Northern plateau (east of Addis Ababa to East of Asela

and/or fissure eruptions, at the side of the main central volcano (Ebinger and Casey 2001). The MER is, therefore, mostly floored by several basaltic fields, silicic domes and calderas. These are interlayered and covered with Plio-Quaternary fluviolacustrine sediments (Le Turdu et al. 1999; Woldegabriel et al. 1992).

Hydrogeology and groundwater occurrence: In the Addis Ababa area, the intersection of Rift faults with an older, E–W trending structure (the Yerer-Tulu-Wellel Volcanic Lineament, YTVL, see Sect. 2.5) has formed transverse faults orthogonal to other rift faults, creating a “hydrogeological window” that enables groundwater flow from the escarpment to the Rift in this area (Kebede et al. 2007). This zone of transverse faults also enables the Awash River to drain the western escarpment, flowing into the Rift and continuing its course on the Rift floor, the only major river to do so (river running E-W south of Addis Ababa in Fig. 2.1).

The role of the Oligocene volcanics in holding and transmitting water in the central part of the rift is unknown however these lithologies are believed to be principal deeper aquifers around Addis Ababa (MWR 2007). At higher elevations on the Rift escarpments (1,900–2,400 masl), fractured basalts when covered by ignimbrites and volcanic ash, form confined to and semi-confined conditions in some places, with depth to water table given as ranging from 0 to 120 m (Kebede et al. 2007). Recent investigation (MWR 2007) reveals that this sequence yield up to 200 l/s and the aquifer is under confined or semi confined condition. The younger quaternary scoraceous basalts and associated ahses form highly productive aquifers in the Akaki and Debrezeyit areas (1,800–1,900 masl), at times with a thick cover of alluvial material (Kebede et al. 2007; Demlie et al. 2007). Borehole depth in the Rift often exceeds 200 m. Rift aquifers around Nazareth (Fig. 2.1 for location) and further east towards Welencheti (in a typical Adama graben, 10 km north east of Nazreth) are characterized by complex interlayering of alluvial/lacustrine sediments, pumice, fractured basalts and ignimbrites in a highly faulted terrain (Kebede et al. 2007). Water-bearing formations in the Lake Beseka area (100 km north of Nazreth) are mainly composed of very young fractured basalts and scoraceous basalts, as well as pyroclastic deposits such as pumice, tuff and volcanic breccias (Ayalew 2008). Alluvial and lacustrine cover is also predominant in this region.



A) Widespread recharge through precipitation occurs on the upper Rift escarpments
B) Groundwater discharges as cold springs or to local streams on the escarpment
C) Rift-parallel groundwater flow (⊙), constrained by prominent tectonic structures (e.g. tilted blocks)
D) Groundwater flow towards the Rift Valley, feeding deep aquifers there

Fig. 2.28 Schematic groundwater flow and dynamics developed from multiple evidence including isotopes, geochemistry and tectonics (from Bretzler et al. 2011)

Vertical structuring of the aquifers apparently occurs, as is observed in the existence of a shallow and a deep groundwater system in the investigation area. Shallow groundwater frequently discharges as cold springs on the upper Rift escarpments, though boreholes also tap deeper sources in this area. Shallow hand-dug wells (depth <20 m) only occur locally and infrequently in the Rift Valley. Associated with active fault zones, numerous thermal springs occur in this transect, especially in the tectonically active Fantale/Lake Beseka area on the Rift floor and around the Bosetti volcano. Figure 2.28 shows groundwater flow and origin schematically stretching from the higher escarpment around Addis Ababa to valley floor around Nazret.

Groundwater geochemistry: Groundwater from the upper and middle Awash basin shows a clear spatial hydrochemical distribution. Water discharging from cold springs at high altitudes (>1,900 masl) on both the eastern and western escarpment is distinguished by low electrical conductivities (median ~300 μS/cm) and a predominating Ca-(Mg)-(Na)-HCO_3 water type. Boreholes on the lower escarpment (1,600–1,900 masl) also show this water type, but an increase in electrical conductivity (median ~600 μS/cm), pointing to longer residence times and increased water–rock interaction. There is a distinct shift from Ca–HCO_3 to Na–HCO_3 dominated waters when moving from the escarpment to the Rift floor. The increasing concentrations of Na+ correlate with a corresponding increase in HCO_3^- ($r^2 = 0.88$) and subsequent decrease in Ca^{2+}. Electrical conductivities in Rift Valley groundwater are the highest in the whole study area (median ~1,100 μS/cm) (Bretzler et al. 2011).

The main chemical process determining the hydrochemistry of Rift floor groundwater is the weathering and hydrolysis of silicate minerals such as feldspars, as has also been confirmed by previous studies (Darling et al. 1996; Gizaw 1996; Rango et al. 2009). This results in an increase in HCO_3^-, Na^+ and K^+ concentrations in the water with increasing residence time and water–rock interaction (Herczeg and Edmunds 2000). Silicate hydrolysis is aided by the high CO_2 partial pressure observed in the Main Ethiopian Rift (Darling et al. 1996; Gizaw 1996), explaining the very high HCO_3^- and Na^+ concentrations especially observed in thermal waters circulating in active fault zones where geogenic CO_2 rises up from mantle sources. As Rift floor groundwater becomes oversaturated with respect to calcite and dolomite, seen in saturation indices >0, these mineral phases precipitate. Cation exchange of Ca^{2+} for Na^{+} on clay minerals is most probably another process, which together with precipitation, is responsible for the near complete removal of Ca^{2+} and Mg^{2+} from solution (Rango et al. 2009).

Tectonics and groundwater flow: At regional scale the flow of groundwater from the highlands in west to the rift center is facilitated by the 'suitable geohydrologic condition of the YTVL hydrogeologic window'. The intersection of the YTVL with the MER created a situation where by groundwater movement from the escarpments to the Rift floor therefore seems to occur orthogonally to the main SW–NE fault direction. When viewed on a smaller scale, groundwater flow paths are affected by local structural setting. One area where the connection of groundwater flow to tectonic structures can be observed are the tilted block structures on the first escarpment step near the towns of Bolo Gyorgis and Arerti (Fig. 2.29). Normal faulting during rifting has resulted in a series of large, tilted blocks dipping towards the Rift border. This dipping block of rocks channel groundwater flow parallel to the dip direction and discharges where the dipping blocks come in contact with the fault scarps. This typical case of the Bolo Gyorgis-Arerti block has resulted in emergence of springs at the Kesme dam axis during recent excavation.[6]

2.11 The Mesozoic Sedimentary Aquifers of Ethiopia

Geology

Mesozoic sediments occur in three regions of Ethiopia. The sediments are exposed in South Eastern Ethiopia (with three sub region including Wabishebele, Genale-Dawa and Ogaden), the Mekelle-Metema and Blue Nile basins (Fig. 1.2 for location). The stratigraphy of the succession is given in Fig. 2.30. In the Blue Nile plateau the wedge of sedimentary rocks, although over 2,000 m in thickness where it is exposed in the steep canyon walls, actually covers but a relatively small surface area of the Blue Nile River Basin in comparison with the area covered by volcanics and basement Precambrian rocks. Mekelle sedimentary basin (in the North) occupy 12, 000 km^2. Abay basin sedimentary basin covers 55,000 km^2.

In Ethiopian hydrogeological reports it is common to find estimation of hydrogeological features (such as permeability, storage properties and aquifer potential) of the Mesozoic sediments adapted from other sedimentary basins based

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[6] The Kesme dam is a dam to be built on the Kesem river for irrigation purpose. While excavation has been taking place to anchor the core to key trench several artisan springs emerged on the dam axis hindering construction activities.

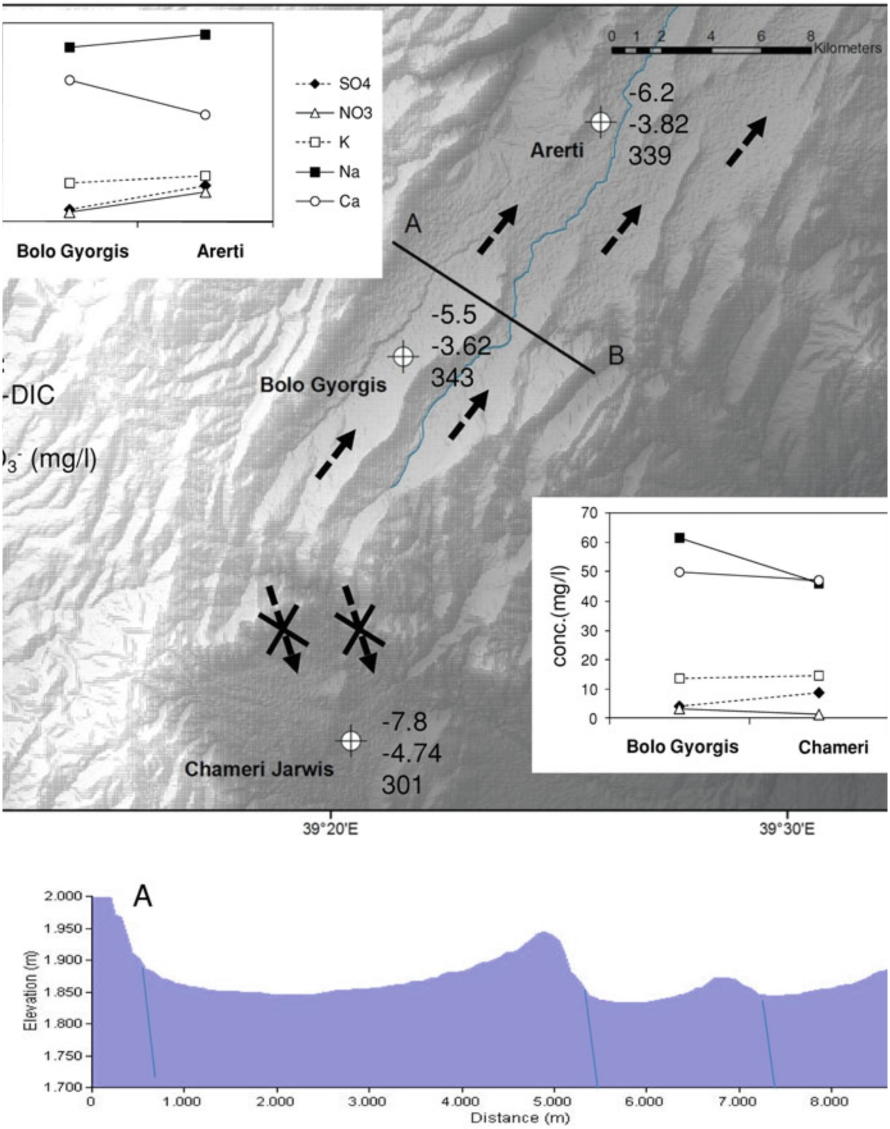


Fig. 2.29 Close-up of the Arerti/Bolo Gyorgis area, including a cross-section showing the morphology of tilted block structures of this region. Changes in hydrochemistry between the boreholes Bolo Gyorgis, Arerti and Chameri Jawis are shown on the plots. Presumed groundwater flow directions, supported by hydrochemical data, are indicated by the *arrows* (Bretzler et al. 2011)

on lithologic similarity. For example the Mesozoic Adigrat sandstone aquifers were anticipated to have similar hydrogeologic properties as that of the Nubian sandstone underlying the vast region of north east Africa (Chernet 1993). However

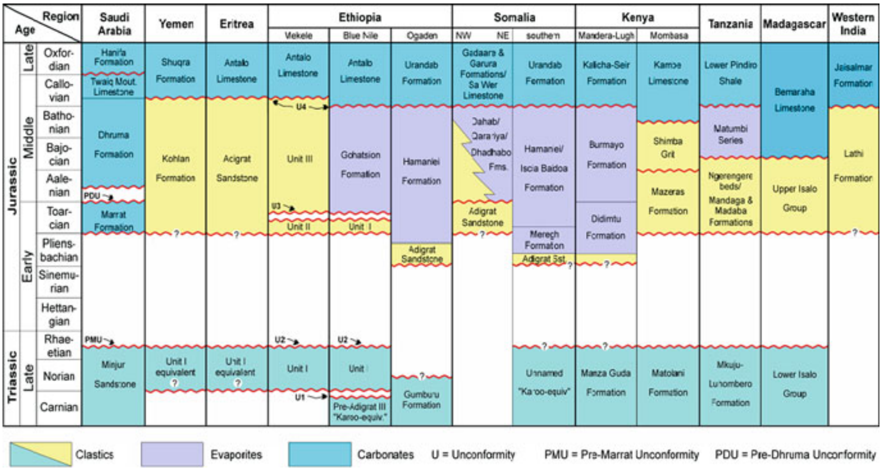


Fig. 2.30 Correlation chart of the Mesozoic successions of the Horn of Africa and Arabia (Enkurie 2010)

there is a major distinction between the geologic history of the Continental-Marine sediments of the Paleozoic–Mesozoic era of Ethiopia and the rest part of Africa and Arabia (Enkurie 2010). In both the East African and North East African sedimentary basins, the sedimentation occurred thanks to the intraplate extensional deformation. But this extensional deformation ceased in southeastern Gondwana (including Ethiopia and Horn of Africa) and was replaced by a major crustal uplift and accompanied intraplate magmatic activity. In contrast, the northeastern part of East Africa and Arabia formed part of stable and slowly subsiding Neotethyan passive margin. These regional scale tectonic cycles have resulted in differences in hydrogeologic properties and groundwater resources potential.

Stratigraphy of the Sedimentary Sequences

A detailed account of the stratigraphy, lithofacies, and correlation of the three sedimentary basins of Ethiopia is given in (Enkurie 2010). The following descriptions are mainly excerpt from this work.

Northern Ethiopia: The Paleozoic and Mesozoic sediments of North Ethiopia can be divided into six stratigraphic units namely Enticho sandstones, Edagaarbi glacial, Adigrat sandstone, Antalo Limestone, Agula shale and Upper Sandstone (Amba Aradom formation).

Central Ethiopia: In Central Ethiopia Paleozoic and Mesozoic succession come in five stratigaphic units namely, the Pre-Adigrat formation, the Adigrat formation, Gohatsion formation, Antalo Limestone, Muger Mudstone and DebreLibanos sandstone.

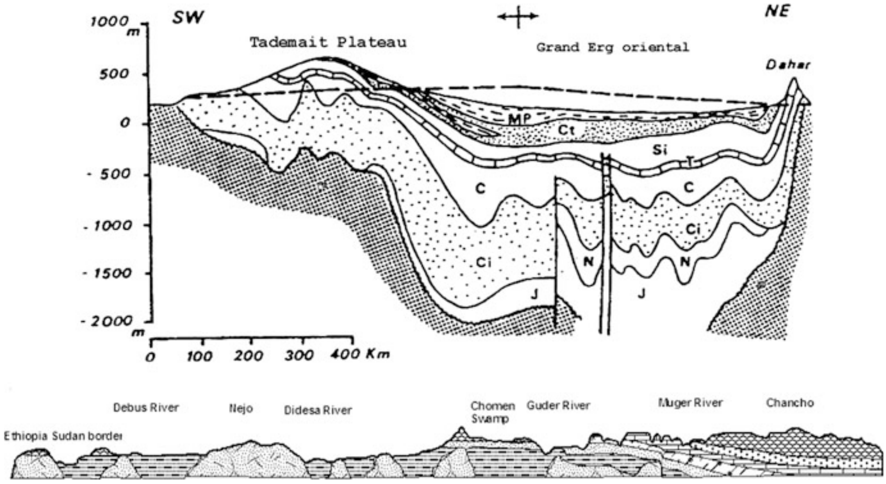


Fig. 2.31 Comparison of cross-sections of geologic structures of sedimentary basins of Ethiopia with that of the Northern Africa. Upper figure shows structural and stratigraphic setup of the Sedimentary basins of North Africa (Algeria-Tunisa) and the lower figure shows the same in sedimentary basins of Blue Nile Plateau. *Upper* figure from Castany (1982) and *lower* figure from USBR (1964)

Southeastern Ethiopia: Grossly the Mesozoic sediments of Eastern Ethiopia is subdivided into three broad stratigraphic units namely the Adigrat sandstone, the Antalo super sequence and the Upper sandstone unit.

In northern Ethiopia the Enticho sandstone has a thickness of 200 m and it overlies Neoproterozoic basement rocks (Fig. 2.34). It is composed of sandstones and channels fill conglomerates. The Edagaarbi glacial consist predominantly of grey, black or purple clay and siltstones that often contain dispersed pebbles or boulders up to 6 m in diameter. The thickness of the succession is highly variable but attains a maximum thickness of 150 m near its type section. The thickness of Adigrat sandstone reaches 670 m. It is composed of well sorted fine to medium grained sandstone at the base and muddy sandstone at the top. The thickness of Antalo limestone varies from 300 to 800 m. The unit is composed of pure limestone cliffs and marl interbeddings. The Agula Shale with a thickness of up to 300 m is composed of fine sandstones, laminated black shales, mudstones, dolomites and gypsum beds. The Ambaradom formation unconfromarbly rest on the Agula shale and consist of white or red sandstones with interbeded silt and mudstones, lateritic paleosols and lenses of conglomerates. The Amba Aradom sandstone correlates with the Debrelibanos sansstone of the Blue Nile basin.

In central Ethiopia the pre-Adigrat sandstones form extensive unit underlying the Adigrat sandstone. They are composed of principally well sorted sandstone. With a thickness reaching 300 m, the Adigrat sandstone here is composed of fine grained sandstone at base, coarse grained sandstone at the base and silty to muddy sandstone at the top. The Gohatsion formation at 450 m thickness consists of dolostones, marlstones, and shales, bioturbed mudstones with thin siltstone intercalations, fine grained sandstones and thick gypsum beds. The Antalo Limestone has a thickness of 420 m and consist of mudstones, marl and limestone intercalations at base followed by interbedding of marly limestone and marls at the middle part and up to 50 m thick limestone cliffs at top. The Muger mudstone ranges in thickness from 15–320 m. It consists of alternating beds of gypsum, dolomite, shale, sand, silt and mudstones. This unit is equivalent to the Agula shale in northern Ethiopia. The Debrelibanos sandstones cap the entire formation. The thickness of the Debrelibanos formation varies between few meters and 172 m. It is composed of alternating beds of mudstone, fine grained sandstones, and massive cliff forming sandstone.

In the sedimentary basin of south eastern Ethiopia the pre-Adigrat formation of the Blue Nile basin and Mekelle Outlier is represented by Karoo sedimentary sequence which is only encountered in drilled petroleum wells. The Karoo sediments are composed of Calub Sandstone, Bokh Shale and the Gumburo sandstone. Unlike the two other sedimentary basins, where sedimentation ended in upper cretaceous, in the South Eastern Ethiopia sedimentation continued until Eocene and thus the entire package of sedimentary rocks is much thicker and lithologically variable. The Mesozoic sequence is composed from base to top the Adigrat Sandstone, the Hamainile-Urandab-Gabredarre Limestone formation, the Korahe formation the Multahil gypsum formation, The Ambaradom sandstone, Ferefer, Belete Uen, Jesoma sandstone, Auradu limestone and Taleh (anhydrite, gypsum, shale and dolostone) formations.

The Hamainile formation is carbonate-clastic-evaporite unit. Urandab formation is dark grey black organogenic shales and subordinate limestone layers. The Gabredarre formation is a thinly bedded alternating oolitic and marly limestone, interbedded in the upper section with gypsum and shale. The Korahe formation is composed of sequence of gypsum, anhydrities, iron carbonates, sandstones, shales, marl and dolomitized limestones. The Mustahil formation is composed of yellowish, fine grained, highly fossiliferous limestone.

Structural Setup of the Mesozoic Sediments and Groundwater Potential

As shown in Fig. 1.3, by volume, the Mesozoic sediments are the most extensive lithologies in Ethiopia. However, the Mesozoic and Tertiary sediments cover less than a quarter of Ethiopia. Outside the zones where these sediments are exposed, the surface structure is little known because of the plateau is covered by a large volume and thick (often exceeding 1 km) volcanic materials which erupted between 40 and 22 Ma.

Notable hydrogeologic and geologic feature of the Mesozoic sediments of Ethiopia are (a) Uplifting and formation of tabular plateaus (b) deep incision by

Table 2.9 Relation of tectonics, climate and hydrogeologic properties of sedimentary aquifers

Subsiding	Paleogroundwaters	Karstic aquifers
	Paleokarsts	Artesian basins
	(*North Africa*, *Middle east*)	Paleogroundwaters (*Europe*, *China*)
Uplifting	Fractured aquifers	Karst aquifers
	Little karstification	Low storage in the basin
	(*East Africa*)	(*Europe*, *China*, *Asia*)
	Low rainfall	High rainfall

river gorges, (c) absence or limited karstification intensity in karistifiable rocks (d) absence of regional folding and flexures at their margins, (e) extensive cover by the volcanics. These contrast with the typical sedimentary basins elsewhere in Northern and Eastern Africa. In contrast to the Sedimentary basin aquifers of northern and Sahel Africa, in the Ethiopian Mesozoic sediments, structural traps such as syncline formed from compressional deformation are uncommon leaving little room for large volume groundwater storage. Figure 2.31 and Table 2.9 compare the tectonic structure of a North African sedimentary basin and that of the Abay basin.

Regardless of their isolation by the thick volcanic cover in some places buried Mesozoic sediments play an indirect role in affecting the shallow groundwater regime in the overlying volcanics (Kebede et al. 2006, see also Sect. 2.5 and Fig. 2.13). In Lake Tana basin and the Yerer Tulu Welel Volcanic Lineament zone the presence of volcanic activity and low enthalpy geothermal systems lead to the heating of the underlying Mesozoic sediments which then liberate a considerable among of carbon dioxide gas and other gases (nitrogen, sulphur and argon). The CO_2 gas emanating from the Mesozoic sediment de-carbonation has led to the formation of numerous naturally sparkling springs, notably around Ambo, Woliso, Diddessa Valley, South of Lake Tana, and Filwuha thermal springs around Addis Ababa.

Groundwaters in the Ogaden Multilayered Sedimentary Aquifers

The sedimentary basins of Southeastern Ethiopia occur in three geologic zones namely the Ogaden, the Wabishebele and the Genale Dawa basins. The western boundary of the Ogaden (Fig. 3.32) is separated from the Wabisheble basin (west of the Ogaden sedimentary basin) by a prominent NNW-SSE running regional fault called the Marda fault.

Groundwater occurrence: In the Ogaden sedimentary basin six aquifer types occur (Fig. 2.32). Detailed account of the groundwater occurrence in the Ogaden sedimentary basin is given in Hadwen et al. (1973) most of the knowledge to date about the hydrogeology of this region is derivative of this study.

In the lowlands of the Ogaden the main near surface aquifers are the superficial deposits confined in the major valleys. Minor aquifers are found in the Mustahil,

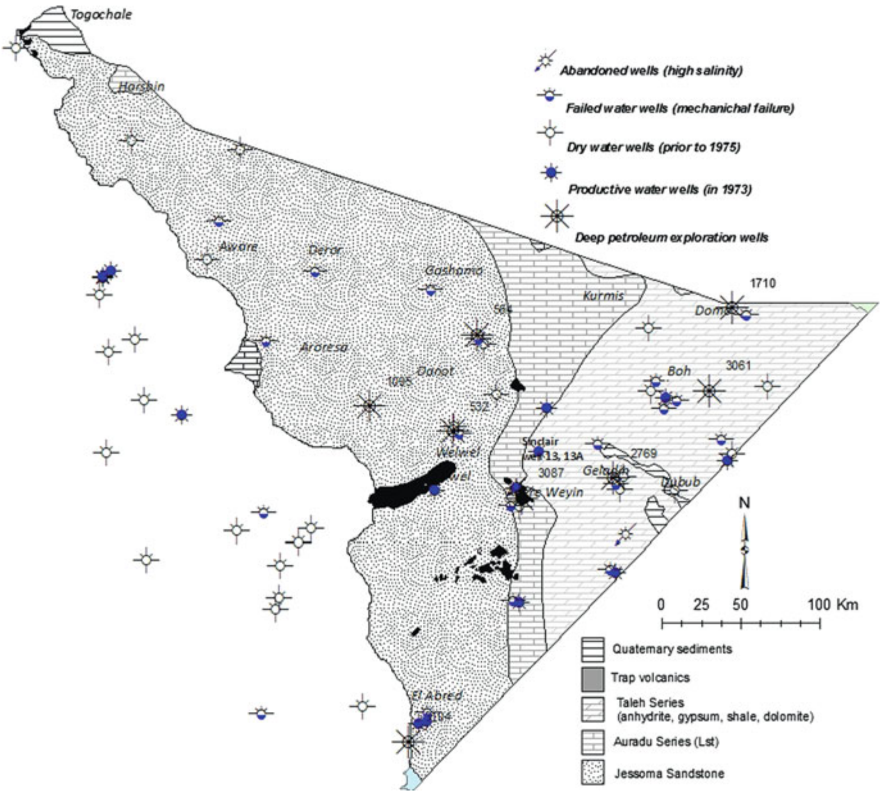


Fig. 2.32 Simplified geologic map and distribution of successful and failed water wells in the Ogaden sedimentary basin. Deep petroleum wells and their depth are also indicated

Belet Uen and Auradu Series, in trap series basalts and in localized superficial deposits. In Jijiga area (Northern most tip of Fig. 2.32) the lower sandstone and Antalo limestone form a single continuous aquifer and are exposed west of the map (not indicated in the map because of scale).

Few kilometers south of Jijiga boreholes drilled for the town water supply, reached the total depth of 70 m after having encountered between 20 and 50 m of water saturated Urandab Limestone and Adigrat sandstone. They have shown a discharge from 7.6 to 16.8 l/s with as specific capacity from 0.6 to 2.6 l/s meter drawdown (Hadwen et al. 1973). However boreholes with much lower discharge have been drilled north of Jijiga which showed an average discharge of less than 1 l/s with a specific capacity of about 0.3 l/s per meter drawdown, having encountered a thickness of only 10 to 20 m of saturated Urandab limestone and Adigrat sandstone. In Jijiga area the quality of groundwater contained in the limestone and sandstone is quite variable, showing TDS content from 1,500 to 2,000 ppm in boreholes located in Jijiga plain. Generally evaporites layers within the Limestone Group, causes splitting, stagnation and salinization of the underground water elsewhere in the Sedimentary basin aquifers in SE Ethiopia.

The Jessoma sandstone covers the most extensive area in the Ogaden. It underlies most of the Ogaden. It is poorly recharged it does not have a regional water table and even perched water lies deeper than 300 m, and moreover because of its friable and uncemented nature the formation gives great difficulties in drilling. Several wells drilled (e.g. at Derar, Gashamo, Aroresa) in early 1970s turns out to be dry or abandoned due to mechanical failure (Fig. 2.32). In Jesoma sandstone drilling data shows water table is deeper than 250 m. However when water is encountered at shallow depth the water quality is potable.

Deeper drilling for petroleum holes reveal salt waters (up to 20 g/l) below depth of 1,560 m and fresh water zones above depth of 1,560 m (less than 10 g/l) in the 3,061 m deep Boh well. Severe circulation loss has been encountered in variety of locations in the Jessoma sandstone.

The Auradu Seiries (Late Paleocene early Eocene limestone) formation is massive limestone and yields some fairly fresh water. There are successful boreholes, notably at Burdar, Agarewein and Ado (Sinclair wells 13 and 13 A). The formation thins westwards, in Somalia it is as much as 450 m thick, but in Ethiopia it seldom exceeds 200 m, though petroleum well at Boh (Fig. 2.32) shows above 430 m thick Auradu series rocks under the Taleh formation. A number of boreholes were not completed due to problems of lost circulation. Most of the water production holes drilled by oil companies were originally capped as there was then no population in areas.

Taleh series is of alternating anhydrite, gypsum and shale with some thin interbeds of dolomite. The unit is of Middle to Early Eocene age. Gypsum does not occur everywhere in the sequence and several boreholes yield potable waters. At Geladi, drilled wells struck mineralized water and sometimes with high ammonia content. At BH-18 water is purgative but used. At Boh several holes were drilled through the Taleh Series into the underlaying formation yielding up to 2 l/s with no evidence of declining yields and in places the wells return potable water.

As concluded earlier by Hadwen et al. (1973) water supply in Ogaden cannot depend on drilling boreholes into the three principal lithologies (Jesoma, Auradu or Taleh formations), except perhaps in areas of Jurassic limestones around Jijiga or in Mustahil formation west of the Marda fault, and even in those areas pockets of tracts of salty water are common.

Alluvial deposits are the most reliable aquifers, and especially in the northern sector of the alluvial valleys considerable storage of good quality water can be safely exploited to a much higher degree (see Sect. 3.16 for details). South of Kebre Dehar (Fig. 3.19) alluvial waters become more and more saline. Alluvial deposits also play great role even in higher grounds of the Wabisheble basin (Fig. 3.16). In Fik shallow wells with hand pumps on Fik stream and water holes on the wadi are the main source of water for the town of Fik. Hamero town's water supply source is a shallow well with hand pump on the bank of Hamero stream. The Fik wadi beds are covered by lose sediments, composed of boulders, gravel and sand.

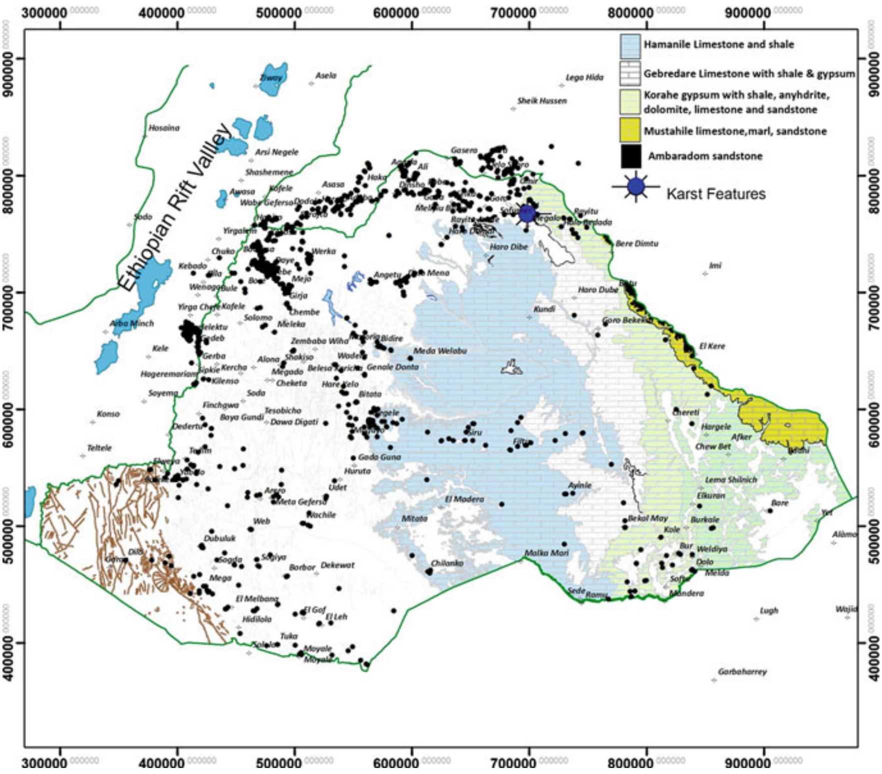


Fig. 2.33 Geological and hydrogeologic features of the Genale Dawa basin

Recharge and geomorphology: The extensive flat surface east of the Marda fault is covered by sandy soils coated with reddish soil or calcareous duricrust (caliche). This limits recharge rate going down to the aquifers. Recharge is considerably low, rainfall is less than 200 mm per year in Eastern most zone and increases only to 500 mm/year in the northern sector of the Ogaden. Vertical recharge that occurs is concentrated along major valleys, especially in their superficial deposits and in fault gouges in valleys that are structurally controlled. In the mountains and foothills erosion is so deep that recharge water soon finds its way towards valley axis, to become streams or subsurface wadi gravel flow.

Groundwater Occurrence in the Multi-Layered Sedimentary Basin of the Genale Dawa Area River Basin

Physiographically the Genale Dawa basin is characterized by low relief tabular plateau made of Mesozoic sediments separated by deep river incisions. The elevation ranges from around 200 m to over 4,300 m in the North.

In the Ganale Dawa basin (Fig. 2.33) the Amba Aradom sandstones are variegated qrtzose sandstones of fluvial and/or littoral origin. In the south and north east, the Amba Aradom is an aquifer of relatively high productivity. Its high permeability and productivity is a result of the moderate to coarse grain size, loose cementation and limited shale intercalation. The Amba Aradom sandstone is exposed in the eastern strip of the Genaledawa basin.

The Gabredarre include oolitic limestones, marls and some gypsum. This formation is horizontally bedded and is characterized by solitary caves and karst features. In this region the limestones exhibits the highest degree of karstification when compared to low degree of overall karstification in karitifiable rocks of the country. The Garbredarre formation has limestone cliffs that are moderately jointed and having intercalations of sand, marl and gypsum beds. It has moderate permeability and productivity and saline groundwater is encountered in wells. The famous Sofomar caves are located in the Garredarre formation (Fig. 3.33 marked as karst). The Gabredarre formation grades down to the underlying Urandab formation that is equivalent of the Antalo limestone.

The Haminile formation has organogenic and oolitic limestones with shale and sandstone. These limestones are well jointed and they have moderate to high permeability. According to the boreholes between Filtu (center of Fig. 2.33) and Negele (west in Fig. 2.33), the groundwater level is very deep (deeper than 200 m). When water table is shallow the Hamanile series limestone has a relatively higher productivity but the depth to water table generally exceeds 200 m in the highlands and midlands where it is exposed. On the Dolo to Negle Borena road around Bidre, the Haminile limestone plateau is observed. This limestone is marly limestone, fractured with thin beds of about 1 m. The Haminile Limestone here has a number of boreholes in a line running in an east west direction. Towards the contact with the Basement to the north, some boreholes did not stick groundwater at depth greater than 200 m.

Around Negele Borena the Hamanile limestone formation come in at least five sub-units characterized by variable lithologies and intercalations. Nearby Negele town the lowest thickness of the succession is recorded. The maximum thickness of this succession is considered to reach about 700 m in the surrounding of Filtu. It is a carbonate sequence constituted by mudstone to grainstone interlayered/interbedded with shale, marl, etc.

The Korahe formation is known as aquifer of low productivity. It is dominated intercalation of sandstone, gypsum, shale, anhydrite beds. Groundwater in this formation is saline and has poor quality.

Groundwater Occurrence in the Mekelle Outlier

The Mekelle Outlier, in northern Ethiopia, is made up of a variety of clastic (Enticho and Adigrat formation) and calcareous sedimentary rocks (Antalo formation) capped by thin layers of clastic sedimentary rocks (Ambaradom formation).

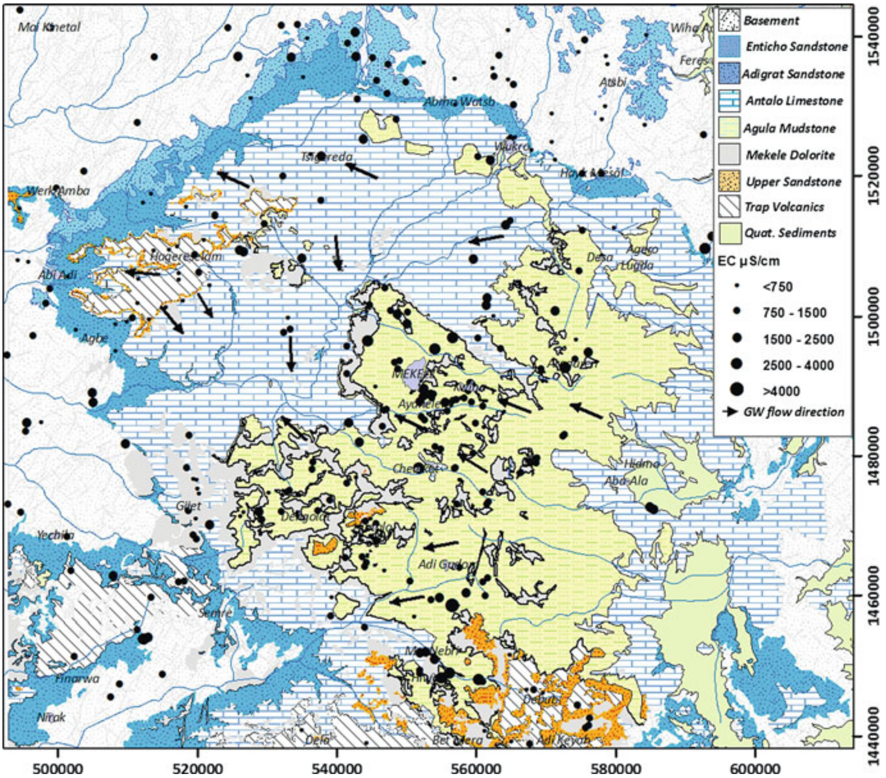


Fig. 2.34 Geological map of the Mekelle Outlier, the map also shows water points and associated groundwater electrical conductivity. The *arrows* indicate direction of groundwater flow

The upper members of Antalo formation are intruded locally by dolerites. The sedimentary outlier is in turn covered by extensive basalt flows (Trap series) in the south and south west. The Paleozoic–Mesozoic sedimentary sequence is bounded in the north, west and east by Precambrian metamorphic rocks (Fig. 2.34). Main structural features noted in the sedimentary rocks include bedding with variable thickness, high degree of fracturing and tilting of the sedimentary bedding in different directions: south, north, west and east.

All the lithologies are known to hold and transmit water at variable rates. The major challenge to groundwater storage is the dissection of the plateau by river incision and regional faults leaving isolated tabular plateau of small lateral extent. The low annual recharge and its concentration to 2 months of the year (July and August) limit the overall recharge rate. When suitable structures exist, high yielding aquifers can be found.

The major regional structural element related to tectonics in the area is normal faults with varying trends, lineaments and fractures. Two systems of faulting are noted in many places. The earliest faulting generally trends WNW–ESE and is the oldest. This system is affected by relatively small N–S faulting dipping to the east or west at higher angles.

2.12 The Karst Aquifers of Ethiopia

Karst

Karst is a geomorphic name of landscape shaped by the dissolution of a layer or layers of soluble bedrocks usually carbonates, limestones or dolomites. Karst can also develop in marbles, sandstones, evaporates and volcanic rocks. Many karst regions display distinctive surface features, with sinkholes, dolines being the most common. However, distinctive karst surface features may be completely absent where the soluble rock is mantled, such as by glacial debris, or confined by superimposed non-soluble rock strata. As it appears the term karst has its origin from Indio-European word Karra meaning stone. Notably several terms of similar Cushitic and Semetic philological linkage and similar connotation are used to describe rocks or geomorphic features. For example Kerasa means rock or dry stream valley in Oromo Language, Kars means open earth, gara means knoll or mountain. Such philological similarities signify how much karst related landforms (particularly caves) must have strong link human with the environment. One of the karstified regions in Ethiopia is Kersa in Eastern highlands.

Worldwide Karst aquifers contribute more than 25 percent of drinking water supply. Most of these prominent karstic aquifers underlie significant portion of countries in the high latitudes (Europe, China, and North America).

Distribution of Karstifiable Rocks in Ethiopia

In Ethiopia more than 20 % of the land is underlain by karstifiable lithologies (limestone, dolomite, marble and sandstone) of which less than one percent is karstified (Fig. 2.35). Of these only few karst landforms and karst aquifers are documented to exist in Ethiopia. For example hydrogeological investigation in the Eastern section of Abay Valley (central region in Fig. 2.35) reveal that structures like stylolites, karsts, and chert nodules, indicative of limestone dissolution, are only observed in very few exposures and mostly towards the bottom of the limestone. The report on the Jema valley (Sima 2009) also shows the degree of karstification as only embryonic. Rather groundwater occurrence in the limestone terrain of Ethiopia is dominated by fissured porosities or dual porosity (fracture and matrix porosity) medium.

Karstifiable rocks occur in three regions of Ethiopia including the Mekele region, the north eastern plateau -Ogaden, the Blue Nile gorge and the Afar

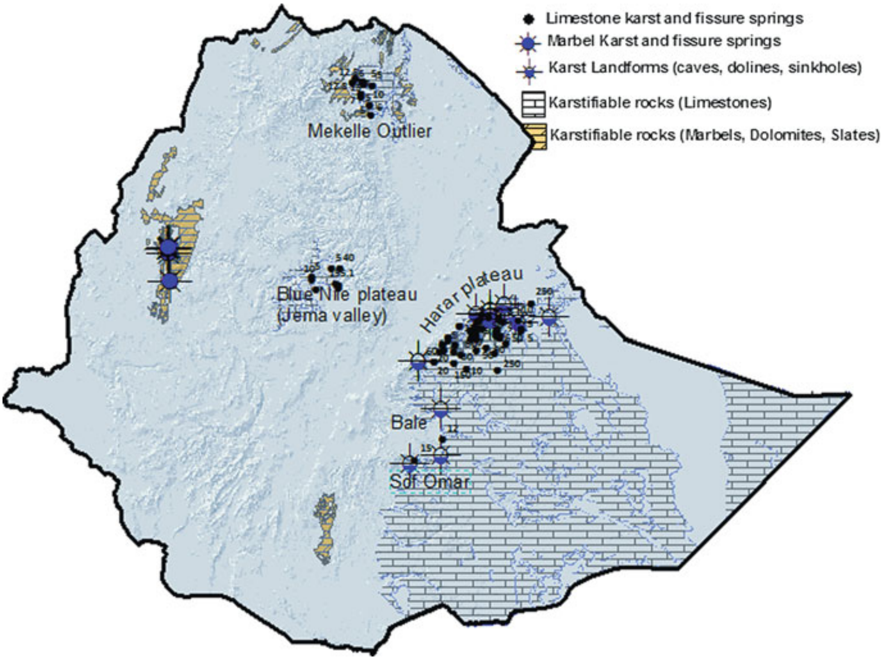


Fig. 2.35 Distribution of major karst features of Ethiopia and extent of karstifiable rocks (mainly Mesozoic sediments: sandstones, limestones, gypsum, shale etc.) and prominent karst features and karst springs (numbers near symbols indicate discharge rate of springs)

depression. Karstified regions in basement aquifers of western Ethiopia is of minor importance because of its aerial extent. In the Blue Nile gorge limestone members of the Antalo formation include a high proportion of marl and clay layers, pure limestones not exceeding 50 m. In the Mekele region, the Antalo limestones outcrop over a large area and attain a thickness of about 800 m, the thickest well exposed succession in Ethiopia. Much of it is marly limestone, however, with many clay and shle layers.

The rarity of well developed karst land from in the Mekelle outlier and the Abay valley is attributed to the small thickness of pure limestone beds as compared to the intercalated marl and shale layers. In Harar plateau and Bale area however the thickness of the pure limestone layers reaches several hundred meters thick allowing development of karst landforms and larger interconnected caves.

By far the most important cave bearing formation in Ethiopia is the Antalo Limestone. As normally defined this formation includes associated shales, siltstones and gypsum, whose thickness may be greater than limestones themselves.

Notable ones include the SofOmar Cave and karst systems, and karst systems of upper Wabishebele basin in Harar plateau (Mechera, Kersa, etc.). A few caves are also noted in the Mekelle Sedimentary outlier with limited or patchy development of cavernous landforms. Some village water supply in the Harar plateau depends partly on karst aquifer resources (example: Kersa, Bedesa, Mechera).

In a number of places high discharge karst springs are reported in marble aquifers of western Ethiopia. A typical example is the Dalati springs in Asosa area. The discharge of this spring is documented to range from 15 to 20 l/s in dry seasons.

In Tigray region of Ethiopia (north Ethiopia) particularly north of Wukro several shallow caves (less than 10 m long) occur in a dark grey Precambrian limestone which has well developed clints and grikes on the hilltops. Similar karstic features are developed elsewhere in northern Ethiopia on limestones and marbles, but no caves or potholes of any bigger size nor large dolines or sinkholes have been reported.

Basement Marble Aquifers of Ethiopia

In northwestern Ethiopia bordering Sudan in number of places marbles corresponding to the basement lithologies show some karstification leading to groundwater storage and flow (Fig. 2.35). The marbles come with spatially recognizable trends of productivity. The marble aquifers in western Ethiopia are the most productive compared to similar rocks in north Ethiopia, principally owing to differences in degree of karstification. High rainfall in western Ethiopia allows karstification of the marble aquifers. Several karst springs from fractures of marbles have been documented to emerge from the marble karsts in western Ethiopia (Fig. 2.35). In general, the highest groundwater accumulation within the marble seems to be near anticlinally (synclinally) folded parts of the marble in which more penetrative vertical joints are developed; or along faults and major joints. The vertical joints easily recharge the karstic aquifers with fresh rainwater, and partly allow the water to flow along other joints that are connected with these sets of vertical joints and the foliation. The faults seem also to cause high brecciating and thereby free groundwater accumulation and flow within the marble outcrop. In Eritrea for instance in zones where there are intense ductile strain or late brittle faulting, the marble layers develop secondary permeability. They are targets of small scale supplies of potable water (Drury et al. 2001).

Karst Hydrogeology

As direct hydrogeological evidence such as pumping test or other methods such as tracer tests are practically nonexistent discharge of springs and their variability from the various carbonate aquifers have been used to derive hydrogeological prosperities (storage, flow properties) of these aquifers (Fig. 2.36) and compare groundwater flow and storage properties in various carbonate aquifers in Ethiopia.

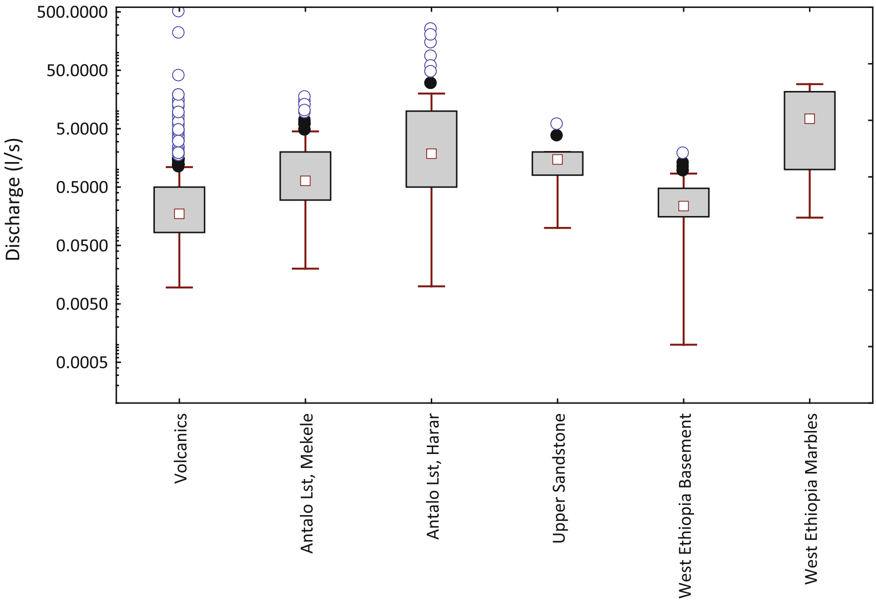


Fig. 2.36 Box and whisker plot showing spring discharge variations in various lithologies including the limestone aquifers of south eastern plateau around Harar and limestone aquifers of the Mekelle outlier. A total of 2504 spring discharge data has been used in the drawing of the box and whisker plots (2044 from volcanics, 250 from basement, 120 from Mekele Outier, 7 from marbles and 40 from *upper* sandsotone and 70 from Antalo limestone of Harar)

Comparison of spring discharge data (Fig. 2.36) shows the Limestone aquifers of the SE plateau including Harar area is characterized by high discharge variability, highest recorded discharges and higher mean discharge of springs as compared to the limestone aquifers of northern, western and central Ethiopia. This discharge variability corresponds to the degree of karst development and recharge rates. It clearly indicate that the Limestones of the higher elevation areas of the SE plateau is more karstified while the limestone of the Mekele outlier and Blue Nile basin can be categorized as fractured limestones.

In the Bale region of the SE plateau, most of the caves are located above the current regional water level in the unsaturated zone, though originally formed under phreatic conditions (ex. Nur Mohammed cave, Sof Omar cave etc.). The present day hydrology of Sof Omar cave varies considerably between the dry and wet seasons, the former lasting from November to March. The wet season has two maximum, the first in April and the second in September. In the dry season the river passage exhibits extensive cobble banks and all the fords are less than 1 m deep. In the wet season the river rises 7 m. There are also sections of the cave that holds ephemeral lakes of various sizes.

In the Upper Wabi Shebele Basin, the highlands bounding the multi layered sedimentary sequences from north and the rift valley from south a number of karsitifed features have been documented. Among these karst geomorphic

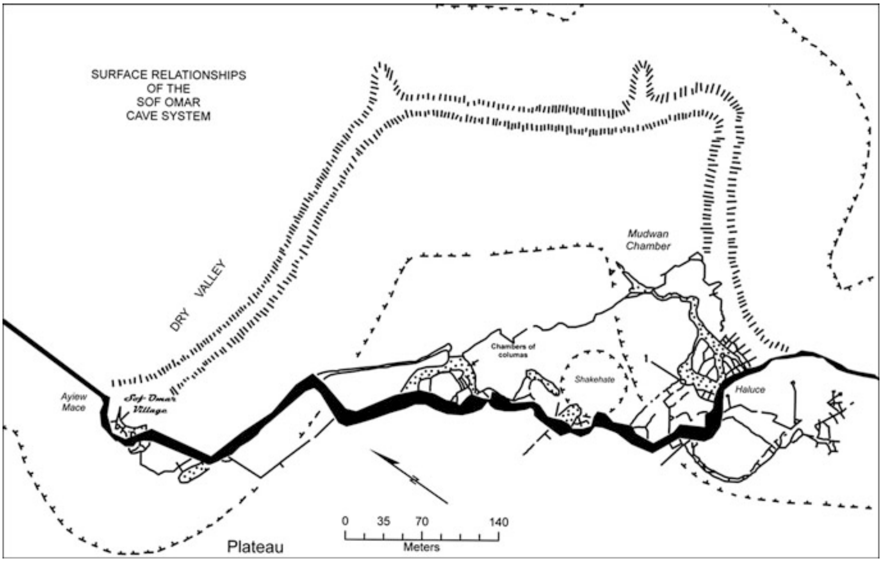


Fig. 2.37 The SofOmar karst features. The cave forms when the meandering Weyib River breaches the limestone plateau until it re-connects with the main channel 1 km downstream

features, sinkholes, dolines, solution cavities and large springs and boreholes yielding large of up to 250 and 15 l/s respectively were obtained from this aquifer. As it appears from the orientation of the Karst features and elongation directions initiation of karstification and its breakthrough appears to be controlled by rift related faults.

Investigation by BSEE (1973) of karst features of Ethiopia reveals that in Northern Ethiopia little evidence exists for the karstification of marbles and dolomites of the Precambrian basement.

Gypsum karst has been previously recorded in the Ferfer formation in the Ogaden (Hadwen et al. 1973). Karstic features are seen in several places, notably in Fafen depression south of Shilabo. There groundwater potential is limited by the high salinity associated imparted to groundwaters by dissolution of evaporate components. The role of the karst in groundwater circulation is largely unknown.

Principal Karst Features of Ethiopia

Caves in Ethiopia have widely been explored and their features documented by the British expedition in early 1970s. The geometric characteristics, origin, structure, hydrology and biological aspect of these caves have been documented in detail in BSEE (1973). The descriptions of these principal caves given below are excerpted from this literature.

SofOmar: The Sof Omar Cave system is one of the most prominent karst feature in Ethiopia (Fig. 2.37). The SofOmar cave is a spectacular example of a floodwater maze developed at three successive levels in horizontally bedded limestones beneath a basalt cap-rock. It is a meander cut-off system that floods frequently during the rainy season. The flood water caves develop in low gradient vados caves where fissure frequency is high. Because of its unique genesis related to combination of scouring and dissolution the SofOmar cave have been widely mentioned in scientific literature on origin of cave (Ford and Williams 2007).

The SofOmor cave forms because of allogenic flash flooding invading a limestone plateau. Floodwater maze development is most significant where caves drain large and rugged allogenic catchments (i.e. where large floods are applied rapidly to one point in the karst) and is most prominent at the upstream end of systems. The flow of the Weyib river itself is controlled by a prominent regional fault that cuts across the sedimentary formation in NW–SE direction.

Melka Mena: At a total length of 294 m Melak Mena (located in Bale) is one of the prominent karst features in South Eastern Ethiopia (Fig. 2.41). The entrances of Melka Mana is drystone formations, which can be seen by daylight. After 75 m, the main passage takes a sharp swing to the south, but a 1 m high passage continues straight forward. This leads to a 4 m climb down into a low chamber with three ways on-all close down rapidly. From the bend the main passage follows the same southerly bearing for 110 m averaging 10 m wide and 4 m high, making an easy walk. Just beyond the bend are several large stalagmite bosses on broken slabs of rock. While there is much evidence of roof collapse the cave shows its phreatic origin in many sections where the roof is arched and obviously following joints. The cave ends as a wide, low bedding less than 0.3 m high (Fig. 2.38).

Nur Mohammed: At 2.5 km Nur Mohammed cave is the second longest cave in Ethiopia. Nur Mohammed is a complex network of passages with four entrances from a cliff. The cave is characterized by solutionally enlarged cavities, dusty rock strewn floor, mud floored tubes, chambers, shallow water pools. Notable small streams emerging and dying within the caves and drip waters are common features. The cave system is located above the current regional water table and river water levels. The entrance in the cliff front is more than 100 m away from a river which is flowing at a lower level than the base of the karstified limestone. The basic alignment of the cave is west east, while the north to south passages and solution features all point to a phreatic origin. Many of the passages take form of rift/joint, though there are sections which show the classic tube shape. Some basalt boulders are noted inside the cave. This combined with large passages in some sites indicate that the cave must have hosted through flow of water in early stages of development. There is little vertical development of the cave except few avens through which water drips down and deposit calcite in forms of tall pillars. But owing to lack of extensive dripping water formation of pillars are rare.

Gara Hakim: Immediately south of Harar lies a hill of impure limestones and marls and several karst features (Fig. 2.39). Topping this is a level plateau of more massive limestone which exhibits karst features. The northern half of the plateau is known as Gara Hakim while the southern part is Gara Barcalle. Three kilometers

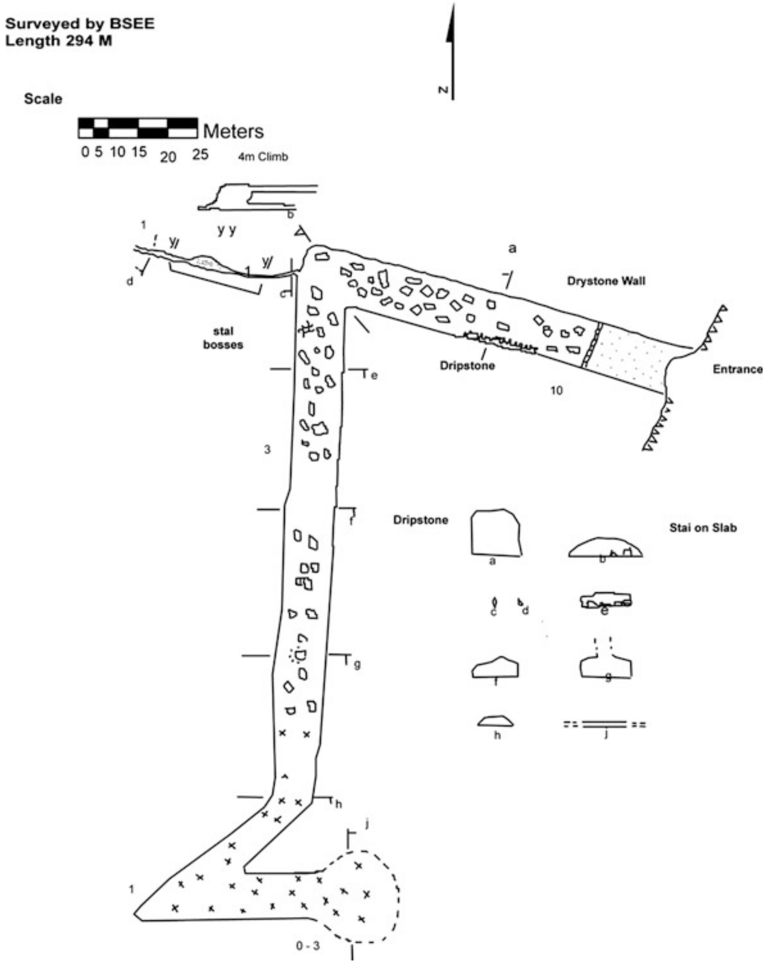
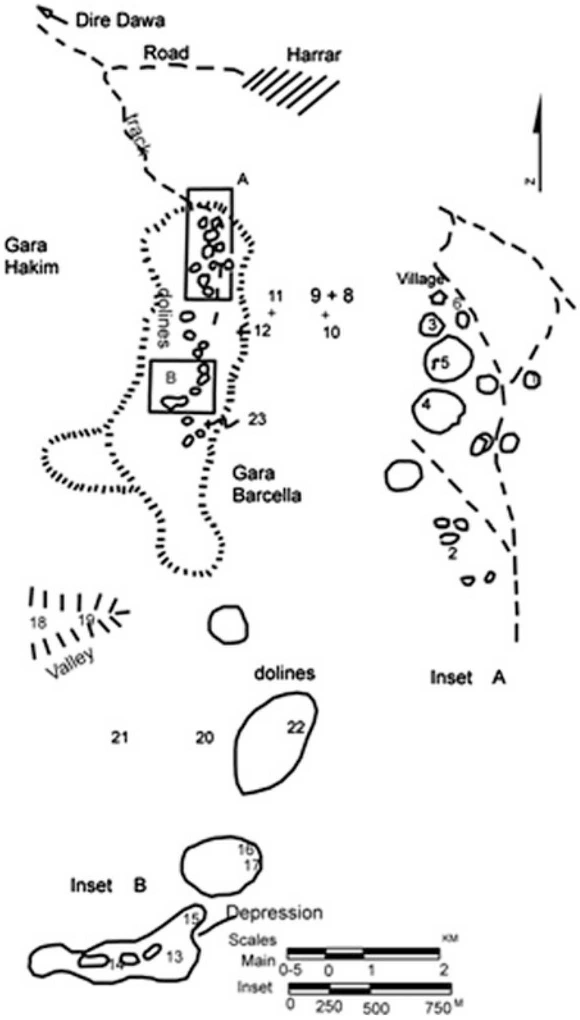


Fig. 2.38 Features of the Melka Mena cave in SE Ethiopia

of the south lay the smaller plateau of Gara Bilalu. This plateau shows a doline karst which was not seen elsewhere in Ethiopia. Most of the potholes where found amongst the areas of limestone pavement which tended to outcrop round the perimeter of the dolines, some of the clints protruding up to 5 m. In general the dolines are shallow, gently sloping, and closed depressions up to 200 m diameter. Parts of the plateau are cultivated, including some of the dolines. Where the limestone outcrops it tends to be well jointed showing much faulting and small scale solution depressions. In some impure lower successions on the eastern side of Gara Hakim several small rock shelters were found developed along bedding planes. Features of these were heavy incrustation of tufa, dense and prickly

Fig. 2.39 Distribution of caves, potholes, dolines in the Harar Gara Hakim plateau



surrounding undergrowth and their inhabitants. Around 23 caves and potholes have been discovered by the British exploration team (Table 2.10).

Table 2.10 Table describing the karst features of the Gara Hakim in Harar highlands

Name	Description of Karst features at Gara Hakim plateau
GH 1	30 m deep pothole ending in a choke, entrance in a rift between clints
GH 2	Entrance in clints, Two neighboring potholes, 10 and 12 m in depth
GH3	A 20 m deep pothole
GH 4	Three entrances among clints unite in a chamber developed in a 1 m thick shale band part way down the 17 m first pitch. 7 m pitch follows, then climb down to chamber with stalactites with passage spiraling down to sump (figure)
GH 5	Several small pots amongst the clints on both sides f this large doline
GH 6	Five entrances in clints lead to two chambers with flowstone on walls (fig)
GH 7	Entrance in clints. Winding cave passable about 40 m long
GH 8	Shallow bedding cave in face of cliff, 5 m long
GH 9	Rock shelter 3 m long
GH 10	Four bedding caves up to 10 m long at various heights in cliff
GH 11	Bedding cave 6 m long
GH 12	16 m deep pothole amongst clints. Two constricted pitches of 7 and 9 m with a squeeze in between
GH 13	Entrance in shakehole to 19 m pitch to steep slope ending in blockage at 21 m
GH 14	From shakehole bottom, 5 m pith leads to a chamber, with unentrable pitch of 20–24 m following
GH 15	Entrance in shakeholes to 27 m deep pothole. Short tight winding passable descents steeply then four short pitches
GH 16	Amongst Clints near edge of doline 7 m deep open pot connected to a 10 m deep pothole
GH 17	Amongst clints, 13 m deep pothole next to 12 m deep open pot
GH 18	7 m deep pothole with small chamber in lower of two shakeholes in small valley
GH 19	13 m deep pothole in clints in upper of two shakeholes in small valley
GH 20	Entrance in extensive limestone pavement. First pitch 33 m in 1 m by 4 m shaft ending in a boulder floored chamber. Squeeze in rift at south end of chamber leads to 4 m climb down to a 12 cm wide rift leading to an pitch of 20–25 m
GH 21	8 m deep open pot in pavement
GH 22	Entrance amongst undergrowth near edge of doline. Open pothole 23 m deep to boulder floor
GH 23	8 m deep pothole

2.13 The Precambrian Basement Aquifers of Ethiopia

Geology

The Precambrian lithology of Ethiopia consists mainly of metamorphic rocks. The rocks are exposed in five regions (Fig. 2.40). In the northern Ethiopia they comprise low grade metavolcanics, greywackes and slates with minor marbles, while in western and southern Ethiopia higher grade schists and gneisses are characteristics. Granitic intrusions locally cut the metamorphic rocks and ultrabasic masses occur in the western part of the country. As will be seen later in this section, the clear difference in the basement rock lithology lead to differences in groundwater and hydrogeologic properties of the basement rocks in Ethiopia.

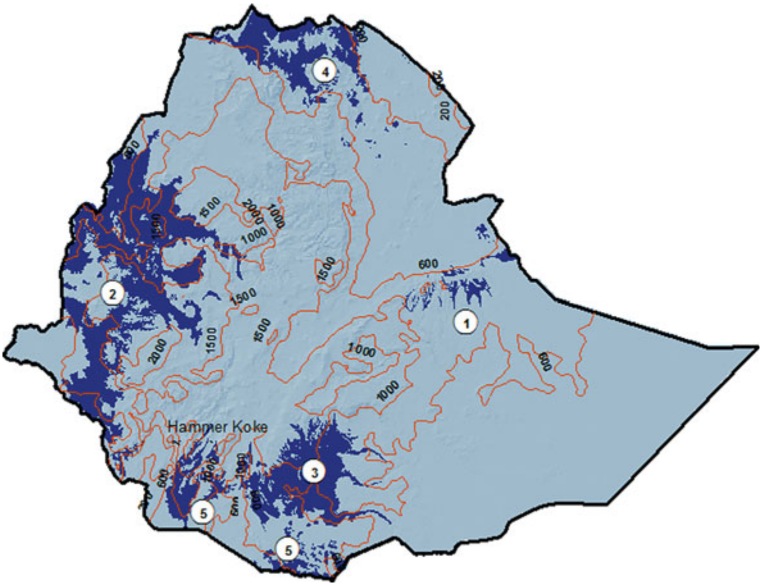


Fig. 2.40 Distribution of the Precambrian basement rocks

Hydrogeology, Groundwater Occurrence, Structures and Regoliths

The productivity of basement aquifers in Ethiopia largely depends of the presence of regolith, fractures, type of metamorphic rocks or grades and sustainability of recharge and topography. Two of the principal control of groundwater occurrence in basement rocks are the density of fractures and the presence of regoliths mantling the basement rocks. Previous groundwater maps of Ethiopia (EGS 1996) and hydrogeological reports (Chernet 1993) put the entire metamorphic rocks of the country as low yielding regional acquicludes. It is widely stated that groundwater occurrence in basement rocks of Ethiopia is mainly confined to fracture zone and to regoliths when such profiles are developed. Nevertheless little previous attempt has been made in order to understand the genesis of regoliths on the basement rocks of Ethiopia.

Topography that favors convergent hydrographic networks is more suitable for groundwater occurrences. In valley bottoms or secluded valleys between adjacent highlands groundwaters convergence to valley bottom enhance groundwater accumulation. The regolith thickness also enhances accumulation of groundwaters. In steeper slopes (hilicrest) regolith thickness is usually small that in gentler and flat topographies (pediments). At the core of the process responsible for regolith development is the cycles of striping and deep weathering which is strongly tied to tectonic cycles of uplifting and tectonic quiescence. Generally porosity in the regolith is orders of magnitude higher than in the fractured bedrock. As a result, the relative amount of extractable water is much higher in the regolith than in the unweathered bedrock.

Depending on the depth of weathering, influence of structures and presence of lower permeability pedocretes, infiltration can be lowered leading to less recharge and more surface runoff. This is typical hydrologic feature in arid areas of Borena (marked 3 in Fig. 2.40) and Northern highlands (marked 4 in Fig. 2.40).

Development of deep weathering profile requires long periods of time under stable tectonic conditions (although still the present day hydrologic processes are also linked to nature of weathering profiles), a few millions to a few tens of millions years. Thus, relatively flat topographic areas are required to avoid the erosion of weathering products (saprolite), but also to favor water infiltration. Thus, such profiles cannot develop in regions of sharp topography where the erosion rate is higher than the one of weathering.

Critical research in geomorphologic history of the Ethiopian basement rocks is scarce. Deeply weathered landscapes occur throughout equatorial regions and are transformed by cycles of deep weathering and stripping. These processes are driven by rainfall that infiltrates the subsurface as groundwater recharge or runs across the landsurface (Taylor and Howard 2000). Deeply weathered landscapes, unaffected by Pleistocene glaciation and aeolian erosion, are common to low-latitude regions of Africa, Asia, South America and Australia. These terrains reflect a prolonged geomorphic history, which is characterized by alternating cycles of primarily mechanical or chemical denudation (Fairbridge and Finkl 1980; Thomas 1989; Taylor and Howard 1998). Mechanical denudation is effected by the action of water running across the land surface and involves the physical removal (i.e. ‘stripping’) of unconsolidated material from the surface by colluvial and fluvial erosion. Chemical denudation is achieved by the movement of percolating rainfall (i.e. direct groundwater recharge) which removes chemically mobile species from the land surface in solution through ‘deep weathering’.

One of the very few work on the geomorphic history of the basement rocks of Northern Ethiopia shows, despite its location in low latitude setting, evidence for presence of deep weathering products in northern Ethiopia is lacking (Coltorti et al. 2007). These indicate that Northern Ethiopia in particular and eastern Africa in general underwent long episodes of tectonic quiescence in Paleozoic during which erosion processes were able to planate the surface at altitudes not too far from sea level (Coltorti et al. 2007).

In Western Ethiopia three phases of saprolite and laterite formation has been recognized (Belete et al. 2004) based on model of Thiry et al. (1999) which characterizes the origin of basement surfaces in Africa. The oldest palaeosurface with weathering mantle covers the crystalline basement. It was formed in hiatus before Mesozoic transgression. The second palaeosurface is over the Mesozoic sediment, which was formed in hiatus before outpour of the tertiary flood basalt. The third weathering mantle on the present surface was formed from tertiary to recent time. There the laterites formed due to climatic conditions, which favor greater mobility of alkalies, alkali earth and Si than Fe and Al as the product of rigorous chemical selection. The laterites were subjected to ferricrete formation, equivalent to climatic conditions with expressed dry season.

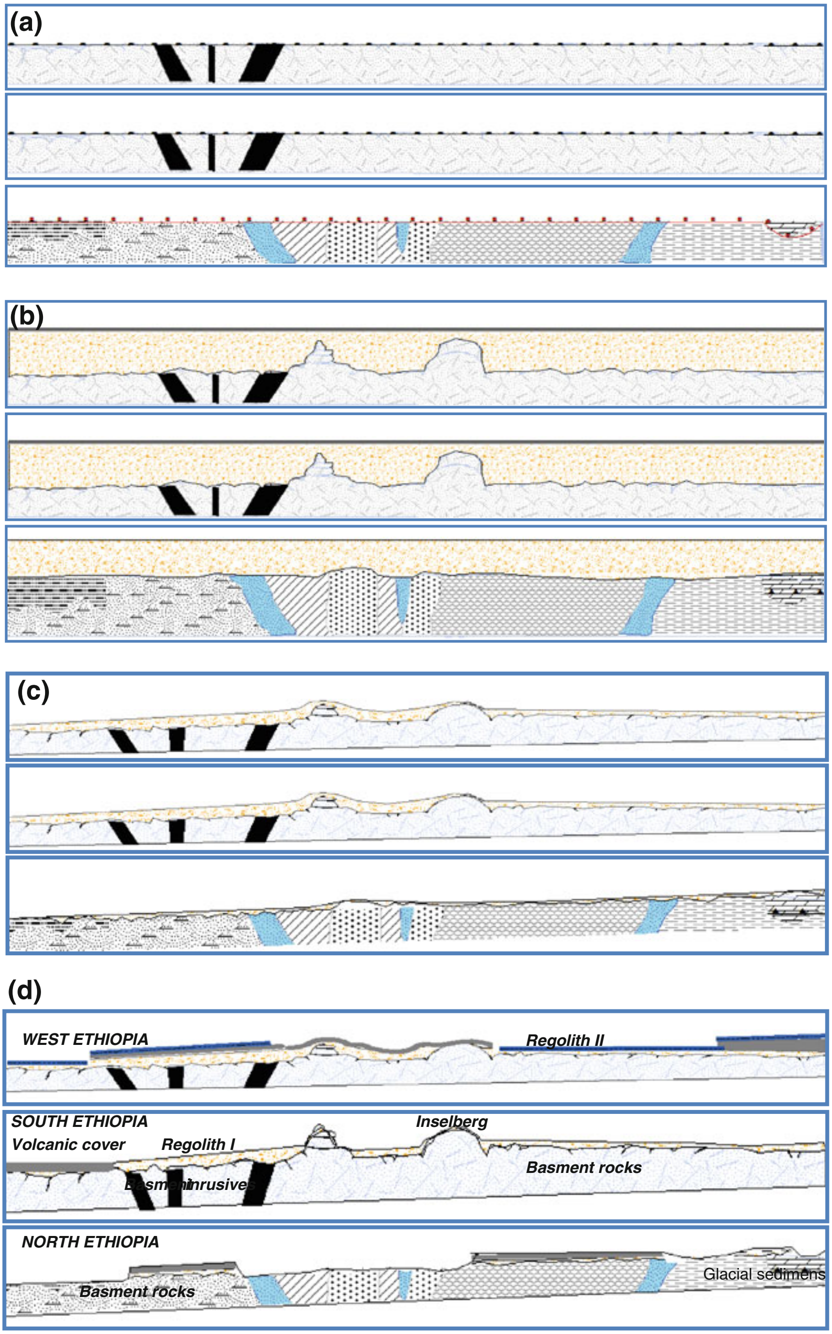
The lithology, texture, and structure of the parent rock govern the characteristics of the saprolite, as many features of the parent rock are preserved in the saprolite (see box ii for details). There is a general tendency for the gneiss and quartzose schist to weather to a sandy, fairly permeable saprolite, whereas the gabbro, metabasalt, and ultramafic rocks weather to saprolite with a higher clay content and lower permeability (Nutter and Otton 1969).

Generally basement aquifers with lowest productivity are located in the northern Ethiopia and the Borena lowlands. Basement rocks in western and south-central part of Ethiopia are generally productive. Yield of springs in basement outcrops bounding the Tekeze River valley in northern Ethiopia rarely exceed 0.1 l/s.

Polycyclic Deep Weathering and Stripping History: Implication for Basement Aquifer Potential

Evidence in many countries and several works in Africa (Tylor and Howard 1998; Tylor and Howard 2000; Foster 1984; Acworth 1987) suggest that tracing the geomorphic evolution of weathered land surfaces and identifying the dominant geomorphic process operating on those land surfaces (i.e. deep weathering or stripping) provide an understanding of the hydrogeological and hydrological characteristics of basement aquifer areas. This is a holistic approach that can provide greater insight. Furthermore, it is of practical importance to planners, because it enables definition of suitable areas for the development of the weathered mantle aquifer and intensive groundwater abstraction from the weathered mantle and fractured bedrock (Taylor and Howard 1998). Such holistic approach in understanding the hydrogeologic potential of basement aquifer of Ethiopia is lacking. Most previous studies suggest in very generic term that groundwaters in basement aquifers occur in fractured and weathered layers without giving any clue on the spatial pattern of such geomorphic processes. For example in the hydrogeological map of Ethiopia, the basement aquifers all over the country are classified as local, less extensive aquifer with fracture porosity. Evidences and model given below (Fig. 2.41a–d) try to develop a comprehensive model of weathering and stripping cycles in Ethiopia since the Phanerozoic taking three regions (North, West and South Ethiopia). This model is aimed at improving the previous models which are regional in nature to the scale of Africa (e.g. Thiry et al. 1999) or localized to explain wreathing and striping history of local significance (e.g. Coltorti e al. 2007). All in all five prominent stripping-deep weathering stages with significant implication to the present day groundwater occurrence and flow, can be recognized for Ethiopia. The evidence for the model largely comes from literature across Africa, consideration of mega geologic events (Table 1.4) in Ethiopia and corroboration of these using field evidences.

Stage I. Erosion of early and middle Paleozoic landscape by Carboniferous glaciation: During this stage Northern Ethiopia in particular and eastern Africa in


(a)
(b)
(c)
(d)
WEST ETHIOPIA
Regolith II
SOUTH ETHIOPIA
Inselberg
Volcanic cover
Regolith I
Basment rocks
Basment inrusives
NORTH ETHIOPIA
Basment rocks
Glacial sedimens

◀ **Fig. 2.41** Proposed schematic model showing the evolution and development of weathering surfaces and their stripping (see Fig. 2.41d for legend). **a** Stage i. Complete stripping of the Paleozoic and Precambrian basement surface by Late Carboniferous/Permian glaciations. Paleozoic rhythmic striping surfaces in at least two stages, all the area is brought to sea level by the glacial erosion and scouring, formation of two cycles of glacial sediments in north Ethiopia—onene during pre Ordovician the second in late Triassic (see also Fig. 1.3) (*top*: South Ethiopia, *middle*: West Ethiopia and *bottom*: Tigray) (see Fig. 2.41d for legend). **b** Stage ii. Cretaceous deep weathering (150 m thick laterite under Oligocene volcanic in Eritrea, laterite soils on *top* of Ambaradom, remnants of the Cretaceous deep weathering profile is still seen in Borena, Western Ethiopia, and elsewhere in the country where it escapes later denudation (see Fig. 2.45d for legend). **c** Stage iii. Cretaceous to *mid* Miocene uplifting, stripping and volcanism (e.g. Isolated mesas and buttes with laterites on *top*). The more pronounced uplifting from sea level to about 3,000 masl reduced the regolith to near abscent to patchs here and there particulary from the areas where it was initially not well developed because of subsidence below sea level. (see Fig. 2.45d for legend). **d** Stage iv. *Mid* Miocene to recent rhythmical and differentiated stripping and deep weathering new regolith on basalts visible in western Ethiopia, following local topography further uplifting and intensification of stripping, unloading of the Oligocene flood basalts and further intensification of stripping aridification recharge decreasing The second lateriazation event is very well preserved in flat depression example in the Dabus plateau etc

general underwent stripping by advancing carboniferous glacier during which glacial scouring left a very flat surface dotted by glacial moraines. The erosion processes was able to planate the surface at altitudes not too far from sea level (Coltorti et al. 2007). As seen in Fig. 2.41a, the relief was similar in the entire region of Ethiopia. The same surface is common elsewhere in central Africa (e.g. Uganda) (Tylor and Howard 1998).

Stage II: *Cretaceous deep weathering* (*Africa surface*): During this stage tectonic quiescence and optimum climate lead to the development of thick regolith in all region of Ethiopia (BSEE 1973). There are evidences for the fact that the early Cenozoic was a low laying terrain (Sengor 2001; Merla and Minucci 1938) that was product of erosion and deep weathering and according to Burke and Gunnel (2008) this surface represent the African surface which is known elsewhere in Africa. This surface is widespread in Africa and is known as Africa surface. The deep weathering is favored by more humid climate which accompanies the new tectonic position of the region north of the equator in subtropical setting (thus high temperature and humidity). The thickness of the regolith varies from region to region depending on the mineralogy and metaphoric grade of underlying basement rocks. Generally higher grade rocks shows higher development of regolith and low grade rocks show low development. In Eritrea for instance up to 150 m thick sediments have developed on the high grade Barka domain rocks. This thick weathering profile is common elsewhere in Ethiopia. According to Drury et al. (1994) humid conditions in the southern part of the Arabian Nubian shield led to the development of Fe-rich lateritic soils during the early Tertiary times. These paleosols are overlain by tertiary flood basalts in part of Eritrea, Ethiopia, Saudi Arabia and Yemen and have been exhumed where the basalts are removed by erosion. In Eritrea, laterites that underlie the 30 Ma basalt represent a widespread and lengthy period of humid conditions in the early

Cenozoic. The laterites cap basement rocks as well as the Jurassic Adigrat sandstones. Lateritazed part of upper sandstone is also visible at Amba Aradom in Tigray (Moeyersons et al. 2008).

Stage III: Cenozoic uplifting and striping: During this time the whole of Ethiopia and East Africa (Kenya for example) underwent uplifting preceding the volcanic activity. Burke (1996) attached particular significance to the absence of a laterite covered African Surface from a roughly circular area ~100 km in diameter center on the Afar Dome. He suggested the erosion as the dome started to rise and before the eruption of the Ethiopian traps began could account for the absence of laterite from the roughly circular region. According to Burke and Gunnel (2008) the absence of laterite in a wider regions is due to a kilometer scale topographic swell that took place 32–30 Ma leading to stripping of the African surface, causing laterite stripping on an upward African surface as well as canyon cutting through the erupted flood basalts and underlying basement. In many areas the laterite cover has been completely removed. The elevation of the Afar plume, the associated eruption of the Ethiopian traps, the establishment of the Ethiopian rift, and the development of red sea and the Gulf of Aden, have led to complex and episodic topographic deformation of the African Surface. In many areas, the lateritic cover has been completely removed by erosion. In southern Ethiopia calcrete, fericrite and silicrite occupying most of the ridges in Borena are indication of stripping of the surface of the rocks. Other indicators of stripping are inselbergs dotting the wider Borena plain in Basement region of southern Ethiopia. However in several locations including the Northern Ethiopia, the flood basalt eruption that follows the uplifting protected further erosion of the Africa surface. In several localities now laterites mark the contact between the basement and the flood basalts sequences (e.g. in northern Ethiopia). In Borena stripping has progressed only moderately leaving extensive tabular residuals (inselbergs) capped by laterite (or silcrete and calcrete) duricrusts which protect the soft underlying zones of the weathered layer on hard rock terrains. Along preexisting fault zones quaternary wadi beds cut across the weathered layers. In the Hammer Koke block (western area basement rocks marked 5 in Fig. 2.40) including the Konso area the rejuvenated and uplifted peneplains under active erosion has the earlier developed weathered layers partly or completely stripped away leaving only spectacular badlands (Fig. 2.42). Figure 2.42c show for instance a 4 Ma old basalt resting directly on the basement rocks with no presence of regolith in between suggesting complete stripping either in early Cenozoic uplifting or since Miocene. In Northern Ethiopia because the low grade metamorphic rocks did not allow widespread regolitization, the accompanying striping event even reduced the regolith much further and only isolated regoliths are noted or the thickness is very small.

Stage IV: Miocene to recent cycles of deep weathering and striping: This stage is a much complex phase with weathering and formation regolith taking place and accompanied by striping and erosion. These complex processes follow regionalization of processes following development of different climate and landscape across Eastern Africa following the Cenozoic uplifting and volcanism. Undoubtedly, the tectonic uplift following the preceding the volcanic eruption resulted in

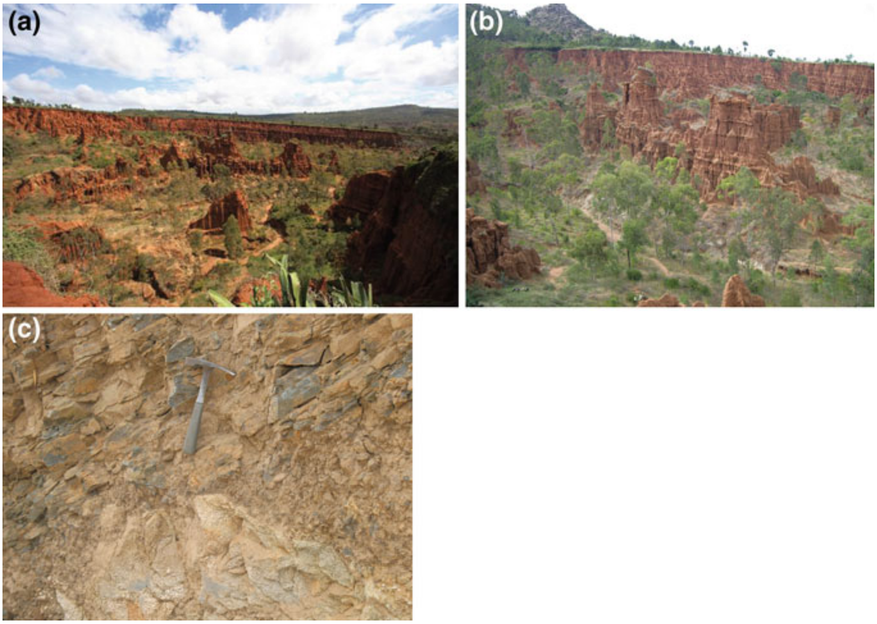


Fig. 2.42 Surfaces typical to the basement surfaces of southern Ethiopia, the badlands are result of stripping of Africa surface since Cenozoicr, **a** and **b** taken from a locality called Konso and **c** is taken from southern end of the south Ethiopian basement

regionalization of climate, rainfall and temperature leading to variability in regolith production rate in different sectors of Ethiopia. The more humid western Ethiopia has been undergoing intensive denudation and regolithizations while the in northern Ethiopia chemical denudation since Miocene lead to less regolith development. Prominent shields (Fig. 2.3) which act as moisture shadows have also been formed during the late Cenozoic (e.g. the Choke shield, the Simen Shield, the Guna, Guguftu) isolating the northern Ethiopian highlands from heavy and prolonged rains which could have resulted in widespread regolitization. Climatic conditions favorable for deep weathering, particularly precipitation exceeds evapotranspiration to produce rainfall fed groundwater recharge occur since Miocene in Western Ethiopia to sustain deep weathering that continued in West but not in east and north. Little evidence in Ethiopia exists to substantiate this however works in Uganda show the presence of such conditions since Miocene (Taylor and Howard 1998).

The regionalization of striping-weathering processes has lead to three distinct present day landscape of the basement regions of southern, northern and western Ethiopia. In Northern Ethiopia, the landscape is a nearly completely stripped basement with only patches of regoliths (Fig. 2.43a–c). When isolated by the volcanic cover, thickness of regoliths may reach 20–30 m (e.g. around Shire Indasilassie). The eruption of the flood basalts leads to protection of the remaining laterite materials in several places. For instance in Shire Indasilassie deep groundwater wells normally penetrate the laterite sandwiched between the basement and the overlying volcanic cover. Continued stripping in northern Ethiopia is affected by a low ratio of annual recharge to runoff. The significantly reduced recharge flux, relative to that the surface of deep weathering, is transmitted to well incised drainage channels by the fractured bedrock and, in places by localized aquifers in the weathered mantle. Discharge is in terms of highly variable stream flow (wadi bed discharge etc.). The extensive wadi beds in the lowlands of Borena and Hammer Koke blocks are typical examples of active ongoing stripping since at least the Miocene time.

In Eritrea, and thus by extension in Northern Ethiopia, the erosional sequence from rising massifs was first the stripping of up to 600 m of Mid Oligocene flood basalts and then the deeply weathered regolith (locally in excess of 150 m, depending on basement lithologies) beneath an Early Tertiary lateritic paleosol. Both source materials weather to clay rich debris (montmorillonite illite from basalts, kaolinite-illite from paleogene laterite and regolith). The bulk of lowland terraces comprise clay rich loams beneath lag gravels shed by basement progressively exposed to erosion by uplift (Durry et al. 2001). Sections through some of these terraces show a sequence from lower dark illitic soils, covered by red kaolinitic soils, originating from later erosion of deeply weathered basement, an inversion of the stratigraphic sequence that remains in higher elevation. Because the terraces have undergone uplift and incision at some stage in this evolution, perhaps as a consequence of erosional unloading, most debris released from unroofed basement that is not affected by Paleogene deep weathering moves not only in the active channels. Much of it passes through lowland areas to be deposited in the lower areas to be deposited in the lower reaches of the main rivers to form gravels, sands and silts that have low fertility. These Recent channel deposits constitute the main soils currently under crops. Because of this uplift, the loams in uplifted terraces have only a thin cover of sand and gravel (Drury et al. 2001).

In Western Ethiopia, Miocene two contemporary deep weathering results from a large ratio of annual recharge to runoff (25–40:1) with recharge events during the major long rainy monsoon seasons. In Western Ethiopia therefore one can see two prominent regolith and deep weathering events. One related to Africa surface and the other developing since Miocene to present. The later regolitization is taking place on basalt outcrop while the former developed on the basement lithologies.

In southern Ethiopia much of the present day surface is characterized by indurated caliche surface, deeply cut regolith badlands, and isolated granite inselberges caped by frecrite and calcrite all indicating active stripping since Miocene or earlier (see Fig. 2.42).

Box 2: Lithologic control on weathering profile development

UNESCO (1984)

The mineralogic composition and lithologic texture of the host rock also play important roles in the development of the weathered layer. These are commonly thickest and contain the most permeable (c) zones on coarse-grained salic rocks such as granites; granodiorites, and orthogneisses. Among all the various categories of hard rock terrains the granite, granodiorites and orthogneisses generally seem to have the greatest susceptibility to deep weathering (as much as 100 m deep in places). Also in these quartz-rich rocks zone (c) layers are commonly thicker and more permeable than in mafic rock terrains. In large and extensive granite batholiths which have been subject to prolonged weathering, zone (c) may range from 10 to 30 m in thickness

All other factors being equal the finer-grained rocks are less susceptible to weathering than the coarse-grained ones. In the inselberg-and-plains terrains of northwest India, for example, fine-grained granites commonly form inselbergs or erosional residuals of unweathered rock and subjacent coarse-grained granites beneath lowland plains are weathered to depths of 30 m or more

On some metamorphic rocks of unstable mineral composition such as slates, phyllites and argillaceous schists, weathered layers may be thin or absent, even when these rocks underlie extensive peneplains in climates otherwise favorable for deep weathering. When developed on mafic rocks such as diorites, gabbros, diabases and dolerites, the weathered layer may be thick but the (c) zones tend to be clayey and poorly permeable. Among the metamorphic rocks in hard rock terrains, quartz mica schists and thin-bedded quartzites may develop fairly permeable (c) zones in the weathered layer. These zones are seldom more than 5–10 m thick in contrast with those in the granites. Massive quartzites, however, commonly resist weathering and form linear inselberg ridges rising above lowlands of other weathered rocks

Examples from Ethiopia

Observation in northern Ethiopia shows; in clastic meta sediments of Shiraro block contain weathering material of reddish laterites. In places the regoliths are completely absent in other places the remnants of yellowish brown badlands are visible on the Eritrean side. The Chila domain metasediments with relatively abundant vegetation and water storage owing to abundance of graphite and soil development. Adwa domain dominantly metavolcanics show less developed or no evident weathered beds. Weathered surfaces are more common on metasediments of Shiraro block and Chila domain than in the metavolcanics

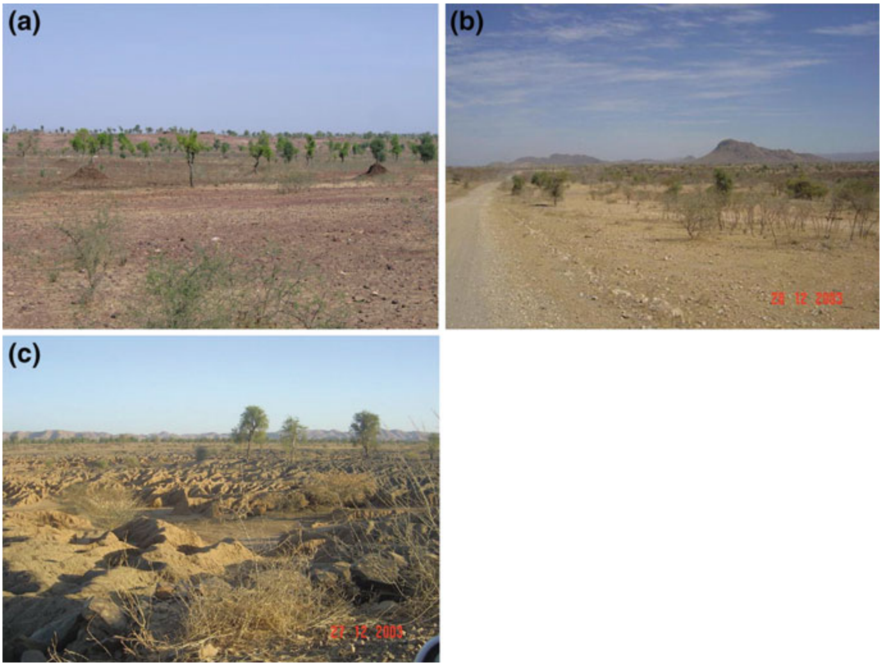


Fig. 2.43 Photo showing the surfaces of present day exposure of the North Ethiopian basement

Implication of Geomorphic History to Groundwater Occurrence

Based on development of regolith, degree of fracturing, water holding capacity and degree of fracturing the five zones of basement aquifer has been discussed separately. A typical basement aquifer with well developed regolith has the form as shown in Fig. 2.44. Nevertheless the complex stripping and deep weathering history of Ethiopia as discussed above led to most of this sub layers not present in Ethiopian case. In the north Ethiopia for instance the whole regolith surface is stripped completely or exists only in patchs (Fig. 2.43), in southern Ethiopia around Borena the regolith thickness tough laterally extensive is reduced vertically. In the western Ethiopia a well developed regolith has similar appearance as the one indicated in the schematic model (Fig. 2.44).

To be significant aquifers with exploitable groundwater, the weathered layer must attain a minimal areal extent and thickness and have sufficient porosity and permeability to store water and to yield it to wells from season to season and from year to year. Extensive and thick weathered layers are likely to contain the most viable and productive aquifers. Thin weathered layers may contain no significant aquifers or, at best, intermittent ground-water bodies which do not persist through long dry periods. Locally, however, even relatively thin weathered layers may sustain perennial aquifers, provided there is prevailing high recharge, either natural

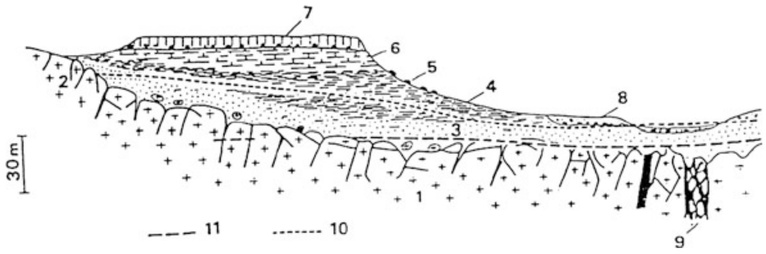


Fig. 2.44 Schematic section of aquifers within the granitic regions. (From Guiraud 1997). *1* Fresh basement, *2* Fissured zone, *3* Granitic sands, *4* Clay sands, *5* Plastic clays, *6* lateritic clays, *7* Lateritic duricrust, *8* Recent alluvial deposits, *9* Crushed zone, *10* Water level during wet season, *11* Water level during dry season (from Guiraud 1997)

or artificial. In some irrigated areas of India, for example, return seepage from irrigation plus natural recharge sustain wells in weathered layers only 5–7 m thick. In most places, however, weathered layers less than 10 m thick do not generally contain exploitable aquifers. Even where the weathered layer is of maximal thickness (as much as 50 to 70 m or even more in some places in the humid tropics) only 10–15 % of the total thickness may contain materials sufficiently permeable to yield water to wells. The thickness of the weathered layer and the presence of permeable zones in it depend on the interplay of a number of factors, among which are climate, topographic position, mineralogic composition and lithologic texture, and the distribution and spacing of the fracture system in the host rock.

The Basement Aquifers of Southern Ethiopia and Borena

Geology: The Precambrian basement of southern Ethiopia (marked 3 and 5 in Fig. 2.40) consists mainly of high grade and low grade metamorphic rocks and granite intrusives (Fig. 2.45). The low grade metamorphic rocks are composed of metasediments and metavolcanics consisting of slates, phyllites, schists and greystones. The high grade metamorphic rocks include gneisses, schists, granites and marbles. Several types of granitic intrusives are present including metagranites (high grade gneisses and granulites, metamorphosed granites), syntectonic granites with abundant pegmatites, and late-post tectonic granites.

Thin but extensive regolith (elluvium) developed over bedrock units ubiquitously occur throughout the Borena high grade metamorphic rocks, covering slopes, foothills, and flat-lying topography. The elluvium developed over basement grounds mainly consist of red to reddish brown sandy soil, with minor silt and clay. It has resulted from weathering of the basement rocks and is less than 10 m thick (Gerra and Abreham 1999). Nodules of limonite, boulders, cobbles and pebbles of various rocks of the underlying basement, and vein fragments litter the soil. The soil thus covers a mantle of weathering of the underlying basement units.

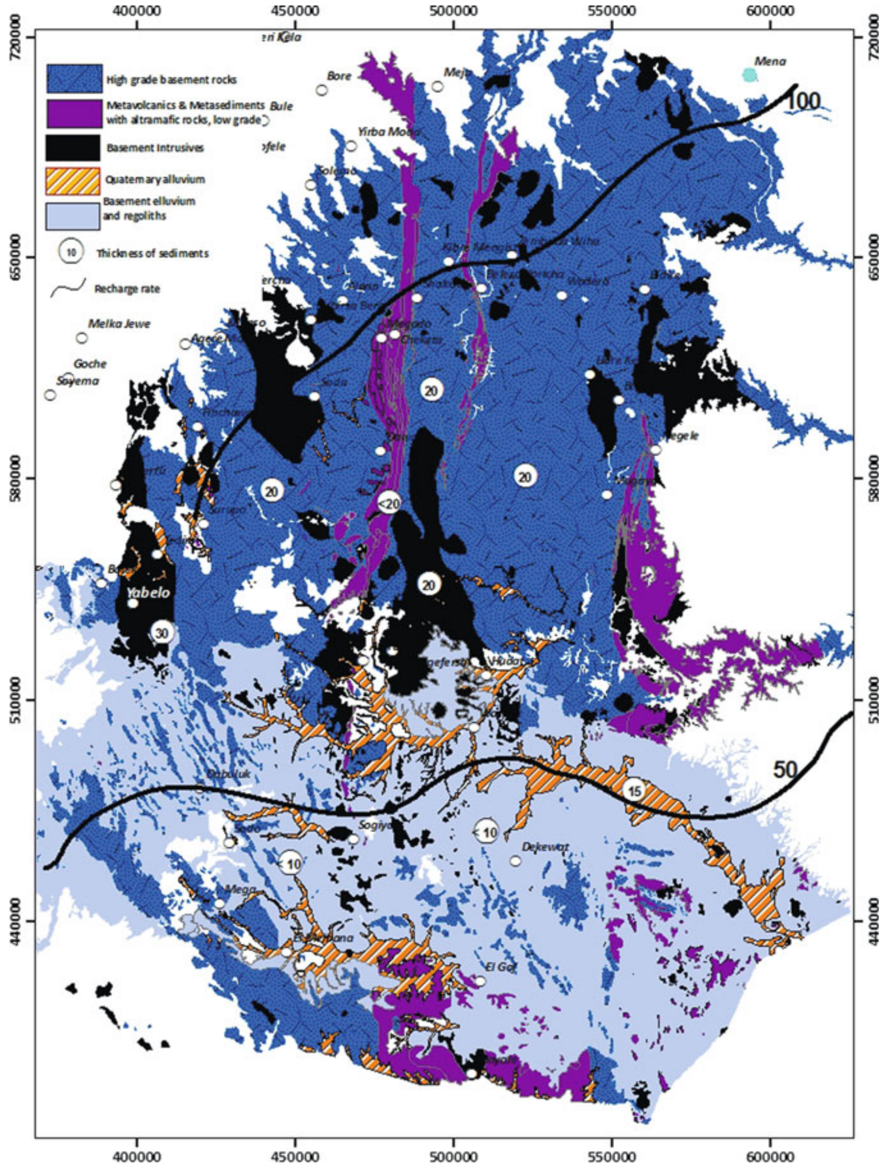


Fig. 2.45 Geologic map of the Borena basement rocks, associated regoliths and some hydrogeologic features

Climate: The area is dominated by a semi-arid climate. Annuals mean temperature varies from 19 to 35 °C with little seasonal variation and these decreases 1 °C with each 200 m increase in elevation. Average annual rainfall varies from 300 to 800 mm distributed within two-rain seasons. Rainfall delivery is bimodal: 59 % of annual precipitation occurs from March to May and 27 % from September to November. A dry year is defined as one in which annual rainfall is less than 75 % of average and this may occur one year in five. The probability that two consecutive years will have average or above average rainfall, one dry year, or two dry years is thus 0.64, 0.32 and 0.04, respectively. At least two consecutive dry years constitute a drought.

Groundwater occurrence: Regoliths and fractures are the main groundwater holding and transmitting media in a metamorphic terrain. The basement rocks of Southern Ethiopia show variable degree of fracturing and regolith development. Groundwater investigation for and production wells drilled in the Yabelo plain between 1972 and 1974 by the ministry of Agriculture show the crystalline hard rocks provide a yield ranging between 0.13 and 0.33 l/s.

The nature of regoliths also varies from parent rock to parent rocks. The northern sector of the region (Fig. 2.45) develops shows typical regolith layers as shown in Fig. 2.44. The southern sector on the other hand is characterized by complex setting of layers made up of in situ regoliths (elluvium) and transported sheet of alluvial material (alluvial sediments). The alluvial sediments are thicker in valleys and low laying areas. The alluvial sediments are also found in broad river valleys in the northern sector of the region.

For example around Kibremengist, alluvium deposits are noted to cover most of the valleys. Here bedrock is encountered at depths of less than 30 m in most places. Most of the groundwater comes from an aquifer in the alluvium, which is both porous and permeable. The underlying low and high grade rocks act generally as an aquiclude. The aquifer is recharged by the high rainfall in the region. Water table in the alluvium and marshy area is in the order of 7–10 m below the ground. The marshes are the result of groundwater discharge to the low laying areas and accumulation over low permeability bed rock.

Granites and gneisses usually weather into sand sized regolith materials. In Yabelo area for example the granitic intrusives are highly weathered into fine sand covered by thick red soils. Weathering products of metagranites in southern Ethiopia give rise of sandy regoliths. Late to post tectonic granites give rise to sandy regoliths and coarse grained materials. The post tectonic granites show exfoliated layers larger than 4 m. At depths greater than 5 m all the granites become massive with wider spacing of joints (5–10 m joint spacing). Some seepages and low discharge springs emerge from the granites fractures when such granites form a domal morphology.

The high grade metamorphic rocks of southern sector of Fig. 2.45, the weathering products are mostly fine grained clay, silt and sand. The thickness of the regolith is usually small and groundwater occurs whenever hydrologic process allows the weathering products to accumulate in nearby areas adjoining river valleys and streams.

In the low grade metamorphic rocks the topography is characterized by broad valleys. This morphology allows accumulation of alluvial sediments and preservation of regolith. There could be fine sand aquifers in the weathered zone and alluvials. Thick (20 m) decomposed fine grained regoliths makes up the weathered parts below the top red soils.

A clear geographic groundwater potential zonation of the basement rocks exists in southern Ethiopia. In basement rocks in the highlands straddling the rift from north, regolith thickness is higher (may reach 30 m in valleys) and recharge rate is higher owing to higher rainfall. Shallow groundwaters occur in the regoliths and alluvial materials in the low laying areas, recharge is relatively higher (around 50 mm/year). At 500–1,500 mg/L, total salt content of the groundwaters are also suitable for domestic water supply. Fractures in granitic intrusive also provide low discharge springs during wet seasons. The schematic model in Fig. 2.44 can very well represent the conceptual groundwater model in the basement aquifers of southern Ethiopia.

In the midlands between the lowlands of Borena and the highlands in the north show thin layers of weathering products, groundwater occurrence is limited to low laying areas in alluvial sediments, total dissolved solids is higher and may exceed 1,500 mg/L.

In southern part of the basement areas quaternary alluvials and eluvials resting on the basement rocks provide shallow groundwater in valleys where recharge is relatively high, they have moderate salinities (1,500–3,000 mg/L). The eluvial lateritic crust in the southern sector of the area consists of clay, silt and fine sand but it has dominantly silt and fine sand, with well developed layers similar to the model given in Fig. 2.44. The materials are promising hydrogeologic features from the point of view of construction of artificial water retention structures such as subsurface dams for water collection and storage. The duricrust capping the eluvium materials have low permeability and small thickness of less than 15 m. The significant reduction in thickness of the regolith is owing to stripping taking place since Miocene under arid condition. The aridity is the process that lead to formation of the extensive duricrust. This duricrust can also be noted capping inselberges dotting the southern sector of Fig. 2.45. Exceptionally thicker weathering products are recorded in the plains of Yabelo reaching 35 m (Alamneh 1989). It could contain shallow groundwaters in low laying areas where they are overlain by some alluvial materials. Traditionally groundwaters from the shallow eluvial and alluvial materials in the lowlands of southern Ethiopia are exploited through large diameter wells called ‘Elas’. To fetch water from elas a number of persons line up and stand on the steps and they convey the water up to the ground surface by giving it to one another in a pot.

In southern part of the area also there are extensive deposits of flat laying alluvial deposits. These deposits generally constitute good aquifers being composed by gravel and sand, like in Udat. Poor water quality owing to high TDS (>1,500 mg/L) is the main challenge for groundwater development in the alluvial materials (especially south of Negele around Bulbul, Boba, Udet, etc.). In these areas, it is usual to find underground whitish salts deposits mainly constituted by sulphates, which are very soluble in presence of water. Again, in Udat area, the water quality worsens with the depth in relation with the presence of salts deposits that increase with the depth. Due to fluctuation of the aquifers levels in these semi-arid areas, availability of groundwater in dry season is limited to areas with thick alluvium. In case of prolonged droughts the static water level can drastically decrease (up to 2–3 m) leaving the hand dug wells dry. On the other hand, deeper water exploitation gives water of worse quality. Due to the distances between the recharging area and the Wachile-Udet plains, there is an out-of-phase recharging cycle, which makes the lowest static water level correspondent with the rain seasons, and the highest static water level with the dry seasons.

The quaternary alluvium (Fig. 2.45) represents deposits of detritus material which is transported by rivers and streams. Valley floors stream courses in the Borena plain are the main areas of occurrences of the alluvial deposit. The alluvial deposit over basement grounds consist of light brown to grayish colored sand and gravel, with minor silt and clay, filling river channels and stream courses of flat areas. Thickness of the unit is generally estimated to be tens of meters; yet, over 50 m thickness may occur when topography allows.

The Crystalline Basement Aquifers of Northern Ethiopia

Geology: Typical characteristics of the North Ethiopian basement rocks is the dominance of low grade metamorphic rocks (meta volcanics and meta sediments) such as phyllites, slates, schists, marble, mainly chlorite-sericite schists, greywackes, ultramafic rocks (gabro, talk chlorite schists) etc. The low grade metavolcanic rocks come in belts running parallel to each other striking north south. The number of such belts with distinct geochronology, metamorphic grade, tectonics and lithology is unclear. Earlier geological mapping (Beyth 1972) identified three belts while (Tadesse et al. 1999) identified seven belts.

Groundwater occurrence: Unlike the basement rocks of western Ethiopia in northern Ethiopia there is a clear rarity of thick regolith materials. Furthermore field observation shows that the low grade metamorphic rocks decompose into fine grained weathering products which often with time fill the basement fractures and reducing the storage properties of the rocks. Generally the basement rocks have low groundwater potential. Groundwaters occur generally in fractures which penetrate the upper few meters of the rocks, in patches of alluvial sediments straddling river valleys and in very thin regolith materials.

In many localities alluvial sediments occur draping the basement lithologies. The alluvial sediments under favorable condition stores appreciable amount of water & are characterized by high water infiltration capacity. Thus being shallow with limited aerial extent the alluvial sediments in the area can considered as perched aquifer with high permeability. Springs and hand-dug wells with yield ranging between 0.05 and 0.17 l/s are inventoried in the alluvial sediments associated with the basement rocks in the region.

The north ward extension of the basement rocks in Northern Ethiopia occurs in Eritrea. Here dilatational structures which post date the basement hold considerable potential owing to their orientation which links high rainfall highlands to the low rainfall midland depressions (Drury et al. 2001). Steeply dipping and highly fractured marbles are known to yield good volume of potable groundwater in

Eretria, alluvium and regoliths on top of granite inselbergs also hold some groundwater. Report shows that over most of Eritrea the earliest Phanerozoic cover is a thin lateritic paleosol that rests on deeply weathered basement and predates the overlying Mid Oligocene flood basalts. Intensive erosion has progressively stripped the Early Tertiary cover, leaving only a few isolated outliers of volcanic plateau (e.g. around Adwa, Axum and around Asmara in Eritrea).

The Crystalline Basement Aquifers of Western Ethiopia

Geology: *The* Western Ethiopian basement rocks are the most extensive Precambrian rocks extending North South from Akobo to the Western Low lands of the Beles basin (Fig. 2.46). The basement covers areas such as Gore-Gambela, Asosa, Gimbi, and Beles lowlands. The Precambrian rocks of Western Ethiopia have been classified into three N–S running zones: the western high grade gneisses, the central low-grade volcano-sedimentary belt with associated ultamafic rocks and the eastern high-grade belt (Abreham 1989). The three belts are intruded by basement felsic and mafic intrusive. Like the Basement aquifers of Southern Ethiopia and unlike the basement rocks of northern Ethiopia, high grade basement rocks are dominant.

From a hydrogeological point of view the most important phenomenon is the deep weathering mantle of saprolite and laterite. There are two principal weathering palaeosurfaces in the western Ethiopia (Fig. 2.43) basement coinciding with the erosion phase of geological development. The oldest palaeosurface with weathering mantle covers the crystalline basement. It was formed in upper cretaceous just prior to the outpouring of the flood basalts. The second weathering mantle on the present surface was formed from tertiary to recent time.

Groundwater occurrence: Unlike the basement rocks of the rest part of Ethiopia, the basement rocks in Western Ethiopia have better groundwater storage. The higher groundwater potential is related to high rainfall which favors continuous recharge, relatively thick regolith which favors groundwater storage, and rugged undulating topography which favor accumulation of weathering products in depression and flat plains allowing groundwater storage and circulation. A number of springs which are not noted elsewhere in other Ethiopian terrain are observed in Western Ethiopian basement owing to high rainfall and well developed regolith zones. The regolith thickness in western Ethiopian basement region reaches 60 m exceeding greatly those in Southern (20 m) and northern Ethiopia. There is also a general variation in thickness of the regolith when the three belts of the basement rocks in the western Ethiopia are compared. Thicker regoliths are observed on high grade belts in the East and west. The middle domain which is characterized by low-grade meatavolcanics and metasediments are characterized by variable thicknesses of regolith. The thickness is higher on granitic instructions and negligible on dioritic and basic intrusive.

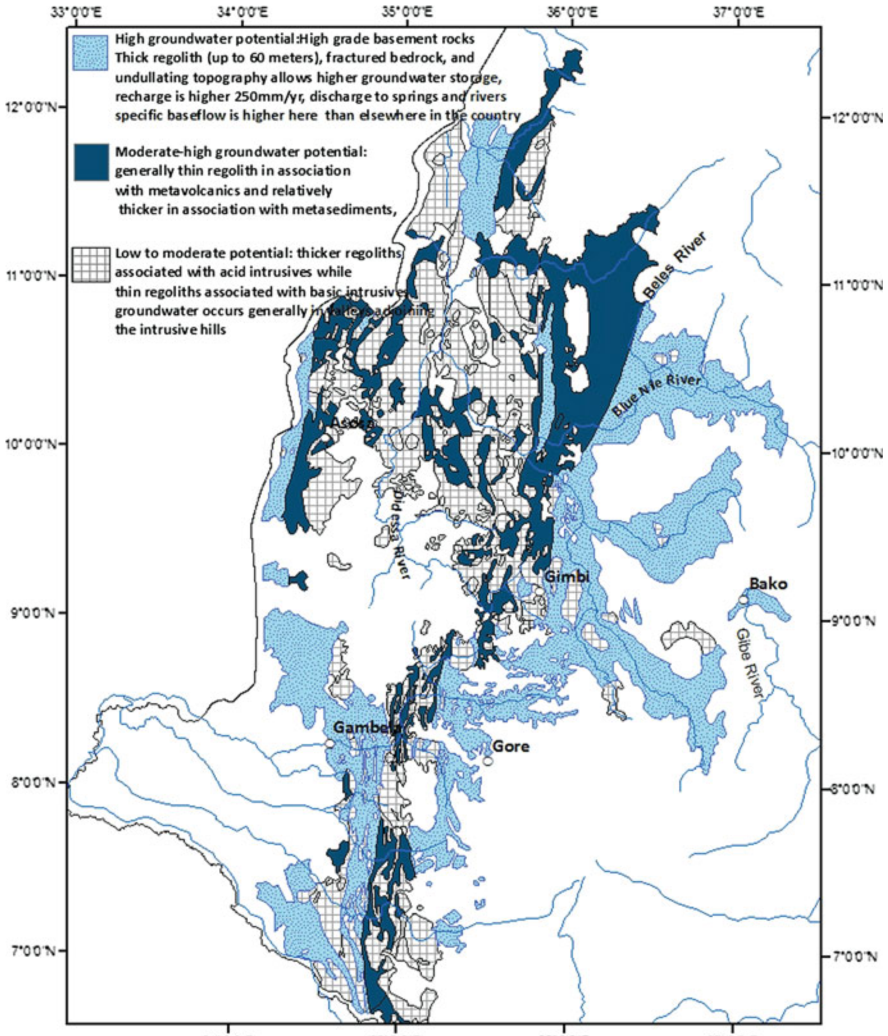


Fig. 2.46 Geologic and some hydrogeologic features of the West Ethiopian basement

Specific baseflow discharge data[7] from river discharge in the Western Ethiopian basement area shows relatively higher values compared to rivers draining the volcanic highlands and the whole Blue Nile River Valley (Belete et al. 2004). This could be indicative of higher groundwater storage potential given recharge is

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[7] Specific baseflow discharge of the whole Abay Basin at Ethiopia Sudan border is estimated at 0.45 l/s/km^2. Specific baseflow discharges for the Hoha, Sirkole, Beles and Gilgel Beles Rivers which drains the basement rocks of Western Ethiopia are estimated at 0.8, 2.42, 0.51, 0.68 l/s/km^2 respectively.

sustainable in the vast basement rocks regardless of the low transmissivity of the basement rocks. This put the basement aquifers of western Ethiopia as non negligible aquifers. Basin discharge is buffered by the high storage capacity of the thick weathered mantle in western Ethiopia.

In upper Gibe basin for example basement aquifers composed of gneiss form an important water sources for urban and rural water supply. The high grade granitic aquifer here represents discontinuous fissures in which flow is mainly in fissures and weathered mantle of crystalline rock (gneiss). It is exposed around Bako town. From lithologic logs of these wells it can be seen that, two major secondary processes enhance the permeability of this unit to be classified as aquifer. Weathering affects the most upper part of the aquifer. The weathered column of this aquifer ranges from 50 m around Bako town. The weathering column is thicker in lower altitude areas which preserves the weathered mantle. The weathering product has significant porosities and specific yield, it therefore, acts as a reservoir, storing infiltrated water and releasing it to the well which has intercepted fractures. The lithologic logs of these wells, confirm this fact, which are samples of highly fractured gneiss was obtained below the weathered column of this aquifer.

Accordingly, from pumping test result of wells drilled in Eastern sector of the area the average yield of wells tapping this aquifer is 5 l/sec (Bako & Abakoran). The hydraulic conductivity of this aquifer varies from 0.12 to 2.3 m/day. Water table fluctuation in the regoliths of western Ethiopia varies by as much as 10 m mirroring seasonal changes in rainfall. Normally during wet seasons water level is as shallow as 1–2 m and during peak dry season it goes down below 10 m below ground surface.

The Basement Aquifers of the Hammer Koke Block

Geology: In the Hammer Koke domain (Figs. 2.40 and 2.47) the metamorphic basement rocks are highly deformed and metamorphosed and reach granulites facies (Davidson 1983) implying they belong to the high grade belt. This belt is chiefly composed of various coarse grained and foliated rocks.

The rocks of this complex are metamorphosed to the highest degree ranging from amphibolites to granulites facieses. Structurally broad and gently dipping synforms and antiforms are characteristic styles. Outcrops of this complex are localized along the South, Southeast, and western parts of Ethiopia and are rare in the northern Ethiopia (Kazmin et al. 1978). In the crystalline basement rocks the variations in structural styles, metamorphic grades and rock assemblages has led to their subdivisions into three domains. The Hamar domain gneisses generally dipping toward the east—northeast, but show some variations from place to place. West of the Chew Bahir rift system (Hamar range), overturned and recumbent isoclinal folds have themselves been folded into open antiforms and synforms that trend and plunge northward. Foliation is generally sub-parallel to the layering sometimes making slight angles to it.

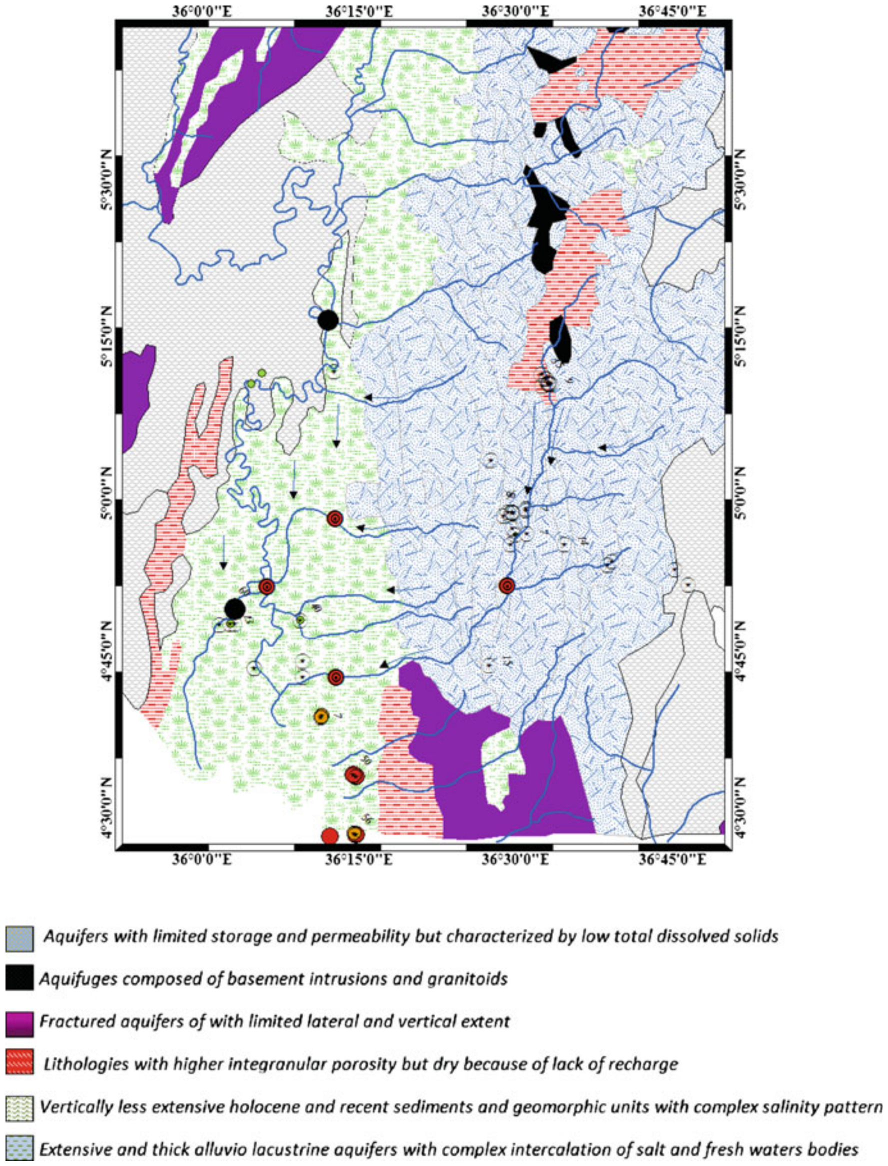

Fig. 2.47 Simplified Hydro-geological Map of the Hamer Koke block and surrounding Omo delta regions. The colored filled circles are EC indicators (small size correspond low TDS) and the open *circles* with star inside stands for water points

Red beds exposed in the northern part of the Hamar Koke block reaching a depth of 10 m and composed of fine sand and silt represent remnant of older laterite deposits formed on the Precambrian basement and later striped by Cenozoic or recent striping processes (Fig. 2.47). Because of their topographic position

Groundwater flow is confined in sandy and silty portions of the Omo basin sediments, sediments are mainly silts, clays. Shallow groundwaters occur in abandoned distributary channels, and beach sands bordering the sediments, water quality distribution is extremely complex and appear to vary with geomorphology, TSD of waters vary between 500 to over 50000 mg/L. High TDS is associated with dissolution of evaportie lenses accumulated along with the lacustrine beds. Drilled wells may turn dry when drilled on clay and silty clay dominated sediments

Groundwater flow is confined in the wadi beds, the wadi beds are developed parallel to the regional NW-SE running foliations or follow contacts between the different units of the basement rocks, there is no obvious deep penetrating fracturing, regolith thickness is in the order of 3 meter maximum, groundwater recharge to the wadi beds and the broad basement takes place from occasional flash floods generated in the higher ground high rainfall area in the north. Principal discharge path way is riparian evapotranspiration. Water quality is often of low TDS and is in the order of less than 1000 mg/L. T

Groundwater flow is confined in sandy and silty portions of the Chew Bahr basin sediments, sediments are mainly silts, clays. Shallow groundwaters occur in abandoned distributary channels, and beach sands bordering the sediments, water quality distribution is extremely complex and appear to vary with geomorphology, TSD of waters vary between 500 to over 50000 mg/L. High TDS is associated with dissolution of evaportie lenses accumulated along with the lacustrine beds.

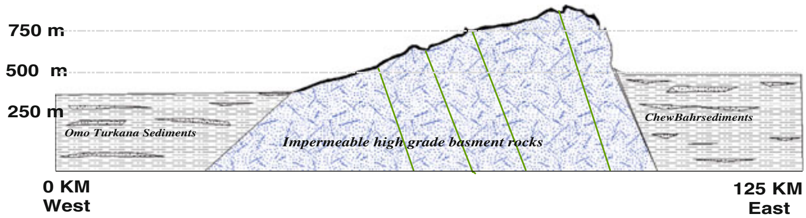

Fig. 2.48 Conceptual groundwater flow and recharge model of Hammer Koke area and surrounding Omo and ChewBahr rifts

and low prevailing recharge in the areas, the regoliths have very little potential as source of groundwater in the region.

For most part of the basement of the Hammer Koke block and the Teltele highlands the yield of wells is less than 1 l/s and mostly less than 0.1 l/s (Sima 1987). Groundwater recharge, flow, discharge conditions of the Hammer Koke block is depicted in Fig. 2.48.

The Basement Aquifers of Ethiopia as Compared to the Basement Aquifers of Africa

Groundwaters in basement aquifers of Ethiopia are mostly associated with low grade mobile belts of the Arabian Nubian shield there generally low grade nature of Ethiopian basement particularly those in the north leads to least developed regolith unlike a well developed regolith on high grade Craton materials of central and equatorial Africa. The complex but persistent uplifting since Cenozoic has also resulted in stripping of the African deep weathering surface (surface that has been formed during stage ii of landscape evolution, see Fig. 2.43). Current rainfall is also lower than the Central Africa leading to runoff exceeding recharge and thus limiting further active regolitization (except in western Ethiopia).

2.14 The Omo Delta and Chew Bahr Rift

The Omo delta is located in southern Ethiopia near the junction of the Omo River with Lake Turkana (marked 13 in Fig. 3.1). Currently the principal source of water supply for livestock and human consumption in the lower Omo and adjoining regions are river bed excavations and hand dug wells drilled into the river beds, and the Omo River. Roof water collection is also becoming an important source of water harvesting technology in the lowlands which do not have access to the above mentioned facilities. For drinking purposes as there is very scarce modern water purification technology, the local people inhabiting the Omo river use root of a plant locally called Gluf (*Maerua Subcordata*) and known to be rich in polysaccharides (*good as coagulating agent*) to physically purify the otherwise turbid Omo river. Of drilled wells in the Omo delta more than 50 % are abandoned due to unsuitable salt content often for both cattle and human consumption.

The Omo depression (Turkana rift) is underlain by Crystalline gneisses and amphibolites with intrusions of granite and pegmatite from the east, volcanic highlands from the north, up to 3 km thick Pliocene to mid Holocene deltaic and littoral beds bounding the lakes and recent deltas, mudflats and beaches straddling the lake Turkana from north (Fig. 2.47). The Omo delta is situated in a complex tectonic depression. Directly overlying the Precambrian Basement Complex are the Tertiary volcanic products. These consist of thick succession of flood basalt and overlying undifferentiated volcanic rocks of horizontally inter bedded flood basalts, trachytes, trachy-basalt and rhyolite, intercalated with tuff and volcanic ash. The tertiary volcanics cover the upstream part of the Omo Turkana basin.

At least seven prominent geomorphic units (Fig. 2.49) can be recognized in the Omo delta. The first six of these units were identified by Butzer (1971). These geomorphic units are presented as follows. The meander belt (1) is characterized by meandering channels with natural levees, cut off meanders, oxbow lakes, clay plugs and restricted flood basins.

The eastern flood plain (2) forms dispersal and gathering streams and non outlet depressions that serve as back swamp.

The delta flat (3) is a broad flat surface that acts as flood basin. It consists of non-functional inter distributary basins, lagoon mud flats and networks of distributary channels. Gathering streams are associated with seepage from meander belts.

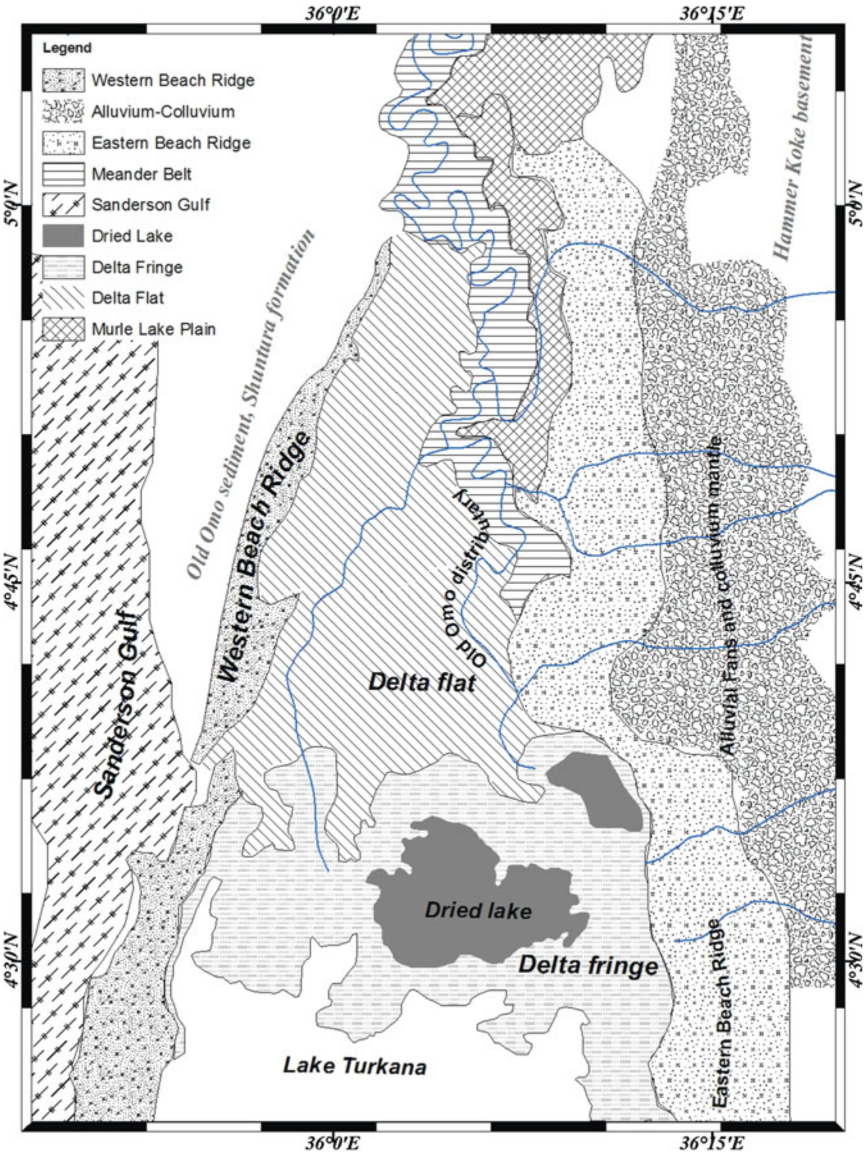

Fig. 2.49 The geomorphology of the Omo delta and Turkana sediments. Modified from Butzer 1981

The delta fringe (4) is a flat surface with bird foot shape and it consists of two active sub deltas (Erdet and Dielrhiele), one extinct sub-delta (Murdizi) and extinct lakes. The Murdizi subdelta is formed at the confluence between an old extinct Omo meander with Lake Turkana. Geomorphic units such as flood plains, inter-

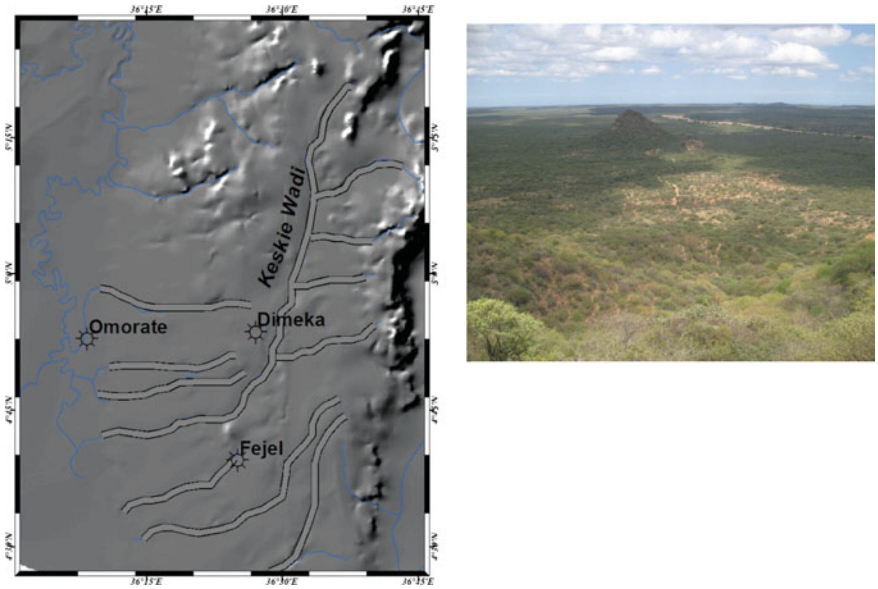

Fig. 2.50 Prominent Wadi beds in the Hammer Koke block. The most prominent of all Wadis is the Keskie which runs North south following the regional trend of the metamorphic basement and the contact between meta sediments in the west and meta volcanic in the east

distributary bays, distributary mouth bars are common. The beach ridge plains (5) are discontinuous belts of sub-parallel, non functional beaches. Most of the beach ridges are narrow (1 km) and topographically prominent. The beach ridges separate the crystalline highlands bounding the Omo valley and the Omo delta sediments.

The murle lake plain (6) is an extensive plain of an old lake floor, fringed by beach ridges. An active Lake Dipa is located within the Murle Lake plain and is connected to the active flows of Omo River.

Recent alluvial fans and wadis (7) form localized or about 2 km^2 alluvial fans composed of sands, gravels and pebbles. The alluvial materials are found at the confluence of the wadi beds draining the Hammer Koke highlands in the east and the Omo valley. The alluvial fans contain distributary channels and sand bars.

The Hamer-Koke block is underlain by extensive North–South trending high grade metamorphic rocks. This highland is bounded from the East and west by the Omo and the Chew Bahr tectonic depressions filled by alluvio-lacustrine sediments. In the Omo Turkana basin, the sediment thickness is estimated to reach 3–4 km accumulates since 4 million years (McDougall et al. 2008). Volcanic rocks of tertiary age are limited to the northern boundary of the area (Fig. 2.47). Some patch outcrops of volcanic materials were also recognized in the center of the Hammer Koke highland and the lowlands bordering Kenya. The volcanic rocks bordering the Ethio-Kenya border are named as Gombe basalts. This lithology is believed to underlie the Omo Turkana sediments.

Wadi bed sediments mainly composed of sands and gravels, and *alluvial fans* composed of gravels, sands and silts at the outlet of the wadis from the highlands and before joining the Omo delta are features with small lateral extent (see Fig. 2.50) for the distribution of the wadi bed sediments). Regardless of their small aerial extents the wadi bed sediments are the principal source of groundwater in the Hammer Koke block.

Elsewhere in the world crystalline basement rocks are known for their low permeability and storage potential. In crystalline aquifers of Central and tropical Africa, the basement rocks are significantly weathered and the thickness of the regolith may reach 90 m. This regolith zone enhances permeability and storage properties of basement aquifer and ultimately provides storage for shallow groundwaters in several regions of tropical Africa (e.g. Uganda, Congo). As described in Sect. 2.13 the basement aquifers of Ethiopia because of the uplifting since Cenozoic and low grade nature of the basement the thickness of regolith is not as pronounce as those seen in central Africa. In the Crystalline block of Hammer Koke, probably owing the low rainfall (<400 mm/year), dry conditions, and prolonged stripping since the Cenozoic, regolith is very thin (in the order of 2 to 3 m). In some localities foliations associated with basement rocks act as storage and transmission medium. In the Hammer Koke block however the basement rocks are high grade (granite to granulite facies). Such rocks lose their foliation related permeability. Therefore the basement rocks of the Hammer Koke block can be considered as the least productive aquifers in the region.

Primary porosity is the principal storage and transmission medium in the wadi beds, alluvial fans and in the Omo delta sediments.

Total groundwater storage in wadi bed sediments has been estimated by assuming a porosity of 0.2, total wadi length of 300 km and thickness of sediment at 3 m and the average width of 10 m. This approximation is the minimum storage as this estimate takes into consideration only prominent wadis. The minimum groundwater storage that can be guaranteed in the wadi bed is estimated at 2–4 million meter cube. The actual storage of the groundwaters in the Wadis varies from place to place. Since the head water of the Keskie Wadi (Fig. 2.47) rests in the northern part of the area where the annual rainfall is in excess of 500 mm/year the wadi sediments have sustainable recharge from the north. Frequent flooding around Trumi (10 km south of Dimeka) of by Keskie wadi associated with high rainfall in the higher grounds in the north is a common hydrologic event.

Groundwater flow and discharge pathways in the Omo sediments are complex. Since the permeability of the sediments unless locally inter fingered by sediments such as sands, and silts is low, discharge of groundwaters to the Lake Turkana should be small. Previous isotope hydrological investigation on Lake Turkana also reveals the fact that groundwater contribution to the lake is insignificant (Kebede et al. 2009). In the **Omo** sediments the principal groundwater discharge path way should therefore be riparian vapor-transpiration.

Groundwater geochemistry here has been used as a tracer of recharge and groundwater flow and also to determine water quality for different water uses. Generally groundwaters in the crystalline highlands have lower total dissolved solids (<1,000 mg/L). The volcanic highlands are also characterized by comparable total dissolved solids. The Omo delta and sediments are characterized by very complex groundwater geochemistry (Fig. 2.47). Here fresh low TDS groundwater zones intervening with saline or brackish groundwaters are common observations. The fresh groundwater lenses is often associated with distributary channels connected to Omo, or with beach ridges bounding the Omo delta from East and West, or with the alluvial fans intruding into the Omo sediments at the emergence zone of the wadi beds from the Hammer Koke block.

TDS, NO_3, F are principal water quality constraints in the region. The high NO_3 are often associated with hand dug wells. In the Omo sediments high F is associated with evaporative enrichment and leaching of F from the sediments while in the crystalline highlands F can have its source from weathering of rock forming minerals associated with the basement lithologies. The fact that high NO_3 occurrence in association with hand dug wells could be suggestive of pollution the waters from lack of hygiene around the water points. One clear example is note in a hand dug well equipped with hand pump in the Dimeka town. The well is located underneath the shade of an acacia tree with no obvious anthropogenic impact on water quality but the well returns water with foul odder.

A well drilled 18 km north east of Omorate in the alluvial fan deposits draping on the basement rocks shows a transmissivity value of 57 m^2/day and yielding 3.9 l/s at a drawdown of about 8.5 m. The alluvial fan material (Fig. 2.49) is composed of silt, sand pebbles and gravels and contains good quality water for domestic water use.

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Chapter 3
Very Shallow and Shallow Groundwaters

3.1 General

Alluvial terrain covers less than 25 % of the land surface of the country (Fig. 3.1) however, major prolific aquifers and larger groundwater storage lay in this zone (Fig. 1.1). Investment on groundwater schemes is, could therefore, much more feasible in the regions underlain by alluvial aquifers.

The shallow and very shallow sediments are formed in Ethiopia since Miocene and their formation continued in Quaternary till present day. Most of these lose sediments are found in eastern Ogaden, Danakil Depression, lower Omo valley, Southern Sidamo, Gambela and western Gondar areas (Fig. 3.1). The main Quaternary deposits are alluvial, lacustrine, and colluvial deposits.

The alluvial deposits are of two types: (1) those which spread out in alluvial plains and (2) those which occupy strips of land and river beds along rivers and streams. Alluvial plains fill up tectonically formed grabens (depressions) and large stretches of flat land in the rift valley and along the whole length of the western boarder of the country. These are troughs in the lowlands where during the pluvial period streams deposited large amounts of sediments carried down from the highlands. The thin strips of alluvium along streams occur in most places both in the highlands and in the lowlands. In the alluvial plains, alternating layers of fine and coarse sediments are characteristics and in many cases, lacustrine sediments could be found in association with alluvial deposits.

The alluvial plains in the Afar region have moderate to high permeability. Those plains at the foot of the eastern escarpment (e.g. Shinile, Fig. 3.1) have relatively coarse sediments of moderate to high permeability and productivity near the mountain front and fine grained silts and clays in its northern sector. On the other hand, those plains east of the western rift escarpment (e.g. Raya valley and Teru graben) up to about half way along the Awash and Mile rivers have relatively finer grained sediments with moderate permeability and productivity. The vast plains of Baro-Akobo drainage (marked 3 in Fig. 3.3) and Omo River (marked 13) have also moderate productivity.

S. Kebede, *Groundwater in Ethiopia*, Springer Hydrogeology,
DOI: 10.1007/978-3-642-30391-3_3,

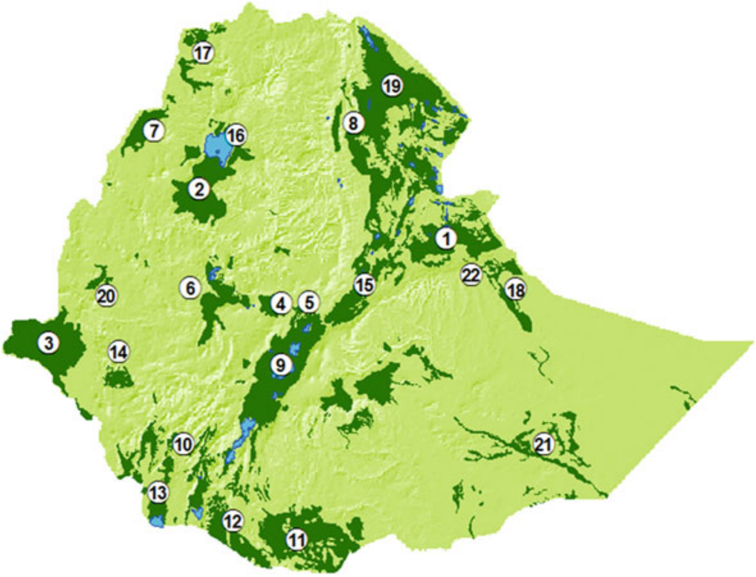


Fig. 3.1 Distribution of principal Alluvio lacustrine sediments in Ethiopia; *1* Shinile marginal graben fill sediments in the foothill of Harar plateau, *2* Lake Tana shallow regoliths, *3* Gambela Miocene Alwero Sands and associated quaternary sediments, *4* Becho plain, *5* Akaki plain alluvium and soils, *6* Headwater of Gibe and Didessa rivers, *7* Rehad alluvium and wadi bed sediments, *8* Western Afar marginal grabens of Raya and Teru, *9* Main Ethiopian rift sediments and volcaniclastics, *10* Gofa basin and range graben filling alluvium, *11* Borena elluvium, alluvium and wadi bed sediments, *12* Ririba valley alluvium, *13* Omo delta sediments, *14* Bonga alluvial sediments and colluviums, *15* River terrace related alluvium in middle awash and associated colluviums, *16* Eastren and Northern Lake Tana sediments of Fogera and Dembia plains, *17* Tekeze and Humer plain sediments, and *18* Wadi bed sediments of the Fafen Valley, *19* Alluvial fans, graben filling alluvio lacustrine deposits of the Afar depression and thin veneers of sediments covering the volcanics, *20* Dabus swamp and associated colluvial, alluvial and basement regoliths, *21* Wabishebele river terrarces and flood plain alluvium, *22* Regoliths and alluvial sediments of the lake Alemaya-Adele plain

Some alluvial plains, which are surrounded by coarse-grained metamorphic and plutonic rocks such as granitic gneisses and granites, consist of course materials and, therefore, have high permeability and productivity (e.g. Gambela). These form local productive shallow aquifers in Tigray and many places in southern basement rocks covered area and in Western basement covered area. Sediments in the Main Ethiopian Rift are mainly lacustrine deposits of purely lake or swamp deposits or those of volcano-lacustrine type. The most extensive lacustrine sediments are located around existing lakes, because they were deposited when these lakes were much larger during the pluvial times. Alluvio lacustrine sediment associated with lakes are localized in central Ethiopia, southern and north western Ethiopia (marked 9, 13 and 16).

These sediments show many differences in their permeability, those showing the highest permeability are the ones consisting of fine sand. Some of them are known to provide more than 10 l/s with no or very little drawdown. On the other

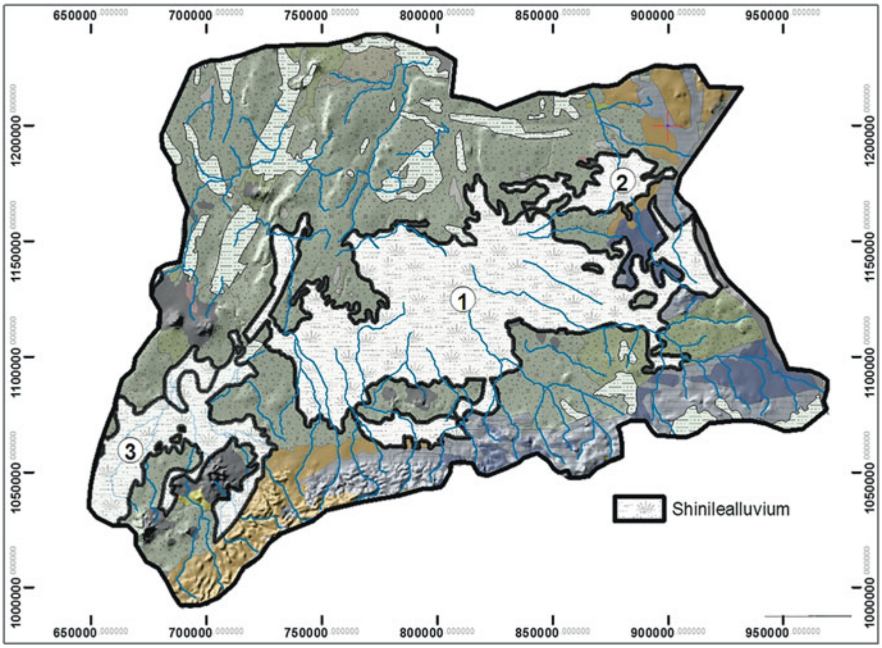


Fig. 3.2 Map showing the extent of Alluvio lacustrine sediments in the Shinile plain

hand, fine-grained sediments with inter-bedding of massive tuffs and fine ash are known to have low productivity in many places (e.g., in Central sector of the Ethiopian Rift). In the eastern part of the country (e.g., in Shinile area around Diredawa), the total thickness of the sediments reaches about 300 m. In most of the outcrops, they consist of conglomerates, sandstone and mudstone, which are gypsiferous and locally bear saline groundwater.

3.2 The Sediments of Shinile and Marginal Grabens of Southern Afar

Geology

The geology of Shinile area comprises recent alluvial sediments, quaternary to recent lava sheets, basalt ridges and Mesozoic sequences. The alluvium is composed of coarse sand, pebbles and gravels. In places the alluvial sediments are dotted by solitary dune sands (Fig. 3.2).

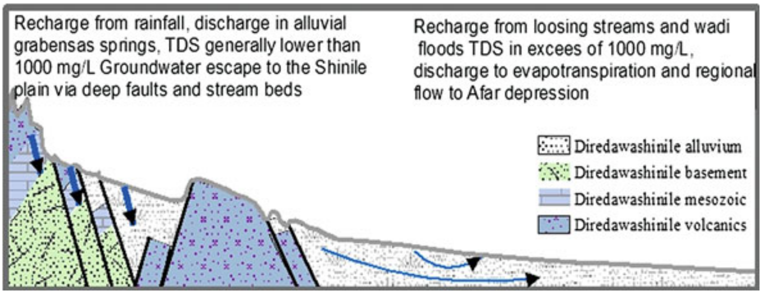


Fig. 3.3 Conceptual model of groundwater flow and recharge in the Shinile alluvio lacustrine aquifers

Groundwater Occurrence

The alluvio lacustrine sediments in the foothill of the Harar plateau occur in three major zones (Fig. 3.2). These are (a) the proper Shinile alluvio lacustrine aquifers marked number 1 in Fig. 3.2 makes up 9000 km^2 (b) the Afdem-Erer alluvio lacustrine sediments which make the south eastern part of the Alidegie plain, and (c) the conglomeratic aquifers bounded between the Adigala plateau and the Dawale block. Total groundwater storage in a small part of the Shinile alluvial aquifers has previously been estimated to reach 12 billion meter cube, however, taking the whole Shinle alluvio lacustrine aquifers which cover 9000 km^2, assuming a saturated thickness of 100 m and porosity of 15 % the total groundwater storage is estimated at 150 billion m^3. The Western Shinile alluvio lacustrine aquifers which make part of the Alidegie plain cover an area of 2500 km^2. In the Ali Degie plain bordering the static water level is on average 70 m below ground level and the water has a temperature ranging from 39 to 43 °C.

Grain size of the alluvial aquifers decreases from South to North. Transmissivity and specific yields obtained for the alluvial aquifer reaches up to 700 m^2/day and 3.2 l/s/m. In several places higher transmissivity have been noted. For example, in the alluvial deposit 150 m deep borehole at the foothill of the plateau in the south has transmissivity of 3012 m^2/day.

There are two principal recharge sources. The first is coming from loosing streams and account for the bulk of recharge and the second is mountain block recharge coming trough aquifers following the subsurface laterally from the mountains in the south. A simplified conceptual model of groundwater flow and occurrence is noted in Fig. 3.3.

The formation is an extensive and productive porous aquifer, covering approximately 50 % of the Afar floor. The formation consists of boulders, gravels, sand, clay layers, wadi gravels and sand and lacustrine sediments. On the basis of pumping tests of 24 boreholes the average transmissivity is 6.1×10^{-3} m^2/s. The higher yield and transmissivity of boreholes is found north of Diredawa, just near the foothill of the mountains. It is the area in which the course alluvial sediments predominate. The lower yield occurs in the central part of the alluvium. The lowland sector the grain size of the materials become fine grained and lacustrine sediments derived mainly from volcanic materials dominates (Zerai and Sima 1986).

Most of the groundwater shows a water table condition while some wells exhibit artesian conditions. The quaternary sediments are composed of alluvium (sand, silt and clay and their inter-bedding) river gravels, fans and travertine. The unconsolidated sediment grain size decreases along the depositional course, northward. The valleys near the escarpment are filled up with coarser fragments of rocks and sandy to clayey matrix. Reworking of the alluvial deposits by aeolian activity is considerable in central part of the area. The superficial deposits at the foothills of the plateau in the south are made up of colluviums containing talus and fluvial sediments and river gravels of thickness 5–20 m. Recent 250 m deep drilling in Shinile-Aydora shows that the alluvial materials are comprised of poorly sorted deposits which comprises, sand, silty-clay, volcanic fragments of basaltic and minor rhyolitic origin.

In the extensive alluvial materials there are a lot of productive shallow wells currently used to exploit groundwater for community water supply. The shallow circulating groundwater can be taped in 10–20 m with in this unit.

Groundwater Geochemistry

The major challenge to groundwater development in the Shinile is the higher salinity of groundwaters. The salinity of groundwater varies spatially following the drainage patter. In the highlands and marginal grabens at the foothills of the Southern highlands, the total dissolved solids is less than 1000 mg/l. TDS in groundwaters increase northward until it reaches in the order of 10,000 mg/l in the northern lowlands and central depressions. In the south Ca, Mg and HCO_3 ions dominate the groundwater ionic composition while in the north high TDS, Na, Cl and SO_4 dominates. This geochemical pattern is typical of arid zone aquifers whose salinity is mainly imparted from dissolution of crystalline rocks in the highlands and dissolution of evaporite lenses from lacustrine sediments in the lowlands. Evaporative concentration of salt also contributes towards the enhancement of salinity in the lowlands. Groundwater becomes more saline as it moves to the north through alluvium. The boreholes drilled in the center of the alluvial plain (Aydora) were abandoned due to high salinity and low yield. The most favorable possibility to encounter groundwater of good quality and yield at the plain is to drill shallow wells or to dig wells as near as possible wadi courses.

3.3 The Quaternary Volcanic and Alluvio Acustrine Sediments of Lake Tana Basin

The Quaternary Alluvial Aquifers within the Lake Tana basin occur dominantly at the eastern part of the basin following the lower Rib and lower margin of Gumera (marked number 16 in Fig. 3.1). It also covers significantly in the north part of the basin at the lower part of the Megech and Western shore of Lake Tana. The distribution is limited compared to the volcanic aquifer units. The productivity of this aquifer is associated with the pores of unconsolidated gravels and sand. The available data on this aquifer indicate high productivity with boreholes yielding more than 6 l/s with depth of up to 60 m.

The quaternary alluvial deposit also covers the Fogera plain (East of Lake Tana), along the bank main perennial stream and Lake Tana. The deposit is up to 60 m near Woreta, which is part of Fogera plain. This is deposit composed of clay to gravel. The lacustrine deposit fine silt and clay covers the bed of Lake Tana overlying the tertiary basalt. The previous investigation aided with drilling on the lake floor shows the occurrence of indicates stiff clay up to 80 m depth. In the center of the alluvial plain the water table depth is in the order to 5–10 m or shallower.

3.4 The Quaternary Sediments of Gambela and Associated Wetlands

In the lowlands of Gambela (marked 3 in Fig. 3.1) four hydro-stratigraphic units can be recognized (MWR 1972). Detailed account on the geology and groundwater potential as well as surface water hydrology of the Gambela area can be found from (MWR 1972). According to this works the four hydrostratigraphic units are (a) the Basement complex aquifers, (b) the Holocene alluvial aquifers, (c) the Quaternary alluvio lacustrine aquifer and (d) the regional sandstone aquifers of the Pliocene Alwero formation (Fig. 3.4). In the basement complex the static water level ranges from 2 to 40 m. Spring discharge in the basement complex is in the order of 1 l/s. The valleys secluded between ridges of basement complex also hold minor storage of locally important groundwater resources. The Holocene alluvial aquifer comprises Holocene alluvium deposited along the alignments of river courses. Such aquifers are generally perched, contain a significant quantity of silt and clay, and are in direct hydraulic continuity with the rivers. The well yields of 0.1–1 l/s has been noted. Water levels in this phreatic aquifer are usually less than 5 m below the ground surface. The quaternary alluvio lacustrine aquifers occur throughout the Gambela plain mostly in the western sector. Deposition of this alluvium aquifer has occurred from Upper Pleistocene throughout Holocene time. It is effectively separated from the underlying regional Alwero aquifer by lacustrine clayey deposits, but is open to infiltration of water from the surface. Well yield ranges from 0.01 to 0.5 l/s. Pheratic water levels in this aquifers range from ground surface to about 7 m depth.

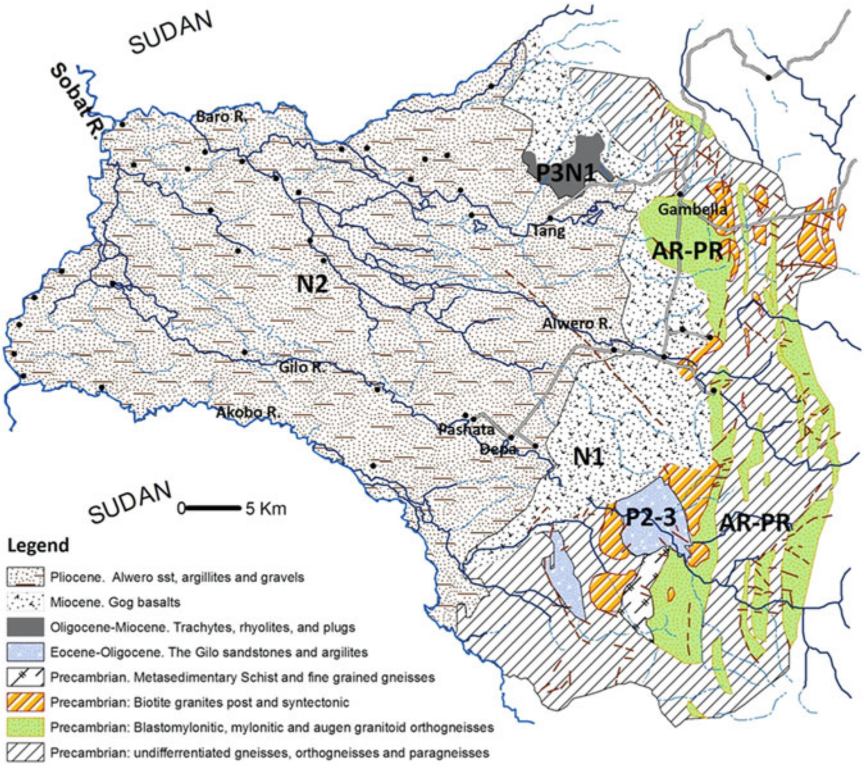
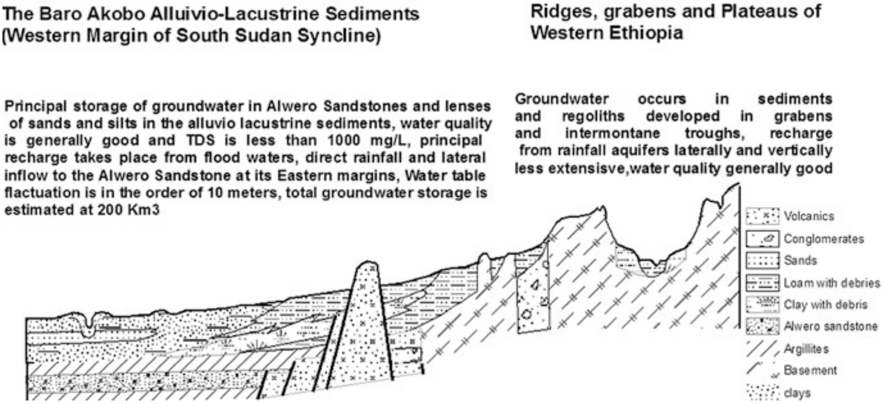


Fig. 3.4 Geological map of the Gambela area

The regional aquifers comprise the Plio-quaternary deposit starting from the Illubabor (eastern most region) plain and continuing beneath the Gambela Plain to and beyond the Ethiopia-Sudan border. The formation comprising this regional aquifer is predominantly the Pliocene Alwero Formation and Lower to Middle Pleistocene alluvial deposits of the Gambela Plain (Fig. 3.5). Transmissivity in the sedimentary formations has been tested to range up to 120 m^2/day while yield varies between 0.01 and 2.5 l/s. Water levels vary from 13.8 to 30.1 m below ground surface (MWR 1972).

Three sources of recharge can be recognized for the whole aquifer complexes. These are direct infiltration from rainfall, infiltration from channels and flood plains and lateral groundwater inflow from the crystalline highlands. Particularly the regional sandstone aquifer gets most of its recharge from lateral groundwater inflows. Water level fluctuation in wells ranges from less than 5 to over 13 m mirroring seasonality of recharges episodes. Total groundwater recharge in the Gambela plain has previously been estimated to reach 128.4×10^6 m^3/year. Total groundwater storage in the basin is estimated at 200 km^3.

Total dissolved solids range from 72 to 955 mg/l making the groundwaters of the region suitable for irrigation uses. Total irrigable area using groundwater can



The Baro Akobo Alluivio-Lacustrine Sediments (Western Margin of South Sudan Syncline)

Ridges, grabens and Plateaus of Western Ethiopia

Principal storage of groundwater in Alwero Sandstones and lenses of sands and silts in the alluvio lacustrine sediments, water quality is generally good and TDS is less than 1000 mg/L, principal recharge takes place from flood waters, direct rainfall and lateral inflow to the Alwero Sandstone at its Eastern margins, Water table flactuation is in the order of 10 meters, total groundwater storage is estimated at 200 Km3

Groundwater occurs in sediments and regoliths developed in grabens and intermontane troughs, recharge from rainfall aquifers laterally and vertically less extensisve,water quality generally good

Fig. 3.5 Schematic recharge and flow model of the Baro Akobo sediments

be estimated at 200,000 ha. This irrigation can be made through shallow to deep wells probably discharging water at 1.5–20 l/s.

The Pliocene Alwero formation lies on the leveled surface of the piedmont through having overlapped a considerable part of the Gog basalt. Kaolinized arkoses and aleurolinites, ferruginous gritstones and argillite like clays, more seldom sands and gravel predominate in their composition. Their thickness increases westward reaching 200–300 m in central part of the Low plain.

Quaternary deposits occurs forming specific geomorphologic units. In the alluvial deposits, long shore bars and Holocene deltaic formations permeability is generally low (k is about 0.1 m/day) and borehole yields vary from 0.1 to 1 l/s, in most cases not exceeding 0.2 l/s. The water table is generally 2–4 m deep, the range being 0–5 m. In Holocene lacustrine deposits (which occur mostly in western part), the thickness increases in the western direction to 10–20 m and probably 30 m. Groundwater recharge is principally from floods. Groundwater discharge to Pibor River and partly evaporates. In most cases water table is between 4 and 5 m.

In the regional Alwero Aquifer gradient is in the order of 0.00077–0.0011. In places the Alwero regional aquifer yields artesian conditions. The Artesian aquifer presumably dips at a small angle to the west escaping Ethiopia and may be encountered within the Upper Nile Syncline (in Alwero formation) at depths from 80 to 200 m. The aquifer recharge is by groundwater seepage through basalts and granites-gneisses in the east. In the whole alluvio lacustrine sediments water table reaches peak in October and lowest level in May.

Groundwater in the quaternary alluvio lacustrine sediments is slightly saline With TDS slightly less than 1000 mg/l. In most cases it vary between 200 and 600 mg/l. The Underlying Alwero formation shows much fresh groundwater chemistry at TDS of 300 gm/l.

Fig. 3.6 The Alluvio Lacustrine sediments of the Belsa plain

3.5 The Quaternary Alluvio Lacustrine Sediments of Belesa Plain

Alluvio lacustrine deposits including gravels, travertine, sand deposits with travertine cement (Fig. 3.6) were observed in the Belesa area (see Fig. 2.10 for location of Belesa plain). The Alluvio lacustrine sediments mantling the Belesa plain are characterized by (a) typical sand and fine sand with graded bedding of fining upward sequences cyclothermic deposits at the base, (b) travertine and lacustrine beds with sediments showing typical laminations and cross beds of gravels, sand, siltstones. The thickness of the Alluvio lacustrine sediments is estimated at 25 m, (c) beds of paleo-soil, and (d) stratified fosiliferous calcareous or diatomaceous beds of 15 cm thickness, (e) reddish and black colored peat. This situation is formed by incomplete combustion of organic materials in a marshy part of the paleolake. The exposure of the alluvio lacustrine deposit nearly covering over 100 km^2 may be indicative of the paleolake on straddling the Lake Tana basin from the North East. Direct evidence of groundwater potential in this plain is lacking. An indirect indicator of high groundwater potential is the higher specific discharge of rivers draining the area. Streams which drain this area sustain their flow in the driest months regardless of the low annual rainfall testifying a higher contribution of groundwater from the alluvial materials for the Belesa plain.

3.6 The Dabus Swamp Area and Associated Quaternary Sediments

The Dabus swamp and associated sediments cover an area of 1650 km^2 occupying a flat laying plain surrounded by volcanic hills and basement uplands. In a regional hydrogeological mapping conducted by the Ethiopian Geological Survey (Belete et al., 2004), the alluvial materials are mapped as moderately productive at 10–100 m^2/day transmissivity and 0.1–5 l/s yield. The groundwater accumulates in the pores of an unconsolidated material. There are three porous formations: The colluvium fills wider valleys formed mainly by erosion (Fig. 3.1), alluvial materials forming along river strips and regoliths mantling the basement rocks underlying the area. The original source material for colluvial as well as alluvial sediments is mainly either from the older Precambrian and/or from the tertiary volcanic formation.

Despite the great lateral variability of alluvial sediments, most of the alluvial deposits have a simple vertical succession from coarse sands or gravels near the bottom of the channels to silts and clays at the top. The Dabus marsh represents important storage of groundwater and is the source of the Dabus River. The spongy nature of the headwater marsh is highly beneficial in sustaining the flow of Dabus River in the dry seasons.

Groundwater recharge to the underlying alluvial material takes place by direct rainfall infiltration while discharge takes place as riparian evapotranspiration, spring discharge and discharge to streams as baseflow.

Among the three types of lithologic units, the alluvial and colluvial sediments represent extensive and moderately productive aquifers where groundwater is under water table conditions. All porous aquifers are expected to be the most promising from the point of using them as irrigation water sources for household or community based irrigation practices. Remarkable challenge to extensive groundwater utilization practice is the marked variation in water table between the dry and wet season. The water table varies by as much as 10 m between the seasons leaving some shallow hand dug wells empty of water.

3.7 The Lake Alemeya-Lake Adele Basin

The Adele Alemeya Lake catchment is underlain by basement complex rocks (granites and gneiss), sandstones and limestone belonging to the Mesozoic and loose sediments made up of colluviums, alluvium and regoliths. Regoliths develop on the Precambrian gneiss and pegmatites (Fig. 3.7, see Fig. 3.1 for location). The regolith thickness in most cases is 20 m and reaches 40 m in places. The alluvial and lacustrine sediment of the area covers the flat surface of the lakes basin. The unit consist mostly of stratified silt, sand, sandy gravel and minor amount of clay at the dry lakes floor. The thickness of this unit generally ranges from 1 m at the hilly parts to 80 m at the center of the lakes basin. The unit covers an area of 140 km^2 and if only the alluvio lacustrine sediments were taken the areas reduces to about 70 km^2. The loose sediments appear to be finer on the top part and coarser at lower parts.

In the Adele Alemeya Lake basin there are three separate depressions which are currently hydrographically disconnected but information obtained from the local community reveals that the now separate sub basins were interconnected via surface water flows- Lake Finkile overflowing to Lake Alemeya. All these lakes have now become dry beds. The surface drainage is characterized by radial pattern, forming a closed drainage system whereby water drains from the surrounding hills into the central plain land. Due to the closed nature of the basin,

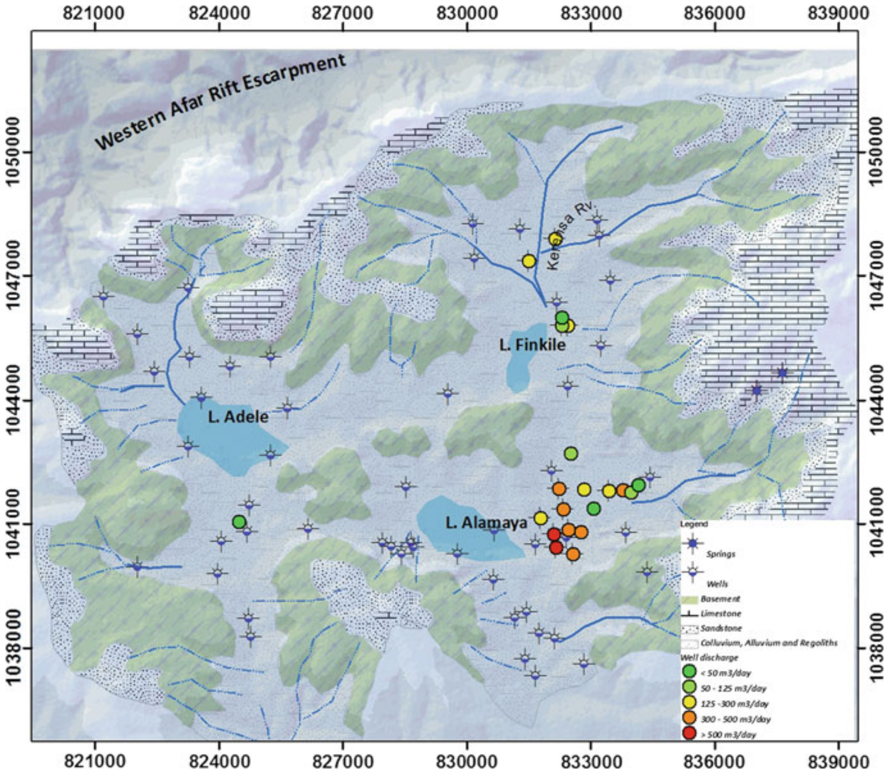


Fig. 3.7 Hydrogeological features of the lake Alemeya-lake Adele catchment

hydrological outlet from the basin is mainly through evapotranspiration and artificial abstraction while inflow to the basin is only from precipitation falling in the lake catchment.

Many hand dug wells were constructed in upper part of the alluvio lacustrine sediments so as so abstract water for household water supply and some for irrigation purposes. All hand dug wells have very low yield which ranges from 0.1 to 0.5 l/s. But, the two springs emerged from the Limestone karst in eastern part of the area (Fig. 3.7) discharge 2 l/sec during dry seasons.

The Alamaya Adele basin is the principal area in Ethiopia where intensive groundwater use is taking place for irrigation principally for Chat plantation (a stimulant plant widely used in East African and South Arabia). More than 600 hand dug wells exist in the basin to abstract groundwater from the top part of the alluvio-colluvial sediments at a rate of more than 1000 m^3/day, more than 60 shallow wells equipped with hand pumps discharging at a rate of more than 900 m^3/day and 16 deep wells discharging at 6000 m^3/day making total groundwater withdrawal from the basin at 2.9 million m^3.

The hydraulic conductivity of the alluvio lacustrine sediments is determined to be 1.5–10 m/d. And the transmissivity ranges from 25 to 400 m^2/day. Groundwater recharge is estimated at 60 mm/year in the basin.

3.8 The Foot Hills of Hagerselam Volcanic Hills in Tigray

The volcanic hills capping the Mesozoic sedimentary sequence of the Mekelle outlier cropping out in several isolated, flat topped hills (Fig. 2.34) holds important local groundwater flow systems. The prominent example is the Hagerselam area west of the Mekelle outlier. Shallow groundwaters with perched water table occur in the trap volcanics (equivalent to Upper basalt unit of the broad volcanic plateau) above lateralized upper Amba Aradom sandstones (Vandecasteele et al., 2010). Perched groundwater in the basalt cap normally discharge as springs at the contact zone between the basalt caps and the underlying Mesozoic sediments (Fig. 3.8). Intercalated lacustrine sediments in the Basalts favor formation of local perched water tables. Compared to the vertisols associated with them the basalt bed rocks have lower permeability and storage potential.

Figure 3.8b shows conceptual model for groundwater recharge and circulation in Hagerselam May Zekzek setting. Recharge principally takes place from rains in the upper basalt cap and discharges to springs and streams draining the higher grounds. Remaining water percolates to the underlying bed rock following fracture zones and bedding planes to form regional water table which if present is several hundred meters below the ground. The percolated water discharges laterally to landslide bodies draping the lowlands (Fig. 3.8a) making the landslide bodies important site for shallow groundwater water exploitation.

3.9 Alluvial Aquifers in the Headwater Regions of Didessa and Gibe

Regardless of their appearance as a single extensive alluvial material in Fig. 3.1 (marked 6) the Didessa Gibe alluvial sediments occupy three river catchments namely the upper head water regions of Gibe, Didessa, Fincha Rivers. Only the first two are described here with a support of a figure.

Gibe: Quaternary soil occurs extensively at the central part of the upper Gibe catchment and further extends southward along the bank of the Gibe River. This unit mainly covers the topographic low areas defining plain land. It covers approximately 583 km^2 (0.2 %) of the total catchment area (Fig. 3.9). This unit consists of three types of sediments: black cotton soil, reddish sandy soil and alluvial. Since these sediments occur mixed with one other, it is impossible to map separately. The black cotton soil is located mainly on the marshy area on the plain south of Bako town. It is black to dark brown, fine grained and has clay texture. This soil has 25–30 m

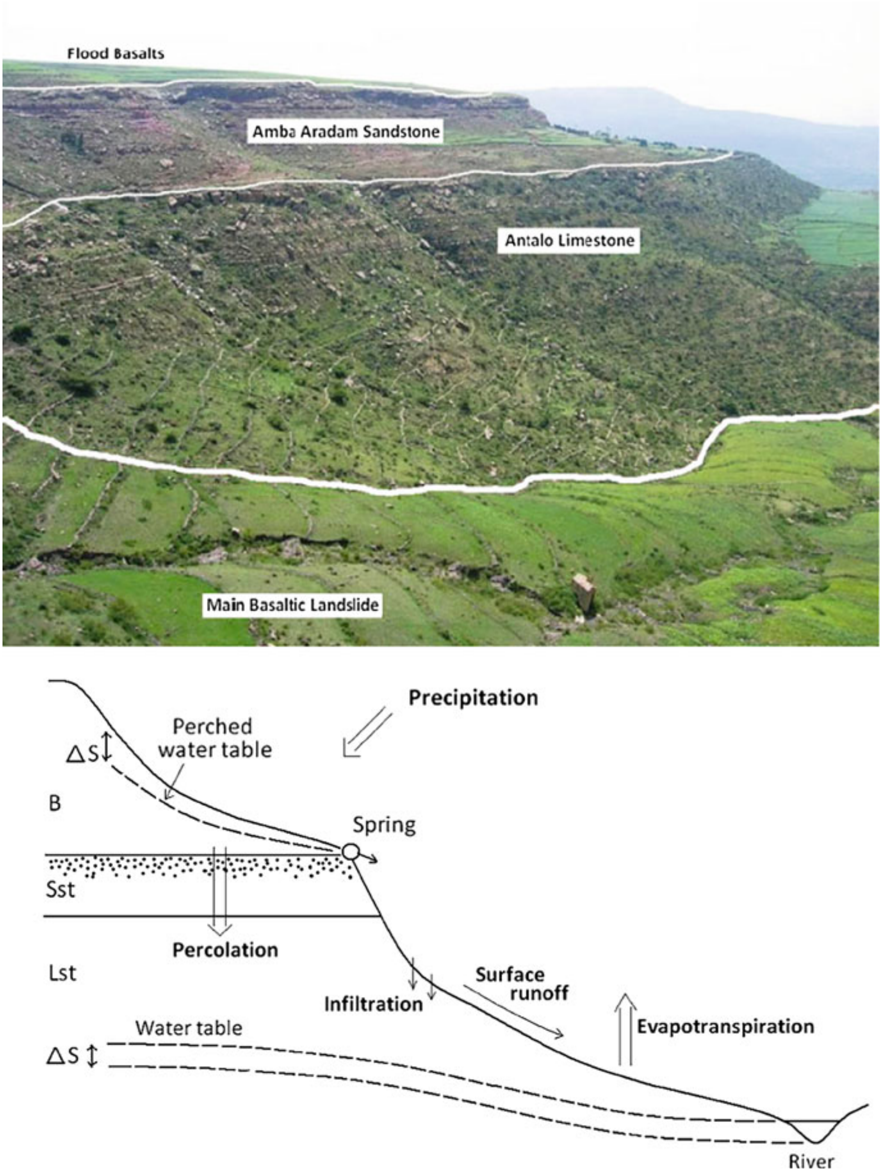


Fig. 3.8 May Zekzek hill containing perched groundwaters in flood basalts and diffuse groundwater discharge in Landslide body. Typical example of similar situation in other regions (from Vandecasteele et al. 2010)

thicknesses and mostly covered by extensive elephant grass. Reddish sandy soil is loose and fine to medium grained. It is composed of angular grains of quartz and feldspar. Major occurrences of alluvial sediments are along the banks of Gibe River. The alluvial sediments mainly comprise a mixture of course to fine sandy sediments

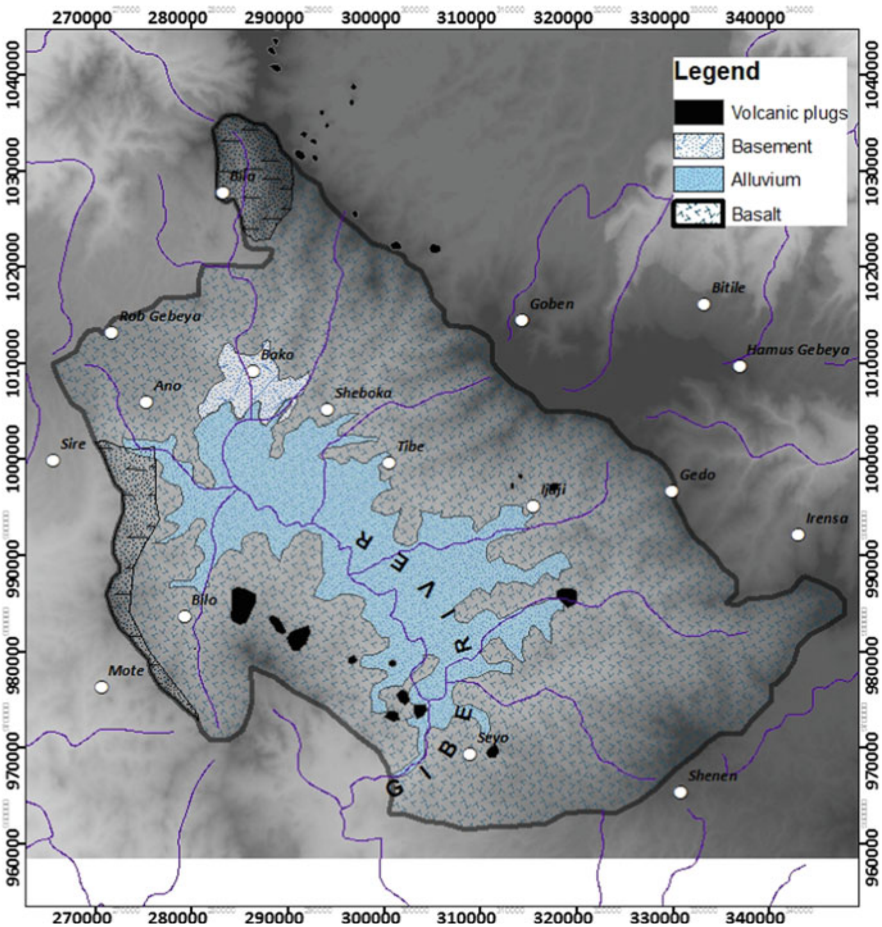


Fig. 3.9 Alluvio lacustrine sediments of the Gibe and Didessa headwaters

These sediments act as aquifer for shallow groundwaters. The porosity of this aquifer is reduced because it lacks sorting (the mixture of coarse and fine sandy soil). There are a few wells tapping this aquifer for water supply purpose and well logs reveals that the thickness of the alluvial sediments reaches 30 m.

Didessa: This unit is exposed in the northern part of the area in the Didessa river valley, its tributaries and small river valleys (just west of the Gibe valley and draining to the Blue Nile River). They are silty to sandy reddish brown (alluvial soils) and black cotton soils (elluvial soils) developed from granitoid, basalt, Mesozoic sandstone and Paleozoic sediments. Elluvial soils are located in most of the plains, locally mixed with alluvial soils mostly developed at marshy areas. The size of alluvial soils along streams and river channels range from clay through sand and gravel to boulder. These types of sediments cover an area of about 854 km^2 (8.6 %). Their topographic location favors conditions for groundwater exploration and exploitation. Alluvial sediments in the area are sediments that are concentrated along rivers and streams. These sediments have sizes ranging from clay through sand and gravel to boulder (WWDSE 2007). They are the most common shallow groundwater aquifers. Their permeability and productivity vary from place to place depending on their grain size and sorting and on their thicknesses.

Colluvial sediments also exist at the transition zone from the plateaus to the river valleys. These sediments are derived from down slope movement of earth materials by gravity and erosion. From hydrogeological point of view they have similar properties with alluvial sediments. Elluvial soils in the area are black cotton soils located in most of the plains overlying the basement rocks, locally mixed with alluvial soils forming marshy areas. The Elluvial soils in western and south western part of Ethiopia, where the rainfall is much higher have a greater thickness and because of adequate recharge, they act as mantle of low productivity aquifer over the metamorphic rocks (Chernet 1993).

Several shallow water wells were drilled in the low lands of Didessa and Wama river valleys for resettlement areas in these sediments. The yields of the wells in these aquifers yield from 0.5 to about 10 l/s. Areas with coarser well sorted materials have better yield than areas with variable size materials.

3.10 The Quaternary Sediments of Bonga Area

The major geological units of in this area (marked 14 in Fig. 3.1) include alluvium, colluvium, elluvium, and agglomerates. The geological description of these units is as follows: The alluvium is deposited mainly along the river banks and valley bottoms. The sediments consist of silts and clays. The thickness of these sediments may vary from 1 to 8 m and is a function of the topography and the depth of the underlying rocks. The colluvial deposits are composed of a heterogeneous mixture of fine particles and course to blocky rock fragments, which were transported and deposited due to gravity and erosion of the hilly areas. They are found along the slope foots. The thickness of the colluviums may reach 10–20 m. There are also in situ developed elluvium sandy sediments on top of gentle sloping areas and hill tops. The thickness of this unit is estimated to be 5–10 m. The elluvium occupies a large part of the area, along the gentle slopes as well as on the tops of the undulating hills.

The entire loose sediment package composed of gravel, sand, clay and silt mixtures in different proportion and is in general considered as moderately productive aquifers with inter-granular porosity. A number of springs discharge out of this materials. However, though most of the springs are perennial, the yields are very small (ranging from 0.1 to 0.5 l/s) and are being utilized by the town community as alternative sources.

From the pumping test analysis result in this formation indicates that its transmissivity is calculated to be 1.69×10^{-3} m^2/s with specific capacity of 8.31×10^2 l/s/m and its discharge is 7 l/s.

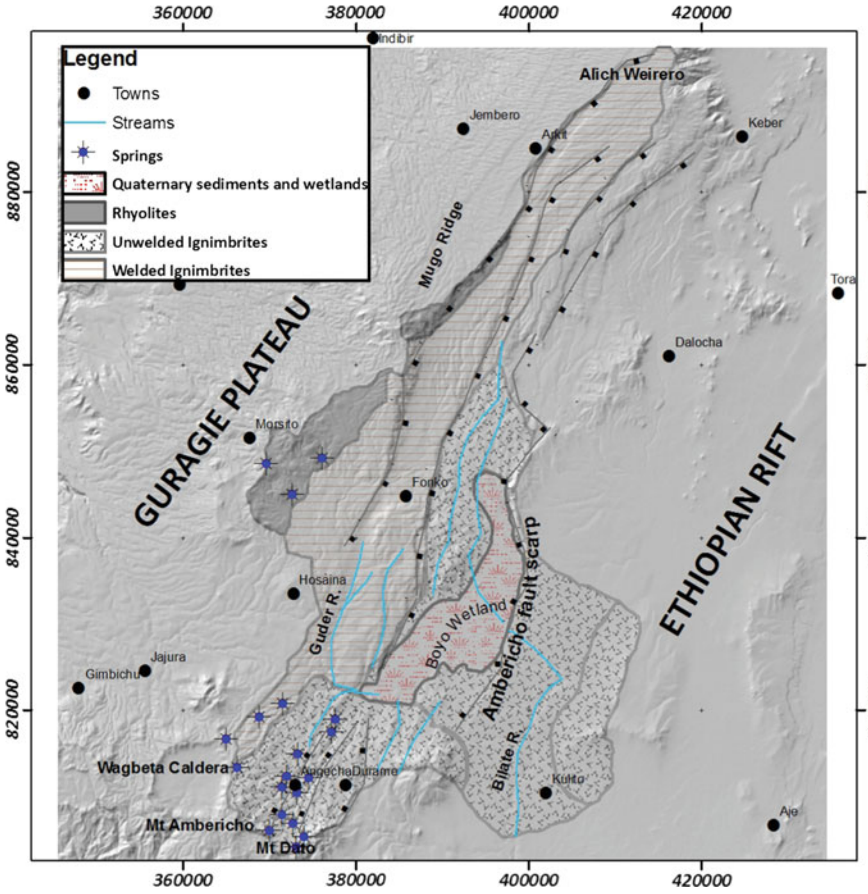


Fig. 3.10 Geologic features of areas bounding the Boyo graben and wetland

3.11 The Alluvio Lacustrine Sediments of Upper Bilate and Boyo Graben

The Boyo graben (Fig. 3.10) is located at the western margin of the Main Ethiopian rift. Unlike the marginal grabens elsewhere in northern sector of the rift valley the thickness of sediment in Boyo graben is significantly low. The Boyo graben is filled up with alluvial sediments of course to medium grain size as well as lacustrine sediments of variable grain sizes.

The alluvial sediments occupy the broad flat area in the center of the graben or occur in thin strips of alluvial sediments occur also along the major tributaries of the Bilate River. The sediments are composed of silt, medium to coarse grained sand and gravel with slight to highly weathered tuff. The depth to water level varies from 1.5 m to more than 50 m depending on the geomorphological condition. Well yield can reach 9 l/s. Their permeability and productivity vary from place to place depending on their grain size and sorting and on their thicknesses. In general, this formation is taken to have moderate to high productivity aquifers.

The Lake beds are believed to be of Holocene in age and occupy 6 km^2 (Fig. 3.10). They are mainly constituted by poorly compacted, well sorted, and friable and fairly reworked yellowish clay and silt material. The lacustrine sediments have a moderate or high permeability and productivity and the permeability is of inter-granular type (Chernet 1993).

Colluvial and outwash debris are also found widespread in the area particularly along the foothills of the major fault scarps.

3.12 Landslide Bodies

The high relief and the rugged topography induced by a strong Plio-Quaternary uplift, the occurrence of clayey horizons within the sedimentary sequences, the dense network of tectonic fractures and faults, the thick elluvial mantles on volcanic outcrops, and the thick colluvial–alluvial deposits at the foot of steep slopes are the predisposing factors for a large variety of mass movements (Abebe et al. 2010).

Traditionally landslides are considered as destructive earth processes causing damage to life and property. Regardless, they are also site of local groundwater storage and moisture retention in an area that would otherwise lose water rapidly to adjacent valleys owing to high slope. Because the lose materials offer intergranular porosity the landslides bodies hold important amount of groundwater which discharge mostly as diffuse flow or as focused discharge to springs. Typical examples of association of landslides with springs are those occurring in the Blue Nile gorge and the Tekeze valley.

Landslides of prominent scale and frequency are known in several parts of Ethiopia (Table 3.1) the summary of occurrence, distribution and triggering factors are discussed in detail in Abebe et al. (2010). In Tigray, a large number of dormant landslide bodies (earth/mud flows or rotational slides), likely generated in climatic conditions wetter than the present ones, are found (Nyssen et al. 2000, Moeyersons et al. 2008, Coltorti et al. 2009). In many cases, they are partially reactivated by the incision of gullies in the landslide mass (Nyssen et al., 2002). In the same region (Moeyersons et al. 2008) identified that the total surface of all landslides recorded in a 400 km^2 area in Central Tigray amounts to 20 % of area standing at 81 km^2.

In several studies that link landslide processes to groundwater resources, it was shown that that springs are generated where the slid blocks and debris masses rested on impervious rocks. Groundwater flow is observed to be localized in the contact between the debris mass and the slide plain (Nayssen et al. 2002). Hence

Table 3.1 Landslide occurrences in Ethiopia their groundwater implication

Region	Landslide characteristics	Groundwater resources
Tigray	More than 200 landslide bodies ancient and modern. A large number of dormant landslide bodies (earth/mud flows or rotational slides), likely generated in climatic conditions wetter than the present ones, are found in the area (Nyssen et al. 2002, Moeyersons et al. 2008, Coltorti et al. 2009). In many cases, they are partially reactivated by the incision of gullies in the landslide mass (Nyssen et al. 2003).	The landslide bodies are sites of diffuse groundwater discharge and wetter slopes. Locally used for crop production. Springs emerge in several locations associated with landsides. Nevertheless Landslide bodies in the Tigray region are mostly dormant and groundwater resources associated with them is of limited importance
Upper tekeze valley	In the upper Tekeze valley a number of landslide bodies are noted to exist. The casual mechanism of the landslides is similar to the case in the Abay valley, except that most of the landslides occur in the volcanic units and the Mesozoic sediments are lacking here	The landslide bodies are sites of groundwater discharge, and most of these landslides are still active.
Abay valley	Several prominent rocks topple, rotational slides, and rock slides rest in the Abay Valley between Gohatsion and Dejen towns. Soft rock levels, such as the Goha Tsion Formation (Assefa 1991), made up of variegated shales, gypsum and marls, are mobilized by rotational slides, especially on concave slope segments where groundwater, fed by the overlying aquifers, springs out (Ayalew et al. 2004). Massive translational slides affect hard rock layers overlying clayey/marly levels. Debris slopes, formed on gently sloping surfaces of weak sedimentary rocks, at the foot of the upper cliffs, are sites of slow-moving rotational–translational slides and debris/earth/mud flows. The study revealed that the most important landslide types are complex and progressive earth and debris slides, dominantly silty clay and clay soils, that associated with colluvial deposits. The large scale landslides involved mainly the loose surficial deposits of alluvial origin overlying the highly weathered basalts. In places, where rock creep and topple, rock falls resulted rolling of large basaltic boulders. Some important earth and soil slumps are also mapped, besides, few old landslide complexes show current signs of reactivation. Landslide of similar nature is also known to occur in the Jema valley between the towns of Muke Turi and Alem Ketema. Most of the landslides in the Abay gorge are still active	Springs emerging at the contact between landslide bodies and underlying bedrocks are used as water supply sources in number of places. Settlements and villages in the Valley rely on these springs for commercial crop production and domestic water supply (e.g. Kurkur, Filiklik etc.). A number of productive springs emerge from the contact zone between the landslide bodies and the underlying bed rocks. Here groundwater plays a triggering role for landslides but the landslides store groundwater for water supply use. In the Jema valley, Inter granular and fracture aquifers in colluvium deposit and scarp basalt was observed respectively. The ground water seeps at the interface of colluvium material and underlying bed rock, and at the contact of basalt layer with the underlying rhyolitic tuff. The rhyoltic tuff deposits between basalt columns are generally porous but not permeable due to fine grain size thus it forms semi-horizontal barriers to water movement down further. When considering the local slope failures the groundwater occurring in colluvium deposit had softened the material shear strength and at the basalt contact it eroded the underlying weak rock. Regarding slope instability triggered by rainfall it would have been better to consider the daily rainfall intensity and duration. But as it was not easy to obtain this data a five year annual precipitation recorded. The lateral flow of groundwater along the bedding plane in volcanic unties leads to the occurrence of massive landslides and discharge of groundwater in the landslide bodies.

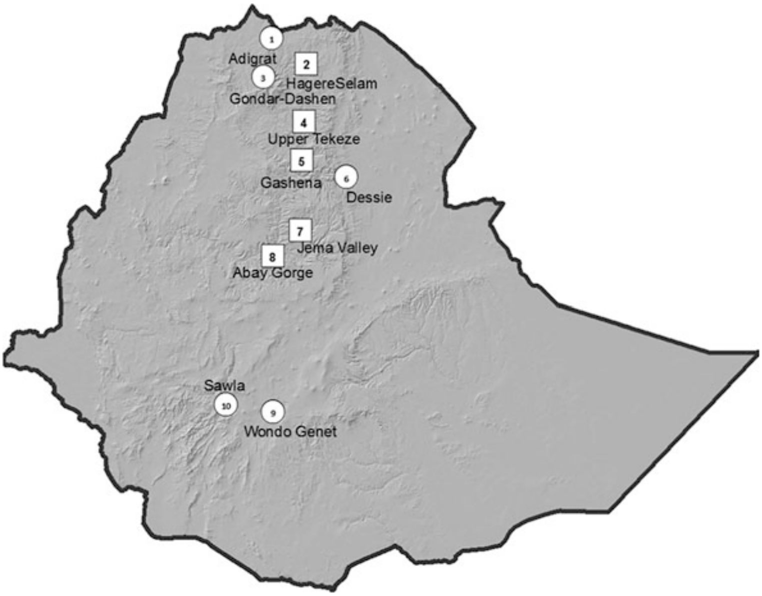


Fig. 3.11 Showing distribution of some ancient and active landslides in Ethiopia. Those marked in square refer where the landslides hold and transmit groundwater for local water supply, those marked in circles refer to active landslides with no major groundwater resources implication. *1* Ancient landslides around Adigrat, *2*Multiple landslides over an area of 80 km^2, *3* Landslides associated with Simen Massif, *4* Landslides in headwater regions of the right tributaries of Tekeze *5* Landslides in Upper Tekeze Valley, *6* Active landslide associated with western rift margin *7* and *8* Multiple landslides exceeding 100 in number covering over 10 km^2 in the Abay Valley *9 and 10* Landslides in high relief high rainfall areas of southern Ethiopia

distribution of landslides could be indicative of sites of modern or ancient groundwater discharge and storage. In northern Ethiopia landslide bodies (ancient and active) have been used as major settlement sites and site of groundwater exploitation (mostly through natural discharge). This is because the landslide bodies contain better soil development and humidity compared to denuded rocky highlands which straddle them. Figure 2.11 show the distribution of landslide bodies (active and ancient) in Ethiopia. Nevertheless the groundwaters associated with landslides are sometimes diffuse flows which may not be tapped as springs.

A number of small communities occupy the landslide bodies in Ethiopia (Fig. 3.11). For example in the Abay gorge, springs emerge at several locations within the landslide body providing local community to exercise commercial irrigation. A number of such examples exist in Northern Ethiopia. Owing to mountainous topography and stratification of hard rocks in association with soft rocks, a number of landslide bodies have been documented. In Hagereselam (Tigray), northern Ethiopia for example, in an area of about 200 km^2, clear traces of at least 17 ancient mass movements have been identified (Nayssen et al., 2002).

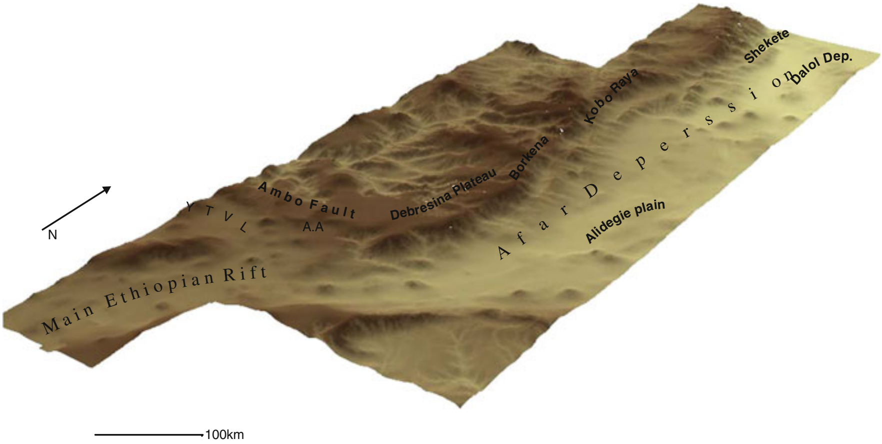


Fig. 3.12 Location of alluvial filled grabens of the western margin of Afar depression and the rift floor. Note the narrow depressions elongated N–S at the junction of the highlands and the lowlands. AA— Adddis Ababa, YTVL—Yerer Tulu Welel Volcanic Lineament

According to Moeyersons et al. (2006), these landslides are indicative of formerly wetter conditions (more developed perched water tables in the area during the late Pleistocene to middle Holocene), and mostly no longer active. The water table is now presumed to be too low for the presence of surplus water to remain the driving force for slump movement. However, a number of them are found to undergo creeping movement because of diffuse and lateral groundwater discharge from the bedrocks. The activation and dormancy of the landslide bodies mirror the wetting–drying cycles of rainfall in the highlands and land use changes.

3.13 The Alluvio Lacustrine Sediments of the Western Afar Marginal Grabens and the Afar Rift Floor

The Afar depression is covered by the most extensive quaternary Alluvio lacustrine sediments. Notable and the most extensive ones are the quaternary sediments along the foothills of the Western highlands bounding Afar and those along the Awash flood plains. These include the Raya valley intermountain alluvial valley, the Alidegie plain, Kobo valley sediments and Borkena valley sediments (Fig. 3.12).

Borkena Valley Sediments

The Borkena River Basin is located in Wollo (Fig. 3.12. It is part of a major graben related to the western margin of the Afar Rift which extends north south from foot hills of the Debresina highlands to Ethiopia and Eritrea border in the North. The Borkena graben is one of the several alluvial filled marginal grabens found at the foothills of the western Afar escarpment. The Upper Borkena covers about 133,500 ha. The total area of the basin is around 1735 km^2. The valley floor is a board area elongated North–South covering about 14,000 ha. The graben is formed by rifting in the western margin of the Western Afar Rift margin. Coarser sediments are found in the northern section near Dessie town where the Borkena River emerges from and the sediments gets finer near the lower elevation along the Chefa swamp. The sediments are principally sands, gravels and clays.

From the west and east the Borkena valley is bounded by volcanic highlands of tertiary age. Groundwaters are found in semi confined and unconfined conditions. The alluvial aquifer has aquifer transmissivity ranging from of 28 to 100 m^2/day and permeability of 1 m/day (Tadesse 1980).

Total dissolved solids for groundwaters of the basin range between 150 and 1000 mg/l. The highest value corresponding to thermal springs emanating inside the graben. The cold groundwaters are mostly Ca–Mg-HCO_3 type and the thermal waters show Na-HCO_3 type chemistries.

Kobo-Girana Valley Sediments

In the Kobo valley the geology is comprised by tertiary volcanics including fissural, silisic and central volcanics. Alluvio lacustrines sediments filling the Kobo graben reaches in thickness 350 m. Yields of wells range from 200 to 400 m^3/day from volcanic aquifer and 300–700 m^3/day can be tapped from Sediments for a drawdown of less than 5 m. In the Kobo Girana valley total groundwater storage has been estimated at 207×10^6 m^3. Total annual recharge in the basin has been estimated at 185×10^6 m^3/year.

Alidegie Plain

The Alidegie plain is bounded by the rhyolitic volcanic ridges and the Eastern Ethiopian highlands from East and by the Awash River from West. The alluvial plain covers approximately 1750 km^2. The thickness of the alluvial materials reaches up to 200 m. Water table depth varies between 60 and 80 m in the alluvial materials. The hydro-geological set up of Alidege plain shows that the alluvial plain is composed of coarse grained sands, gravel and pebbles. The aquifer is recharged from seepage from Awash River and subsurface inflow from adjacent highlands in the south and south west.

Teru-Digdiga Grabens

Teru graben and plains are located in the Denakil depression covering an area of 4800 km^2 (Fig. 3.13). The whole graben is an association of four plains named (Awura, Gulina, Digdiga and Teru) each fed by rivers emanating from the Western highland. These rivers originate from the horst bounding Raya from East but draining the Kobo and Raya marginal grabens and disappear in the plains. Major part of the Teru graben and plains are covered by basalts belonging to the Afar Stratoid and alluvio lacustrine sediments. Depth to water table ranges from less than 10 m to around 100 m and there is a general increase in depth to water table from south to north following the drainage pattern. The rivers originating from the south west mostly disappear in the southern part of the Teru plain before fully crossing the alluvio lacustrine sediments. The Alluvio lacustrine sediments gets most of its recharge from at least three sources including loosing streams, direct precipitation, and lateral inflows from the Zobel Mountains in the west. The streams themselves get there flows from the localized groundwater outflow from the Raya and Kobo valleys following E-W fault related incisions through the Zobel Mountains (mountain separating the Teru graben from Raya and Kobo).

The sediments are commonly found in association with river courses and flood plains. These sediments are dominantly fluvio-lacustrine deposits occasionally including channel and fan layers. Fluvio-lacustrine sediments consist of unconsolidated or poorly cemented thin beds of clay, silt, sand and gravel. The thickness of these deposits is unknown as their lower contacts are not exposed. Geophysical investigations show that the deposits reach a thickness of 300 m beneath Raya and Teru plains.

The western boundary of the alluvial plains are marked by elongate, N–S to NNW-SSE trending uplifted block mountains (e.g Zobil) bounded on the western side by major normal faults down thrown to the west. They form strongly faulted and tilted terrains exposing older Mesozoic sediments and/or Oligocene flood volcanics. These rock formations are affected by a large number of parallel, steep to low-angle normal and reverse faults that have resulted in rotated blocks generally tilted to the east.

Among the four plains the Awura plain is dominantly covered by older sediments (0.2–2.0 Ma) of fluvio-lacustrine origin and consists of layers of poorly cemented gravel, sand, silt and clay with variable mixing and thicknesses. The depth to ground water varies from a minimum of 7 up to 100 m. The deepest part corresponds to the southern part of the plain where the elevation generally forms a higher ground and the shallowest part is in the Northeast where normally the groundwaters discharge to a sandy salt plain.

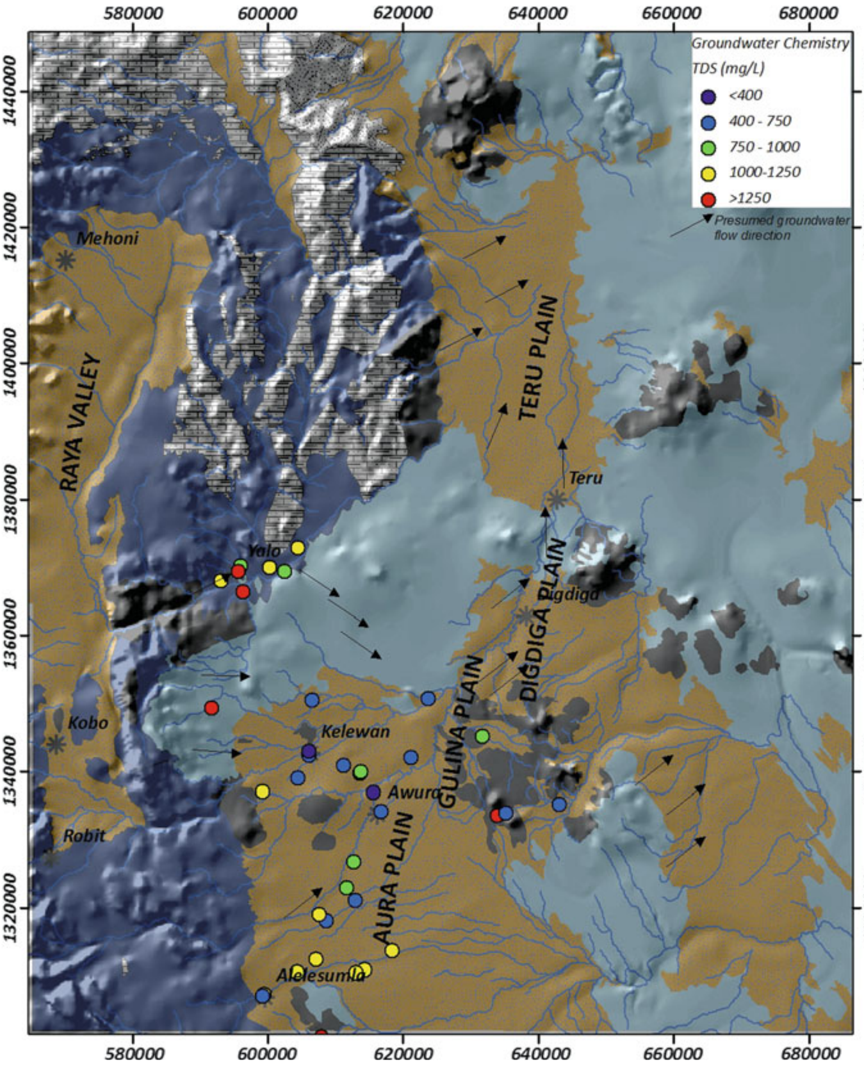


Fig. 3.13 Simplified map showing water points and their chemical characterstics of Teru-Digdiga graben

Groundwater TDS is generally less than 1500 mg/l. Groundwaters near the outlet zones of the Raya valley presumably connected via lateral groundwater inflow show the highest TDS while those which are directly recharged from local floods and rains (lower elevation part) show lowest salinity. Discharge from the alluvial plains instead takes place to sandy salt plains at the junction with the Dabahu shield (Northeastern corner) before entering into the Dallol depression through fractures and faults.

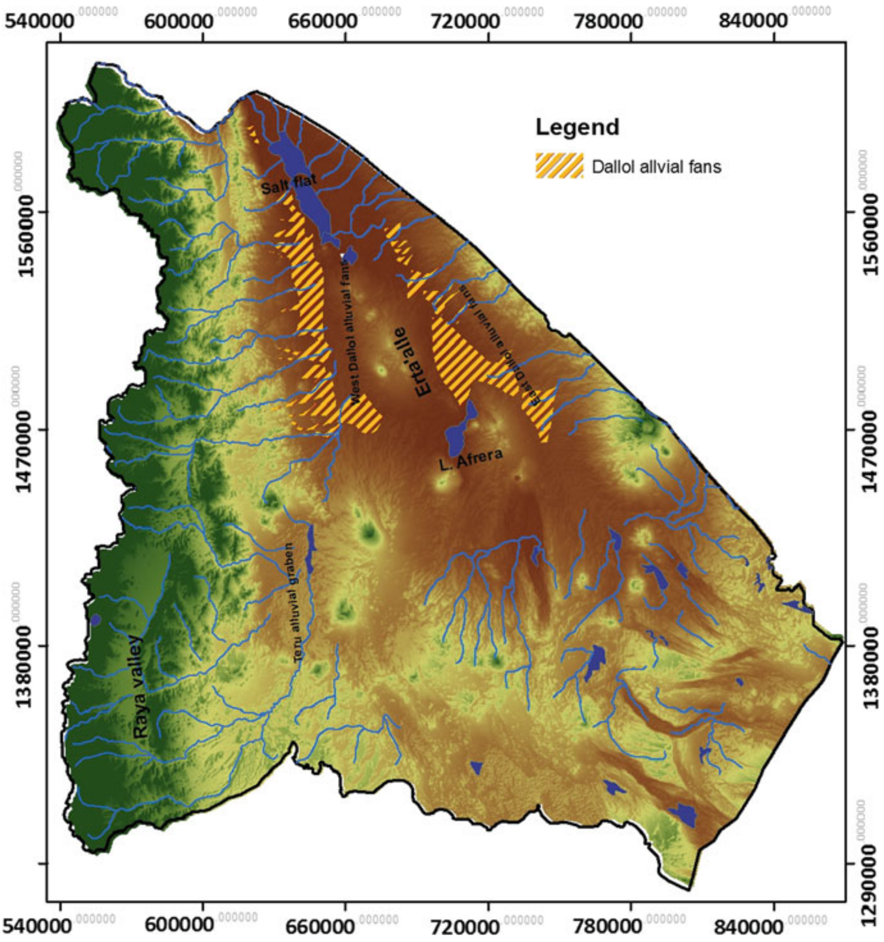


Fig. 3.14 Alluvial fans of the Dallol depression

The Alluvial Fans Bordering the Dallol Depression

The Dallol depression is separated from the Red Sea along its eastern boundary by hills which rise to 2218 masl and which drain form their drier western slopes into the depression by deep wadis which peter out in a series (exceeding 35 solitary or coalesced) of narrow fans, aligned in parallel SW-NE along the eastern side of the floor of the depression just above and below sea level (Fig. 3.14). A similar series of wadis and pans, with similar parallel alignment is present on the opposite side of the depression but is far less well developed, no doubt as a consequence of the greater aridity on that side. The prominent example of such wadis and associated alluvial fan is the Musley alluvial fan (Fig. 3.15). A number of alluvial fans and

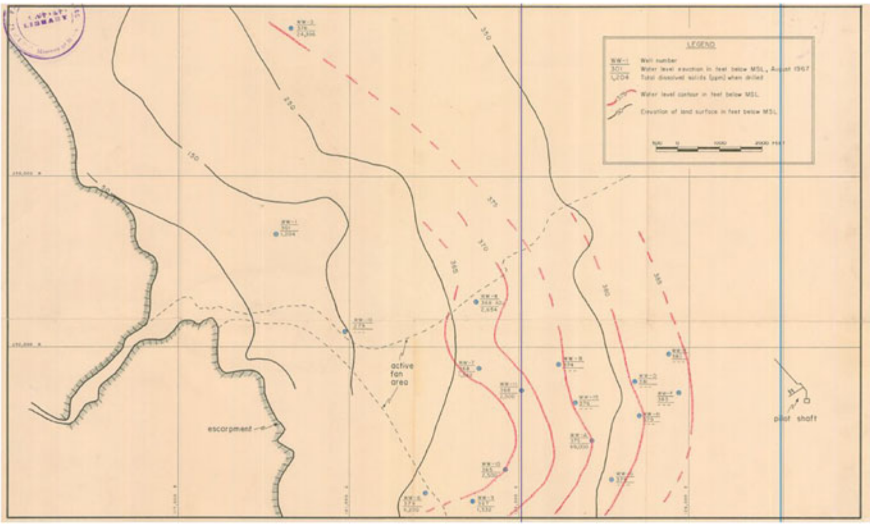


Fig. 3.15 Ground water level map of the Musley fan located in the northern most extreme of the alluvial fans of the Dallol alluvial fans-Fig. 3.14

wadi bed sediments occur bordering the Dallol depression storing relatively fresh water in an environment that is otherwise harsh desert and the lowest place on earth. Most of the alluvial fans are found in the western sector of the Dallol depression. The alluvial fans extend over an area of 2500 km^2. The most studied[1] and well known of these alluvial fans is the Mulsey fan (Fig. 3.15) adjoining the central Dallol depression from West. The Dallol salt flat is located east of the Musley fan. The Musley fun is documented in detail by (Ralph M Parsons Co. 1968) The alluvial fan deposit consist of deposits consist of inter-fingering layers and lenses of sand, gravel, and clay. The beds of sand and gravel are porous and highly permeably. The principal source of recharge to the alluvial fans is flash floods originating from the Musley canyon draining the escarpment to the west. Minor recharge is also possible from lateral inflow of groundwater from volcanic block in the west and from intermittent local rainfall. Pumping test data indicates that average transmissivity of the water bearing beds in the fan is about 870 m^2/ day. Salinity of groundwater increases from west to east.

The Musley alluvial fun is composed of inter-fingering layers and lenses of sand, gravel and clay. The beds of sand and gravel are highly porous and

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[1] The Musley fan has been studied in detail because of the groundwater flooding problem faced by Potalsh mining company while trying to excavate shafts into the potash bearing horizons which is found east of the alluvial fan deposits. The groundwater storage, flow, recharge and quality has been studied using sesmic geophysics, test well drilling, pumping test, and water quality measurements. Early in 1960 six wells has been sunk in the alluvial fan out of which four returned good quality water with TDS less than 2000 mg/L while two of them show TDS in excess of 20 g/l. One of the wells has been used for water sourcing the earlier mining camp.

permeable. The Musley alluvial fan is bordered from the west by an escarpment of basaltic outcrop and from the east by salt flat that is mined for Potash since 1960s. Water table data from several test drilling conducted in 1960s show west to east movement and discharge to the salt flat. Available sources of recharge consist of rainfall and stream infiltration, and perhaps underground movement of groundwater from the escarpment. Water table depth varies from less than 2 m to over 60 m. The amount of total dissolved solids in test wells range from 760 ppm to over 23,396 ppm.

The largest of the Alluvial fans in the Dallol depression occurs in the south western part of the depression where wadi floods running from western basement and volcanic escarpment run down the slope carrying large bed load and truncate against the Erta'ale volcano in the center of the depression. The large size of the alluvial fan is also maintained by higher rainfall in this part of the Dallol and the larger catchment area of the Wadis. The drainage of some wadis extends up to the plateau reaching the Mekelle outliers in the west.

3.14 Alluvio Lacustrine Sediments of North Western Lowlands

Patches of dominantly alluvial and colluvial sediments with lacustrine sediments exist draping over the basement lithologies or volcanic bedrocks (marked 7 and 17 in Fig. 3.1). The materials either occur at the foothill of highlands bordering them from the east, or filling tectonic valleys or at the mouth of wadi beds and rivers originating from the eastern highlands and widening at the flat areas bordering Ethiopia and Sudan. The groundwater accumulates in the pores of the unconsolidated material. The bases of the mountain slopes are fringed by alluvial fans composed largely of great porosity gravel and sand. The effective porosity of the fan deposits as well as their hydraulic gradient decrease away from the mountain margin. The consequences are the deterioration of water, quality and decreasing groundwater potential. Despite the great lateral variability of river-valley sediments, most of the valley deposits have a simple vertical succession from coarse sands or gravels near the bottom of the channels to silts and clays at the top. These alluvial sediments occur in association of Dinder and Awjamis Rivers that are located in the northern part of the area.

3.15 Alluvial and Colluvial Plains of the Gofa Basin and Range Complex

In the Southern sector the Gofa basin and range complex extends into the Chewbahir rift (marked 10 in Fig. 3.1). Along with the southern western sector of the Abaya Chamo Lake and the Chewbahir rift the Gofa basin and range sediments

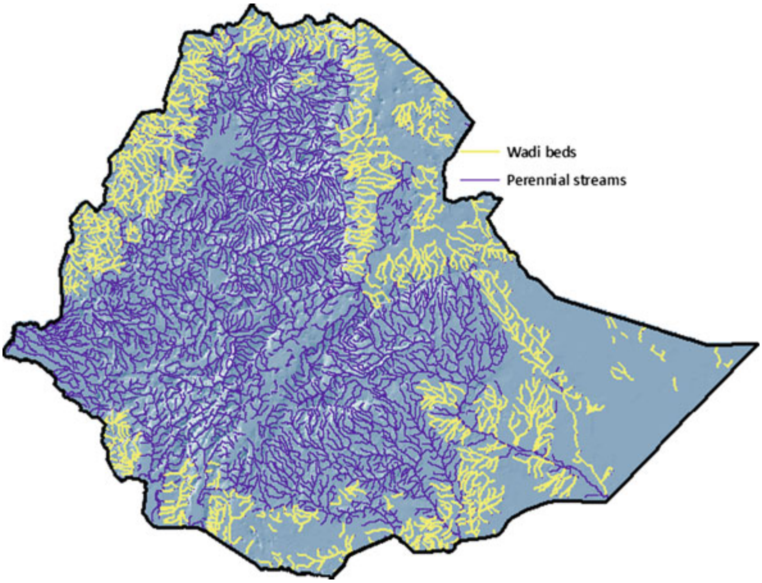

Fig. 3.16 Distribution of wadi beds with potential water storage

form a complex inter-fingering pattern of colluvial, alluvial and lacustrine sediments.

This refers to alluvial and colluvial deposits that overlie early flood basalts in the narrow tectonic grabens in the area between Sawla and Sodo. The unit consists of several cycles of fine to coarse sediments of basaltic origin down to at least 80 mbgl. Based on borehole information obtained from Danan plain, it appears that several sandy gravel aquifers could be encountered with increased depth of drilling giving at least 4 l/s for excellent quality of groundwater with a drawdown of about only 4 m during pumping. IN many cases the water table does not exceed 50 mbgl but with the possibility of water tables being deeper than this, it is recommended that drilling in these areas should target the interval between 50 and 100 mbgl.

The yield of alluvial sediments in the northern sector of the Chew Bahr rift reach 1.2–2 l/s representing transmissivity values of $1.2–2.9 \times 10^{-9}$ m^2/s. In the Chew Bahr basin shallow groundwater (50–100 m) form a coherent body of groundwater under water table condition (Sima 1987), but under artesian conditions in the central part of the Main Ethiopian rift and Turkana rift. An artesian overflowing borehole and several perennial shallow water holes were found at Gatto Fuchaca village about 15 km northeast of Konso.

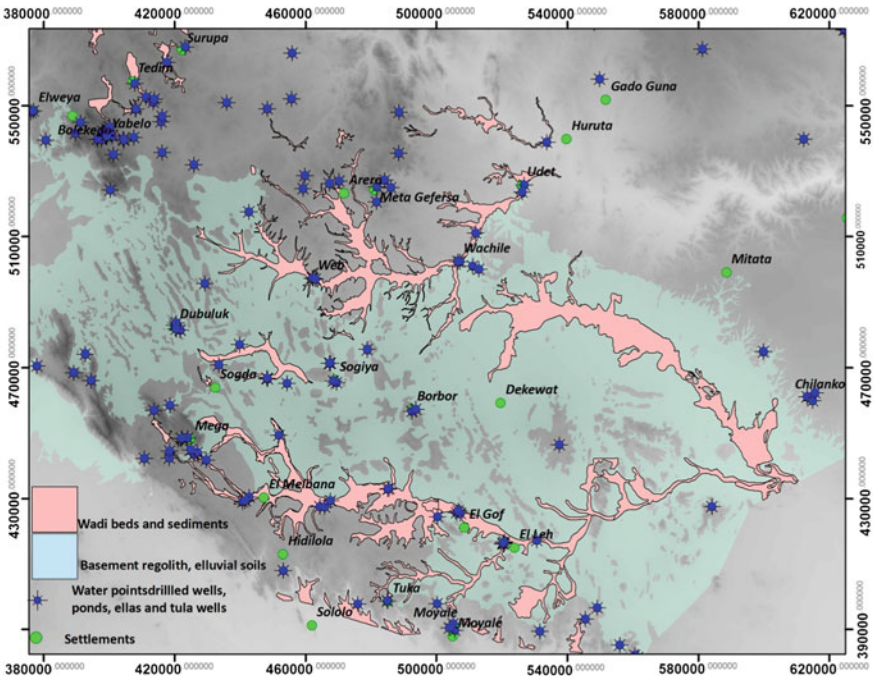

Fig. 3.17 Distribution of wadi bed sediments in the Borena lowlands

3.16 Wadi Bed Aquifers

Regardless of their high potential in otherwise water scarce arid and desert setting, the Wadi bed aquifers are the least documented and often characterized as local inter-granular aquifer of minor importance (Chernet 1993). In Ethiopia Wadi bed length reach more than 30, 000 km (Fig. 3.16) and storage in these aquifers potentially reach 3 billion m^3 (Kebede 2009). The most important wadi which are supporting the livelihood of millions pastoral community in Ethiopia include those in Borena, Lower Omo, Ogaden, Western Lowlands bordering Sudan, and those in Afar depression. The best wadis from which water can be produced productively are those with sandy and gravely sediments with little clay mixture. The best criteria for selection of wadi bed sediments for exploitation is listed in box iv.

Wadi Bed Aquifers in Borena

In Borena wadi bed complexes occur in two major zones—the first in southern part of the Borena plain north of the Ethiopia-Kenya border and the second in the central plain of the Borena lowlands in the north (Fig. 3.17). Almost 75 of water points in the Borena plain area associated with these wadi bed sediments. Water quality in the wadi bed sediments is generally good for human and livestock consumption. However, groundwater salinity increases from where their head water rests to the outlets of the Wadis. That is groundwater total dissolved solid content increases down the gradient following the wadi flood directions. The wadi bed aquifer gets their recharge from flood waters that originate in March–April and October through December.

In southern Borena wadi complex (Lagasure), the wadi beds are composed of alluvial sediments of medium to coarse grained clean quartz sand. At their outlets from their river channels the wadis of the Borena lowland form extensive flat laying alluvial fans. The highest yielding borehole in the area as well as in the whole wadi system is the El-Gof borehole. This borehole which taps the intergranular aquifer of sand and gravel overlain by lacustrine sediments has a yield of 5 l/s. Other boreholes in Elleh discharge at 4.3 l/s.

Box iv. Best Wadis

1. Have thick sand and gravel with minor admixture of clays (associated mostly with basement terrains)
2. Headwaters connected to high rainfall highlands and obtain flows during significant period of the year
3. Flood intensity is regular during most of the time, channel section is stable, so as not to damage water extraction facilities
4. Evapotranspiration is low enough to keep salinity low and storage be sustained over long dry periods
5. Underlain by impermeable bedrocks so that water is retained in the associated alluvial materials
6. Limited exposure to erosion

In Yabelo area alluvial sediments show variable thickness ranging from 10 to 160 m and yields ranging from 0.5 to 8 l/s (Alemneh 1989). Pumping tests conducted in the Yabelo region in the alluvial sediments show transmissivity ranges from 7.99×10^{-5} to 1.59×10^{-3} m/sec, while specific capacity ranges from 0.1 to 0.5 l/s/m drawdown.

Wadi Beds in South-Eastern Ethiopia and the Ogaden

In the Southeastern Ethiopia and the Ogaden lowlands the importance of superficial deposits associated with Wadi beds to groundwater occurrence and water supply is immense (Hadwen et al., 1973). The same author has described the wadi bed sediments in great detail. According to this work, alluvial deposits, often exceeding 30 m in thickness and covering more than 3000 km^2 are found almost exclusively on the flanks of perennial rivers where they formed as a result of

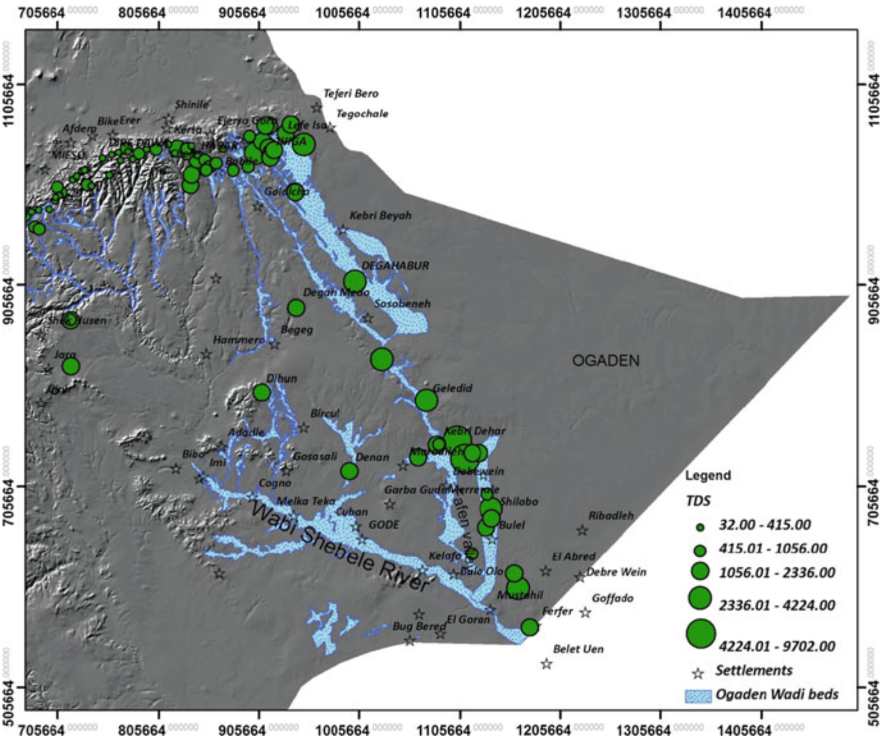

Fig. 3.18 Extent of the wadi bed sediments and water quality of groundwaters associated with the Wadi beds

seasonal flooding (Fig. 3.18). The total areas covered by wadi bed sediments may extend over 15,000 km^2. They are well sorted sandy silts and clays, with rare gravels and coarse sands in well marked layers. Considerable vertical lithological variations occur, but laterally the deposits are fairly continuous, and individual beds can be traced over considerable distances. Where derived from volcanic regions, as in the western tributaries of the Wabishebele, they are rich in ferro-magnesian minerals. Eastern tributaries contain a high proportion of limestone and clay. The deposits, especially the sandy lenses, have moderate to good aquifer properties. Silty units have good retention properties and yield water slowly but reliably to dug wells, except where deposits are of very fine grain, such as those south of Gode. In some instances, as at Kebredehar, dug wells pass through the alluvial deposits into limestones and impermeable marls below and tap water from bedrocks as well as from the alluvium itself. In other regions alluvium rests on the impermeable main gypsum formation. The alluvial aquifer has a considerable volume of stored water that is recharged from river flooding. There is scarcely any seasonal rise and fall in the water table, even at times of flooding or at times of intense local rainfall.

Alluvial plains have their greatest development south of latitude 7°N, flanking the Wabi Sheble. At Gode and south of Gode the plains are 15–20 km wide; a belt 5 km wide wadi beds occurs between Gode and Imi and extends some 50 km further upstream. Southwards the alluvial deposits (fine sand, silt and clay) become finer grained with poorer aquifer properties, and their contained water becomes more and more saline. This is partly because the deposits include increasing amount of gypsum, and partly because of very low groundwater movement. Dry season supplies are also less dependable further south, where increasing distance from the main rainfall region means that flooding to give recharge may not occur. The challenges with developing permanent water source along the alluvial sediments are their dynamism. Flood waters often breach its own deposits during high water stage leading to damage of the water points.

Extensive alluvial deposits occur south of Kebredehar at the downstream end of the Fafan intermittent stream. The many dug wells there are fairly reliable sources, but they are increasing saline southwards. North of 7°30' alluvial deposits occur in the large valleys of the highlands and foothills. They are fairly thick wadi gravel deposits which mostly contain an abundant perennial and fresh water supply. Such coarse deposits have high permeabilities and can be developed in some of the larger valleys as a source of irrigation water. The aquifers lose some of their water to permeable limestones that underlie them.

In the more arid part of the Ogaden, especially east of the Fafan valley, a calcareous cemented crust is developed on most formations. This caliche crust contains abundant silicieous and clay impurities derived from the underlying rock. It is formed by rainfall soaking into the ground and then being drawn back to the surface by intense solar radiation: the water evaporates and precipitates its contained minerals at or near the surface. The crust offers a fairly impermeable cap to the bedrock, but in places has sufficient cavitation or pore space to tap water. Dug wells in several places, notably, east of Kebredehar, derive water from this source.

In the Jijiga plain (Jarer, Elbayeh, Burka and Waj streams) the alluvial deposits generally formed from fine to silty clay deposits derived from limestone and basement rocks crop out. They range in thickness from a few meters to a maximum of 36 m in the wells located south of Jijiga town. The elluvial cover occurs in the northern, eastern and south eastern part of the project area. These are thin blankets with soils derived from in situ alteration of underlying rocks. Furthermore colluvial deposits, alluvial fans characterized by heterogeneous grain size and irregularly distributed talus debris and alteration cover beds exist in some areas especially north and south west of Jijiga. The alluvial deposits hold shallow waters which are being exploited by shallow hand dug wells with total depths ranging between 10 and 32 m and a static water level of around 10–30 m.

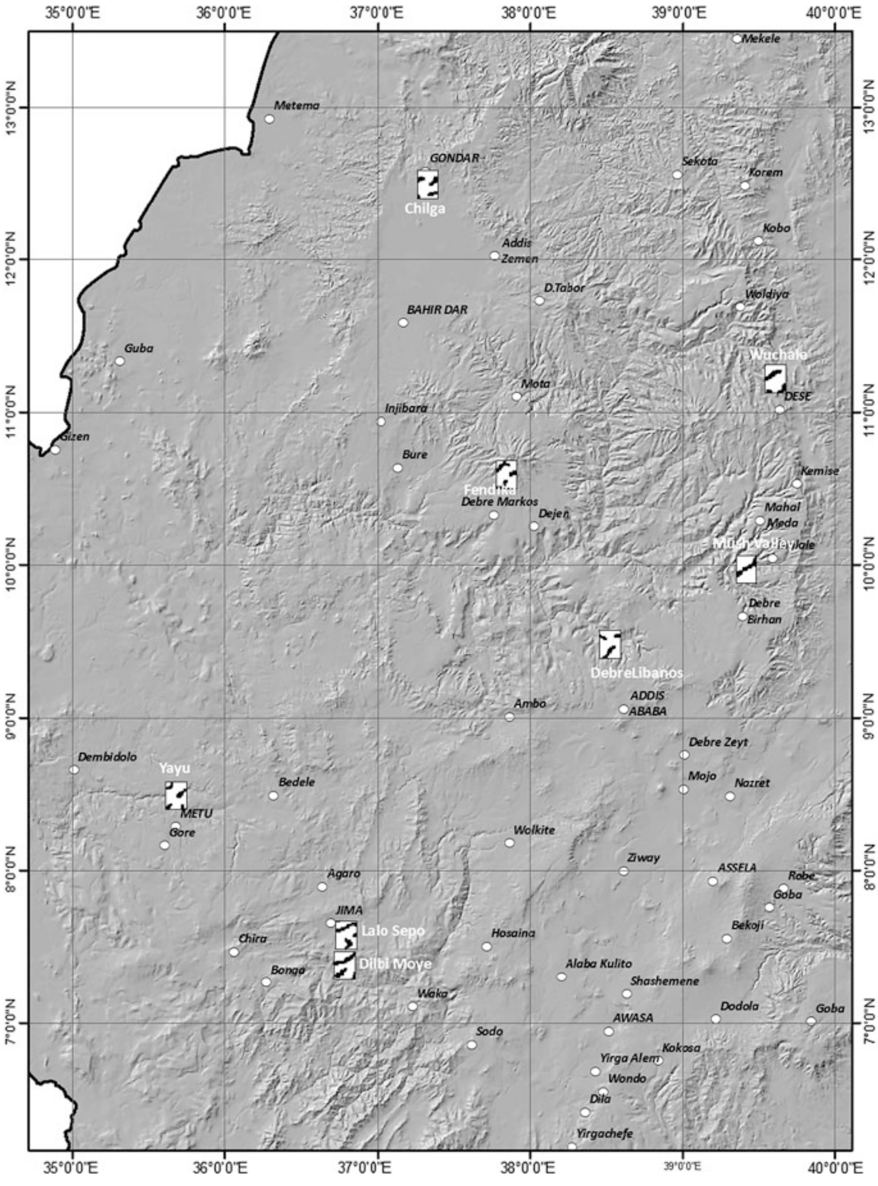

Fig. 3.19 Location of prominent miocene sediments in Ethiopia

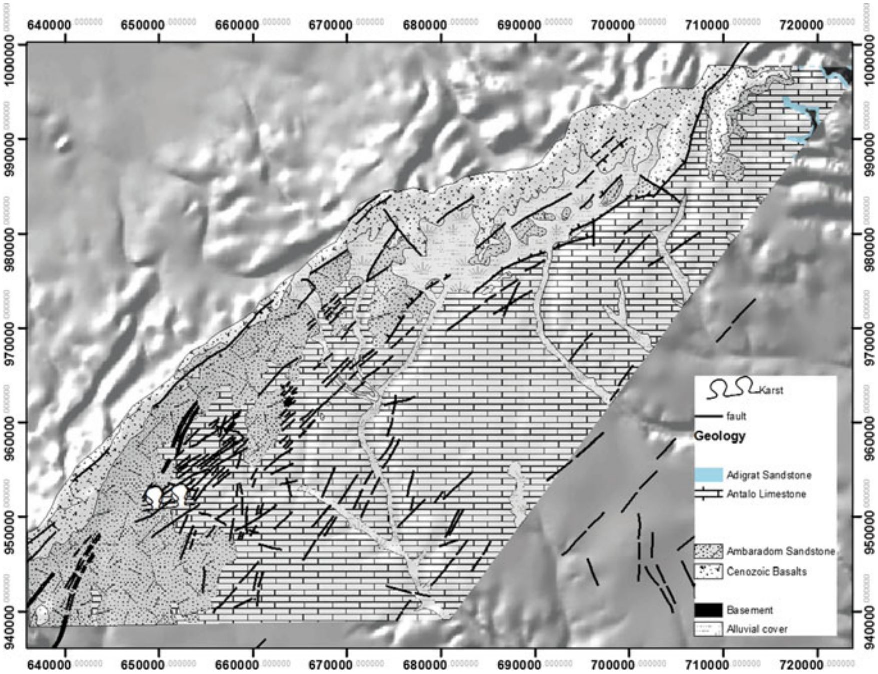

Fig. 3.20 Simplified geological map of the Bedesa-Gelemso graben in the Harar plateau

3.17 Inter-Trappean Sediments

Accompanying the various geologic hiatus in the Cenozoic particularly the time gaps between the 30 Ma dated flood basalts and 15 Ma shield volcanic and the 8 Ma old pre rifting Miocene volcanics there are extensive erosion and sedimentation. The sediments have been accumulated in several sectors of Ethiopia (Fig. 3.19) including Chilga graben, west Tana escarpment, Gambela lowlands, the Omo delta, and Chewbahir rift, Yayu, Dilbi Moye, Lalo Sapo, Gojeb Chida, Nejo, Wuchale and Mush Valley. In variety of other places these sediments are buried under basalt flows which postdate them.

The groundwater potential of these sediments or their role in affecting groundwater storage and circulation is largely unknown. However, in a number of places inter-trappean sediments (alluvial gravels, palosoils, weathering surfaces) are omnipresent in drilled wells sandwiched in the volcanic aquifers. Drilling of water wells reveal in several localities the sediments sandwiched between the basalt flows are the most promising horizon yielding water to wells. In Lake Tana basin the coal bed exposed to heating by quaternary dykes resulted in emergence of hyperalkaline low TDS waters (Kebede et al. 2005) although the presence of the coal beds are not observed directly at the site of emergence of the springs.

In the central Gojam massif stratigraphically, the Tertiary sediment (poorly sorted sand with clay matrix) occurs overlying the lower basalt. This covers a very limited extent, west of Debremarkos in the type locality of Fendka village (Fig. 3.20). It is reddish brown, medium to coarse grained, cross bedded sandstone with mudstone and shale layers overlying it. The sandstone which is coarse grained, weathered and with less cementing matrix shows a good productivity (Meten 2009). For example the water supply for Fendka village comes partly from such sandstones. The dry month discharge of the developed spring emerging from sandstone at Fendika village is 0.2 l/s. The thickness of the tertiary sediments ranges between 2 and 15 m. Associated with the tertiary sediments are pyroclastic sediments ranging in thickness between 7 and 40 m. The pyroclastic deposit consists of highly weathered tuff with a maximum vertical thickness of 50–75 m. Discharge of springs from this unit is lower than 0.1 l/s. At Dilbi Moye the basin consists of volcanics (lower basalt, middle basalt, upper basalt, acidic-intermediate rocks), and sediments (upper and lower sedimentary formations). The lower basalt forms the substratum of the Delbi-Moye Basin, which is dated to be 31 Ma (Davidson and Rex 1980). The present basin configuration is characterized by faulting with vertical displacement of up to 200 m. Two boreholes drilled by the Hydrocarbon Division of the EIGS indicate that artesian condition occurs in the area. This is observed at the borehole drilled in the vicinity of the coal & oil shale exposure in the Legamisi stream. The third borehole is located at Walla village west of Dilbi. It is reported that, groundwater was encountered while drilling to map extent of coal beds (Haile et al. 1996).

3.18 Tectonic Valleys with Limited Sediment Accumulation

Number of tectonically induced small grabens filled by locally derived alluvial sediments and bearing important quantity of shallow groundwater resources is common in the rift margins particularly in the Harargie region. A prominent example is the alluvial graben of the Bedessa-Gelemso graben.

The alluvial sediment, in Bedessa-Gelemso graben, consist particles of varying sizes from silty clay to boulder. The alluvium covers an area of 170 km^2 (Fig. 3.20).

This is a small area, located at upper reach of Hursa—a tributary stream of Dhungeta River between Bedessa-Wachu-Gelemsso, characterized by localized unconsolidated sediment deposits (alluvial, colluvial, talus, etc.) and sandstone outcrops (Fig. 3.20). The graben/trough is bounded by Chercher Plateau basalts in the north to northwest and by limestone and sandstone fault scarps in the south. It is intensively traversed by rift-parallel faults and fractures. The aquifers in the graben are close to areas of annual replenishment by precipitation and surface runoff and groundwater discharge in the form of springs from the adjacent Chercher volcanic plateau. Thus, the groundwater in the graben area is expected to be relatively shallow and is of good quality for drinking and irrigation.

Groundwater in this zone may occur close to the volcanic plateau escarpment as suggested from existing data (from dug wells and boreholes) and field observation. Even though, areal extent is not so large it could be considered as a good zone for further groundwater investigation and development. These include alluvial deposits (coarse sand and gravel) and floodplain deposits (fine sand, silt and clay) mainly found to occur along the Dhungeta River and in the Bedessa-Wachu-Gelemso graben.

As the area is bounded by highlands, it receives most of water from adjacent mountains of Chercher and Gera Muktar; besides direct recharge from precipitation. Almost all shallow wells sunk in this sediment are productive. In addition, alluvial aquifer in wide and gently sloping major rivers is productive; and has large yield with promising hydraulic characteristics. Well yields may reach 25 l/s with around 2 m drawdown.

3.19 Alluvial Fans[2]

Arid and desert environments by definition have limited water resources. In such environments the best available shallow ground water resources are often associated with alluvial fans. Alluvial fans occur in a variety of environments, particularly in arid and semi arid or seasonally dry regions, where there is a large sediment supply to a point where accumulation can occur. Such locations are particularly common along faulted or tectonic mountain fronts. Depending on the magnitude and persistence of the fluvial processes, the radii of alluvial fans can vary from a few hundred meters to tens of kilometers. Smaller fans commonly have gradients of 3–6° or less, steepening to some 10° near the apex where they may grade into marginal screens laying at angle approaching 30°.

For sediment accumulation to occur there must be an accommodation space for the material carried by the flood water to be deposited and preserved where the channel flow expands. The Ethiopian rift valley, with (a) its arid setting which favors flash floods, (b) its variable quaternary climate which favors coalescence of alluvial materials (c) its steep slopes which generate floods and (d) its flat rift bottom which favor accumulation of sediments is the site of a number of old and modern alluvial fans. Previous studies of alluvial fans in Ethiopia are related mostly to their importance in climate reconstruction (Gasse and Street 1978, Gasse 1990, Benvenuti et al., 2002). A very classical example of alluvial fan hydrogeology has been investigated for an alluvial fan in the Dallol desert (Sect. 3.13, Fig. 3.15). From north to south Ethiopia alluvial fans are known to occur in

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[2] In this particular case alluvial fans refers to those alluvial deposits with fan shaped morphology and occurring in solitary or collapsed forms occupying desert environments in Ethiopia. Other alluvial deposits such as intermountain alluvial valleys, flood plain related alluvial deposits (fluvial deposits) or any other form of alluvio lacustrine sediments such as valley fill alluvial sediments are not included.

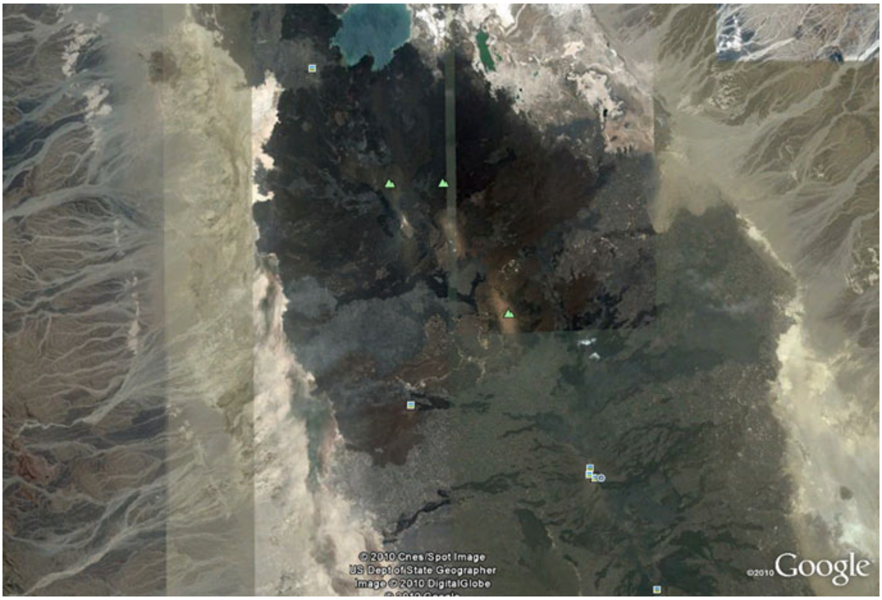


Fig. 3.21 Google earth image showing solitary and coalescing alluvial fans extending down to the Dallol rift in Northern Ethiopia

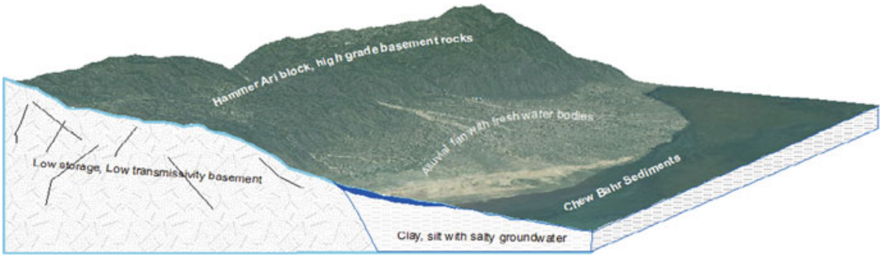
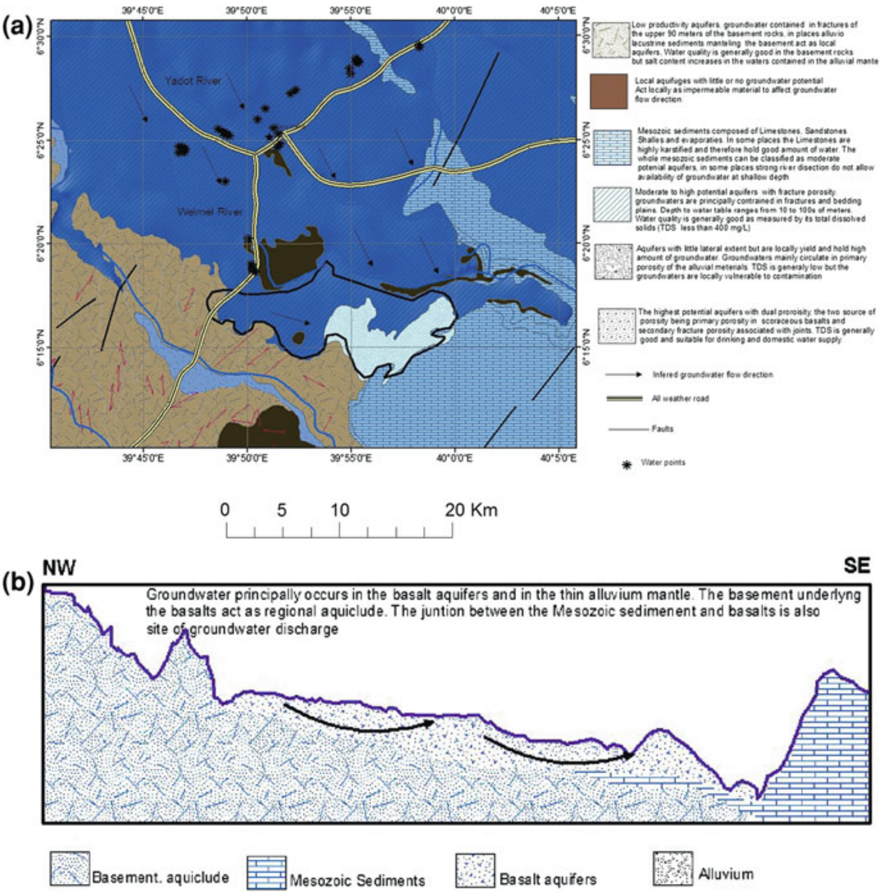


Fig. 3.22 A typical example of an alluvial fan adjoining the Hammer Koke highlands in the west and the Chewbahir rift in the east

various localities. This include (1) the Dallol depression which hosts alluvial fans extending over an area of 2500 km^2 (Fig. 3.21) (2) Alluvial fans adjoining the escarpments of the Chew Bahir Rift (see Fig. 3.22 as an example of solitary alluvial fan extending down from the Hamer Koke highlands to the Chew Bahir Rift) and covering an total areas exceeding 700 km^2. The alluvial fans at the foot hill of the western Escarpment of the Middle and Lower Awash valley have previously been mapped by Hailemeskel (1987). They were recognized as 'high level terraces along river beds at the lowland margins (inter-fingering of coarse and fine sediments) with very high permeability, (3) alluvial fans extending from the Mega horst in Borena down to the Ririba fault area (see Fig. 2.19) etc. All of these



Low productivity aquifers, groundwater contained in fractures of the upper 90 meters of the basement rocks, in places alluvio lacustrine sediments manteling the basement act as local aquifers. Water quality is generally good in the basement rocks but salt content increases in the waters contained in the alluvial mante

Local aquifuges with little or no groundwater potential Act locally as impermeable material to affect groundwater flow direction

Mesozoic sediments composed of Limestones, Sandstones Shalles and evaporaties. In some places the Limestones are highly karstified and therefore hold good amount of water. The whole mesozoic sediments can be classified as moderate potenial aquifers, in some places strong river disection do not allow availability of groundwater at shallow depth

Moderate to high potential aquifers with fracture porosity. groundwaters are principally contrained in fractures and bedding plains. Depth to water table ranges from 10 to 100s of meters. Water quality is generally good as measured by its total dissolved solids (TDS less than 400 mg/L)

Aquifers with little lateral extent but are locally yield and hold high amount of groundwater. Groundwaters mainly circulate in primary porosity of the alluvial meterials. TDS is generaly low but the groundwaters are locally vulnerable to contamination

The highest potential aquifers with dual proroisity, the two source of porosity being primary porosity in scoraceous basalts and secondary fracture porosity associated with joints. TDS is generally good and suitable for drinking and domestic water supply

Groundwater principally occurs in the basalt aquifers and in the thin alluvium mantle. The basement underlyng the basalts act as regional aquiclude. The juntion between the Mesozoic sedimenent and basalts is also site of groundwater discharge

Fig. 3.23 Simplified hydrogeological map of Welmel plain (**a** *above*) and conceptual groundwater flow model of the Welmel Plain (**b** *below*)

alluvial fans contain appreciable amount of groundwater and these groundwater resources can further be developed for water supply sources of pastoral communities occupying the alluvial fan areas.

3.20 Other Alluvial Aquifers of Limited Extent

The Simeno Plain Around Lalibela

The Simeno plain is bounded by the Abune Yoseph Shield volcano in the North and East and the North Wollo (Wegel Tena) plateau from south (Fig. 2.10). The plain is drained by Shumsha River and the head streams of the right tributaries of Tekeze River. The plain is underlain by alluvial sediments along the River flood plains. At the foot hill of the Abune Yoseph mountain shield a few springs emerge. Important groundwater sources are probably contained in the alluvial fill of the lower Simeno valley and in the Kechen Abeba river system near the Lalibela strip.

The Alluvio Lacustrine Sediments of the Becho Plain

The alluvio lacustrine sediments of the Becho plain (marked 4 in Fig. 3.1) have a thickness of 5–15 m depth throughout the plain. At the base of the alluvio lacustrine sediment is extensive tuff deposit. The material is dominated by silt and clay. Recharge to groundwater takes place from flood plain and seasonal rains. In situ permeability test show the permeability of the sediment ranging from 2.3×10^{-2} to 8.6×10^{-3} m/day. Water table depth is from 0 to 5 m below ground in a rainy season and 2–10 m in a dry season. Groundwater flow gradient is in the order of 0.0002–0.0003.

The Quaternary Sediments of Welmel Plain

The Welmel plain (Fig. 3.23a) is located in southern foothill of the Bale Mountains near the head water of one of the tributaries of the Weyib River. It covers an area of 4000 ha. SWL data show that the water table depth in upstream of the Welmel plain is shallow and ranges between less than 10 and 50 m. The presence of shallow groundwater is favored by the high storage capacity of the alluvial sediments couple with the basement lithologies underlying the volcanic terrain acting as low permeability trap. Combination of geological information, recharge, and water table depth and water quality has been used to draw a conceptual model for groundwater occurrence and flow in the Welmel and Surrounding area (Fig. 3.23b). As shown in the figure the Mesozoic sediments are assumed to exist beneath the basaltic cap. The availability of shallow groundwater and perennial flow of the Welmel River is an ideal case for a conjunctive use of groundwater and surface water for irrigation purposes in the plain.

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Chapter 4
Geochemistry and Water Quality

4.1 Why Water Quality

Water quality is the measure of physical, chemical, radiological and biological property of water. Water quality poses limits on the suitability of water use for a particular development purpose.

1. A number of morbidity, physical and mental impairments and mortality are tied to water related diseases
2. Water quality poses limits on beneficial use of water for particular development purpose (agriculture, industry, livestock rearing, recreation etc.)
3. Water quality determines the general environmental integrity and its health.

A multitude of economic cost/loses have also linkages with natural or anthropogenic water quality degradations. These may include among others:

1. Costs to expand water treatment facilities and to develop alternative potable water sources.
2. Degradation or loss of habitat and biodiversity and related loss in tourism revenues.
3. Direct and indirect costs of disease, including treatment costs and reduced economic productivity through mortality and morbidity.
4. Loss in agricultural production from increasingly salinity in irrigation water, or inability to use severely polluted water.
5. Loss, or increased cost, of industrial production due to impaired water quality.
6. Cost of social unrest and population migration associated with extremely degraded aquatic environments.

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DOI: 10.1007/978-3-642-30391-3_4,

4.2 Geochemical Characteristics of the Groundwaters

As shown in Fig. 1.1 as much as 36 % by volume of groundwater storage in Ethiopia is characterized by high salinity which is not directly available for purposes such as agricultural water use. This is because of the high salinity of the waters which exceed 1000 mg/l. Mirroring the four major lithological classes of the aquifers in Ethiopia, namely the basement aquifer, the Mesozoic sediments, the volcanic aquifers and quaternary sediment four distinct groundwater geochemical types can be recognized. The piper–trilinear plot (Fig. 4.1) shows the various water types that correspond to the four principal aquifers. Typical features are (a) in volcanic aquifers the dominant cations range from Ca–Mg to Na–K dominance while HCO_3 is almost exclusively the dominant anion (b) in the Mesozoic sedimentary aquifers Ca and Mg are dominant cations while SO_4 and Cl dominate the anions, (c) the basement aquifers have similar water types with volcanic rocks. However they show more variability in their SO_4 and Cl (d) the quaternary sediment aquifers show the highest variability with no apparent dominant of one ion over the other but generally they are of higher Cl and SO_4.

There is regionally coherent geochemical zonation of groundwaters of Ethiopia. The regional geochemical pattern is the reflection of rock type, climate, vegetation cover, and rainfall regimes. Figure 4.2 generalizes the expected range of plots of water geochemical characteristics from the four principal aquifers.

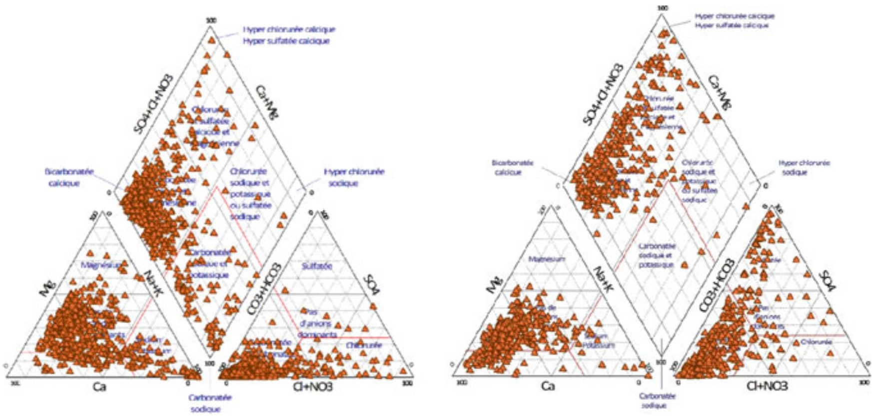
As will be discussed in more detail in Sect. 4.6 in detail the composition of groundwaters in Ethiopia is the product of three principal processes. Namely

(a) Lithologic variation—Rock type is an ultimate control of water quality as it determines the minerals available to undergo rock water interaction and release the ions to the groundwaters. As in crystalline volcanic and basement rocks the major type of geochemical reaction is ‘hydrolysis’ in the presence of atmospheric or geogeneic CO_2, the ions that are produced from such process are Ca, Mg, Na, K and HCO_3.

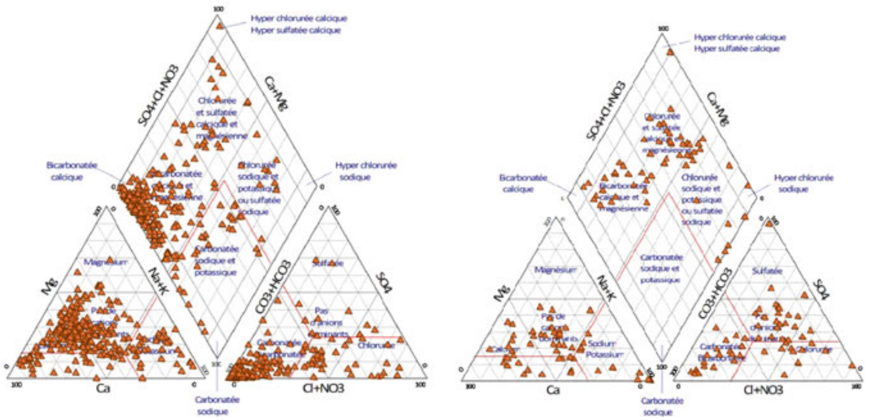
(b) Evaporative enrichment prior to recharge—prior to recharge, incidental recharge water can acquire some ions because of evaporation. In arid and semi arid regions where evaporation is the dominant hydrologic process enrichment of ions such as Ca and SO_4 occurs. Dissolution of trace salts from the soil zone imparts ions such as SO_4, Cl, Ca and Na and this process is common also in arid areas where top soil is salinized because of evaporation of available soil moisture and accumulation of trace salt in the soil zone.

(c) Thermodynamic control-rock type or evaporative process alone may not lead to the variability observed in the geochemistry of groundwaters. The role of thermodynamics is to control which kind of reaction is possible under a given rock type, temperature, saturation indices, and ionic activity.

Among ions dissolved in groundwaters, in Ethiopia, certain ions attract more attention than others because of their health significance. The importance of these chemical constituent relates to both deficiencies and excess of the ions in



(a) ***Volcanic aquifers*** **(b)** ***Mesozoic sediments***



(c) ***Basement*** **aquifer** **(d)** ***Quaternary sediments***

Fig. 4.1 Piper plots of groundwaters from the four principal aquifers in Ethiopia

groundwaters. Among the most notorious ions of health significant the geochemistry of fluoride, iodine and selenium is discussed below. Fluoride in excess of 1 mg/L causes dental and skeletal florists—a serious health hazard in Ethiopia. High fluoride is mostly associated with volcanic rocks which are common in Ethiopian rift. Figure 4.3 shows the geographic distribution of F in groundwaters in Ethiopia.

4.3 Geochemistry of Fluoride

The most salient feature of fluoride is its ability to easily exchange with the OH-ion, which has an ionic radius similar to that of the ion. Any rock forming mineral which has OH-ion in its mineral structure tends to host F-ion as well. Some

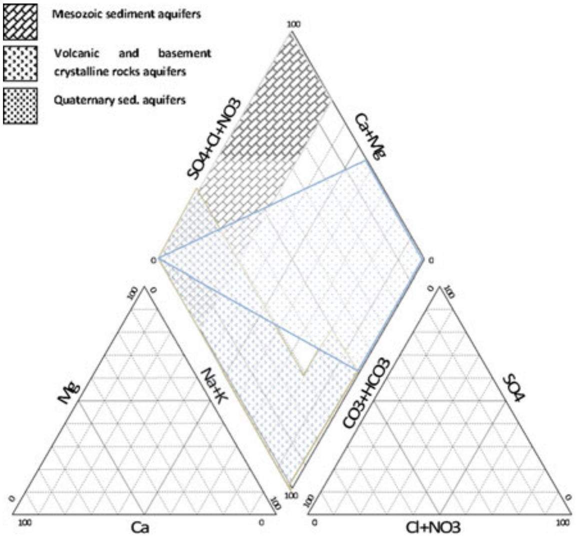


Fig. 4.2 Generalized ranges of water class for different aquifers in Ethiopia

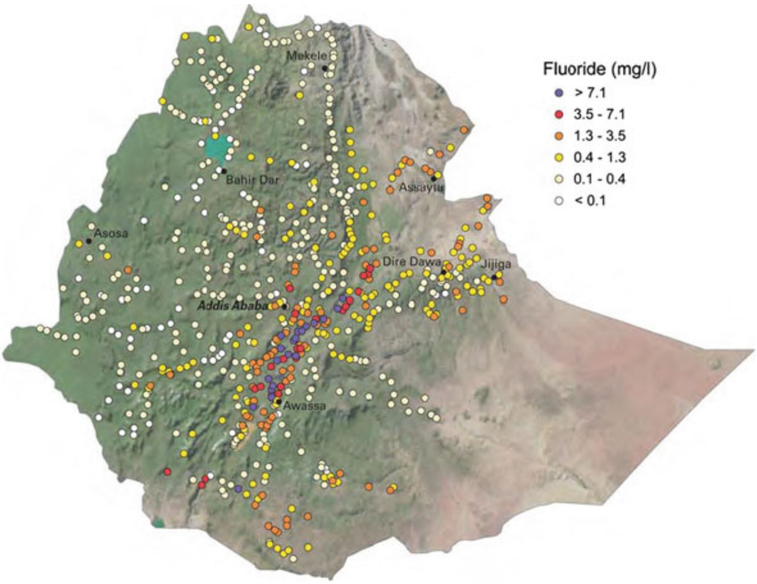


Fig. 4.3 Geographic distribution of fluoride contamination in groundwaters

examples of OH containing silicate rock forming minerals are alkali amphiboles, hornblende, and biotite. The principal reservoirs for F ion in nature are rock forming silicate minerals containing OH ion in their structures. Assemblages of these rock forming minerals are also known to form a group of rock commonly named as acid igneous rocks (e.g. Rhyolites, ignimbrites, pumice, obsidian, granites, hornblende gneiss etc.). A less abundant rock types or mineral assemblages also host significant amount of F ion. Examples include coal beds, shales, apatite ($Ca_5F(PO_4)_3$), fluorite (CaF_2), sellite (MgF_2), villiaumite (NaF).

That there is abundant F containing mineral in the aquifer matrix is not the only factor as to the eventual degree of enrichment of F in groundwaters. In the presence of F containing aquifer matrix, the degree of enrichment of F in groundwaters is controlled by thermodynamics and thermodynamically controlled reactions (mineral saturations, precipitation, ion exchange reactions, and completion between ions and ion pairs etc.). To some extent physical processes such as evaporative enrichment enhance the F content in groundwaters. A significant portion (though not quantified[1]) of F also comes from direct input from Juvenile (magmatic) gases. The following findings have been reported in literature for enrichment/depletion mechanism of F in groundwater of Ethiopian Rift and other regions of Ethiopia.

(a) *Ca content in soils* (Ashley and Burley 1994): In a comparative study between the Wonji Sugar plantation area with that of Metahara Sugar plantation areas, two sites in the Main Ethiopian rift, Ashley and Burley (1994) found significant difference between Ca content of soils in the two sites. The low Ca in Wonji soils eventually lead to higher enrichment of F in shallow groundwaters. The model or the premise is that abundant Ca in soil tends to fix F to form and remove F from waters as CaF_2.

(b) *Mineral saturation/solubility control* (Kilham and Hecky 1973; Darling et al. 1996; Gizaw 1996; Chernet et al. 2001): Groundwaters in volcanic terrain rapidly reach saturation with respect to carbonates of Ca and Mg (calcites, aragonites, magnesites) prior to carbonates of Na and K and mineral of F (e.g. $Ca_5F(PO_4)_3$, CaF_2, MgF_2, NaF). The fixation of Ca to carbonate minerals will lead to significant under-saturation of groundwaters with respect to CaF_2. This will lead to eventual uncontrolled enrichment of F in groundwaters of the rift. An important note here is that as groundwaters move from the recharge areas near the highlands to the discharge zones in the rift the Ca and Mg content in groundwaters diminish. This is mirrored by increase in F concentration along the highland-rift transect (Kebede et al. 2010). The viability of this model has been tested in a number of research works using geochemical modeling (e.g. Kebede et al. 2005) to explain F enrichment in certain sectors (e.g. Around Wonchi Volcano) of the Blue Nile Basin.

(c) *Base cation softening* (Rango et al. 2009): The role of base cation softening is similar to that of mineral saturation/solubility control but instead of removal of Ca by carbonate precipitation, base cation softening removes Ca by exchange with Na in the rock matrix. As groundwater ages or moves along its

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[1] The proportion of F coming from direct input from the geothermal systems to that of rock leaching is unknown though Chernet (1998) subjectively guess that to be 20:80 %. This will remain unsolvable question since F has no isotope. Isotopes are the best indicators of sources of certain ions, or elements in nature.

flow path Ca tends to be fixed to rocks and Na is removed from rocks instead. Though this process is a common process in mineral reactions, the viability of this model is not widely tested in the rift setting.

(d) *Double enrichment model* (Chernet 1998): This enrichment mechanism shows that F ion initially leached from rock forming minerals tends to accumulate in groundwaters. Following short or long term changes in hydrology of the rift, water table fluctuates, lake levels changes, and sediment deposition and erosion takes place along with hydrological variations. Fluoride ion in groundwaters is fixed to clay minerals or sediment surfaces when water level is lowered and sediment accumulates (e.g. the shrinkage of the Ziway Shalla lakes from one single mega lake to four isolated lakes over the Holocene left extensive lacustrine sediments). Along with the deposition of extensive alluvio-lacustrine sediments in the rift F which was initially in the waters is now fixed to the sediments. This makes the alluvio-lacustrine sediments secondary reservoir of F ion. Groundwaters now circulating in the alluvio lacustrine sediments remove F from the sediments to lead to a significant enhancement of this ion in shallow groundwaters. This model has been shown experimentally by doing extensive leaching (lixiviation) experiment by Chernet (1998) and Rango et al. (2009) to isolate the sediment grain size which contributes the highest F in waters.

(e) *Porosity and permeability control* (Yirgu et al. 1999): In a comparison made between two aquifers of similar rock geochemistry and mineralogy (Pumice vs. Ignimbrite—both being rhyolitic composition but one granular and the other fractured aquifer), the authors found that groundwaters of the Ethiopian rift hosted in pumice (a rock with inter-granular porosity) contain high F than groundwater contained in fractured ignimbrites. The explanation for this is that surface area of rock–water interaction affects the enrichment of F. In pumice because of high water–rock interaction surface area F gets transferred from the rocks to the waters much easily.

(f) *Reverse weathering vs F depletion from the waters of the rift* (Von Damm and Edmond 1984; Kebede 1999): This process removes F ion from lake waters in the rift regardless of the fact that none of F containing mineral reached saturation. A process of reverse weathering also called ‘clay mineral neo-formation’ is a process whereby clay is formed at high pH values and is removed from waters (particularly from the lakes). Along with neo-formation of clay minerals and their eventual removal to lake beds or to the aquifers, F ion is also removed by being fixed to the clay minerals. The role of reverse weathering in removing F ion from lake water and moving it to lake bed sediments has been shown by conducing mass balance modeling (Von Damm and Edmond 1984) for Ziway Shalla Lakes, Kebede 1999 for Bishoftu Crater Lakes). The models, which combines hydrologic model with geochemical model, show annual flux of F to the lakes is far greater than the annual accumulation of F in the lake water. A significant portion of F is lost. With no obvious saturation with respect to F containing minerals, the plausible pathway for loss of F should be fixation of the ion to newly formed clay minerals. This model has been performed in the Ziway Shalla Lakes in the time when enough hydrological data was not available. Although the recent work by Kebede (1999) shows the same process to take place in the Bishoftu Crater Lakes; comprehensive mass balance modeling should be conducted on the wider lakes of Ethiopia in order to validate this findings.

(g) *Evaporative enrichment* (Chernet 1982; Gizaw 1996; Kebede 1999): Lake waters in the Rift Valley (Chernet 1998; Gizaw 1996) and the Bishoftur Crater Lakes (Kebede 1999) show the highest F content (this is regardless of removal of F by neo clay mineral formation as discussed in f). Several previous studies attribute this to evaporative concentration of F in the lake waters.

(h) *Accumulation along groundwater flow path* (Kebede et al. 2010): This work shows how F content in groundwater varies along transects of groundwater flow path from the highlands bordering the rift to the rift center. A regular increase in F content is noted with sharp peaks near volcanic centers. This is suggestive of successive accumulation of F along the groundwater flow path.

(i) *Geothermal Influx* (Darling et al. 1996; Gizaw 1996; Ayenew 2008; Reimann et al. 2003): Direct geothermal input of F is widely mentioned in the literature as pathway of F input to the hydrologic systems in the rift. The challenge though is to address what proportion of F in the groundwaters of the rift is from direct magmatic input. The proportion of *F* coming from direct input from the geothermal systems to that of rock leaching is unknown though Chernet (1998) subjectively guess that to be 20:80 %. This will remain unsolvable question since F has no isotope. Isotopes are the best indicators of sources of certain ions, or elements in nature and help in deciphering mixing ratios.

(j) *Leaching of Shale*: Groundwaters in the Mekelle Outlier particularly from the Agula Shale show enrichment with respect to F (0.1–1 mg/L). This most likely is attributed to leaching of Shale rock in the Agula Unit of the Mesozoic succession.

(k) *Other notes*: The following points worth investigation (and need detailed studies) in any attempt to understand and deal with F geochemistry and its enrichments or when dealing with defluoridation processes. These points are: (i) recent investigation (Kebede et al. 2010) shows that F ion concentration co varies with other undesirable trace elements (U, As, Li, B, Mo, V), (ii) F has been proposed (Chernet 1998) to a potential paleo climate indicator, (iii) Earlier works (Kilham and Hecky 1973) speculated the impact of F on the rift ecology (e.g. On silica[2] secreting diatom population-this line of research has been not been enhanced yet).

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[2] It should be noted that silica in water exists in as SiO_2, SiF_6 or other forms. Diatoms are siliceous planktons. The fact that F makes part of silica ion pair may lead to some relation between F and lake ecology, particularly diatom population.

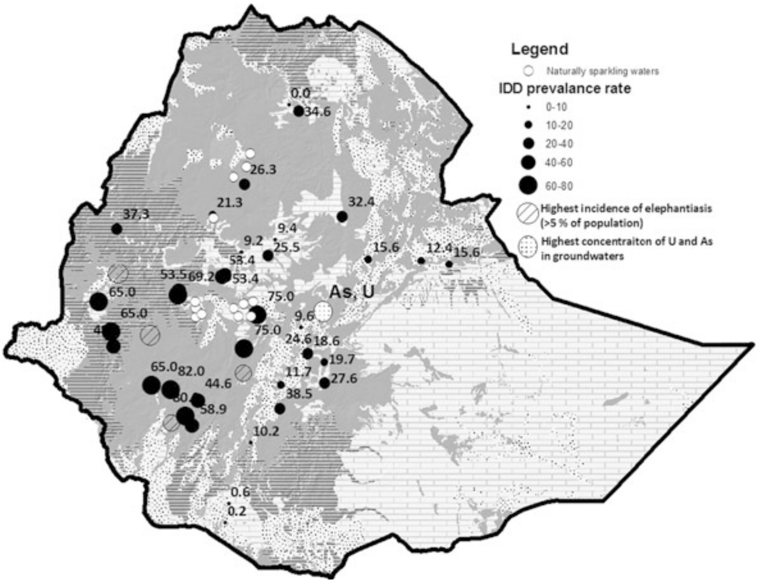

Fig. 4.4 Prevalence of IDD deficiency (data for IDD from WHO database) plotted against geology, altitude, and climate setting

4.4 The Geochemistry of Iodine

Geo-Environmental Sources of Iodine

Sea water with a mean concentration of 58 ppb of iodine is the most important reservoir for terrestrial iodine and this markedly influences the distribution of iodine in the secondary environment (Fuge and Johnson 1986). Marine carbonate and sedimentary rocks contain iodine ranging from 2.5 to 30 ppm (Dissanayake and Chandrajith 1999). Ground and surface waters are among the most important media that act as a bridge between rock, rainwater and soil geochemistry and human physiology (Dissanayake and Chandrajith 1999). In Ethiopian groundwaters iodine concentration is lower than the marine values (Kebede 2009).

Iodine Deficiency Disorder

Lack of adequate iodine in foods and drinking water could lead to Iodine Deficiency Disorder (IDD). This causes goiter, cretinism, poor pregnancy, still birth, mental retardation and infant mortality. Iodine deficiency is the world's most common cause of mental retardation and brain damage and goiter incidence.

Causal Mechanism of Iodine Deficiency Versus Geo-Environmental Setting

Figure 4.4 shows spatial pattern of goiter prevalence rate in Ethiopia. Medical sciences research in Ethiopia have previously recognized that risks of IDD is associated with (a) Living in high altitudes, (b) Cassava and Millet consumption and (c) Leaching of iodine from top soil by erosion and flooding. However none of these works show the underlying mechanism of iodine enrichment and depletion with the geo-environmental setting. Two regions of Ethiopia with similar altitude shows different degree of prevalence in goiter (Fig. 4.4). Therefore altitude alone cannot be the underlying mechanism of high incidence of goiter. The correlation between goiter prevalence and geo-environmental setting at regional scale leads to drawing up of the following hypothesis for the casual mechanism of iodine deficiency in Ethiopia.

1. Goiter prevalence is significantly lower in the lowlands of Borena and the rift valley both regions known for their high salt content in the groundwaters owing to evaporative enrichment of groundwaters prior to recharge and salt dissolution from lacustrine sediments. Iodine concentration in groundwaters of the rift is also higher than global average and the marine concentration owing to diffusion of trace gases from the mantle through rift faults.
2. The highest goiter prevalence is observed in south western Ethiopia which is under the influence of the South westerly monsoon driving its moisture from the Atlantic Ocean and the advective moisture engulfed from the Congo vegetation basin. The dilution of the marine moisture by advected moisture from the Congo vegetation should be responsible for depletion of iodine in the monsoon rains. Furthermore the high rainfall intensity and associated strong leaching of the rocks could lead to elimination of iodine from availability (as groundwaters or biologically).
3. In south eastern Ethiopia goiter prevalence is lower. The region is under the influence of the Indian Ocean moisture which because of short moisture trajectory could contain higher amount of marine iodine. The survey by Riemann et al. (2003) also shows high concentration of iodine in groundwaters from the Harar and Arsi plateau bordering the rift. The Marine sediments dominating the south eastern Ethiopian region contribute also to lower prevalence of goiter.
4. In North western Ethiopian plateau goiter prevalence generally decrease from south to north. Rainwater collected from these sector of Ethiopia shows a north ward increase in salinity (Kebede 2004) owing probably to admixture of dust and aerosols derived from the Sahel and Arabian continent. The decrease in goiter prevalence could be related to increase in salinity of rainfall. Furthermore the northern part of the north western plateau is mostly underlain by Mesozoic marine sequences (Fig. 4.4) which could directly or indirectly contribute to the natural availability of iodine in the environment.

5. Variation is goiter prevalence in a single geo-climatic zone generally increase with increase in altitude. For example data from altitudinal transect in Tekeze valley shows that in goiter prevalence is higher in high lands than in lowlands (Fig. 4.4). This being related to increase in salinity of groundwaters owing to higher evaporation in the lowlands and absence of such a process of salt enrichment in highland.

4.5 The Geochemistry of Selenium

Geo-Environmental Sources of Selenium

The chemistry of selenium is similar in some respects to that of sulfur, but selenium is a much less common element. Some species of the genus Astragalus are particularly notable for taking up and accumulating selenium from the soil, and some plants have been found to contain several thousand milligrams of selenium per kilogram of dry plant parts. Its mobility is high under acid and oxidizing conditions, very high under neutral–alkaline conditions and very low under reducing conditions.

Selenium Deficiency and Excess Diseases

The selenium content range between toxic and deficient concentration is very narrow. Selenium, at trace levels, is essential in the human and animal diet and its deficiency has received much attention. It causes symptoms such as muscular degeneration, impeded growth, fertility disorders, anemia and liver disease. Keshan and Kaschin–Beck diseases, reported on a regional scale from China, are caused by Se deficiency. At ingested concentrations of 10 mg/day and higher, gastro-intestinal ailments, skin-discoloration and tooth decay may occur. Selenium is an integral part of the enzyme glutathione peroxidase (GSH-Px) in human and animals. This enzyme can protect the organism against oxidative damage by reducing lipoperoxides and hydrogen peroxide.

Selenium in Ethiopian Groundwaters

Selenium content in groundwaters has been measured in few occasions. The measurements made by Riemann et al. (2003) shows Se content in groundwaters generally is very low. Concentrations observed in Rift Valley drinking water ranged from 0.015 to 7.6 mg/L. Median Se values were lower in spring and river

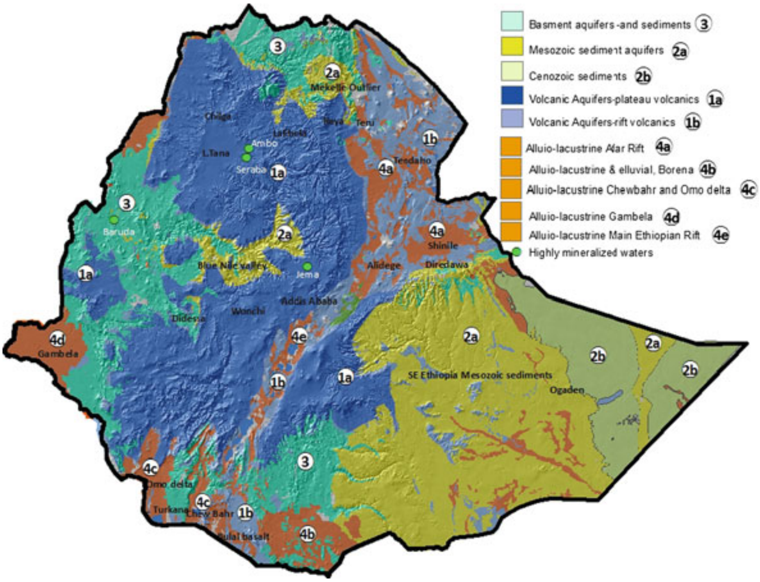

Fig. 4.5 Geochemical groups and subgroups of groundwaters

water than in the wells. In Raya Valley measurement shows that Se is lower in bedrocks bounding the alluvial valley and higher in the alluio-lacustrine sediments deposited along the foot hill of the volcanic highlands. Here Se content in groundwaters varies between 0.001 and 0.015 (from deficient to toxic level). The health effect of Se in the Ethiopian people and animals is far from known.

4.6 Water Quality Groups of Ethiopian Aquifers—Origin of Water Quality Parameters

Groundwater quality is measured by its physical, chemical and biological constituents. Description made here refers to the natural geochemical composition of groundwaters. Groundwaters naturally contain most elements of the period table in variable quantities. The natural geochemical composition of groundwaters is one of the factors that affect the potential of aquifers for water resources development. Corresponding to the lithologic variation and climate at least four broad categories of geochemical groundwater groups can be identified (Fig. 4.5).

Group 1a

Geochemical and Water Quality Characteristics

This group represents groundwaters hosted in the vast basaltic plateau aquifers, associated minor acid volcanics, and prominent shield volcanoes. Typical groundwater geochemical features are the low total dissolved solid (salinity) often less than 500 mg/L. These groundwaters are monotonously dominated by three principal ions Ca, Mg and HCO_3. With depth Mg and Na content increases while Ca decreases. In deeper regional flows content of Na increases accompanying HCO_3 and total dissolved solids. In few localities other ions may become important though not dominant. For example relatively elevated SO_4 may be encountered when aquifers tap inter-trappean sediments and oxidation of sulphide minerals takes place or when evaporation enhances level of SO_4 in recharge waters. In the later case high SO_4 accompanies higher Cl contents. In few localities when regional tectonics and quaternary volcanism is visible thermal waters may emerge at the surface along the volcanic aquifer. The thermal waters contain high $p\mathrm{CO}_2$, Na, HCO_3, SO_4, Cl (e.g. Thermal springs on the limbs of the Wonchi volcano and at its foot, the Filwhua thermal waters in Addis Ababa, the thermal waters in Didesa valley and thermal waters in the Lake Tana graben). Higher fluoride content is only noted in few localities when groundwaters are associated with acid volcanic rocks (e.g. around Wonchi Volcano). In shallow waters there is a recent increase in Cl and NO_3 contents because of lack of well head protection. Always higher Cl accompanied by higher NO_3 is precursor of presence of incipient pollution. The groundwaters of the vast volcanic plateau are geochemically the most suitable for domestic water supply, irrigated agriculture and industrial uses. This group of water are also characterized by near neutral pH where $6.5 < \mathrm{pH} < 8$.

Water Quality for Water Use and Risks

In this group of groundwater low Total dissolved solids and low sodium content make them the most suitable waters for any type of water use (irrigation, domestic water supply etc.). Nevertheless in some places incipient pollution is noted in shallow unprotected wells and springs.

Group 1b

Geochemical and Water Quality Characteristics

This group represents groundwaters in extensive younger volcanics of the main Ethiopian rift, the Afar depression and the Borena lowlands. Like their counterpart in the Ethiopian volcanic plateau (group 1a), groundwaters of the volcanics of the rift are characterized by high HCO_3. However Na is dominant over Ca and Mg. In cases where the aquifers have lateral or vertical connection with sediments associated with them or when evaporative concentration of flood waters is important prior to recharging the groundwaters Cl and SO_4 ion become dominant anions. Total dissolved solids range from 500 to over 2000 mg/L. Most of these aquifers also contain higher F, As, U, B and Mo, all related to dissolution of trace elements from the geothermal systems and acid volcanic rocks. In some cases fluoride content reaches 300 mg/l and affects the health of the population who live in this area. Furthermore, the alkaline and sodic characteristics ($8 < \text{pH} < 10$ and $0.9 \times 10^{-4} < \text{Na} < 0.35\ \text{ML}^{-1}$) of these waters destroy the soil for agricultural use (Chernet et al. 2001). An elaborate work by Chernet et al. (2001) using analysis of 320 water samples from the main Ethiopian rift of the Ziway Shalla basin shows that the waters issuing from volcanic rocks are characterized by a positive alkalinity residual of calcite (i.e. $(HCO_3) > 2(Ca + Mg)$ when compared in their meq/l unit). When they concentrate due to the effect of evaporation, the precipitation of calcite causes a decrease in the chemical activity of calcium. This results in an increase in solubility of fluoride, previously controlled by equilibrium with CaF_2, and the element concentrates without being significantly affected by the precipitation of fluorite. As water concentrates, the low concentration of dissolved calcium emphasizes the alkaline characteristics. As a consequence, the pH reaches very high values (9–10) which make the waters unsuitable for agriculture. Typical geochemical reaction that is responsible for higher alkalinity, fluoride and Na has been extensively discussed (Gizaw et al. 1996; Darling et al. 1996). The principal reason for the bicarbonate in the area is high rate of carbon dioxide out gassing from mantle and which enhances rock water interaction at shallow depths. This combined with acid volcanics, geothermal heating, low Ca and low salinity, is also one of the causes of high salinity, alkalinity and fluoride in the volcanic rocks of the central Ethiopian rift.

Typical reaction that gives rise of high alkalis and bicarbonate are:

1. $CO_2 + H_2O + \text{Na, K-silicates} \Leftrightarrow HCO_3^- + \text{Na, K} + \text{H-silicates}$ (common)
2. $CO_2 + H_2O + \text{Ca, Mg-silicates} \Leftrightarrow HCO_3^- + \text{Ca, Mg} + \text{H-silicates}$ (rare)
3. $\text{Ca, Mg} + HCO_3 \Leftrightarrow (\text{Ca, Mg})CO_3$ (common)
4. $(\text{Ca, Mg})X_2 \Leftrightarrow (\text{Na, K})X$ (rare cation exchange reaction)
5. Evaporative enrichment of certain elements and remobilization of trace salts from the unsaturated zone by subsequent rains and remobilization of salt from sediments associated with the volcanics.

In the Afar depression the dominance of basalts over acid volcanic rocks lead to low F content in groundwaters. Salinity of groundwaters in Afar is generally higher than those in the main Ethiopian rift. However owing to the abundance of lacustrine sediments, and lenses or layers of evaporites sediments in the region, salt remobilization leads to higher SO_4, Cl in the groundwaters. In case where salt remobilization is taking place groundwaters also contain higher Ca and Mg (e.g. in the Bulal basalt of southern Ethiopia).

Unlike the volcanic aquifers of the Main Ethiopian Rift and the Afar depression the groundwaters in western volcanic lowlands of Borena region (See Bulal basalt, Fig. 4.5) are dominated by or contain substantial amount of SO_4, Cl, Na, and Ca. This is the result of importance of dissolution reactions and interaction with alluvio-lacustrine sediments in imparting salinity. The Bulal basalt aquifer (an extensive aquifer occupying a half bowl shaped depression between the Borena and Teltele highlands) is mantled by up to 30 m thick alluvio lacustrine sediments. Salt dissolution is an important process controlling the salinity of groundwaters in the region. There is a significant co-variation between Na, Cl, SO_4, and Ca in groundwaters of the Bulal basalt aquifers. This is indicative of salt dissolution in imparting salinity. However HCO_3 strongly co-vary only with Mg suggesting hydrolysis reaction is imparts Mg ions. The groundwater containing relatively higher Mg and HCO_3 are located in south eastern corner of the vast plain (Megado Biliko) a region where the Basalts are covered by quaternary scoracious basalts and maars. The groundwaters containing higher Na, SO_4, Ca and Cl are located in the central sector of the depression straddling the N–S running Ririba fault system.

Water Quality for Water Use and Water Quality Risks

Most of the regions are known for higher alkalinity, sodicity and salinity groundwaters. The rift is on the other hand a high potential site for irrigated agriculture because of availability of extensive flat land and surface water resources emerging from the highlands. Given that irrigation practice does not factor the risk of salinization significant damage can be caused if that the water table is raised to the surface by agricultural drainage. This salinization of soil because of water table rise has been noted in several places in the rift. Higher F is risk for flourisis.

Group 2a

Geochemical and Water Quality Characteristics

This represents groundwaters hosted by the Mesozoic sediments of Ethiopia which are exposed in the South Eastern Ethiopia, the Mekelle Outlier and the Abay (Blue Nile) valley. The EC of groundwater in Mesozoic sediments of the highlands of south eastern Ethiopia ranges between 100 and 1500 μS/cm with outlier values exceeding 1500 μS/cm. The value is generally low as compared with same in groundwaters in Mesozoic sediments of Mekele Outlier where EC value can go up to 3000 μS/cm. The difference in the two basins may be related to the proportion of marl and shale intercalated within the sediments. The proportion of marl and shale is lower in south eastern plateau leading to lower SO_4 content and lower TDS. Generally in south eastern plateau SO_4 content increases towards the Ogaden lowlands. Notable feature of the groundwaters in the Mesozoic sediments is that the Total dissolved solids value though higher do not generally exceed 2400 mg/L. This corresponds to the solubility of gypsum in water at 25 °C (2.4 g/l). Groundwaters in the Mesozoic sediments of the south eastern Ethiopia are generally high in their HCO_3, SO_4 and Ca contents. In case of purely sandstone aquifers as in lower sandstone (Adigrat) or upper sandstone, Ca strongly correlated with HCO_3 and SO_4 content. In the lowlands of the south eastern Ethiopia part of the basin in limestone terrain, there is good correlation between Ca and SO_4 but poor correlation between Ca and HCO_3. Na is generally low. EC is generally less than 1500 μS/cm. The groundwaters in the Sedimentary aquifers of the Abay basin show similar property as that of the Mekelle outlier owing to their similarity in lithologies and proportion of marl and shale intercalated in the limestones. Alluvial sediments occurring in association with the Mesozoic sediments (e.g. alluvio lacustrine sediments occupying the river valleys and wadi beds in SE Ethiopia, Fig. 4.5) hold water with higher total dissolved solids (exceeding 2000 mg/l), higher Na, Cl and SO_4. This higher value over their bed rock aquifer implies evaporative concentration of salt prior to recharge and subsequent dissolution of salt from the sediments. Unlike the bed rock aquifers the groundwaters in alluvial sediments contain dominant Na and Cl. In places where halite exists in association with the Mesozoic sediments TDS often exceeds 3000 mg/l.

Water Quality Risks

In the Mekelle Outlier water quality is the principal challenge for groundwater resources development. Around 50 % of the investigated water points return waters with TDS in excess of 1000 mg/l. However the upper limit of the TDS is around 2000 mg/L. Given the water scarcity in most of the areas underlain by the Mesozoic sediment, majority of groundwater sources may satisfy the water quality requirements. However the groundwaters pose greater salinity hazard but low sodium absorption ratios. For example 50 % of groundwaters sampled from the Mekelle sedimentary outlier shows high or very high salinity hazard though most of them are of low sodium adsorption ratios. The high hardness of the water also is known to cause scaling of water ways and industrial pipes.

Group 2b

Geochemical and Water Quality Characteristics

This group represents waters similar to group 2a in most cases but with variable chemistries. In the extreme east of Ethiopia the groundwaters are found to contain higher ammonia while the unique nature of geochemistry of the Jesoma sandstone is the fact that the principal process that imparts salinity is evaporative enrichment of salt prior to recharge. Groundwaters have generally moderate to high salinities ranging between 2000 and 3000 mg/l.

Water Quality Risks

The waters have higher mineral content for human consumption but generally acceptable for livestock watering.

Group 3

Geochemical and Water Quality Characteristics

This group represents groundwater hosted in the basement aquifers and associated regolith or alluvial sediments. The groundwaters are dominated by Ca and HCO_3 ions. TDS generally is less than 500 mg/L and can be as low as 15 mg/l. When groundwaters are hosted in the metamorphic bed rocks HCO_3 dominates the anions and Ca and Mg dominates the cations. The following types of reactions are responsible for generation of the composition of these geochemical groups

$$3H_2O + 2CO_2 + \underset{\text{Anorthite}}{CaAl_2Si_2O_8} \Rightarrow \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + Ca^{++} + 2HCO_3^-$$

$$2H_2O + 2CO_2 + \underset{\text{Anorthite}}{CaAl_2Si_2O_8} \Rightarrow \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Calcite}}{CaCO_3}$$

$$2H_2O + 2CO_2 + \underset{\text{Calcite}}{CaCO_3} \Rightarrow Ca^{++} + 2HCO_3^-$$

$$\begin{aligned} 3H_2O + 2CO_2 + \underset{\text{Plagioclase}}{Na_4Ca_1Al_6Si_{14}O_{40}} \Rightarrow {} & \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Albite}}{4NaAlSi_3O_8} + Ca^{++} \\ & + 2HCO_3^- \end{aligned}$$

Groundwater geochemistry in the basement regions is not only the function of the basement rock mineralogy but also that processes such as evaporation processes taking place prior to recharge. When evaporation prior to recharge is prominent or when direct evaporation takes place from shallow aquifers Cl ion may be important. For example relatively high bicarbonate water with diagnostic high Cl content (without apparent high NO_3) has been encountered in the basement aquifers of Eastern Ethiopia around Harar and Diredawa and in eastern sector of the Northern Ethiopian basement around Mekelle. These waters are localized mostly in the shallow regolith aquifers associated with the basement aquifers. The high Cl is indicative of evaporation effect on the waters or direct evaporation taking place from the aquifer.

Marble aquifers associated with the basement are dominated by Ca and HCO_3 waters with TDS around 500 mg/l. Owing to shallow depth of groundwater in basement regions pollutants particularly NO_3 can get rapidly into the water table. In many encounters in western Ethiopia and Harar plateau higher NO_3 level is a common water quality problem.

Water Quality Risks

The waters in basement rocks fulfill most of the requirement of domestic water supply, irrigation, livestock watering and industry. Because of their low mineral content increasing the hardness of the waters may be required to improve the health impact of the waters. Their highest vulnerability to pollution requires protection of well heads and the aquifers.

Group 4a

Geochemical and Water Quality Characteristics

This group represents groundwaters in the loose alluvio lacustrine sediments occupying the extensive plain at the foothill of the southeastern Ethiopian plateau. The waters show strong spatial and depth wise variation in total dissolved solids. Generally groundwaters near the plateau and in the coarse grained sediments just at the foot of the highlands contain low total dissolved solids (<1000 mg/l) while in the fine grained sediments in the northern sector and central part of the alluvial sediments and at deeper level salinity exceeds 1000 mg/L and reaches 3000 mg/l. The high salinity waters are dominated by Ca, Na and SO_4 ions while in the lower salinity waters contain abundant Ca and HCO_3 ions. Evaporative enrichment prior to recharge and dissolution of trace salts from the sediments is the principal source of ions in the waters. The groundwater in the central part of the alluvial plain and in the northern half of the alluvial graben is Ca–SO_4 and Na–Cl type with TDS 1000–4000 mg/l and fluoride content is near 1.5 mg/l.

Water Quality for Water Use and Water Quality Risks

The waters of this group are characterised by low alkalinity and sodium hazard but high salinity hazard if used for irrigation. The salinity hazard occur in groundwaters in northern and central part of the alluvial plain. Most of the waters particularly in the southern part of the alluvial plain poses little salinity challenge if used for domestic water supply.

Group 4b

Geochemical and Water Quality Characteristics

This group of waters represents generally highly variable water geochemistry in the lowlands of Borena associated with loose elluvial and wadi bed sediments. The waters contain higher Ca, Na, SO_4, HCO_3 and Cl. TDS ranges between 500 mg/l to over 3000 mg/L. Water types are Ca–SO_4, Na–Cl, and Na–HCO_3–Cl types in most of the cases. The principal source of salinity is dissolution of salt crust from the unsaturated zone. The salt crust is formed by evaporative drying of flood waters. Successive evaporation cycle leads to accumulation of salts principally gypsum and calcrete. Later dissolution of these salts gives rise to higher salinity, Ca, SO_4 and Cl.

Water Quality for Water Use and Water Quality Risks

Principal water use in this region is for livestock rearing. The waters are mostly acceptable for livestock water consumption with exception of the few high salinity water wells. Salinity and SAR are the main challenges to use some of the water points for irrigation uses. The groundwaters in wadi beds and in the crystalline sediments are generally of acceptable quality for domestic water supply and agricultural uses.

Group 4c

This group represent groundwaters in the thick (exceeding 1 km) alluvio lacustrine sediments of the Omo delta and Chewbahir rifts. In the delta area, groundwater geochemical variation comes in a complex but predictable patters. Generally total dissolved solids in groundwaters range between 1 and 50 g/l making the groundwater unsuitable for domestic water use or livestock watering. The fresh groundwater lenses is often associated with old distributaries channels beds connected to Omo river, or with beach ridges bounding the Omo delta from East (Fig. 2.49), or with the alluvial fans intruding into the Omo sediments at the emergence zone of the wadi beds from the Hammer Koke block. Geochemical modeling shows the groundwaters obtain their salinity principally from dissolution of halite and gypsum inter-bedded in the Omo and Chew Bahr rift sediments. Unlike most groundwaters in loose sediments of Ethiopia, here the groundwaters show highest concentration of Cl accompanying Na accompanying TDS which reaches 50 g/l. In higher grounds of the lower Omo basin (e.g. in Gofa Basin and range) although similar mechanism of salinization is noted, owing to the low abundance of evaporate materials, the total dissolved solids show lower values (oven less than 1500 mg/l).

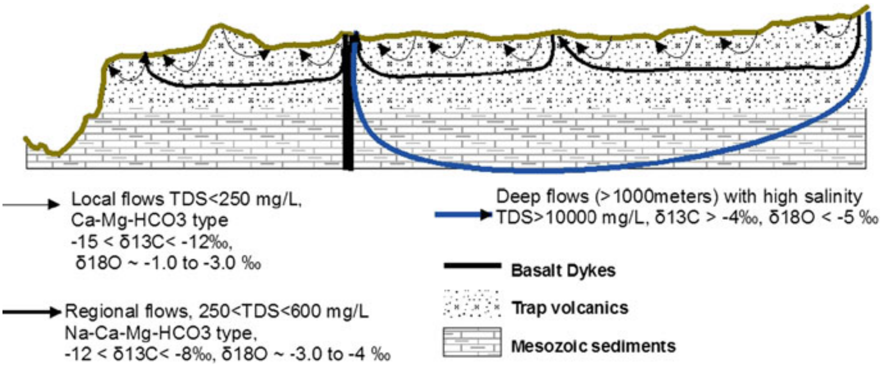

Fig. 4.6 Section drawn based on typical profile in the eastern part of the Blue Nile basin (Jema valley)

Table 4.1 Chemical composition of highly mineralized waters associated with basement rocks (units in meq/L)

Sample source	TDS	Na	Ca	Mg	K	HCO_3	Cl	SO_4	F	SiO_2
Hashimal Baruda spring 1	1742	38.9	5.7	0.08	2.25	0.4	13.4	1.36	0.32	66
Hashimal Baruda spring 2	2288	40	8.7	9.5	3.0	0.4	20.5	2.2	0.05	88

Water Quality Risks

The Omo delta region is recognized as a high potential site for surface water irrigation. On the other hand the groundwaters underlying the vast plain of the Omo delta contain highest groundwater salinity. There is a prominent salinization risk given that proper precautionary measures are not taken if mechanized irrigation is to start. Except the fresh water lenses, the salty groundwaters are unsuitable for uses such as domestic water supply, irrigation or livestock watering. Almost 70 % of water wells drilled in the region have been abandoned owing to return of high salinity waters.

Group 4d

Geochemical and Water Quality Characteristics

These groundwaters represent the multilayered Miocene to Quaternary alluvio lacustrine sediments of Gambela lowlands in Western Ethiopia. Groundwater in the quaternary alluvio lacustrine sediments is slightly saline with TDS slightly less than 1000 mg/L. In most cases it varies between 200 and 600 mg/l. The Underlying Miocene Alwero formation shows much fresh groundwater chemistry at TDS of 300 gm/l. The groundwaters are dominated by Ca cation and HCO_3 and SO_4 and Cl anions.

Water Quality for Water Use and Water Quality Risk

No major risk is posed by these water types for domestic water use or agricultural uses as most of them are characterized by low salinity and low sodium.

Group 4e

Geochemical and Water Quality Characteristics of the Waters

This group represents groundwaters hosted in the volcaniclastic sediments of the central rift valley. These groundwaters fall in the Na–HCO_3 water type in the Piper plot and contain relatively high sodium content and very limited calcium and magnesium contents. HCO_3 dominates the anions with relatively higher proportion of SO_4 and Cl. The TDS ranges between 500 and 1500 mg/l. Higher F is typical property of these waters.

Water Quality for Water Use and Water Quality Risks

The waters are mostly suitable for livestock watering. High sodicity and alkalinity make them unsuitable for crops but can be used for other agricultural products. The high F content also limits their use for domestic water supply.

4.7 Highly Mineralized Groundwaters in Ethiopia

Unlike ordinary saline waters associated with evaporation and dissolution of salts, highly mineralized water here refer to groundwaters of complex mineralization history associated with basement and volcanic rocks. Highly mineralized waters are reported to occur in three localities including (a) the Basement rocks of Western Ethiopia (Baruda), the volcanic plateau near Addis Ababa (Jema) and the Lake Tana basin (Ambo) (see Fig. 4.5).

Highly Mineralized Waters Associated with Volcanic Plugs, Dykes, and Intrusions

Typical characteristics of these groundwaters are their very low discharge, high salinity and close association with dykes and plugs. They are common in the DebreTabor graben of the Eastern Lake Tana basin. They are not only confined to tectonically prominent areas but are also observed in the flat lying plateau such as the Jema area. Several prominent examples have been noted in north western Ethiopian plateau. Figure 4.6 shows schematic model of the genesis of the highly mineralized waters associated with volcanic rocks in Ethiopia.

In the Jema River valley in central Ethiopia, the mineralized water is discharged at the bottom of the Jema valley and/or along the vertical dyke composed of coarse grained volcanic (basaltic) rock (Sima 2009). The dyke penetrates the full sequence of the overlying aquifers developed in sedimentary as well as volcanic rocks and forms a vertical drainage for groundwater accumulated in these aquifers. The continuation of the dyke also provides a pathway for CO_2 coming from deeper sources. These circumstances give the water in this spring a unique chemical composition leading people to use it for medical purposes. Highly mineralized water has laxative properties (affection) and is used by local people for cleaning the digestive system. The spring has a distributed discharge that can be characterized as very low 0.01 l/s.

Highly Mineralized Waters Associated with Basement Aquifers

Deep circulating waters in basement shields showing high total dissolved solids and falling in category of brines are common features in several basement shields of the world. Highly saline groundwaters have been encountered in the western Ethiopian basement at a place called Baruda. Like their equivalent in basement shields in elsewhere in the world the notable features of the groundwater geochemistry is the occurrence of brines at depth (often deepest level), with a characteristic Ca–Na–Cl chemistry (see Table 4.1 as an example). In general, Cl can be contributed to the water by hydrolysis of biotite, leaching of fluid inclusions and water loss due to formation of anhydrous secondary minerals during weathering. Sodium of mineral waters is likely to be related to plagioclase weathering since the albite (Ab) component is the only potential source of Na.

Three theories have been proposed for the origin of these kind of brines elsewhere in the world: (1) they represent modified sea water or basinal brines (2) they result from leaching of fluid inclusions or (3) they result from intense rock water interaction at temperatures as low as 100–150 °C. The absence of any prominent salt water intrusion from old or modern saline waters from seas lead to the hypothesis that the saline brackish waters of the western Ethiopian basement results from downward percolation of fresh meteoric waters mixing with brines.

High TDS groundwaters in basement shields are normally Ca–Na–Cl type owing to sink in Mg and K to cation exchange with the rock forming minerals. HCO_3 and SO_4 content are also low owing to precipitation of calcite and gypsum. TDS in basement shields may reach up to 250 g/L. The manifestations of the Na–Ca–Cl water at shallow depth in the western Ethiopian basement could be related to upwelling of the deep brines by thermal convection following regional fractures and shear zones.

Basement rocks in Eritrea have been noted to have similar water quality issues. According to Drury et al. (2001) the Neoproterozoic basement include substantial layers of sulphidic, carbonaceous phyllites, and common occurrence of sulphide rich hydrothermal mineralization, pyrite (FeS_2) readily oxidizes to ferric oxy hydroxides and sulphuric acid during lateralization to form a source of sulphate ions (hydrothermal pyrite also may contain high As). Combined with Mg ions liberated from mafic lithologies in the basement by deep weathering, sulphate release poses health problems in the form of epsomite ($MgSO_4 \cdot 7H_2O$), a purgative Epsom salts. Many outcrops show efflorescence of various salts, confirming the paleosols are still active source of soluble compounds.

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Chapter 5
Isotope Hydrology in Water Cycle Studies in Ethiopia

5.1 Why Isotope Hydrology?

Isotope hydrology is a proven tool in understanding hydrological processes such are recharge rate and recharge mechanism, surface water groundwater interaction, time scale of processes, origin of pollution etc. The tool is even more powerful when used in understanding of hydrology of arid and semi arid regions. Given that half of Ethiopia is an arid or semi arid region, isotope hydrology could provide the much needed knowledge for groundwater resources management. The purpose of this chapter is therefore to first briefly describe the tool itself and then to show some cases studies where isotopes have been used to retrieve hydrological information in Ethiopia.

5.2 Isotope Basics

Almost all chemical elements of the periodic table have isotopes. Isotopes are atoms of same elements with same number of proton (atomic number), but with different number of neutron (or mass number). Isotopes of same element therefore have slightly different masses. The mass difference between isotopes of same element is larger for light isotopes (or isotopes of lighter elements ex hydrogen, oxygen, sulfur, boron, nitrogen, carbon, helium etc.). For example the heavier stable isotope hydrogen ^{2}H is twice as heavy as the lighter isotope ^{1}H equivalent.

This small difference in mass leads to different physical propriety of the molecules. During the hydrologic processes involving phase changes (e.g. evaporation, condensation, sublimation, freezing, etc.) and geochemical reactions isotopes of same element behave differently leading to isotopic fractionations ultimately resulting in different natural isotopic abundance in different hydrologic compartments (e.g. lakes, oceans, rivers, atmospheric water, groundwater etc.). Isotope fractionation is the physical phenomenon which causes changes in the relative

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DOI: 10.1007/978-3-642-30391-3_5,

Table 5.1 Isotopes used in water cycle studies, standards used, natural isotope ratios and their applications

Isotopes	Standards	Standard	Use	Remark
^{1}H, ^{2}H	V-SMOW	1.5575×10^{-4}	Recharge rate, recharge mechanism, origin of water and salinity, mixing	
^{3}H			Residence time estimation, recharge rate	Radioactive 12.36 years half life
^{16} O, ^{17}O ^{18}O	V-SMOW	2.0052×10^{-3}	Recharge rate, recharge mechanism, origin of water and salinity, mixing	
^{12}C, ^{13}C	VPDB (belmenide fossil from Pee Dee Limestone formation in USA) PMC (percent modern carbon)	1.1237×10^{-2}	Sources of C in pollution, adjunct to ^{14}C dating	^{14}C
^{14}N, ^{15}N	Atmospheric nitrogen	3.677×10^{-3}	Nitrate pollution; tracer studies	
^{14}C			Dating groundwater	Radioactive
^{32}S, ^{33}S, ^{34}S	CDT (meteorite)	4.5005×10^{-2}	Sulfur pollution; tracer studies	
^{86}Sr, ^{87}Sr	Absolute ratio		As a tracer for mixing between aquifers from different geological formations	

abundance of isotopes due to their differences in mass. This can occur as a change in isotopic composition by the transition of a compound from one state to another (example: liquid water to water vapor). The isotopic fractionation depends on the temperature at which the isotope fractionation takes place. This feature allows us to use the isotopic variations in nature as tracers of climatic processes. The stable isotopic composition of water is modified by meteoric processes, and so the recharge waters in a particular environment will have a characteristic isotopic signature. This signature then serves as a natural tracer for the provenance of groundwater. The radioactive decay allows us to establish a temporal scale in the natural processes.

Isotopes of hydrogen and oxygen are the most widely used in the hydrologic studies. This is because these isotopes are integral part of the water molecule and therefore can trace the history of water, its movements, its interactions and mixing etc. Other isotopes used in the hydrologic studies are mostly isotopes of light elements (O, H, He, S, Cl, C, N, B). This is because by rule, isotopes of lighter elements are abundant in the hydrologic and atmospheric systems than isotopes of heavy elements which are fixed to the lithosphere and solid part of the earth. An exception to this is isotopes of strontium (^{87}Sr/^{86}Sr), radon (^{222}Rn) and other radioactive isotopes (Kr, Ar) which are often also used in hydrologic studies (Table 5.1).

The determination of an isotopic concentration of specific isotope in a given water system is very difficult. This is because the isotope concentrations/abundance of heavy isotopes is extremely small. It is therefore easier to express isotopic abundances using the isotopic ratio R ($R < 1$).

$$R = \frac{Abundance\ of\ rare\ (heavy)\ isotope}{Abundance\ of\ abundant\ (light)\ isotope}$$

R is normally a very small number (In nature $^{18}O/^{16}O = (2005.2 \pm 0.45)\cdot 10^{-6}$), and $^{2}H/^{1}H = (155.76 \pm 0.05)\cdot 10^{-6}$)) and are cumbersome to use them. For practical reasons, instead of using the isotope ratio R, isotopic compositions are generally given as δ (delta) values, the relative deviations (in per mil- ‰) with respect to a standard value, as defined by:

$$\delta^{18}O(‰) = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample} - \left(\frac{^{18}O}{^{16}O}\right)_{standard}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} x\,1000 \delta^{2}H(‰) = \frac{\left(\frac{^{2}H}{^{1}H}\right)_{sample} - \left(\frac{^{2}H}{^{1}H}\right)_{standard}}{\left(\frac{^{2}H}{^{1}H}\right)_{standard}} x\,1000$$

$$\delta^{13}C(‰) = \frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample} - \left(\frac{^{13}C}{^{12}C}\right)_{standard}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} x\,1000 \delta^{15}N(‰) = \frac{\left(\frac{^{15}N}{^{14}N}\right)_{sample} - \left(\frac{^{15}N}{^{14}N}\right)_{standard}}{\left(\frac{^{18}N}{^{16}N}\right)_{standard}} x\,1000$$

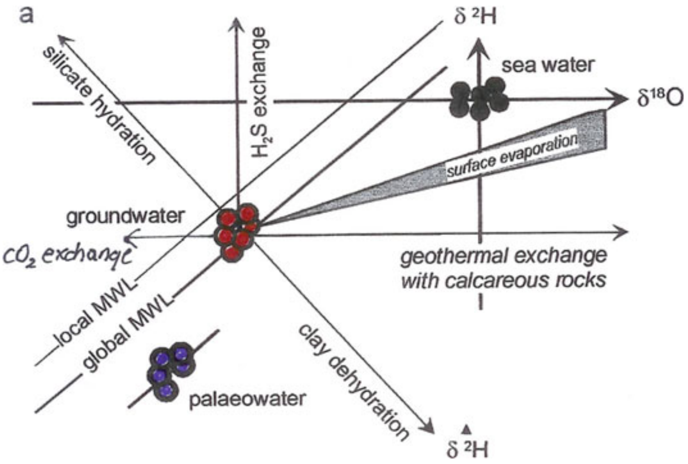


Fig. 5.1 Figure showing the LMWL, GMWL, and isotopic composition modifications accompanying hydrological and geochemical exchanges in the hydrologic compartment

5.3 Stable Isotopes of Water-Theory

Among all isotopes used in hydrology, stable isotopes of water ($\delta^{18}O$ and $\delta^{2}H$) are the most widely used in Ethiopia. Case studies presented in the next sections are cases which have used stable isotopes of water and in few cases isotopes of carbon and ^{3}H (tritium) for hydrological studies.

Two important concepts are useful to better understand the stable isotopes of water application in classical hydrologic studies. These are the meteoric water line and the isotope effects. As early as 1961 Craig and Gordon (1965) and Dansgaard (1964) found a relation between the $\delta^{2}H$ and $\delta^{18}O$ values of precipitation from various part of the world. The plot of these isotopes on an x–y graph fall on a line defined by the following equation called the Global Meteoric Water Line or Craig Line.

$$\delta^{2}H = 8\delta^{18}O + 10$$

Depending on the humidity and temperature conditions locally the $\delta^{18}O$-$\delta^{2}H$ plot of local rains may deviate from the GMWL and form a local meteoric water Line (LMWL). This line is the reference against which comparison can be made to understand isotope effects that have taken place to understand the processes of recharge, evaporation, mixing etc.

During the hydrological cycle, the most frequent processes are condensation and evaporation. Water evaporation leads to enrichment (increase in heavy isotope content with respect to the light) in the stable isotope composition in the residual water fraction. Every precipitation event depletes the vapor remaining reservoir. Water with heavier $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratio forms the initial water droplets of rains and as vapor mass continue to lose its heavy isotopes it becomes more depleted in heavy isotopes. Meteoric water in a given environment when it undergoes phase changes related to hydrological processes, its isotopic composition also changes accordingly. Figure 5.1 shows processes that modify the initial isotopic composition of given meteoric water in and environment.

The processes of depletion or enrichment of heavy isotopes in a given hydrologic compartment can be related to ‘isotope effects’ which have wider implication in hydrological studies. Some of the isotope effects are:

Altitude effect: At higher altitudes where the average temperatures are lower, precipitation will be isotopically depleted. For δ^{18}O, the depletion varies between about -0.15 and -0.5 ‰ per 100 m rise in altitude, with a corresponding decrease of about -1 to -4 ‰ for 2H. This altitude effect is useful in hydrogeological studies, as it distinguishes groundwaters recharged at high altitudes from those recharged at low altitude.

Latitude effect: At higher latitudes, precipitation tends to have more negative δ^{18}O values due to the strong relationship between δ^{18}O content and temperature. The depletion in δ^{18}O values with increasing latitude is clear while flat gradients are observed in the tropics regions.

Evaporation effect: Evaporated water bodies and waters exposed to vapor loss such as lakes, wetland waters, running waters, reservoirs and oceans tend to enrich in their heavy isotope content with respect to the vapor derived out of them. Residual waters that have undergone evaporation plot along a local evaporation line whose slope vary between 4.6 and 5.6 (Fig. 5.1). Another form of evaporation effect results from evaporation of rainfall while the rain droplets are making their way to the ground. In arid and semi arid environments significant evaporation of rain droplets in dry atmosphere can take place resulting in enrichment of rainwater’s and deviation from the global meteoric water line.

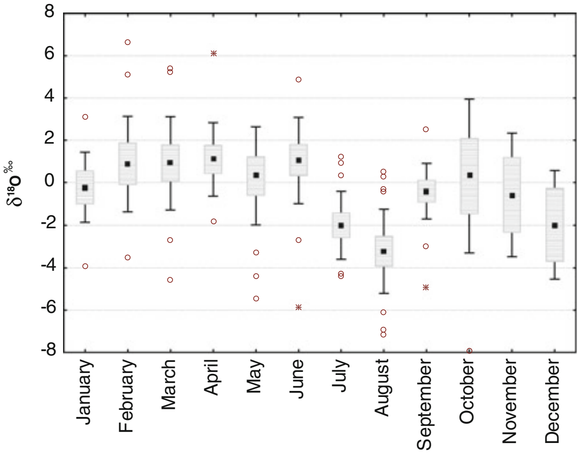
Amount effect: Heavy rainfalls tend to be depleted in heavy isotopes compared to lighter isotopes. This is related to several factors principally the limitation of evaporative fractionation of rain droplets in case of heavy rainfalls.

Seasonality effect: Greater seasonal extremes in temperature generate strong seasonal variation in isotopes of precipitation. These variations in δ^{18}O and δ^{2}H give us an important tool to determine rates of groundwater circulation, watershed response to precipitation, and the time during the year when most recharge occurs.

Continentality effect: As a vapor mass moves from its source region across a continent, its isotopic composition evolves more rapidly due to topographic effects and the temperature extremes that characterize continental climates. Continental stations are characterized by strong seasonal variations in T, which is a reflection of distance from moderating marine and latitude. Coastal precipitations are isotopically enriched, while the colder inner continental regions receive isotopically depleted precipitation with strong seasonal differences.

Paleo-climatic effect: Given the good correlation between isotopes in precipitation and groundwater, climate change should be recorded in fossil or paleo-groundwaters. Temperate climates have experienced significant changes in temperature since late Pleistocene time. Such climate changes are manifested by a shift in the stable isotope content of precipitation, and in deuterium excess

Fig. 5.2 Box and whisker plot showing seasonal variation in $\delta^{18}O$ content of rain waters at Addis Ababa for monthly data between 1965 and 2007



(Fig. 5.1). This paleoclimatic effect is one the most important tools in identifying paleogroundwater. Late Pleistocene paleogroundwaters from temperate regions will be isotopically depleted with respect to modern waters and shifted along the GMWL towards negative values. The paleoclimatic effect in arid regions is manifested by depletion in stable isotopes with respect to modern waters. In arid regions like the Eastern Mediterranean and North Africa, the modern MWL is characterized by a deuterium excess value of 15–30 ‰. However, in the past, humid climates groundwaters tend to plot on or even below the GMWL.

Geothermal $\delta^{18}O$ *exchange* (*negative and positive oxygen shifts*): Silicates rocks are natural reservoirs for heavy isotopes of oxygen compared to atmospheric and hydrologic waters. In geothermal systems interaction of rock and water at higher temperature results in release of heavier isotopes of oxygen from the rock and sink of lighter isotopes until equilibrium is reached. This will lead to enrichment of geothermal waters with respect to their heavy isotopes. On the other hand in CO_2 gas reach geothermal systems exchange of oxygen isotopes of water with relatively depleted oxygen isotope of CO_2 leads to depletion of heavy isotopes in waters. Both exchange processes does not affect the hydrogen isotope ratio. Isotope exchange accompanying rock-water interaction in geothermal waters lead to a process called positive or negative oxygen shift (Fig. 5.1).

5.4 Stable Isotope Composition of Ethiopian Meteoric Waters

Isotopic Composition of Rainwaters

The rainfall water at Addis Ababa IAEA/WMO station shows the highest ^{18}O and ^{2}H enrichment compared to any station in the region and the globe. This is regardless of the high altitude and low mean annual temperature of Addis Ababa. The weighted mean $\delta^{18}O$ and $\delta^{2}H$ composition of the summer rainfall waters of the Addis Ababa IAEA station is −1.56 ‰ in $\delta^{18}O$, +1.48 ‰ in $\delta^{2}H$. The spring rainfalls have a weighted mean composition of +0.47 ‰ in $\delta^{18}O$ and +17.36 ‰ in $\delta^{2}H$. In the $\delta^{2}H$-$\delta^{18}O$ plot (figure not shown) the monthly rains of Addis Ababa plot defines a local meteoric line (AA-LMWL) defined by: $\delta^{2}H = 7.2\delta^{18}O + 11.9$. A similar plot on summer rains at Addis Ababa has the relation: $\delta^{2}H = 7.6\delta^{18}O + 13$ and that of the spring rains is $\delta^{2}H = 6.05 * \delta^{18}O + 13.7$. The $\delta^{18}O$ of the Addis Ababa rainfalls and the two-year rainfall isotope data from MER stations are characterized by a notable seasonal variation (Fig. 5.2).

The depletion in the summer rainfall relative to the spring rainfall is related to the difference in source of moisture and to local meteorological processes. The summer rainfall (75 % of rainfall in Addis Ababa) is derived from the admixture of the Atlantic Ocean and the South/Equatorial Indian Ocean air masses. The small variability in $\delta^{18}O$ of the summer rains (Fig. 5.2) suggest either nearly constant ratio of contribution of the two sources over the last 40 years (which is unlikely since the Ethiopian rainfall amount has varied at least by ±20 % during this time (Conway 2000) while the inter-annual variation in isotopes nearly remain constant) or that one of the two monsoons is the predominant source for Addis Ababa summer rains.

The spring rainfalls are the most enriched compared to the summer rains. During this time, the oceanic moisture reaches the area from Northern Indian Ocean. The enrichment of the rainfalls during spring time may be related to three factors, (1) as the Ethiopian highland is geographically closer to the North Indian Ocean and the moisture that reaches the area represents the initial stage of condensation which did not undergo major rain out fractionation effect (Joseph et al. 1992); (2) the high temperature, the low atmospheric humidity and the low amount of rainfall during this time favors evaporation of rainwater leading to enriched rainfalls and low d-excess; (3) the high sea surface temperature over north Indian ocean favors the formation of enriched vapor coming to Ethiopia.

Isotopic Composition of Lakes and Rivers

The $\delta^{18}O$ and $\delta^{2}H$ enrichment in lakes is the result of isotope fractionation that takes place during evaporation (Craig and Gordon 1965). However, the intensity of enrichment, the absolute isotopic content and the slope of the Local Evaporation Line (LEL) are the result of interplay of processes involving the isotopic composition of inflow waters, ambient vapors, and humidity (Kebede et al. 2009). The initial isotopic composition of inflow waters which represent the composition of meteoric waters in the region can be retrieved from the intersection of the LEL with LMWL.

Figure 5.3 shows the $\delta^{18}O$-$\delta^{2}H$ compositions of major East African Lakes along South North transect. Figure 5.3d shows $\delta^{18}O$-$\delta^{2}H$ composition of river

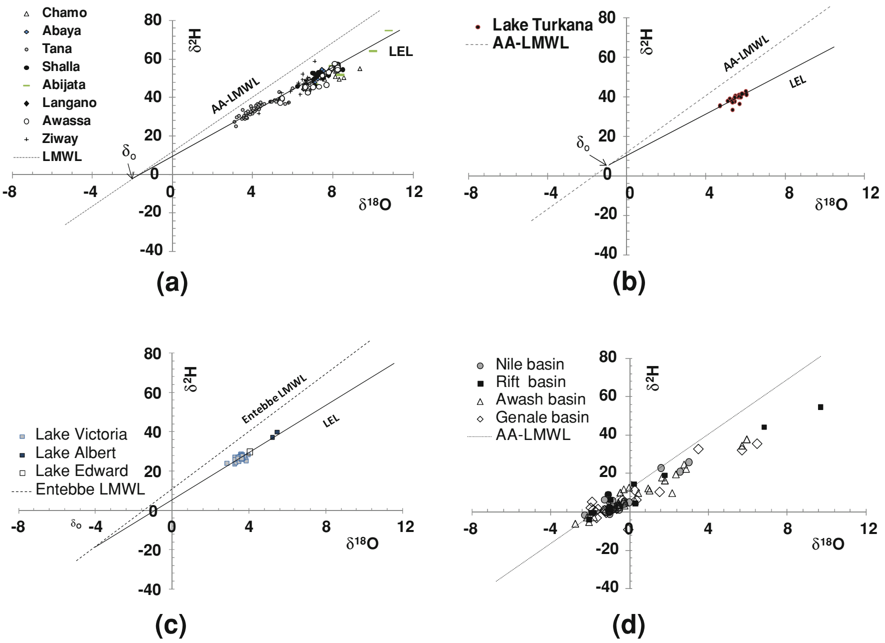


Fig. 5.3 The δ^{18}O-δ^{2}H plot of East African Lakes (**a**, **b**, **c**) and river waters from four major basins in Ethiopia (**d**)

waters from four drainage basins of Ethiopia. The observed δ^{18}O varies ca. −1 to +14 ‰ while δ^{2}H varies from ca. +0 to +80 ‰.

5.5 Isotope Application Cases Studies from Ethiopia

Isotopes in Reservoir Leakage Investigation, Koka Lake, Mamo and Yokota (1998)

Site characteristics: The Koka dam (Fig. 5.4) was built on the Awash River, Ethiopia, in 1960 for hydropower and irrigation purposes. The dam is a concert gravity type with a height of 25 m, crest length of 458 m and a reservoir capacity of 1880 million m^{3}. The dam and reservoir is located in the axial zone of the northern Main Ethiopian Rift, i.e. the active Wonji fault belt. Ignimbrites, pumice and tuff deposits, basalt and rhyolites with different age (Miocene to Holocene) constitute the Koka reservoir banks and its surrounding area in addition to younger fluvial and lacustrine sediments. Slightly consolidated lacustrine sediments of fine to medium grained sand cover the reservoir area. Moreover, thin river sediments of silt cover the lacustrine deposit at the reservoir floor. NNE-SSW and NE-SW

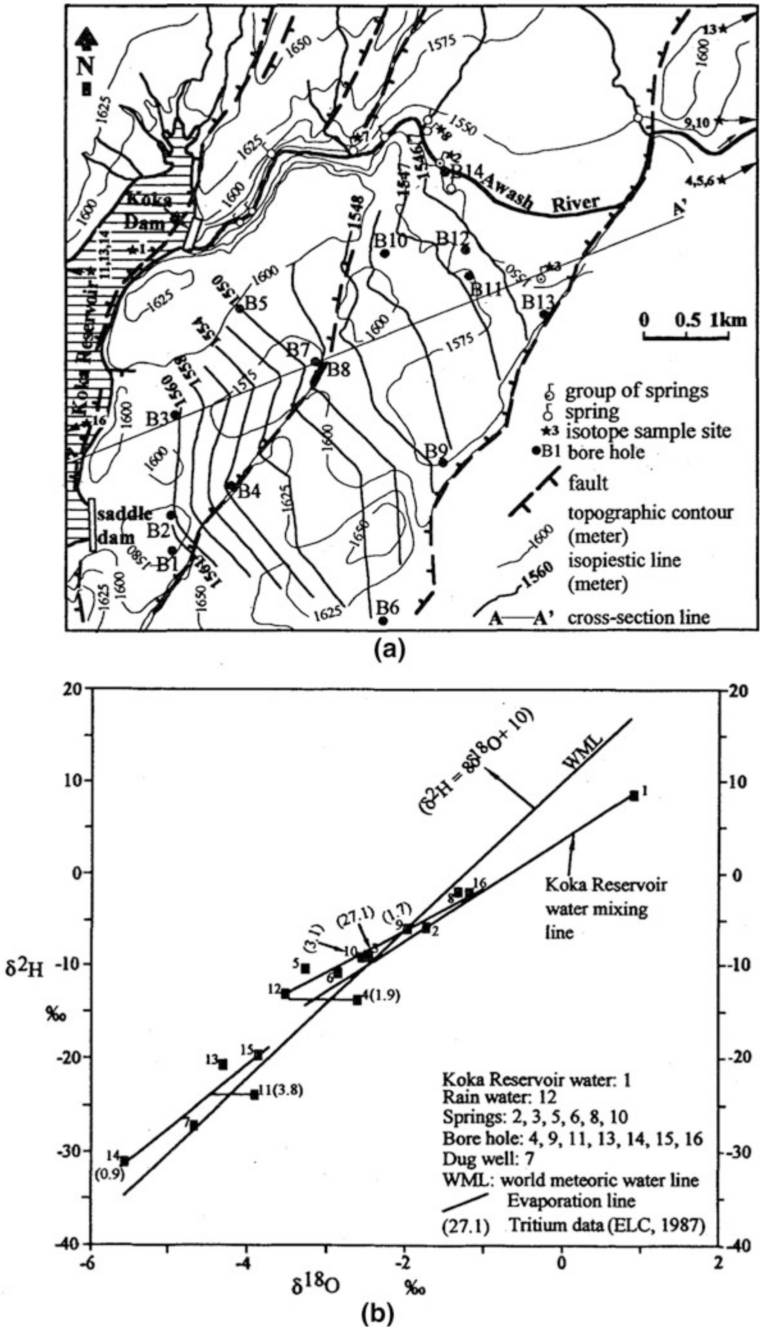
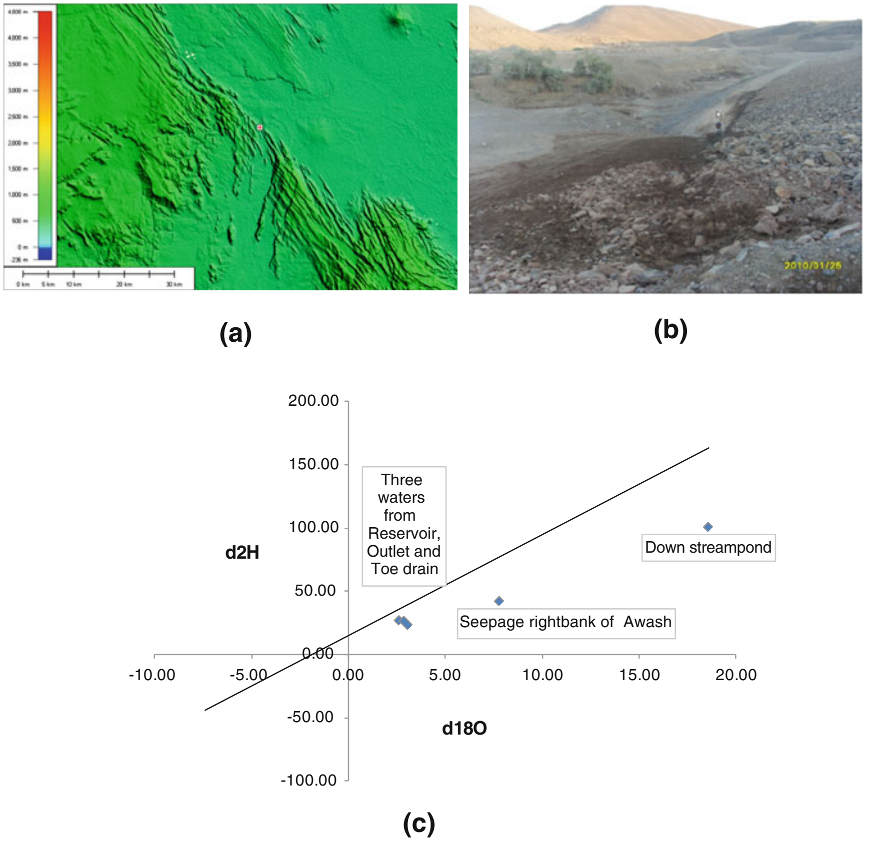


Fig. 5.4 Hydrogeologic map of the reservoir area and the dam site of the Koka reservoir (**a**) and the water sampling sites for isotope analysis (**b**) and the δ^{18}O-δ^{2}H plot of meteoric waters from around the reservoir (**c**) from Mamo and Yokota (1998)



(a) (b) (c)

Fig. 5.5 Location of Tenaho Dam (**a**) and seepage points (**b**) and δ^{18}O-δ^{2}H plot of the reservoir, seepage and a downstream pond (**c**)

striking fault swarms and transverse faults cut these rocks into strips and form horst and graben structures.

The problem: The foundation of the rock mass of the main dam was initially treated by curtain grouting on a single line, and no serious problem on leakage was reported beneath the dam. However, the reservoir leakage has been reported since the construction of the dam. Some studies have been conducted following this and provided a very diverse estimate on leakage rates without specifying the pathways through which leakage is taking place. According to these studies leakage rate various between 90 and 435 million m^3/year and they have concluded leakage takes place throughout the whole reservoir floor.

Figure 5.4c shows that the most enriched groundwaters are observed south of the profile line A-A’ suggesting leakage is taking place specifically around the saddle dam following the NNE-SSW oriented fault belts (see Fig. 5.4a for faults). Reservoir water mixing with local groundwater is taking place along groundwater flow direction in the northeast reservoir vicinity. Reservoir water contribution ranges between 27 and 41 % into groundwater wells is estimated on the basis of $\delta^{18}O$ and $\delta^{2}H$ respectively. Reservoir water contribution decreases away from the reservoir. Leakage is detected therefore to take place along the right downstream shore of the reservoir.

Isotopes in Reservoir Seepage and Dam Safety Investigation (Tendaho Reservoir)

Site characteristics: Tendaho dam is constructed on the main Awash river in lower Awash basin. The dam is located some 580 km northeast of Addis Ababa close to the town of Loggia. The dam is located within what is known as the Tendaho Graben. Except the boundary of the Tendaho Graben represented by step marginal faults most of the area can be characterized by the flat to rolling topography. The rift plains along the course of the Awash River is dotted with small volcanic hills mainly scora and basaltic. In the reservoir area these hills form small islands. This condition is favorable from slope stability point of view.

Both the left and right abutments are occupied by volcanic rocks mainly basalt with thin layers of tuff. Exploratory drilling at the left abutment indicates that the basaltic rocks extend up to 340 m below ground surface. There is no indication of alluvial and lacustrine sediments. Hence, the true abutment rock is basaltic with thin layers of tuff. The basalts are extremely fractured and mainly aphiantic in texture. Few vesicular basalts are evident in the right abutment area and in the boulders of the rock fill materials of the dam.

The valley floor characterizes most of the reservoir areas and the sites where the toe drain exists. The major dam structures stands on the valley floor formations. The valley floor is mainly covered with top clay loam soil and riverine alluvium. Previous geotechnical studies display that recent alluvium extends to elevation 367 m along the axis of the dam while it is limited to elevation 378 m upstream and downstream of the dam axis. The alluvial sediments are underlain by lacustrine sediments that include argillites, and conglomerate resting on volcanic rocks at an elevation of 358 at the dam axis and 363 m upstream and downstream of the dam axis. It was recommended that this formation should be removed or excavated up to 365 m elevation before starting the construction of the core of the dam.

The Tendaho dam is a part of the Tendaho Dam and Irrigation Project which aims harnessing the inflow of Awash River at Tendaho for irrigating sugarcane plantation in an area of of around 70,000 ha of land. The engineering works impounding rainy season inflows of river Awash and diverting the water into the network of canals mainly comprise of a storage dam across river Awash at Tendaho, a spillway required for passing any flood that may impinge when the reservoir is at full retention level so as to avoid overtopping of the dam, and an

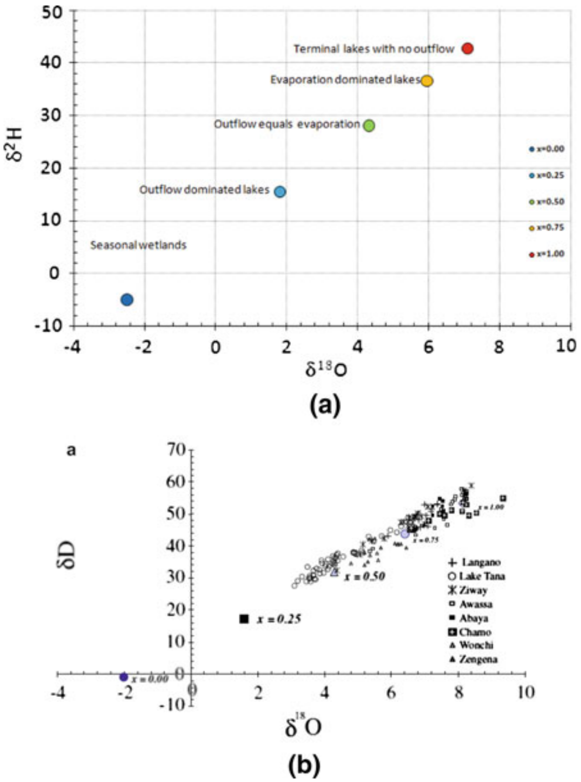


Fig. 5.6 Hypothetical enrichment values for different E/I ratios of open water bodies in Ethiopia (**a**) and figure showing the isotopic content of the lakes compared against hypothetical evaporation to inflow ratios (**b**). For examples in lake Tana 50 % of water loss is to evaporation and the rest to surface water outflow, source from Kebede et al. (2009)

irrigation bottom outlet (tunnel in the left abutment hill) for drawing the water from the reservoir to the distribution system of canal net work.

The problem: Seepage in the dam has been observed soon after the reservoir retained water at point indicated in the DEM of Fig. 5.5(a, b). The first seepage was observed at an elevation of 395 m close to the left abutment. Later the most important elevations where large seepage occur are elevations of 387.418 and 387.488 m. The maximum and minimum water levels in the reservoir so far are 367 and 395.5 m respectively. Currently the water level is at 393. Although the seepage rate has been declining with time close to the left abutment, the total seepage has increased progressively with time.

Samples have been taken from the reservoir water, seepage water and a pond water few tens of meters downstream. The waters are analysed for their δ^{18}O and δ^2H

Isotope application on detecting seepage: From the plot in Fig. 5.5c the following conclusions can be drawn:

1. The seepage at the toe drain has exactly similar isotope ratios as compared to the reservoir water indicating the seepage water at the toe drain gets 100 percent of its water from the reservoir.

2. The pond downstream of the embankment shows the highest degree of isotope enrichment indicating the pond water has no hydraulic relation with the reservoir water. The highest isotope ratio enrichment in the pond is indicative of extensive evaporation of the pond related to the decrease in its size.
3. The seepage in the right bank of the Awash River which has been recently formed shows isotope enrichment higher than the seepage at the toe drain. The slightly higher enrichment of this seepage could be related to mixing of evaporated water into the seepage water before it emerges to the surface. Estimate from the mixing ratio from the figure shows probably this seepage water obtain up to 20 % of water from the flood water which is located downstream of the embankment.
4. The fact that the seepage in the right bank of the river shows more enriched isotope content than the seepage at toe drain and the exact similarity of the toe drain water with the reservoir water all show regional groundwater (which is often more depleted than surface waters) plays no role or no input to the seepages as often this can easily be speculated.

Quantitative Lake Water Balance Determination

The power of isotopes of water is that given the isotopic composition of meteoric waters are known the other parameters such as ungauged catchment inflow, surface water groundwater interaction, evaporative water loss in the floodplains and groundwater flux around the lakes, can be determined independently without reverting to the knowledge of catchment hydrographic properties or gauged hydrometric records. The principle is that by combining water balance and isotope mass balance equations one can arrive at estimating total inflow or total outflow to lakes measuring only isotopic composition of waters (lake and its inflows) and knowing some constant parameters. The method has been widely used worldwide since late 1960s. In Ethiopia the method has been applied in quantifying the groundwater flux around more than 30 lakes (Kebede et al. 2009). See Box 1 for details of the steps used in isotope balance method.

Based on the theoretical background given in Box 1, Kebede et al. (2009) has proposed a graphic approach whereby one can rapidly estimate the water budget (particularly the Evaporation to inflow ratio) of any lake or reservoir water from Ethiopia given the δ^{18}O or δ^{2}H or both are measured on the lake or reservoir of interest. Figure 5.6 a give the expected/modeled δ^{18}O or δ^{2}H composition for different E/I ratios of Lake and open water bodies in Ethiopia. It should be noted that ‘x’ in the figure represent the evaporation to inflow ratio (E/I). Based on such approach, Fig. 5.6b shows the δ^{18}O-δ^{2}H of Ethiopian Lakes plotted along with the hypothetical values in order retrieve the lakes water budget. For example Lake Tana water plots around E/I = 0.5 indicating 50 % of the water inflow is lost to evaporation, consistent with independent water balance estimates.

Box 1. The Isotope balance method-theoretical background

Quantitative estimation of lake water budget components using isotope method is based on mass balance considerations. By combining water budget (Eq. (5.1)) and the isotope budget equations (Eq. (5.2)), two selected unknowns can be estimated. For instance, one can derive total inflow- I (surface groundwater and rainfall combined) and total outflow- Q (groundwater and surface water outflow combined) if other component (evaporation rate) is known.

$$\frac{dV}{dt} = I - Q - E \tag{5.1}$$

$$\frac{Vd\delta + \delta dV}{d} t = I\delta_I - Q\delta_L - E\delta_E \tag{5.2}$$

where V is volume, I is total inflow, Q is total outflow, E is evaporation, and δ are $\delta^{18}O$ or $\delta^{2}H$ composition of flux with which they are associated. All parameters appearing in the equations (Eqs. 5.1 and 5.2) are directly measurable except δ_E which stands for isotopic composition of the evaporation flux. Craig and Gordon proposed a linear resistance model to derive expression for δ_E which relates the isotopic composition of instantaneous net evaporation flux to measurable environmental parameters:

$$\delta_E = \frac{(\alpha^* \delta_L - h\delta_A - \varepsilon)}{(1 - h + 10^{-3}\Delta\varepsilon)} \tag{5.3}$$

where ($\alpha^* = 1/\alpha$) is the equilibrium vapor–liquid isotope fractionation at the temperature of evaporating surface. At 20 °C α is equal to 1.0098 and 1.0084, for $\delta^{18}O$ and $\delta^{2}H$, respectively (Majoube 1971). δ_A is the isotopic composition of the atmospheric vapor unaffected by vapor from the lake, and h is humidity normalized to surface temperature of evaporating surface, ε stands for total isotope separation factor which is the sum of the equilibrium ε^* and kinetic ($\Delta\ \varepsilon$) separation factors. The kinetic separation factor $\Delta\varepsilon$ is formulated by Craig and Gordon (1965) and has much complicated form (Eq. 5.4). The equation contains fractionation from molecular sub layer and from the turbulent sub layer. The turbulent sub layer is often assumed to be non fractionating so that Eq. (5.4) can be reduced to Eq. (5.5).

$$\Delta\varepsilon = E_{\rho M}\left[\left(\frac{D}{D_i}\right)^{n} - 1\right] + E_{\rho T}\left[\left(\frac{D}{D_i}\right)^{\frac{2n}{2+n}} - 1\right] \tag{5.4}$$

$$\Delta\varepsilon = E_{\rho M}\left[\left(\frac{D}{D_i}\right)^n - 1\right] \; or \; \Delta\varepsilon = \theta C_k(1-h) \tag{5.5}$$

where D and Di are the molecular diffusion coefficients in air of the normal and isotopic species of water. In Eq. (5.5), the parameter n can range between 0.5 and 1 depending on the degree of turbulence present in the system and roughness of the evaporating surface. The value of n = 0.5 was suggested as the most representative for evaporation of open water bodies located in continental settings. *E ρ, M* and E *ρ*, T are the resistance of vapor transport through the laminar sub-layer and turbulent sub-layers, respectively. The D/Di ratio determined based on kinetic theory of gases, has the value of 1.0324 and 1.0160 for oxygen and deuterium isotopes, respectively. These values were found to be in disagreement with the experimental data. Experimentally determined the ratios Di/D to be 0.9723 and 0.9755 for oxygen and deuterium isotopes respectively. This corresponds to Ck of 14.2 and 12.3 for δ^{18}O and δ^2H, respectively. The term θ is considered to be close to unity, except for large surface water bodies which substantially perturb the atmospheric boundary layer above them. Combination of the preceding equations can lead to the estimation of total inflow to the lake without reverting to the any physical measurement of flows except estimating evaporation and measuring isotope enrichment of meteoric waters (Eq. 5.6). Given that precipitation on the lake and total surface water inflow from gauged catchments are known, thus the only unknown will be flows to the Lake from ungauged catchments or any other unaccounted flow to the lake from groundwater.

$$\frac{I}{E} = \frac{m(\delta^* - \delta_L)}{(\delta_L - \delta_I)} \; or \; \frac{Q}{E} = \frac{m(\delta^* - \delta_L)}{(\delta_L - \delta_I)} - 1 \tag{5.6}$$

where

$$m = \frac{h - \varepsilon/1000}{1 - h + \Delta\varepsilon/1000} \quad and \quad \delta^* = (h\delta_A + \varepsilon)/(h - 10^{-3}\varepsilon)$$

Qualitative tracing of groundwater flow around lakes has water management implication. The simple fact that the salinity of lakes in East African rift vary from very fresh to hyper saline implies the difference in their water budget. Lakes with little or no outflow (groundwater or surface water) are usually saline compared with through flow lakes. Some lakes with no apparent surface water outflow however still maintaining low salinity are common in the Ethiopian rift. Such lakes are supposed to lose significant portion of their water to adjacent groundwaters. This has been demonstrated by several studies in the Ethiopian rift (Darling et al. 1996; Kebede et al. 2002). For example, inferred direction of groundwater flow from Bishoftu Crater Lakes has been demonstrated (Fig. 2.20). Figure 5.7 shows spatial

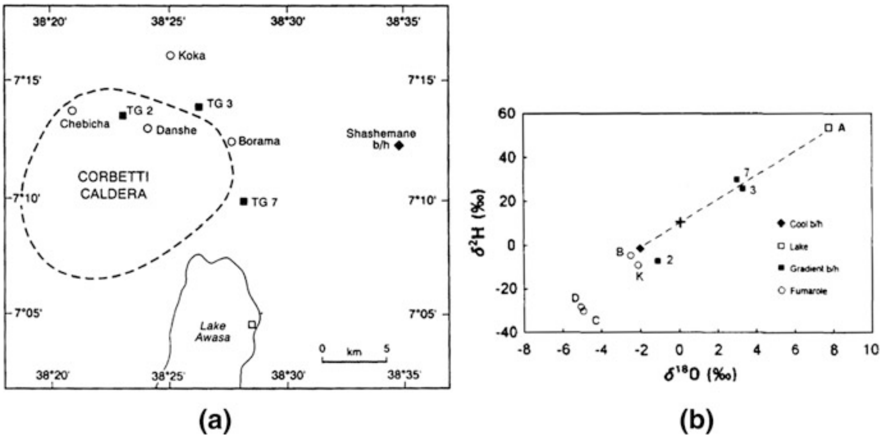


Fig. 5.7 Water points around Lake Awasa central Ethiopia (**a**) and the δ^{18}O-δ^2H content of the waters (**b**) from Darling et al. (1996)

variation in δ^{18}O in thermal and cold groundwaters around Lake Awasa. As can be seen from Fig. 5.7b the thermal groundwaters in Awasa contain as much as 60 % of their water from Lake Awasa and the remaining 30 % from cold groundwaters.

Isotopes used in discriminating origin of salinity in Tana wetlands (Kebede et al. 2011)

Lake Tana is bordered by extensive wetlands particularly in its Eastern, Northern and Southern sectors. As increasing areas of these wetlands are being developed for mechanised irrigation one concern is the salinization of the wetlands and the floodplain soils and waters. Recently (Admasu 2010) identified the presence of brakish groundwaters in the wetlands of Lake Tana. A number of processes can cause high salinity in wetlands including evporation, salt dissolution, inflow of high salinity waters from adjacent aquifers, or intensive transpiration. A simple δ^{18}O vs Cl plot can give insight on origin of salinity in wetlands (Fig. 5.8).

The δ^{18}O vs. EC plot (Fig. 5.8) of the shallow groundwater in the wetlands indicate no apparent ^{18}O enrichment compared to the river waters and groundwaters in the adjacent basalt aquifers and commensurate with the EC values. This precludes the role of evaporation in imparting salinity to the wetland shallow groundwaters. Since evaporation prior to recharge can be precluded the most plausible explanation for the origin of high salinity could be the dissolution of salts from the alluvio-lacustrine sediments. However, the salt must have accumulated in the sediments following complete evaporation of flood waters following each rainy season. The accumulation of salt occurs in pockets of evaporation pools dotting the floodplains. The dissolution of salt thus imparts high TDS to the shallow groundwaters in localized areas where such pools and sediments are leached.

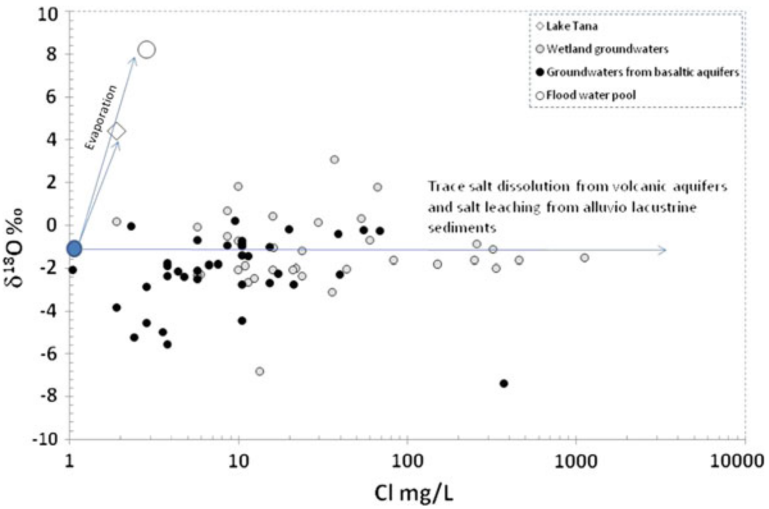


Fig. 5.8 The δ^{18}O-Cl plot of shallow and deep groundwaters from the Wetlands of Lake Tana and adjacent basaltic aquifers

As the aquifers are mostly silt and clayey and hydraulic gradient is low the wetlands groundwaters retain the salt for longer period of time.

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Chapter 6
Functions of Groundwater

6.1 Environmental Function of Groundwater: General

Groundwater has storing, filtering and transforming capacities, and regulates atmospheric, hydrological and nutrient cycles. Groundwater stores and partly transforms CO_2, energy, plant nutrients and other chemical substances. Groundwater can act as sink in the carbon cycle. Groundwater can immobilize or break down a multitude of pollutants, for example from waste disposal. Contaminants may build up and subsequently be released in different ways, in some cases exceeding regulatory thresholds. Sustaining biodiversity is an essential ecological function of the land. In turn, the biological activity on the land and in the soil contributes to its properties and characteristics, which are essential for its productive functions. Groundwater maintains wetlands and their ecosystems. Groundwater makes part of base flows of rivers and support river in ecosystem. Groundwater is principal pathway though which solute (such as silica, nitrate, and cations) enters into lake and ultimately supports the phytoplankton and zooplanktons. Groundwater sustains aquatic ecological functions in rivers, lakes, riparian zones and estuaries require huge volumes of water. Fresh water sustains biomass growth in terrestrial ecosystems, and provides key ecological services —maintaining biodiversity, sequestering carbon and combating desertification. Groundwaters are principal pathways of essential and non essential exotic trace elements in nature to get to the human metabolism.

The purpose of this chapter is provide generic information about the role of groundwater in Ethiopia in various sectors such as maintaining wetland hydrology and other environmental functions as well as it social economic functions. These will be supported by generic as well as site specific cases studies from Ethiopia.

S. Kebede, *Groundwater in Ethiopia*, Springer Hydrogeology,
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6.2 Groundwater Dependent Ecosystems (Wetlands and Hyporehic Zones)

Wetlands and hyporehic zones accompanying stream courses are two landscape features that could depend on groundwater as their water source which in turn support wildlife and ecosystem. Here an account is made on wetlands in Ethiopia. Other known groundwater dependent wetlands including peat lands are briefly discussed.

Distribution and Classification of Wetlands and Their Relation to Groundwater

Wetlands are water-saturated environments and are commonly characterized as swamps, bogs, marshes, mires and lagoons. The total areas of Ethiopian wetlands amount to about 20,000 km^2 (2,000,000 ha) (Fig. 6.1). The largest of this are the flood plains of Lake Tana, the flood plains of the Baro Akobo (Gambela), the wetlands of south western Ethiopia, the Dabus wetland and the wetlands surrounding the Fincha Lake in western Ethiopia. Seasonally inundated flood plains occupy the largest share of the wetlands (47.2 %) followed by freshwater lakes (30.6 %), swamps and marshes (12.6 %) and the rest is occupied by the other types of wetlands.

The relation between wetland hydrology and groundwater dynamics is an important parameter in managing and using wetlands and groundwater resources associated with them. In cases where groundwater feeds wetlands, excessive abstraction of groundwater for agricultural use and industry can result in drying up of wetlands leading to irreversible environmental damage.

In Ethiopia, genetically, at least four types of major wetlands can be recognised. Floodplains wetlands, groundwater fed wetlands, wetlands associated with lake waters and wetlands associated with headwaters of river valleys. Table 6.1 lists major wetlands and their origin, groundwater dependence and environmental function and challenges. Some of the wetlands are briefly discussed below:

Playas: Shallow, ephemeral ponds or lagoons that experience significant seasonal changes in water depth and volume. The flood plain lakes have high salinity often exceeding 10 g/L. The Gamari flood plain lakes (marked 5 in Fig. 6.1) are typical examples of this kind of wetlands.

Lake Tana flood plains: These are wetlands located adjacent to or at the mouth of river banks and receiving water during high water stage (marked 3 and 4 in Fig. 6.1). In the Lake Tana wetlands flooding starts at beginning of June and it disappears end of September. As it was observed from satellite images taken at different seasons, the flooded water the way the flood water diminishes indicates that most of the water does seem to either evaporate back to the atmosphere or join the rivers (Daniel 2007). Flood water recharging the aquifers underneath is

Table 6.1 Some wetlands in Ethiopia, their extent, hydrology, function and associated challenges

Wetland name	Extent km^2	Dependence on groundwater	Environmental function	Challenges
Chomen	600	Yes	Regulating flows	
Dabus	900	Yes	Regulating flows, wildlife sanctuary	Pollution
Bale Mountains peatlands		Yes: shallow groundwaters discharges to the peat	Regulating flows, wildlife sanctuary	
Lake Budameda		Yes		Evaporative water loss
Melo-Adigala		Yes, 100 %	Support complex vegetation and dunes	
Abeya head water of Meki		Yes	Regulating flows	
Becho plain		No	Regulating flows	Flooding, drainage
Gola-North chew bahr		Yes	Wild life sanctuary, support salt tolerant vegetation	
Shatamata swamp		Yes		
North lake Abaya shore		Yes		
Gewane swamp complex	36	Yes		Evaporative water loss
Gamari flood plain		Yes	Wildlife sanctuary	Salinity
Boya wetlands	8	No	Water supply	Flooding, siltation
Lake Tana wetlands	1,000	Yes: Wetland groundwaters are laterally connected to groundwaters in the basaltic plateau	Sediment trap, Biodiversity	Salinity, evaporative water loss, flooding hazards, water logging
Cheleleka swamp Bishoftu		No	Sediment trap	
Cheleleka swamp Awassa	12	Yes: Groundwater discharge from eastern escarpment to Cheleleka swamp and lake Awasa.	Flow regulation, wildlife support, pollution sink	Pollution, sedimentation
Machar swamp, Gambella	6,700	No?	Biodiversity, wildlife, regulation of flow	Evaporative water loss of the Nile water resources

(continued)

Table 6.1 (continued)

Wetland name	Extent km^2	Dependence on groundwater	Environmental function	Challenges
Aba Samuel swamp		No	Pollutant sink of drainage originating from Addis Ababa city	Pollution
West of Lake Chamo Sile sub basin		Yes: Alluvial fan deposits overlying basalts and lacustrine deposits (?) gentle topographical slope toward Lake Chamo, with groundwater at shallow depth. Wetlands formed at low areas of groundwater discharge		
Borkena-Chefa	55	Yes: site of groundwater discharge emerging from the highlands and the alluvial plains	Sediment trap	Inundation of Principally highway between Addis Ababa and Dessie during high flood stage
Gedebasa swamp	330			Evaporative water loss in excess of 500 MCM
Omo delta wetlands	120	Yes	Wildlife watering	Tse Tse fly infestation, flooding
IlluAbaBor wetlands (2)	1,650	Yes: the wetlands represent several patches extending over few hectares to several hundred ha. Most of these wetlands are fed by springs emerging from higher grounds surrounding the headwaters of river valleys where they occur	Dry season grazing, water supply from wetland springs, agriculture	Wetland conversion to agricultural land

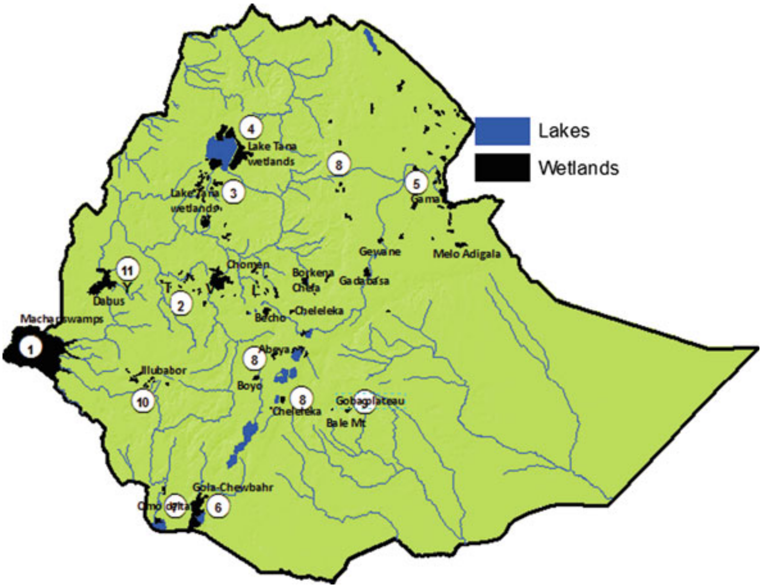

Fig. 6.1 Wetlands and open water bodies in Ethiopia; YTVL- is an E–W running volcano-tectonic lineament zone with a width of 60 km and hosting several wet lands in western Ethiopia; names of wetlands are given in text

Table 6.2 Location of some prominent peats bogs and wetlands associated with intra-montane valleys in Bale massif

Locality	Site location	Lat.	Long.	Elevation	Summit
Bada	Mr Bada glacier and Bog	7.88	39.4	4,133	4,430
Bale	Tamsaa swamp on N side of Bale Mts	7.17	39.83	3,000	4,370
Bale	Garba Goracha lake, Togona valley	6.91	39.91	3,950	4,370
Bale	Near E edge of plateau N of Bedegesa Hill	6.85	39.77	4,000	4,370

precluded (Kebede et al. 2011) Most of these wetlands have shown to be groundwater dependent (see Sects. 2.3 and 5.4).

Bale Mountain peats and swamps: A number of swamps and small lakes occupying pre glacial landscape in the Bale area and adjacent Arsi Mountains (Table 6.2) above elevation of 2,500 masl mostly occupying intra-montane depressions or in other depressions where drainage is poor (marked 8 and 9 in Fig. 6.1). No glaciers exist today on the Bale Mountains but a preglacial landscape is present above 4,300 masl (Hurni 1989). These swamps and wetlands contain peat and abundant organic matter. Most of these peats are dated to 2,500 years BP or younger corresponding to late Holocen humid climate in this sector of Eastern Africa (Mohammed and Bonnefille 1998). From 2,500 ^{14}C years BP on, there is an important peat accumulation in Bale (Mohammed and Bonnefille 1998), which corresponds to a moist phase during the generally dry late Holocene. Some of the

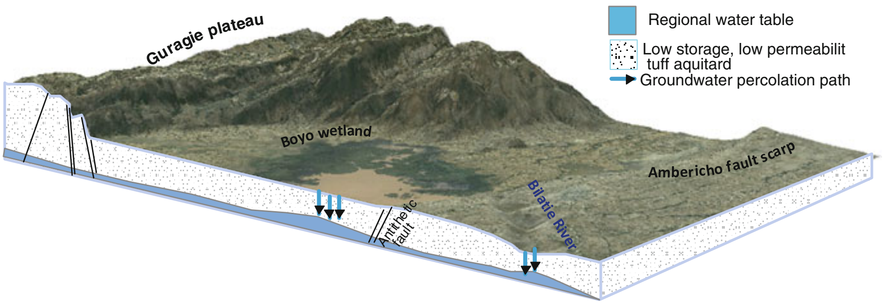

Fig. 6.2 Figure showing the origin of the Boyo wetland in South Western Ethiopia by two prominent faults with opposite throws (one to the East and the other two the West). The depression in between allows accumulation of surface water leading to formation of wetlands. The presence of the wetland is further enhanced by the constriction of the Bilate River valley which drains the wetland

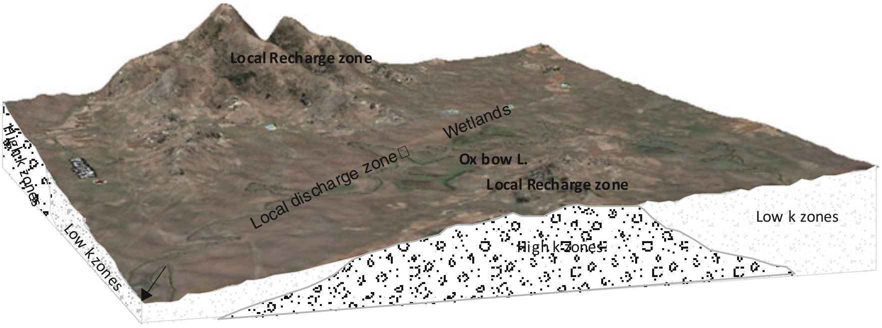

Fig. 6.3 Wetlands associated with headwater regions of streams in Blue Nile plateau, depressions are low permeability zones while higher ground are high permeability zones. The difference in permeability is the prime reason to have a contrasting landscape-highland from where flood and groundwater is generated and lowlands where surface water accumulate and groundwater discharges to

intra-mountain depressions are carved by glaciations. Garbra Gurach Lake which lies at 6°52′N, 39°49′E; 3,950 m altitude occupying a glacial cirque at the head of the northeast-facing Togona valley is typical example. The lake is about 500 × 300 m in size, with a maximum water depth of 6 m, fed by surface runoff from the valley sides, and presumably by shallow groundwater. An outlet stream flows from its northern edge over a boulder-covered rock bar, feeding the Togona River. Moraines also enclose the lake, especially near its western margin.

The Chomen Swamp, *Dabus and Machar (Baro Akobo) wetlands*: The Chomen Swamp from which the Fincha River originates covers an area of about 600 km^2 south of Blue Nile and northwest of Addis Ababa. It is a shallow and although there is some fluctuation in the water surface between the dry and rainy seasons, the swamp is covered with papyrus reed water grasses. The Dabus swamp in the

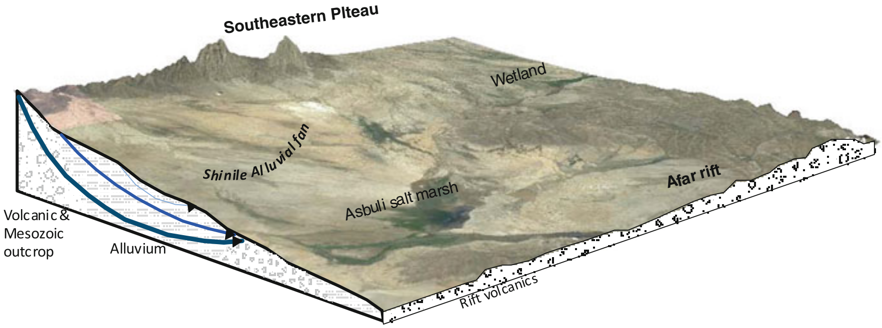

Fig. 6.4 The Asbuli wetland in the foothill of the SE plateaus adjoining the Afar depression. The wetland is formed by capillary rise of the water table as well as groundwater discharge during high water level

southwest part of the basin is at the headwaters of the Dabus River and is the largest swamp in the basin. At about 900 km^2 in extent, it also is covered with papyrus and swamp grasses. The Drainage basin of the River Baro is characterized by the loss of not less than 35 % of its annual yield due to spillage over the plain and also the feeding of the Khors, which flow through the Machar swamps. The area of these swamps has been estimated at 6,700 km^2. Nine billion m^3 of water is lost in the Machar swamp.

Origin of Wetlands

The prerequisite for existence of a wetland is the presence of geomorphologic processes that lead to delay of water flow leading to excess water (surface or ground) over that can be removed by evaporation or runoff and accumulation in a wetland environment. Based on their mode of origin at least six principal type of wetlands can be identified. There are:

Wetlands of simple tectonic origin: Several marginal grabens associated with rifting exist all along the N–S transect of the rift valley (e.g. Raya, Borkena, etc., Fig. 3.12). Under favorable hydrologic, tectonic conditions wetlands occur in association with marginal graben. Marginal grabens form along the margins of the Rift valley result in depressions that get their water from later inflows from groundwaters from adjacent highlands and from runoff draining the escarpments. The accumulation of water in wetlands associated with marginal grabens are also enhanced by lower hydrologic gradient that is formed by antitetic faults whose fault throw is in the opposite direction to that of the principal rift defining faults. A graben that is formed can be filled by surface or groundwater. These kinds of wetlands are strongly linked with shallow and deep groundwaters and act as discharge zones of groundwater. A number of examples can be noted in Fig. 6.1 these kinds of wetlands are marked with number 8. The Boyo swamp in SW Ethiopia (marked 8 in Figs. 6.1 and 6.2) is an example of a wetland with simple tectonic origin fed by surface runoff from both escarpments that define the graben. The impermeable nature of the bed rock leads to little role of the groundwater in maintaining the wetland hydrology in case of Boyo. The wetlands in Borkena, Raya and Kobo represent the crossing of water table with the land surface.

Wetlands of complex tectonic origin: Major volcanic eruptions or large scale tectonic movements can temporarily (from few year to millions of years) intervene into the natural courses of rivers leading to temporary accumulation of water upstream of the volcano tectonic activity leading to formation of wetlands. Such areas remain permanent lakes in absence of active and rapid drainage development. These temporary water bodies can later be drained by head ward erosion of streams from any direction often leading to river captures. The Yerer Tulu Welel Volcanic Lineament is a typical example whereby a complex interplay of quaternary tectonism and volcanism has affected the drainage networks of the Blue Nile, the Omo Gibe, the Awash and the Baro Akobo drainage basins. A region which extends from central Ethiopia (Addis Ababa) to Western Ethiopia Dimbi Dolo is a typical zone where such wetlands are formed and a number of geomorphologically evident drainage capture is noted (Becho, Chomen, Dabus etc.; Fig. 6.1). The capture of Didesa River which was originally part of the Omo Ghibe drainage basin, capture of head waters of the Walga River which was originally part of the Didessa River and several other drainage captures happened in this area. Examples of wetlands formed by drainage capture and tectonic depressions of scales of changing river course include Chomen swamp, the Dabus swamp, and wetlands in the upper Didesa and Upper Ghibe basins and the Becho plain in Central Ethiopia.

As can be seen from Fig. 6.1, wetlands frequency is higher in the western sector of Ethiopia running E-W along the so called the Yerer Tulu Wellel Volcanic/ Tectonic Lineament. This lineament should be responsible for the temporary or permanent damming of river ways, and drainage capture leading to a complex pattern of wetland occurrence in Western Ethiopia.

Wetlands associated with Lakes: Wetlands may form adjacent to major lakes. The waters in the wetlands can originate from at least four principal sources: backwater flow from the lakes, precipitation in wetlands, over flow water from rivers, or groundwater discharge to wetlands from adjacent aquifers. The relative importance of these water sources is the function of local topography and climate. Nevertheless groundwater which is often neglected in maintaining wetland hydrology has recently been identified as principal hydrologic component in several wetlands associated with lakes. Examples include the wetlands of Lake Tana (Kebede et al. 2011). Likewise Lake Awasa is buffered by the Shallo swamp.

Wetlands associated with headwaters of Rivers: These are generally smaller in size and form at the foothills of higher elevation areas where surface and groundwater emerging from the higher ground is unable to be removed rapidly from the lowland terrain. Most of these wetlands are riverine in origin and form in local depressions or small flat plains. Figure 6.3 shows a typical wetland associated with meandering head waters of the Blue Nile River in the Salale plateau. The

Table 6.3 Documented ground fissures in the Ethiopian rift valley and associated damages

Year	Location		Remarks
	E	N	
1956	8.90	39.9	Fissure with subsidence pits close to railway line near the town of Metahara following rain
1966	8.70	39.5	Fissure crossing railway line 17 km north of Wolenchiti, disruption of transportation for a few days
	8.50	38.9	Fissure to the east of Mount Zuqala (reported in Gouin and Mohr (1967))
1970	8.55	39.9	Fissure 10 km east of ton of Nazareth, a farmer lost his oxen
1971	8.60	39.2	Cracks and subsidence pits several hundred meters long opened in the town of Mojo following heavy rain
1976	7.00	38.4	Fissure at the southern Awasa basin in the town of Muleti. No damage was reported at the time because settlement was just beginning
1981*	8.90	39.9	Subsidence pits connected by cracks opened in Awra Melda, near Fentale, following rain six months after an earthquake swarm caused cracks
1983	8.00	39.0	Fissure to the east of Lake Ziway following heavy rain occurred parallel to the rift axis, causing disruption of activities of farming communities and cutting the road
1986	7.90	38.7	Fissure occurred 25 km west of the town of Ziway in middle of the farming community following heavy rain. It caused destruction of houses, arable land and communication lines
1987	8.10	38.5	Fissure in Meki, North west of Lake Ziway, 2 km east of the main road and parallel to the rift axis. This occurred following rain, caused damage to road and farm
	8.00	38.7	Fissure 5 km west of Ziway town that occurred following rain, caused damage to farms and crossed the Ziway to Butajira road disrupting communication
1996	7.00	38.4	Fissure in the town of Muleti in Awasa during heavy rain, caused destruction of arable land, houses and loss of property swallowing up two tons of maize where it crosses a grain store

formation of the depression itself relate to permeability contrast within the landscape. The most permeable zones are resistant to erosion and forms higher grounds which are sources of groundwater and surface water which accumulate in the lowlands that are formed in low permeability zones of the basalt plateau. The low permeability leads to erosion of the landscape relatively rapidly compared to the adjacent high permeability zones and formation of flat bottomed lower grounds. Because of the low flows and flat topography the rivers draining this landscape are mostly meandering in nature. Cut of trenches form oxbow lakes and local small wetlands.

Groundwater dominated wetlands: These are wetlands whose existence is attributed to geomorphological and hydrological factors. Lagoons or impounded water areas are formed where low depression intersects the shallow or regional water tables or where groundwater is close enough to the surface to allow capillary rise to form wetlands. The latter case is discussed below. Most of wetlands in the marginal graben of the Ethiopian rift and Afar depression are such examples where the water table intersects with topography to form wetlands (wetlands marked 5 in

Fig. 6.1). A number of small wetlands in the flat topped basalt capped plateau of the head water of drainage basins are formed where shallow groundwater table intersects with the topographic depressions. The topographic variation itself is attributed to the differential erosion of the tertiary basalts owing to their permeability contrast.

Shallow depressions form in less resistant basalts, low permeability zones of basalts and cliffs or higher grounds form in highly resistant, relatively permeable basalt sub units. These differences in topography and permeability allow formation of wetlands in the lower low permeability grounds. Thousands of such wetlands ranging in size from less than a 1 km^2 to over several thousand km^2 dot the Ethiopian plateau (particularly the Blue Nile Plateau and the Arsi-Bale highlands).

Wetlands associated with capillarity of groundwaters: In areas where the groundwater is shallow but not crossing the regional topography capillary rise keep soil moisture content near saturation and maintain the landscape as wetland (Fig. 6.4). Such cases are common in the Afar depression of Ethiopia where regional water table is shallow, evaporation rate is high, and the landscape is covered by sediments which allow upward capillarity. The permanent wettening of the surface is enhanced by high salt content of the soils which favor the moisture be trapped in the soil even after the capillary rise has been reduced because of decrease in water table. Examples of such wetlands include Melo in South eastern Afar depression, Asbuli downstream of wadis draining the highlands of Harar and entering the southern Afar depression and several wetlands in the Dallol depression. The saturated conditions of wetland prevail as long as the water table drop does not overcome the capillary force's ability to translocate water from the water table to the root zone. These kinds of wetlands are characterized by highly saline soils and waters owing to successive evaporative concentration of salts in the soils zone but limited loss of salt downstream. The mudflat surrounding the Dallol salt deposits (wetlands located north of region marked 5 in Fig. 6.1) is an extreme example of wetland where the wetness is maintained by deceased evaporative rate due to salt content in waters, shallow groundwaters and hygroscopic effect of the salts.

Wetlands associated with old glaciated terrains: About 100 small lakes, each a few hectares in area, and many bogs are set in the quaternary basalt of the Goba plateau well above tree line in the Bale Mountains (marked 9 in Fig. 6.1). This is a glaciated area and most lakes occupy depressions curved out by ice. Other has been filled in, but retains water permanently and support wetland vegetation.

6.3 Groundwater Triggering Land Subsidence, Collapse and Ground Fissuring

The same groundwater which plays vital role in sustaining the environmental integrity though water and solute supply and flux can also cause undesirable development related environmental hazards. The most notable hazard related to

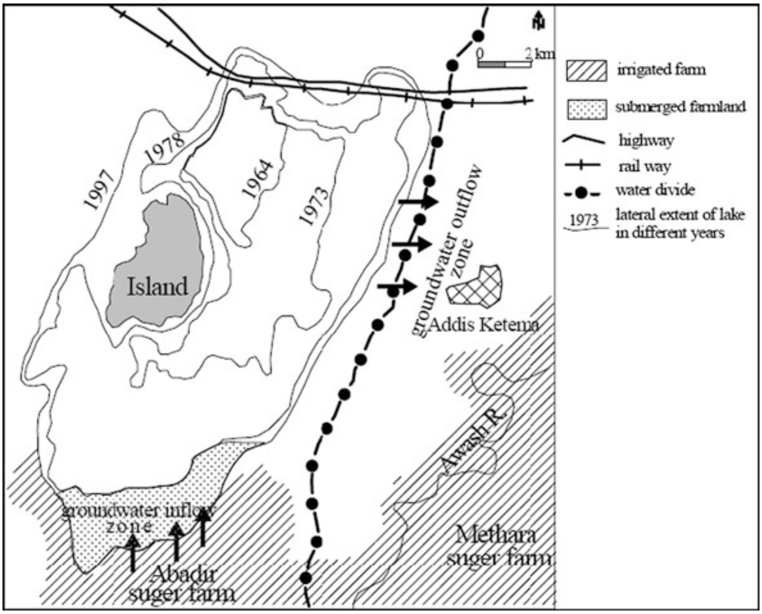

Fig. 6.5 Expansion of Lake Beseka since 1964 in response to groundwater inflow from sugarcane farm and increased discharge of groundwater in Western sector of the lake (Alemayehu et al. 2006)

human, animal and environmental health is discussed in Chap. 7. In addition to health related hazards groundwater processes are known to be the principal cause of a number of geologic hazards including water logging, land subsidence, flooding of mining and construction sites, and salinization irrigable land and associated soils. All of these lists of hazards are known to occur in Ethiopia at different times and incur economic cost. Some examples are:

Groundwater Driven Ground Fissures in Ethiopia

Ground fissures (sedimentary or volcanoclastic fissures): Fissures have been described previously at several locations in the MER (Gouin and Mohr 1967; Gibson and Tazieff 1970; Williams 1981; Asfaw 1982; Asfaw 1998; Mohr 1987). Asfaw (1998) summarizes 12 fissures whose appearances were reported between 1956 and 1996 (Table 6.2). These occur in the thick unconsolidated lacustrine and volcanic sediments which cover the Rift floor.

Ground cracks, also known as earth fissures or ground fissures, surface faults, are long, linear tensile structures occurred at the land surface with or without vertical displacement. Ground cracks are known hazard features in the Central Ethiopian Rift Valley which is a similar geologic setting compared to the mid section (Nazareth to Asebeteferi) of the railway traverse. Hazards associated with ground fissures and its impacts on road and railway has been reported to occur along the Ethiopia Djibouti railroad traverse. According to Asfaw (1982) the first report of fissures causing damage in the MER came from railway engineers who observed them under a railroad near the town of Metehara in Main Ethiopian Rift in 1956 (Gouin 1971). The next report of fissures was in 1966 and was from a place 17 km north east of the town of Welenchiti, again in the Main Ethiopian Rift. This fissure which was studied in more detail, occurred in sediments estimated to be as thick as 100 m. In this event, the fissure crossed the railroad (Gouin and Mohr 1967), disrupting the transport service for a few days. Systematic mapping of ground fissures along the railroad traverse line has never been conducted for the purpose.

Ground Fissures and Groundwaters

Ground fissures generally appear as narrow cracks, which may be several hundred meters long, connecting subsidence pits up to several meters wide. In almost all cases they were revealed as a result of subsurface erosion by groundwater and consequent slumping following heavy rains. The cracks sometimes appear to close as they become covered by a veneer of vegetation and sediment, and subsequently to reopen. Such sedimentary fissures are almost certainly more widespread than those observed, since only those which have an impact on human habitation or activities are reported. The date of their manifestation may considerably postdate the time of their formation. Notable features and genesis of the fissures is that they are related to heavy rainfall but their orientation follow the general trend of the rift faults. Ground-fissures are also known to occur in various sector of the Ethiopian Rift (Ayalew et al. 2004 for details). The exact causal mechanism of ground fissuring in soft sediments is still subjective debate (Ayalew et al. 2004). None of the preceding works in the Rift on the origin of ground fissures exclude the role of groundwater in triggering fissuring and collapses of land.

6.4 The Expansion of Lake Beseka Through Groundwater Input

In contrast to many East African terminal lakes, Beseka has recently been growing as a result of increase in the net groundwater flux into the lake (Kebede et al. 2009; Alemayehu et al. 2006). Air photos taken at different times have shown that the area covered by the lake was about 3 km^2 in the late 1950s; currently the total area is a little above 40 km^2 (Fig. 6.5). The changes in Lake volume has been accompanied by changes in water quality and limnology. EC of the lake changed from over 200 to 6.3 mS/cm. Lake Beseka has undergone a major water level rise (e.g. Williams 1981), the onset of which has not been dated. The rapid expansion of the lake has severe implications: Since 1993 Lake Beseka has partially flooded and salinized the Abadir Farm. Damages on the farm as well as on the nearby railway line and highway caused a loss amounting to several amount dollars. In response to this threat, an embankment has been built to prevent further damage to crops. The road on the northern shore, Ethiopia's sole access to the seaport in Djibouti, needed to be raised twice.

6.5 Groundwater, Dewatering and Mining Operations

Groundwater discharge to mine site is one of the most challenging processes to mining operations. Dewatering of mine site is costly, time consuming and often is responsible for abandonment of mining operations. The earliest document impact of groundwater in mining operation in Ethiopia is that of the Potash Mining activity in the Dallol Depression (Ralph M Parsons Company 1968). Recently groundwater dewatering is also being conducted in Legadembi gold mining site in southern Ethiopia. Report by Ralph M Parsons Company (1968) shows that the earliest mining operation in Dallol Ethiopia has been hampered by groundwater flooding the potash mining site. A number of dewatering wells had to be constructed to pump groundwater from an alluvial fun (see Fig. 3.15) adjacent to the mine site and responsible for discharge of groundwater into the mining site.

Placer gold mining in Shakiso belt of Southern Ethiopia also faced this challenge. Most of the sediments hosting the placer gold deposits are site of groundwater discharge. Of the several pits dug into the sediments most of them fall below the water table before reaching the gold bearing horizons.

6.6 Economic Function of Groundwater

Access to safe drinking-water is important as a health and development issue at a national, regional and local level. In some regions, it has been shown that investments in water supply and sanitation can yield a net economic benefit, since the reductions in adverse health effects and health care costs outweigh the costs of undertaking the interventions. This is true for major water supply infrastructure investments through to water treatment in the home. Experience has also shown that interventions in improving access to safe water favor the poor in particular, whether in rural or urban areas, and can be an effective part of poverty alleviation strategies.

Groundwater is the principal source of water supply in urban and rural areas alike. Groundwater supports irrigation. Groundwater is the principal source of industrial water in Ethiopia. Recreational water such as swimming pool has their origin from heated groundwater. Water bottling plants that exploit groundwater currently employ more than 20,000 people in Ethiopia. Livestock rearing is becoming increasingly dependent on groundwater. Groundwaters emanation points are sites of recreation and tourism (Wondogenet, Ambo, Woliso, Ghion, Sodere, Awash, Dilla, Wonji-Gergedi). The recreational and touristic value of groundwater translates into jobs and markets. Sectors such as fruit and vegetable processing industry—including fresh-pack and processing sectors; the meat and poultry processing industry—water for chilling, scalding, washing, cleaning and conveying waste; the food and beverage industry-water plays a large role in transporting, cleaning, processing and sanitation; textile industries—water is used extensively in processing extensively depend on groundwater use.

The economic benefits of investing in drinking-water and sanitation have been investigated by WHO (Hutton and Haller 2004) and come in several forms:

1. health-care savings by health agencies and individuals;
2. productive days gained per year (for those 15–59 years of age) and increased school attendance;
3. time savings (working days gained) resulting from more convenient access to services;
4. value of deaths averted (based on future earnings).

6.7 Groundwater in Income Generation

An elaborate study by Gebregziabher et al. (2009) demonstrate that in northern Ethiopian region of Ethiopia average income and income from off farm activities of irrigating households is greater than that of non irrigating households by as much as 50 %. According to this study, when three irrigation schemes are compared (micro dams, river irrigation and groundwater irrigation) Irrigators with a micro-dam as their irrigation water source had significantly higher income than the comparable non-irrigators. They also had higher off-farm income. Similarly, groundwater irrigators had significantly higher income than the corresponding comparable non-irrigators. However, they had lower off-farm income, though the difference is not statistically significant. On the contrary, there was no significant difference in the overall income and off-farm income between irrigators with river diversion as their water source and the comparable no irrigators. When comparing the three irrigation typologies, the income effect of groundwater irrigation is highest. According to the study groundwater irrigators had lower off-farm labor participation than comparable non-irrigators. It might be that groundwater source is dependable, thus providing incentives for farmers to use their irrigation plots intensively rather than engaging in wage labor employment.

6.8 Social Function of Groundwater

A great many religions add to the simple fact that the water is located below the surface of the earth, a whole package of properties more suited for superstition: it is attributed with fabulous curative power, cleans ones sins, and has transcendental values.

Spring waters have enormous social value. In northern Ethiopia springs are considered as sacred water with therapeutic values.

An eloquent summary and investigation (Tiki et al. 2010) groundwater wells play a pivotal role in Borana pastoral production, cultural identity, and the institutional organization of water management (Helland 1980; Dahl and Megersa 1990; Cossins and Upton 1987). Indigenous well-water system of the ancient Tula wells that has had a critical function in the sustainable management of savanna grazing lands in southern Ethiopia. The indispensable role of the wells is expressed by their connection to human and livestock fertility, continuity of lineages, clan solidarity, and the peace of Borana (nagaa Borana) (Dahl and Megersa 1990). In this ancient water system, water changes the meaning of landscape by transforming the land into a cultural landscape (Burmil et al. 1999) and it conserves useful indigenous environmental knowledge for managing the water system (Goodall 2008). The combination of hydrological and engineering systems, social institutions, and regulatory customary laws (aadaa seeraa) that evolved around water created strong environmental–human systems that have been exploited by Borana pastoralists on a sustainable basis for several centuries (Helland 1998).

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Chapter 7
Groundwater Potential, Recharge, Water Balance: Vital Numbers

7.1 Criteria in Determining Groundwater Potential

Groundwater potential is measured by (a) recharge rate and mechanism, (b) aquifer storage and transmission properties, and (c) suitability of the water from water quality point of view and (d) the response of the aquifer to changes such as climate, seasonality, artificial withdrawal and pollution.

Ethiopia's total internal renewable water resource (surface and groundwater combined) is estimated at 122 billion meter cube per year. Internal renewable water resources (IRWR) include the average annual flow of rivers and the recharge of groundwater (aquifers) generated from endogenous precipitation—precipitation occurring within a country's borders. For long time the groundwater contribution to surface water flows have not be estimated to the appropriate detail. However, a number often referred to as is 2.6 billion m^3. New estimate as the annual active flows and the storage in the aquifers is given in section below. Global estimates for groundwater recharge in Ethiopia ranges from less zero to over 250 mm/year. This varies significantly in space and time.

7.2 Recharge Rates-Previous Studies

Groundwater recharge rate is the major factor that determines sustainable use of groundwater because the maximum amount of groundwater that may be withdrawn from an aquifer without irreversibly depleting it, under current climatic conditions, is approximately equal to long-term (e.g. 30 years) average groundwater recharge. Yet estimating recharge rate accurately is the most challenging exercise in hydrogeology, particularly in arid and semi arid setting.

Figure 7.1 shows the mean annual groundwater recharge estimated from base flow separation of major rivers (Chernet 1993). Recharge rate in Ethiopia varies between 0 and around a maximum of 400 mm/year. The highest recharge

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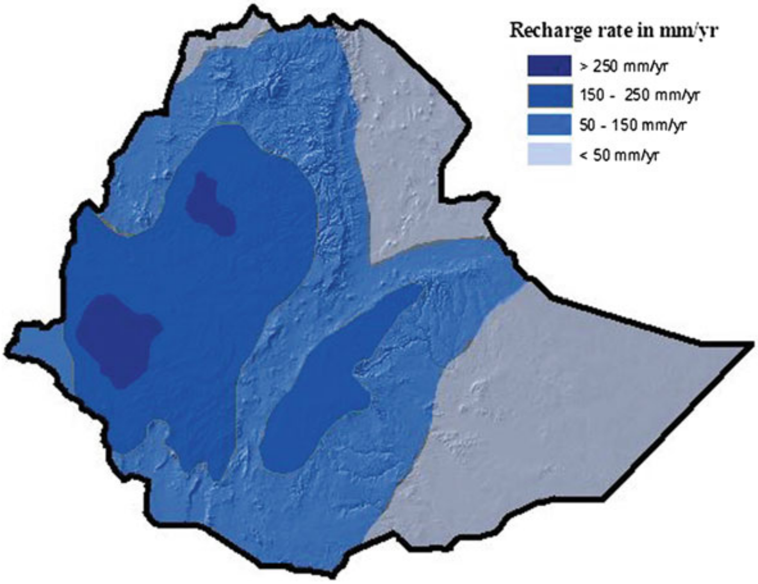

Fig. 7.1 Groundwater recharge rate in Ethiopia obtained from base flow separation method (from Cherenet 1993)

corresponds to high rainfall area in SW Ethiopia and north central plateau. The basis of estimating groundwater recharge in Fig. 7.1 is river discharge records (that is by separating base flow component from the total runoff and assuming the annual base flow of the rivers is equivalent to recharge). The annual base flow of total runoff is assumed to equal the groundwater recharge in the catchment at which the discharge measurement has taken place.

The recharge rate is function of rainfall amount, permeability of the rocks, the geomorphological setup and the availability of surface water bodies. Based on individual basins groundwater baseflow separation method and estimates from global remote sensing data (Doll and Fiedler 2008) total groundwater recharge in Ethiopia has been estimated at 36–47 × 10^9 m^3/year (see Sect. 7.4).

7.3 Recharge Mechanisms

In the face of climate change and variability, recharge mechanism is equality important if not more important than recharge rate in determining groundwater potential of aquifers. This is because seasonal and long term difference in the system responses (e.g. water table fluctuation, groundwater availability) is tied to the way rainfall pulse is transmitted to the aquifers. More than ¾ of aquifers in Ethiopia receive localized and indirect recharge as the dominant mechanisms for recharge. This also challenges the validity of recharge rate estimate from baseflow separation methods. Mechanism of recharge has an implication in aquifer response to climate change. A simple example can be that the higher the intensity of rainfall under a future climate change condition (which is IPCC' prediction for Ethiopia under the climate change-most IPCC models predict intensification of rainfall extremes, Bates et al. 2008) and given that the recharge processes mainly involve indirect and localized recharge mechanisms, one can expect overall increase in the available groundwater recharge.

The IPCC Technical Paper VI states that heavy precipitation events in more humid areas 'may result in the infiltration capacity of the soil being exceeded more often' and thus result in a decline in groundwater recharge (Bates et al. 2008). This would be the case in humid and semi-humid areas such as the Western Ethiopian highlands with think soil cover and higher rainfall (Fig. 7.2). In semi-arid and arid areas (such as the Ethiopian rift), however, increased precipitation is expected to have a positive impact on groundwater recharge, as only high-intensity rainfalls are able to infiltrate fast enough before evaporating into the air. Because alluvial aquifers such as those underlying the rift valley are recharged mainly by inundations due to floods, the increase in floodwater flows from the highlands and midlands would increase the groundwater base in the lowlands. Recent non-IPCC studies corroborate such findings (e.g. Taylor and Howard 1996; Eilers et al. 2007; Owor et al. 2009).

Drought buffering capacity of groundwaters largely depends on the current recharge rates and equally on the mechanism of recharge. While recharge rate determines the overall groundwater potential at a given time, the mechanism of recharge is an important indicator of how changes in environmental conditions (land use, land cover and climate changes) would affect the groundwater availability.

Based on field evidence, hydrologic data, isotope and geochemical studies groundwater recharge mechanism for Ethiopian aquifers can be outlined as shown in Fig. 7.2. A number of Isotopic evidence (Kebede et al. 2005, 2007) shows that the principal recharge pathway in the highlands of Ethiopia, is recharge taking through fractures from heavy rainfall fractions rather than recharge taking place from soil moisture excess. Recharge to aquifers takes place in a variety of mechanisms (Fig. 7.2) including (a) direct diffuse recharge, (b) indirect recharge from flood waters during high flood stage, (c) mountain block and mountain front recharge, (d) fast selective recharge from heavy rains and (e) recharge from loosing streams and flash floods.

(a) *Direct or diffuse recharge*: Direct or diffuse recharge is defined as water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone. This mode of recharge is spatially distributed (diffuse), and results from widespread percolation through the entire vadose zone. This type of recharge refers to rain water which directly passes through the soil zone ones the soil water holding capacity is filled. A number of parameterization

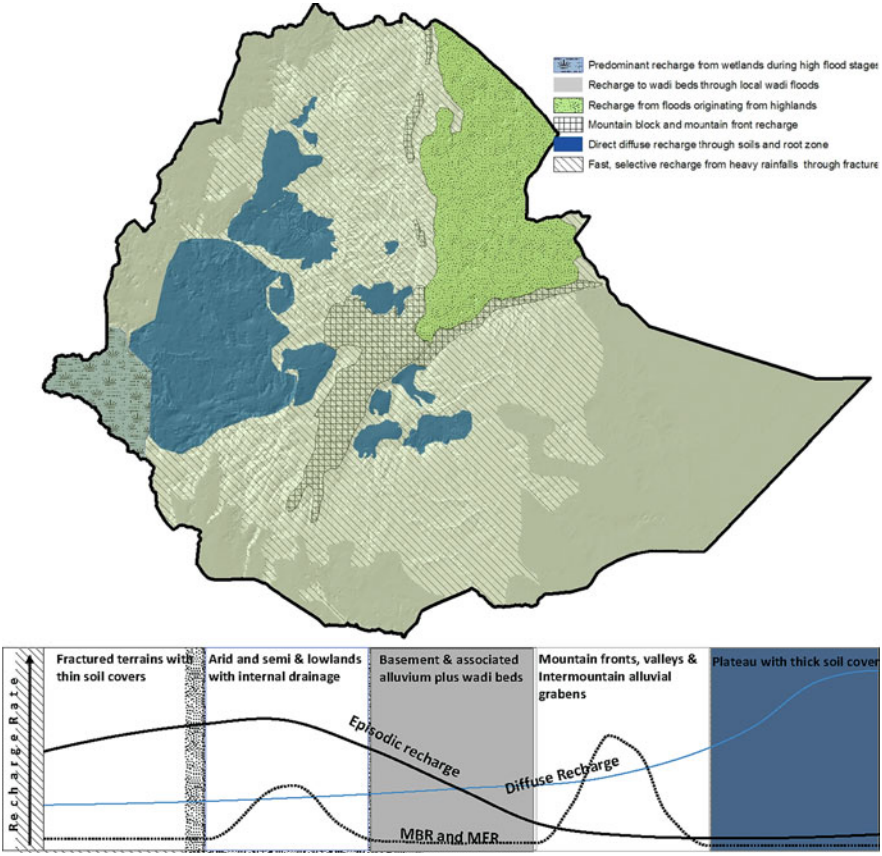

Fig. 7.2 Recharge mechanism for different geoenvironmental setting in Ethiopia (**a**) and relative importance of recharge mechanism in the various regions of the country (**b**)

exits to describe how rainfall water pass through the soil and root zone and reaches the water table. Recharge estimate which accounts for the soil moisture water balance accounting can provide the most appropriate recharge rate estimation in such conditions. It is typical process of humid western highlands of Ethiopia and Central Eastern Plateau. ‘Surprisingly enough’ only a small portion of Ethiopia gets this kind of direct diffuse recharge from rainfall. It is typical of humid western highlands of Ethiopia and Central Eastern Plateau because frequent, regular precipitation maintains a high water content in the soil, so that there is little additional storage capacity in the vadose zone. Thus infiltration can be routed quickly through the vadose zone to the saturated zone. This recharge raises the water table, which leads to increased stream flow. Therefore, in humid western Ethiopia and east central highlands flowing perennial streams are typically groundwater discharge areas, sustained by diffuse recharge in the basin.

(b) *Indirect recharge from flood waters*: In arid climate setting, indirect recharge from flood waters and depression storage are the most common recharge mechanism and account for more than 20 % of recharge taking place in Ethiopia. Floods leading to recharge can emerge from the area where recharge is taking place or can originate from highlands bounding the arid lowlands. There is a clear evidence for this type of recharge in dominating recharge mechanism in Afar depression (Kebede et al. 2007). Under this typical condition future intensification of rainfall would lead to increased groundwater recharge. Two types of indirect recharge from floods can be noted for Ethiopia. The first category is those in which the flood waters recharge the underlying aquifers and the aquifers and the aquifers located in the basins can be exploited for their water resources. The second category is those which are related to wadi bed floods. In wadi bed recharge the principal storage of recharge water is the wadi bed sediments, owing to low permeability of the underlying rocks. Wadi bed recharge to wadi bed sediments is the most common recharge type in areas underlain by basement rocks in the peripheral lowlands.

(c) *Mountain front and mountain block recharge*: In semiarid climates, a significant component of recharge to basin aquifers occurs along the mountain front either directly from lateral inflows of groundwater to aquifers in the lowlands or from streams originating from the highlands and losing their water to groundwater upon emergence from mountains. Mountain block recharge can take place as diffuse recharge from the mountain (DS), or diffuse recharge from surface (DR) along mountain front, focused recharge (FR) along transverse faults, focused recharge from losing streams (FS). Most areas at the interface between the Ethiopian rift and adjacent mountains get their recharge from mountain front-mountain block recharge. Figure 7.3 shows the different recharge pathways involved in mountain block recharge. Groundwaters connected to such kind of recharge shows low response to seasonal variations in rainfall and rather respond to long term changes.

(d) *Fast selective recharge through fractures*: In fractured terrains with barren grounds and little soil and low vegetation cover low intensity rains normally evaporate back to the atmosphere. Recharge and runoff therefore takes place selectively from heavy rains. This is the most common recharge mechanism in fractured terrain of Ethiopia, particularly in the Blue Nile Basin (Kebede et al. 2005). Future intensification of rainfall would increase recharge.

(e) *Groundwater recharge from high flood stages*: This is common process in more humid setting. Groundwater recharge from flood waters depends on the level of flood waters with respect to the water table. Unlike case b whereby recharge takes place from intermittent flush floods originating locally or from adjacent landscape here recharge takes place from perennial Rivers when the water level in the rivers is higher than the water table in adjacent aquifer. Reverse flow from aquifer to rivers takes place when river water stage is lower. This kind of recharge appears to be common in wetland areas of Ethiopia including the Gambela lowlands, the Lake Tana wetlands etc.

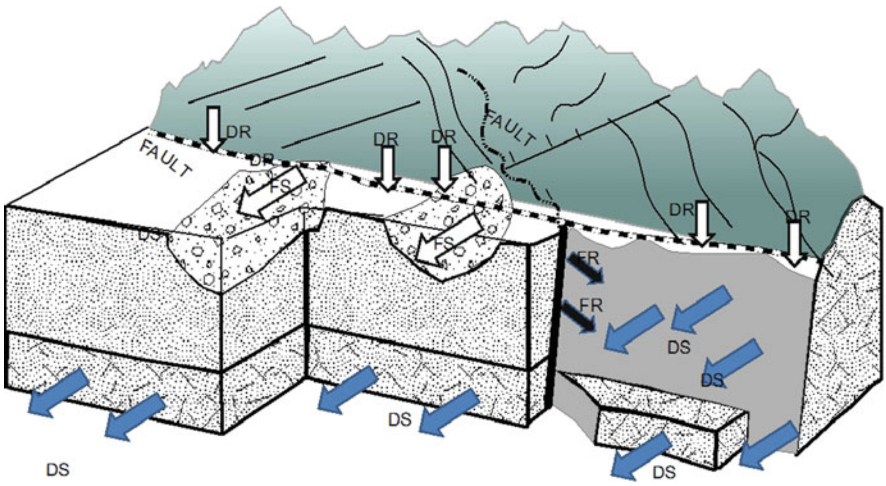

Fig. 7.3 The different mechanism of recharge in a mountain bound valley aquifers (diffuse mountain block recharge (*DS*), direct recharge from surface (*DR*), focused recharge from surface (*FS*), focused recharge from mountains (*FR*)

More than ¾ of aquifers in Ethiopia receive localized and indirect recharge as the dominant mechanisms for recharge. Understanding groundwater recharge mechanism is an important step towards understanding the impacts of climate change on groundwater resources availability. Because of non linear response of recharge to rainfall variation such an affirmation cannot always be conclusive but indicative. While for instance heavy intensive rainfall could lead to higher recharge in fractured terrain of Ethiopian and in the rift valley which gets much of its recharge from flood waters, under such rainfall conditions recharge in the soil covered western Ethiopia can significantly decrease. Decrease in rainfall would immediately impact recharge rates in the vast region of Ethiopia, while the central part of the rift and the area in center of Ethiopia which receives most of its groundwater recharge from lateral inflows from the mountains can still get sustained inflows decreasing the vulnerability of the groundwater resources to short lived climate shocks.

7.4 Groundwater Recharge, Storage, and Groundwater Contribution to Surface Waters

Recharge Amount and Variation

The groundwater potential of Ethiopia has long been believed to be of limited extent. This relates partly to recharge rate and aquifer storage. According to WAPCOS (1990) the feasible total annually exploitable groundwater potential

Table 7.1 Estimated annual groundwater recharge, mean annual surface runoff, and groundwater contribution to surface waters in Ethiopia

Hydrologic basin	Estimated groundwater recharge (Mm^3/year)	Annual runoff (BM^3/year)	Catchment area	Groundwater contribution to surface water fraction
Awash	4,074	4.6	1,12,700	0.89
Abay	9,461	52.6	1,99,812	0.18
Wabi shebele	1,100	3.15	2,00,214	0.35
Genale-dawa	2,244	5.8	1,71,050	0.42
Rift valley lakes	1,080	5.6	52,740	0.19
Omo ghibe	10,000	17.9	78,200	0.56
Tekeze basin	2,500	7.63	89,000	0.33
Baro akobo	128.4	23.6	74,100	0.01
Aysha		0	2,200	0
Ogaden		0	77,100	0
Mereb		0.26	5,700	0
Afar danakil	3,600	0.86	74,000	1
Whole Ethiopia	(30,700) (47,000)[a]	122	11,36,816	0.37

[a] 47 billion meter cube annual groundwater recharge is estimated from the Global Recharge map of Doll and Fiedler (2008) assuming mean annual weighted recharge over Ethiopia of 39 mm/year and 1.2 × 10^6 km^2 land area. It should be noted that this amount of recharge reference of recharge that takes place across the entire Ethiopia as diffuse recharge. The 36 billion meter cube estimate is from compiled data of local studies from individual catchments and river basins in Ethiopia

(here potential refers to annual recharge) of the country is estimated to be about 2.6 billion m^3/year. It should be noted that this number refers to the annual exploitable ground water and has been assumed to be equivalent to 10 % of total annual recharge (WAPCOS 1990). Thus the total recharge in Ethiopia from WAPCOS 1990 stands at 26 billion m^3. From basin master plan studies and literature sources compilation of estimated annual groundwater recharge, annual runoff, catchment areas and groundwater contribution to surface waters is given in Table 7.1 and Fig. 7.4. The figure and table show the newly estimated annual groundwater recharge for the entire Ethiopia stands at 36 billion m^3/year. A regional study for recharge estimation in the entire African aquifers puts mean annual diffuse recharge over Ethiopia of 39 mm/year which means a total mean annual recharge of 47 billion m^3 (Doll and Fiedler 2008).

As shown in Fig. 7.4 the largest groundwater contribution to surface waters takes place in the Omo-Gibe and the Awash basins. In the Omo Gibe basin, higher annual recharge, and well developed soils enhance recharge rates while in the Awash basin intensive fracturing of the aquifers channel groundwater from

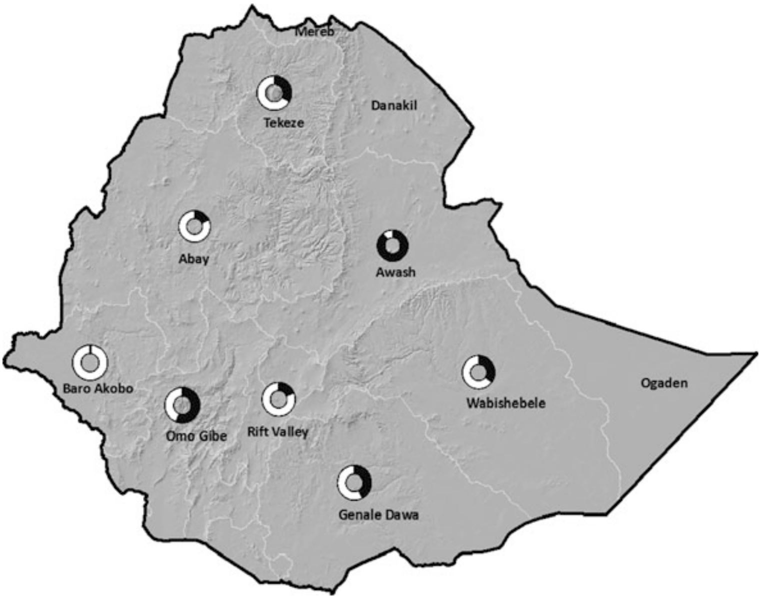

Fig. 7.4 Groundwater contribution to surface waters in basins in Ethiopia

adjacent highlands as mountain block recharge contributing to high groundwater component in the available water resources. Dissected regions such as the Blue Nile, the Wabishebele, the Tekeze show lower groundwater contribution to surface waters owing to higher dissection, higher slope which leads to rapid runoff from the terrain with little contribution from groundwaters.

Groundwater Storage Potential

Groundwater storage potential here refers to the total amount of permanent storage that exists in the aquifers. Groundwater storage potential is the function of the porosities of the rocks and amount of open space in rocks that could store water. Compared to other aquifer regions in Africa the groundwater storage potential in Ethiopia is significantly lower (Table 7.2). However, it should be noted that the low storage potential is compensated for by the aquifers connection to modern day recharge from rainfalls. The low storage potential is because of higher slope of drainage basins, dissection of the aquifers into smaller pockets, and lower storage capacity of crystalline rocks (volcanic and basement rocks) which cover most of the Ethiopian landscape.

Storage is principally affected by porosity of rocks and favorable topography. Worldwide and in Africa groundwater storage constitutes the most voluminous fresh water available for human consumption. Ethiopia's hydrogeology is can be

Table 7.2 Comparison of permanent groundwater storage in aquifers of sedimentary basins of Africa and aquifers in Ethiopia

Aquifer name	Area (million kilometer sq)	Storage (billion m^3)	Connection to modern recharge	Country
Nubian aquifer	2.00	75,000	No (or little)	Chad, Egypt, Libya, Sudan
North Western Sahara aquifers	0.78	60,000	No (or little)	Morocco, Algeria, Libya, Tunisia
Ethiopia	1.2	1,000	Yes (30.7–47 billion m^3)	Ethiopia

See box i for details on how this has been estimated

described as 'aquifers with complex structures/storage' with small storage volume but frequently replenishable system. Table 7.2 shows for instance compares groundwater storage of various aquifers of Africa and that of Ethiopia. Regardless of its minimum storage volume Ethiopia's and unlike the voluminous aquifers of Africa, Ethiopia's groundwaters are connected to modern day recharge from meteoric waters. Using the approach depicted in box i, total groundwater storage in Ethiopia is estimated at 1 trillion m^3.

7.5 Actual and Virtual Water Balance of Ethiopia Vital Groundwater Numbers

Actual Water Balance

Ethiopia is quite often mentioned as 'water tower of Africa' owing to the high surface water flows which stands at 122 billion m^3. Nevertheless, the contribution of other water sources (e.g. rainwater, groundwater) in the water potential description of the country is rarely viewed holistically. A holistic view of water resources availability is in a given terrain is to look at the water balance-which refers to the amount of incoming water in various forms and the amount of loss of water from the terrain (Fig. 7.5 upper block). In Ethiopia rainwater remains the largest available water resource. Estimates from the meteorological stations all over Ethiopia give an annual rainfall volume over Ethiopia of 798 billion m^3/year. This is against the commonly held assumption that 'Ethiopia is endowed with rich surface water resources'. Nevertheless only a small fraction (15 %) of the rainfall water converts to river discharge (from groundwater and surface waters). The remaining 85 % of incoming rain evaporates back (accounting for 668 billion m^3/year) from the landscape. This water will ultimately forms local rains or leaves the landscape as atmospheric vapor. The remaining 3 % of incoming rainwater is used for green water use (2.5 billion m^3) and blue water use (5 billion m^3). Green water is the water that is required for crops production and blue water use is water that is

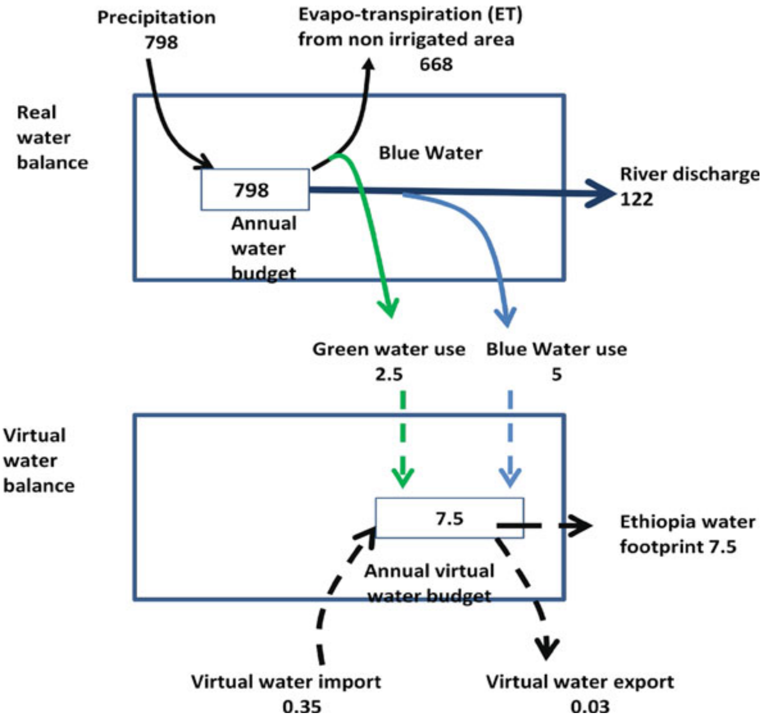

Fig. 7.5 The real (*upper corner*) and virtual water (*lower corner*) balance of Ethiopia. Data for virtual water is taken from from Hoekestra (2003). This real water budget is estimated from available hydrological and meteorological data

used directly for domestic water supply, livestock watering, industrial and non industrial uses etc.

Virtual Water Balance

Virtual water is the water ‘embodied’ in a product, not in real sense, but in virtual sense. It refers to the water needed for the production of the product. The virtual water content is defined as the volume of water that was in reality used to produce the product This will depend on the production conditions, including place and time of production and water use efficiency. Producing one kilogram of grain in an arid country for instance can require two or three times more water than producing the same amount in a humid country. Virtual water can also be defined as the amount of water that would have been required to produce the product at the place where the product is needed.

In a practical sense virtual water can be seen as alternative source of water. Using this additional source can be an instrument to achieve regional water security. From an economic point of view it makes sense to produce the water-intensive products demanded in this world in those places where water is most abundantly available.

The lower block of Fig. 7.5 shows the virtual water budget based on data taken in 2003. It can be seen that regardless of the huge real water availability the country's virtual water export stands at 0.03 billion m^3. Furthermore the virtual water import exceeds the virtual water export. The ecological and environmental look at the virtual water balance rests in the countries or per capita water footprint. The water footprint being the cumulative virtual water content of all goods and services consumed by one individual or by the individuals of one country. It can be used as a tool to show the impact of countries or individuals on the environment. The country's water footprint stands at 7.5 billion m^3, while the per capita water foot print is a mere 7.5 m^3/year.[1] Caution is needed since the estimates are based on scarce data sources on water use, crop water requirement and export and import data taken from literature.

7.6 Vital Water Graphic

In addition to assessing the available groundwater and surface water resources in a country, other vital numbers are essential to provide an insight into to important questions in water resources management and policy making. The questions may include. Can we provide safe drinking water, irrigation water or industrial water for the coming generation and under growing demand? What is the maximum amount of available water resources be extracted per capita in 2020? What are opportunities and challenges around the available water resources? What is the state of current water use with respect to the state of available freshwater resources in the country? Table 7.3 aims at providing an overview of the state of water resources in Ethiopia and providing answers to these important questions. This numbers are synthesis of data and figures obtained in the preceding chapters of this book.

7.7 Paleo-Groundwater and Paleo-Hydrogeology

Availability of groundwater and surface waters shapes the history of civilization of countries and regions. Abundant rain, rich groundwater resources are drivers of boom in agriculture and trade leading to flourishing civilizations in the past.

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[1] In comparsion with water footprint of other countries per capita water footprint of Ethiopia is among the lowest in the world (per capita water footprint of China = 419 m^3/year; Netherlands = 2377 m^3/year; Kenya = 111 m^3/year; Sudan = 545 m^3/year; Egypt = 1138 m^3/year; Djibouti = 194 m^3/year).

Table 7.3 Some vital numbers of Ethiopian water resources

Groundwater and surface water vital numbers			
Features of groundwater			Remark
Annual groundwater recharge to aquifers (annual renewable groundwater resource)		36 BMC	Base flow separation methods
		47 BMC	Water balance approach
Exploitable groundwater availability		3.6 BMC	Base flow separation methods
		4.7 BMC	Water balance approach
Per capita internally renewable groundwater resource for population of 82 million		439 m^3/year/person	Base flow separation method
		572 m^3/year/person	Water balance approach
Per capita annually renewable surface water resource		1,488 m^3/year/person	
Per capita annual water footprint		25 m^3/year/person	
Per capita annual groundwater storage		1,25,000 m^3/person	Non renewable resource
Per capita annually available rainwater resource		9,730 m^3/year/person	
Permanent groundwater storage in aquifers		1,000 Billion m^3	Equivalent to 8 years of flow of all Ethiopian rivers
Average of mean residence time (MRT) of groundwaters in the aquifers at country scale		28 years	
Average of mean residence time (MRT) of surface waters in surface water storage (lakes + wetlands)		5 years	
Total surface water storage	Natural lakes	~650 km^3	
	Artificial reservoirs		
Per capita surface water storage (as of 2010) in artificial reservoirs		40 m^3/person	
Per capita groundwater water storage (as of 2010)			
Transboundary groundwater outflow to neighboring countries		28 million m^3	Bulal basalt aquifer
Number of identified transboundary aquifers		Ethiopia Kenya 1 Ethiopia Djibouti 1 Ethiopia Sudan 1	Bullal basalt aquifer with Kenya, Alwero sandstone aquifer with Sudan and the Galafi-Hanle with Djibouti
Total annual livestock water consumption		4 billion m^3/year	
Number of hours lost for water collection		4.3 billion h	

(continued)

Table 7.3 (continued)

Groundwater and surface water vital numbers

Features of groundwater		Remark
CO_2 sequestration potential of Ethiopian rocks and waters	500 Gigatones	
Gross virtual water import	0.35 BMC	Hoekestra 2003
Gross virtual water export	0.02 BMC	Hoekestra 2003
Ethiopias water footprint	24.77 BMC	
Number of jobs created in production of bottled waters and soft drinks	6,939	
Volume of bottled water produced in 2001 ec	4,95,227 Hecto Lit	
Population under fluoride hazard in Ethiopia	2,00,00,000	
Population under iodine deficiency in Ethiopia	4,20,00,000	

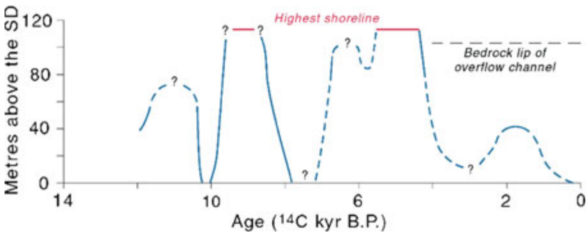
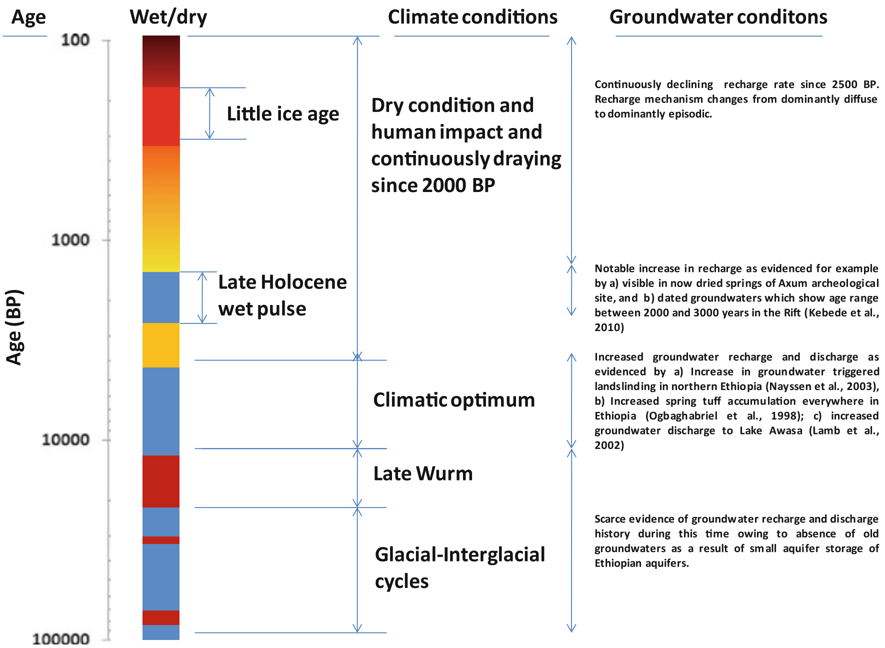


Fig. 7.6 Lake level stand of the Lake Abe reconstructed from lake sediment records from Gasse and Street 1978



Continuously declining recharge rate since 2500 BP. Recharge mechanism changes from dominantly diffuse to dominantly episodic.

Notable increase in recharge as evidenced for example by a) visible in now dried springs of Axum archeological site, and b) dated groundwaters which show age range between 2000 and 3000 years in the Rift (Kebede et al., 2010)

Increased groundwater recharge and discharge as evidenced by a) Increase in groundwater triggered landslinding in northern Ethiopia (Nayssen et al., 2003), b) Increased spring tuff accumulation everywhere in Ethiopia (Ogbaghabriel et al., 1998); c) increased groundwater discharge to Lake Awasa (Lamb et al., 2002)

Scarce evidence of groundwater recharge and discharge history during this time owing to absence of old groundwaters as a result of small aquifer storage of Ethiopian aquifers.

Fig. 7.7 Paleoclimatic and paleogroundwater condition in Ethiopia

The role of groundwater in shaping the history of civilization in Ethiopia is largely unknown. Here attempt is made to synthesize paleo-hydrological condition over Ethiopia over the last 1,00,000 years. Little knowledge exists about the paleo-groundwater conditions of Ethiopia. The paleo climate of Ethiopia and its paleo hydrology is highly documented. The groundwater occurrence, recharge and discharge conditions that accompanied paleo climate variation particularly that of the quaternary is largely unknown.

Extensive paleo climate research documented that the past 1,00,000 years (late Pleistocene to present) have experienced fluctuations in rainfall, river discharge and lake levels (Fig. 7.6). There is well documented agreement that the late

Pleistocene (20,000–12,000 ^{14}C years BP[2]) was cold and dry, with (1) low lake levels in the Rift Valley, (2) large debris fans on the flanks of Lake Abhe′ basin, and (3) the Blue Nile transporting coarse bed load. Then, a period with abundant and less seasonal rains existed between 11,500 and 4,800 ^{14}C years BP. Around 5000–4800 ^{14}C years BP, there was a shift to more arid conditions and more soil erosion until the present day type of climate is established. Nevertheless the drying phase which started 5,000–4,800 ^{14}C years BP has been interrupted by wet episodes around for example 2,500 ^{14}C years BP.

Little that can be said about paleo groundwater condition is the following (also see Fig. 7.7). (1) Cold water travertine deposits that are known to occur in localities such as the Mekelle outlier, the foothills, in the Upper Tekeze basins straddling lake Tana and the slopes of Wonchi volcano and in the various other locations are indicators of higher groundwater recharge and discharge at the time of deposition of the travertines. Most of these travertine deposits have been dated at 4,500 ^{14}C years BP corresponding to the late Holocene high rainfall. (2) in a number of aquifers underlying the rift along the deeper aquifers of the Upper Awash basin and in the Afar depression deeper groundwaters have been dated at 2,000–3,000 years ^{14}C BP corresponding to higher recharge in the late Holocene phase corresponding to the high rainfall episode at 2,500 years ^{14}C BP (Kebede et al. 2007; Kebede and Travi 2011). The present day recharge conditions are the imprint of the general drying since Late Holocene period that Horn of Africa has known over the 4,500 years. Groundwaters showing carbon 14 age ranging from 2,000 to 3,000 years have been widely encountered in the Rift valley of Ethiopia including the deep aquifers of the Upper Awash basin, the rift floor between Nazareth and Lake Beseka and in deep groundwaters of the Afar depression. Spring water discharging into Lake Abe for instance has been dated to be 1,500 ^{14}C BP. The presence on the Ambaradom sandstone cliff of tuff deposits of Holocene age and abundant landslides are proof of mid Holocene high water table, extensive aquifer and increased recharge (Van de Wauw et al. 2008). In Djibouti deeper saline groundwaters dated by ^{14}C return age varying between 1,500 and 4,000 years reveling the existence of humid pulses in late Holocene (Houssein and Mohamed 2008).

The long term variation in groundwater condition has a greater implication for rise and fall of civilization. According to Butzer (1981) the Civilization of Axum, spanning the first millennium AD had its settlement core on the now denuded, sub humid plateau of northern Ethiopia. Axum a new city, began AD 100 as a ceremonial center, growing to over 10,000 people as a prosperous emporium for international trade. Intensified land use led to mass movements in slope soils before AD 300, but a range of clayey stream deposits also implicates strong periodic floods and seasonally abundant moisture. The paleo-climatic ensemble suggests that stronger and more reliable spring rains allowed two crops yearly without irrigation, compared to only of one with modern summer rains. The springs in the ancient

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[2] BP—age counting from now to the date the event started- Before Present.

Axum city also supports domestic water supply implying the presence of higher groundwater recharge and corresponding to late Holocene pulsed wet phases.

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Chapter 8
Groundwater Human Health and Sanitation

8.1 Groundwater as a Buffer Between Health Agents and Human

Chemical and biological materials circulating or stored in the environment get to human body via different pathways including the food we eat, the water we drink and the air we breathe, the materials we touch. Groundwaters play a unique role in acting as pathway via which certain exotic chemical and biological materials are introduced into human physiology. The introduction of certain exotic chemical constituents into groundwaters takes place because of the following conditions:

1. ***Thermodynamic conditions*** which would otherwise be nonexistent in surface water systems exist in groundwater media. For example groundwater media offer conditions of varied red-ox condition. Particularly reducing conditions are rare in running surface waters and shallow lakes. Reducing conditions are common in deep circulating groundwaters and certain type of aquifer. Reducing thermodynamic condition increases mobility of toxic elements such as Arsenic, Molybdenum, Boron, Vanadium, and Iron. On the other hand infiltration through the root zone and degassing of the earth's crust introduces CO_2 (g) into groundwaters. This increases the aggressiveness of water to leach more chemical constituents from rocks.
2. ***Residence time*** of meteoric waters in their respective environment is variable. Water in the atmosphere has residence time in the order of few weeks, waters in the surface environment has residence time in the order of months, and water in the aquifers has residence time ranging from few months to several millions of years. The longer residence time of groundwater favors leaching and enhancement of the bulk salinity and other trace elements in groundwaters.
3. Earth materials, rocks and soils are reservoirs for certain kind of minerals and chemical elements. Groundwaters circulating in the rocks have ***access to these minerals*** and increase its chance of mobilizing chemical elements which would not otherwise be accessible to water environment.

S. Kebede, *Groundwater in Ethiopia*, Springer Hydrogeology,
DOI: 10.1007/978-3-642-30391-3_8,

8.2 Groundwater Related Health Problems in Ethiopia

Worldwide a number of chronic or groundwater intake related health accidents have been documented since several millennia. These include (a) Linkage between lignite aquifers, pathogenic microbes, and renal pelvic cancer in northwestern Louisiana, U.S, (b) Nephrotoxicity of high-molecular weight organic compounds in drinking water from lignite aquifers (Bunnel et al. 2007), (c) Neurodegenerative disorders such as Guam amyotrophic lateral sclerosis/parkinsonism-dementia complex and Alzeimer disease may involve mis folding of specific proteins and, in some cases, are specific to certain geographical locations such Guam, West New Guinea, and the Kil Peninsula of Japan (Sahai 2007).

The linkage between (a) Iodine deficiency Diseases and geo-environmental setting, (b) between basalt weathering and elephantiasis, (c) fluoride and dental and skeletal flourishes has been long established (Dissanayake and Chandrajith 1999). The linkage between environmental setting and cattle's health is also observed in several locations including Ethiopia (Pugliese 1992). Dissanyake and Chandrajith (1999) reports that arsenic is a toxic and carcinogenic element present in many rock-forming minerals including iron oxides, clays and in particular sulphide minerals. When this arsenic gets into the groundwater through oxidation and subsequently into human body through drinking water, serious health hazards occur. Well documented cases of chronic arsenic poisoning are known in several parts of the world (Bangladesh, India, China).

Kebede (2009) shows the presence of clear spatial pattern of geochemical and geological diseases in Ethiopia. The patterns in geochemical diseases follow regional climatic, geologic and topographic situations of the country. The most prominent geochemical diseases recorded in Ethiopia include Elephantiasis which affect millions of people, iodine deficiency disorder which affect 42 million people, flourisis affecting more than 20 million. In Ethiopia high As concentration has been reported in groundwaters (Riemman et al. 2003; Kebede et al. 2010) in limited localities in the central sector of the rift but its consequence on health is not visible. Table 8.1 summarizes some geochemical elements and their health effect.

Non Filarial Elephantiasis

Non filarial elephantiasis is non infectious swelling of the feet (Price 1974). Its cause is not strictly related to groundwater. However, it is closely linked to rainfall, temperature and geology. Elephantiasis is common disease in all sectors of Ethiopia. However, previous reports (Price 1974, 1976) and field observation shows that the hot spots are located in South Central Ethiopia, Western and North Western Ethiopia. Elephantiasis is common in red soil covered areas of Woin-adega (humid high temperature area) climate and the incidence drops significantly as one move out of the red soil covered areas (Tekola 2005).

Table 8.1 Geochemical elements of major health concern and their effect on human health (*DD* deficiency disease, *ED* excess related disease)

Geochemical element	DD, ED or health benefits	Population affected 10^6	Remarks
Iodine	Lack of adequate iodine in foods and drinking water could lead to Iodine Deficiency Disorder (IDD). This causes goiter, cretinism, poor pregnancy, still birth, mental retardation and infant mortality. Iodine deficiency is the world's most common cause of mental retardation and brain damage and goiter incidence	42 deficient in I	Non guideline value exist
Fluorine	Dental caries increasing risk of dental fluorosis, and progressively higher concentrations lead to risks of skeletal fluorosis.	20 Excess F	Up 40 % of drinking water sources in the rift and up to 5 % elsewhere
Selenium	Deficiency in se causes symptoms such as muscular degeneration, impeded growth, fertility disorders, anemia and liver disease; excess may be toxic above 10 microgram/L, long-term selenium exposure are manifested in nails, hair and liver	Not known	Less than 1 % of water points from raya valley show se in excess of 0.01 mg/L
Arsenic	Excess cause: Toxic, dermal lesions such as hyper- and hypopigmentation, peripheral neuropathy, skin cancer, bladder and lung cancers	Not known	1 % and may reach 30 % in groundwaters in thermal water input
Nitrate	Methaemoglobinaemia	Not known	1 % Nationwide and up to 7 % in rift groundwaters

(continued)

Table 8.1 (continued)

Geochemical element	DD, ED or health benefits	Population affected 10^6	Remarks
Sulphate	Excess may have laxative effects and relate to gastrointestinal diseases	10	Up to 7 % of waters in the rift and higher in Ogaden and around Mekelle
Magnesium and Calcium	Reduce cardiovascular diseases (Mg) and reduces Osteoporosis (Ca)	10	
Boron	Excess may be related to toxicity	Not known	Up to 5 % of groundwaters in the rift and higher for groundwaters related to thermal waters, non of groundwaters from basaltic plateau show higher values
Uranium	Nephritis is the primary chemically induced effect of uranium in humans	Not known	Up to 1 % water points in the Ethiopian rift return U value above the WHO (10 microgram/L limit)

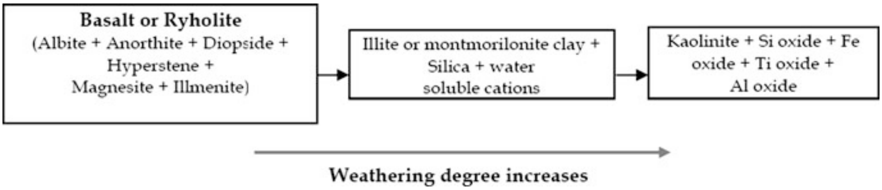


Fig. 8.1 Geochemical reaction model for the enrichment of elephantiasis causing agents in volcanic terrains of Ethiopia. (Note that any volcanic rock with initial alkaline or tholeitic composition may produce similar weathering end members.)

Apparently little research in earth sciences discipline is conducted as to investigate the correlation between volcanic rock geo-chemistry and elephantiasis prevalence. Despite this at the scale of African continent, correlation has been noted to exist between alkali basalt provinces and elephantiasis prevalence (Harvey et al. 1996). It is widely mentioned that intensive weathering of alkaline basalts yield particles of size less than 5 μm. These particles, when they get into human circulatory system via skin, are responsible for blockage of lymph. This is because the particles enter into the blood vessel and clog easy circulation of blood in the lower part of the feet. Microanalyses of particles from elephantiasis affected tissue show that particles are composed of Si, Al, Ti and Fe (Price 1974).

Regardless of the extensive research in geo-chemistry of volcanic rocks in Ethiopia the detailed investigation of the correlation between basalt geo-chemical variation in Ethiopia and elephantiasis prevalence remains unclear. However, the preliminary elephantiasis prevalence map in Ethiopia (Fig. 4.3) shows no apparent correlation between regional variations in volcanic rock geo-chemistry. In contrast to the suggestion made by Harvey et al. (1996) that elephantiasis prevalence correlation with alkaline basalt domains, basalts in elephantiasis prevalent area of Ethiopia are transitional or tholeitic in their mineralogy (Pik et al. 1998; Ayalew et al. 1999). This may suggest basalt geo-chemistry alone may not be responsible but degree of weathering should be responsible. However, there is a clear correlation between temperature, rainfall amount, altitude, rock and soil type and elephantiasis prevalence. The most prevalent areas correspond to intensive monsoon rain, highly leached laterite soils, high temperature, altitude varying between 1,000 and 2,500 m and volcanic rock cover. All this combination leads to the formation of thick red brown kaolinitic soil rich in Fe, Ti, Si and Al. The typical geochemical reaction which may lead to higher Fe, Ti, Si and Al in soils is shown in Fig. 8.1. Elephantiasis risk map (Fig. 8.2) has been drawn based on geology, elevation and rainfall information over Ethiopia. High risk area corresponds to basalt outcrop, rainfall in excess of 1,000 mm/year and topography ranging between 1,500 and 2,500 masl.

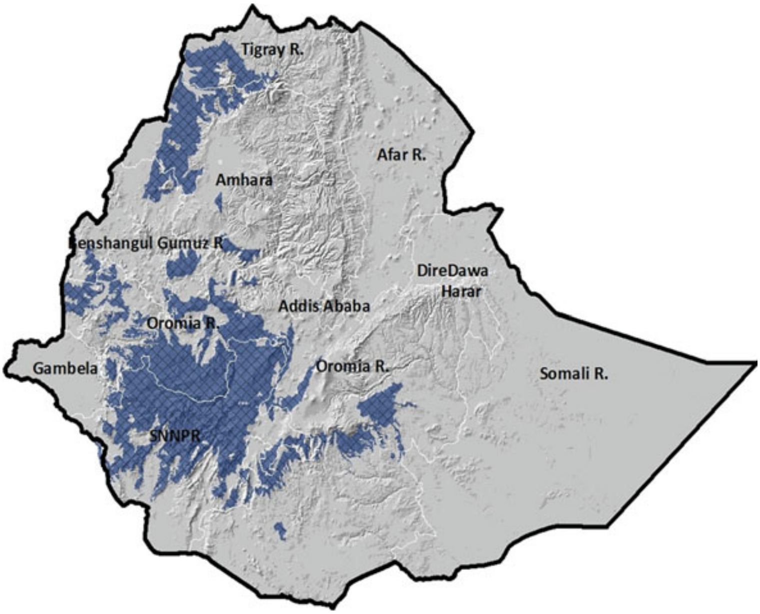


Fig. 8.2 Non-filarial elephantiasis risk zones

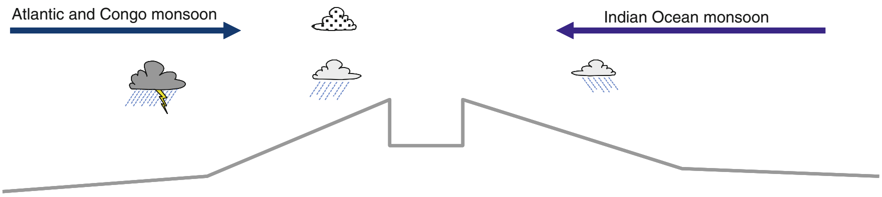
Iodine Deficiency Disorder (IDD)

The detail of geochemistry of iodine is discussed in Sect. 4.4. As more than 70 % of population in Ethiopia use groundwater for drinking purposes groundwater is one of the pathways through which iodine is introduced into human metabolism. The ultimate reservoir of iodine in the environment is sea water. Normally regions closer to see receive higher I content in rainfalls while inland continental setting contain little iodine in rainfall waters.

Western Ethiopia gets most of its rainfall from vapor that is derived from continental setting (the Congo vegetation basin in particular) which is presumably devoid of iodine content. Eastern Ethiopia gets its rainfall from a nearby Indian Ocean monsoon which because of its nearness to the moisture source presumably contains higher iodine content. Leaching of sediments in areas underlain by sediments (ex. Rift and SE Ethiopia) release I from sedimentary rocks of marine origin. Figure 8.3 shows the prevalence of IDD in Ethiopia. Figure 8.3 shows the causal mechanism of IDD prevalence in Ethiopia and Fig. 8.4 shows the IDD risk zones.

Mineral Waters and Health

There is no standard definition of mineral water. The World Health Organization does not have a separate standard for mineral waters. Often, groundwaters which



SW lowlands	NW highland	Rift	SE highland	
Warm; intensive chemical weathering, altitude 1000-2000 masl	Cold; orographic rain; lower degree of chemical weathering; rain total dissolved solids is higher	Warm and dry, high degre of Evaporation	Cold and wet, rain water dissolved solids is higher because of proximity to the ocean source	**Temperature**
Heavy monsoon, moisture from Atlantic & Congo vegetation, Low Iodine	Influx of dust particles from Sahel and Arabian continent, rain with relatively higher I	Low intensity rainfall, rain shadow effect	Monsoon moisture from Indian Ocean, higher Iodine owing to proximity to moisture source; rainfall amount lower than the NW plateau	**Rainfall derivation**
Highly leached, Fe, Al, Si reach regoliths and red brown soils dominate	Black cotton soil dominate the landscape, soils are thin on higher grounds	Salt reach, regosols and alluvio lacustrine soils	Black cotton soils dominate the landscape	**Soil**
Basalts and Metamorphic	Basalts with marine sediments in places	Acid volcanic rocks, basalts and lacustrine sediment, mantle fluid influx	Basalts and marine sediments in some places	**Geology**
Prevalent Elephantiasis **Prevalent Goiter**	Less prevalent goiter in intervening valleys and in sediment covered areas, less prevalent elephantiasis	Less prevalent goiter and elephantiasis, prevalent flourisis	Less prevalent Goiter, lower prevalent elephantiasis	**Geochemical disease**

Fig. 8.3 Schematic model of geochemical disease prevalence and geo-environmental setting in Ethiopia

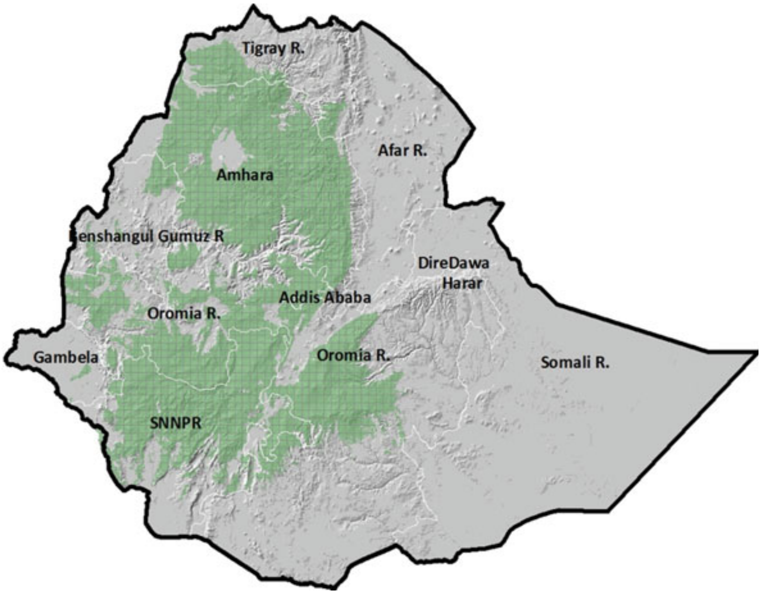


Fig. 8.4 IDD risk map

Table 8.2 Comparison of chemical composition of ordinary groundwater (OW) and naturally sparkling groundwaters (MW)

Locality	PH	TDS	K	Mg	Na	Ca	HCO_3	SO_4	Cl	F	NO_3	Type
Ambo	6.7	1651.9	27.5	39.4	314.0	52.9	1159.0	13.0	42.5	0.5	2.6	MW
Keseme kebena	8.2	1445.3	34.2	0.4	335.7	2.1	786.0	69.8	108.8	3.8	1.5	OW

Both (OW and MW) contain similar amount of total dissolved solids but the mineral waters show more balanced distribution of chemical constituents. Data from Kebede et al. (2005) and (2010)

are naturally carbonated, sparkling, warm at point of emergence, containing balanced constituents of mineral species, and contain appreciable amount of trace elements are considered as mineral water. Generally, mineral waters contain higher total dissolved solids. Unlike ordinary groundwaters naturally sparkling mineral waters contain most of the dissolved constituents at balanced and similar proportions. This is the result of CO_2 joining the waters and keeping the mineral constituents in dissolved forms. Table 8.2 shows the chemical composition of an ordinary groundwater and a naturally sparkling mineral water. It can be seen that regardless of their similarity in overall total dissolved solids the sparkling water contain balanced composition of all major elements.

Mineral waters by definition should provide balanced and rich elements for health. In normal waters, because of thermodynamic processes and separation of geo-chemical facies along ground-water flow paths, conditions are unfavorable to have similar abundance of each chemical element and rich mineral content. Ordinary groundwaters are rich in certain types of elements but not in others (e.g., higher in Na and K but negligible content of Ca and Mg). The presence of rich and diverse chemical elements in mineral waters makes them suitable for human metabolic functions and health.

Naturally sparkling groundwaters are rare worldwide. A rare combination of geological and geo-chemical processes is responsible for the occurrence of mineral waters. This requires natural source of carbon dioxide from deeper sources, cold and shallow groundwaters circulating at shallow depths, heat from deeper geologic sources, etc. In Ethiopia such a combination occurs in regions surrounding the Wonchi volcano, and in the Lake Tana graben (Fig. 4.4). Some naturally sparkling groundwaters are also noted in the Didessa valley. Reference can be made to see Sect. 2.14, and Fig. 2.13 on the origin of the naturally sparkling mineral waters.

8.3 Groundwater Pollution

Over all Ethiopia's groundwater aquifers show low level of anthropogenic pollution. Nevertheless natural pollution from Fluoride is the most prominent water quality challenge. Survey sponsored by UNICEF, WHO and Ministry of Health Ethiopia (Tadesse et al. 2006) shows, out of the 1,570 sites tested for thermo tolerant coliforms, fluoride, arsenic and nitrate, overall compliance with respective

WHO GVs and national standards is 68 %. When looking at individual supply technologies, overall compliance is highest for utility piped supplies (ca. 80 %) and lowest for protected springs (44 %). The most common source of pollution is from coliform bacteria related to lack to well head protection.

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Chapter 9
Groundwater as Strategic Resource

Groundwater resource is the pillar of socio-economic activity and environment functions. Unlike in most part of Africa where groundwater is stored in extensive continental scale groundwater reservoirs, the groundwater resources of Eastern Africa are known for their low storage and shallow circulation (UNESCO 2006). Therefore, the full attainment of guaranteeing food and water security and sustainable development under global environmental change largely depends on (a) the capacity of the water system to buffer the impact of global environmental change and (b) the degree of dependence of the socio-economic and environmental systems on water resources availability.

Surface waters are seasonal in their availability and respond immediately to climate change. Groundwater plays much enhanced role in buffering seasonality and long term trends. Beyond this function as climate change buffer, groundwater also plays important strategic role as instrument of reduction of rural poverty, as instrument of economic growth, as storage medium for CO_2 sequestration, as a tool of drought emergency response, as a tool in guaranteeing urban water supply, as a tool in dealing with guarantying the sustenance of livelihood of pastoral communities etc.

9.1 Groundwater as Moderators of Global Climate Change

The linkage between global climate change and local water resource availability lies in the fact that (a) aquifers, by storing and transmitting recharge waters, link/buffer/regulate the impacts of global climate changes on water resources availability and this in turn eventually impact socio economic functions and livelihoods, (b) the way (speed, volume, quality) aquifers respond to climate change varies from aquifer to aquifer. This variation in aquifer response is reflected in water resources availability (spring discharge, depth to water table, seasonality, quality, resilience of impacted

S. Kebede, *Groundwater in Ethiopia*, Springer Hydrogeology,
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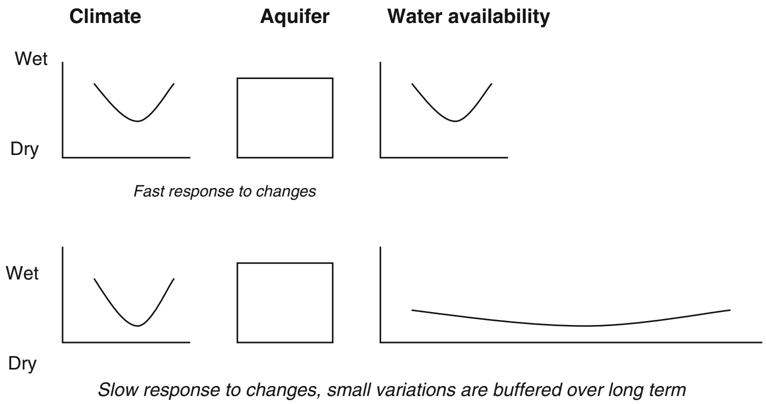


Fig. 9.1 Simplified diagram showing how aquifers respond to decrease in rainfall. The response of the aquifers, is the function of aquifer storage, amount of change, transmission, size etc. In the first case the aquifer responds rapidly to decrease in rainfall while in the second case response of the aquifer is felt over long period of time

water resources systems etc.). Aquifers also pose a physical limit/constraint on the maximum water availability in a given region. Figure 9.1 shows how different aquifers respond differently to climate changes or variability.

9.2 Groundwater as Buffers of Rainfall Seasonality and Buffering Capacity of Aquifers

Groundwater is the most important source of water during dry seasons, as well as during prolonged drought. Long after surface water sources like rivers and streams dry up, groundwater can still be accessed through wells, springs, and boreholes. This ‘buffering’ capacity—or the capacity of aquifers to store and transport water once recharge, or replenishment, to the aquifer (e.g. through rainfall) is reduced or stops—can vary significantly across different areas, and in some places, under certain conditions, groundwater sources can fail (Calow et al. 2002). A seasonal water calendar (Coulter 2008) shown in Fig. 9.2 demonstrate how a groundwater well supply water to the community throughout the year while other alternative water sources such as seasonal ponds and pools which dry immediately few weeks after the rainfall season, pons. Adequate number of wells in a village can guarantee water sourcing for the domestic water supply and livestock watering throughout the year. As can be seen from the figure challenges associated with use of pools and ponds for community water supply relate with incidence of certain kind of water borne diseases.

Groundwater resources as tool for climate change adaptation, rural poverty reduction and productive water depends on the capacity of the groundwater

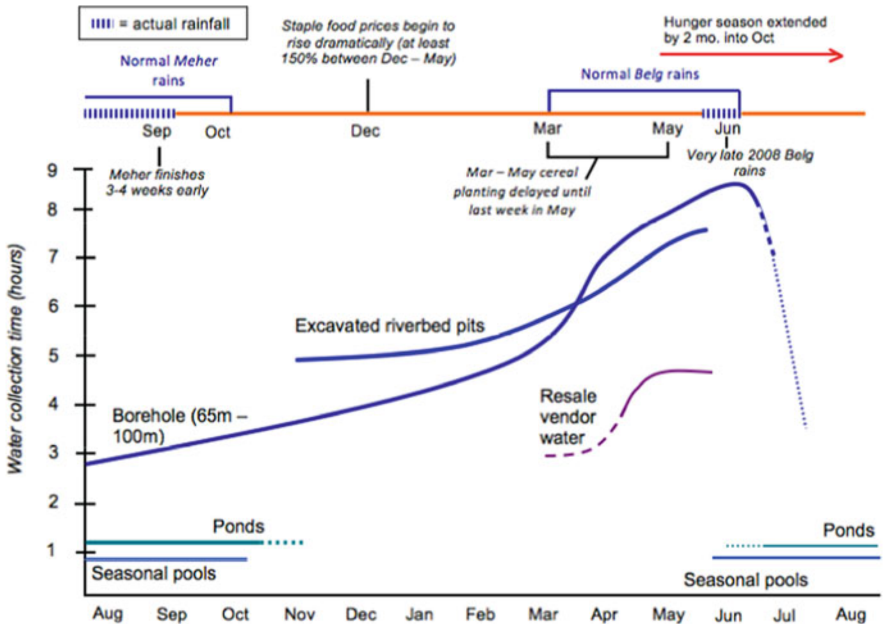


Fig. 9.2 Seasonal water calendar for the Alaba area in Ethiopian Rift. Figure shows that ponds and pools dry soon after the end of rainy season. The waiting time to collect water from the well in dry season can be reduced by drilling additional wells

aquifers to buffer the external changes (e.g. seasonality, increase or decrease in rainfall intensity, drought and flooding etc.) and local forcing (water abstraction rates). While total groundwater storage and total annual groundwater recharge are indicators of the potential of groundwater, two hydrologic properties are the determinants of the capacity of aquifers to buffer climate change, these are aquifer storage and recharge mechanism.

Loose sediments have the highest storage capacities while fractured volcanic rocks, fissured and karstified sedimentary rocks, indurated sedimentary rocks and lastly basement rocks have lower storage properties in that order. Figure 9.3 shows aquifer vulnerabilities to drought in Ethiopia. The loose sedimentary aquifers of the rift valley and rift bounding grabens, the shallow volcanic aquifers surrounding Lake Tana and the Alwero sandstone and associated sediments in Gambela show the lowest vulnerability to drought. The most vulnerable aquifers to climate change are the basement aquifers covering northern Ethiopia, Borena, and Western Lowlands.

Recharge mechanism refers to the way rainfall water gets to the aquifers. Principally five different ways can be recognized for Ethiopia (Fig. 7.2). Volcanic basement aquifers of western Ethiopia and Central Eastern highlands which are overlain by thick and well developed soils and regolith gets there recharge directly

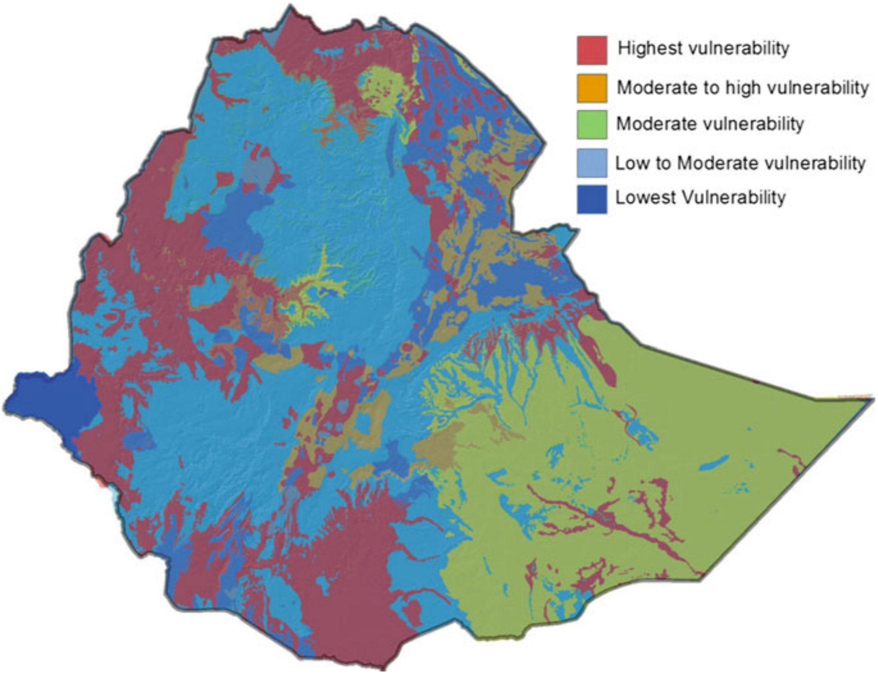


Fig. 9.3 Groundwater availability during drought periods. The lowest vulnerability corresponds to the highest storage potential of the loose sediment aquifers in the Rift valley and Gambela. The highest vulnerability correspond to shallow aquifers in the basement rocks

from rainfall via diffused sources once the soil zones exceed their moisture holding capacity. However, vast volcanic highlands and areas covered by basement rocks with thin regolith development and significant portion of the indurated sedimentary aquifers of Ethiopia gets their recharge from fast and selective recharge from only heavy rainfalls (light rainfalls evaporate back to the atmosphere in these regions) and discharge takes place usually to springs and streams. Aquifers in the rift valley and in grabens at the foot hill of the rift bounding faults get a significant portion of their recharge from lateral groundwater inflows from the mountains. In the Gambela lowlands and several other small places not indicated in the map aquifers get their recharge from flood water when the flood stage is higher. In this case the floods waters originate from the very basin were recharge is taking place. In arid marginal lowlands of Ethiopia recharge to groundwater come from local wadi floods and groundwater storage is also in the wadi beds.

The recharge mechanism map of Ethiopia has several implications in climate change adaptation. In future drought events characterized by short duration intensive rainfalls for example recharge is expected to increase in Afar, the areas which get their recharge from fast selective recharges. Recharge would decrease in areas that get their recharge from diffuse sources. As the extensive areas in the marginal lowlands of Ethiopia get their recharge from wadi bed floods and storage in wadi bed floods, the most appropriate technology for development of groundwater appears to be subsurface dams and sand dams. In the areas characterized by fast selective recharge from heavy rainfalls and fast discharge to springs and streams, the most appropriate technology for groundwater exploitation appears to gravity schemes or drilled wells.

9.3 Groundwater as Instruments in Reduction of Poverty

Risk Reduction and Rural Empowerment

Water availability through rain fed agriculture has proven to be unreliable, other water conservation and water harvesting programs (under SDPRP-Sustainable Development and Poverty Reduction Program 2002–2005) resulted in mixed results, groundwater could be a suitable recourse in some areas of Ethiopia. Because water interventions often have long-term impacts and consequences, if planned for properly, it would also strengthen prospective risk management.

There is no better example than Indian and Pakistan on demonstrating how groundwater exploitation lifted mass of rural people out of poverty in the last decades (Calow and McDonald 2009). Groundwater now contributes more to agricultural wealth creation than any other irrigation source (surface water or other schemes). In many developing nations groundwater has emerged as the primary democratic water source for poverty reduction. There are several advantages of using groundwater over other water sources in reducing poverty in rural livelihoods:

- Groundwater is democratic: Individual households can have access to water groundwater sources within their plot of land for self supply. Having control over their water means farmers invest more in their crops and so can get higher yields.
- The possibility to use groundwater for irrigation from shallow water holes opens new opportunities in micro-scale irrigation.
- Groundwater can buffer the effect of seasonal drought. In times of drought and towards the end of the dry season, use of groundwater for livestock watering can reduce migration in search for water supplies.
- Conjunctive use of shallow groundwater allows production of cash crops with high crop water requirements that cannot survive long periods between irrigations.
- The benefits of groundwater for farmers and irrigators are that the water is produced at or near the point of use, needs little transport, can be supplied “on demand” and “just-in-time”. In addition, because it entails significant incremental costs for lift, farmers tend to economize on its use, and therefore maximize application efficiency.

Calow and MacDonald (2009) argued although there is considerable potential for tapping groundwater in Ethiopia, the potential for irrigation on large scales is less favorable, as evidenced by a comparison of situations in Africa and Asia, where use of groundwater for irrigation is widespread. The success of groundwater-based irrigation in parts of Asia was made possible through infrastructure development, access to cheap energy, easy credit and market integration, which all served to catalyze private investment. In many parts of Ethiopia and Africa, however, these prerequisites have been missing and are difficult to achieve. Furthermore, 'low permeability of aquifers with limited storage account for 80 % of Ethiopia land area, so that while they are adequate for domestic use and small-scale, supplemental irrigation, they cannot support the kind of intensive development that has emerged over large areas of India, Bangladesh, or northern China'. Groundwater now sustains almost 60 % of the country's irrigated area.

Regardless of the assertion by Calow and MacDonald (2009) currently in Ethiopia massive investment is being made on groundwater use for irrigation accompanied by infrastructure development, increasing access to credit and market integration. This is possible through the various strategic development programs (see Sect. 9.4). Therefore Ethiopia can attain the same success stories that the South East Asian sub continent countries have attained over the last decades. Regardless of the low general storage of aquifers in Ethiopia compared to the alluvial aquifers of south east Asian sub continent, estimates show as much as 2 million ha of land can be irrigated using groundwater. The largest portion of this land is located in areas where highest groundwater storage and recharge are available. Examples are the intermountain grabens of western Afar depression, the Shinile alluvio lacustrine sediments, the Gambela lowlands, and various other areas underlain by alluvial sediments. Furthermore more recent studies (MWR 2007) show the yield of basaltic aquifers in central Ethiopia could reach 50–100 l/s, when they are under artesian condition and this could lead to feasible small to large scale commercial farming in areas covered by the quaternary basalts and the upper sequence of the trap basalts, given this aquifers are connected to sustainable recharge.

An elaborate study by Gebregziabher et al. (2009) demonstrate that in northern Ethiopian region of Ethiopia average income and income from off farm activities of irrigating households is greater than that of non irrigating households by as much as 50 %. According to this study, when three irrigation schemes are compared (miro dams, river irrigation and groundwater irrigation) irrigators with a micro-dam as their irrigation water source had significantly higher income than the comparable non-irrigators. They also had higher off-farm income. Similarly, groundwater irrigators had significantly higher income than the corresponding comparable non-irrigators. However, they had lower off-farm income, though the difference is not statistically significant. On the contrary, there was no significant difference in the overall income and off-farm income between irrigators with river diversion as their water source and the comparable non irrigators. When comparing the three irrigation typologies, the income effect of groundwater irrigation is highest. According to the study groundwater irrigators had lower off-farm labor participation than comparable non-irrigators. It might be that groundwater source is dependable, thus providing incentives for farmers to use their irrigation plots intensively rather than engaging in wage labor employment.

Groundwater Considerations in Economic Growth Strategies (SDPRP, PASDEP and GTP)

The country has embarked on three development strategies since 2000. These are the SDPRP between 2000 and 2005, The Program for Accelerated and Sustainable Development to End Poverty (PASDEP) between 2005 and 2010 and the Growth and Transformation Plan (GTP) between 2010 and 2015. Recognition of role of groundwater is increasing continuously in these successive strategic plans of Ethiopia.

At the core of the SDPRP was the Government's Agriculture Development Led Industrialization (ADLI). ADLI places a very high priority on agricultural growth, which remains the core of the government's poverty reduction strategy (SDPRP for 2002–2005 and PASDEP from 2005–2010). In this strategy, agricultural growth is expected to stimulate overall economic growth through higher farm incomes, providing a market for non-farm products and inputs, supplying cheaper food and raw materials for agricultural-based manufacturing, and mobilizing savings to finance investments. Conversion of ADLI into practice requires in addition to technology packages guaranteeing stable source water for agriculture. In pursuit of ADLI the government has put in place a series of policies. One such policy is the initiation of strong focus on safety nets, programs to build assets of food insecure households, resettlement, and soil and water conservation (especially water harvesting and small scale irrigation). At the end of SDPRP over 2,00,000 water-harvesting schemes has been constructed (MOFED 2005). Groundwater use did not extend beyond exploitation for domestic water supply. More investment in water conservation has been made in water insecure areas (moisture deficit highlands and lowlands). Little investment has been made in sustainable land management in moisture secure areas. According to a World bank (2007) for example, in the densely populated and lower rainfall highlands, many of the Government's programs of food security, land management, reforestation, and water harvesting have focused on supporting farmers in these areas.

In PASDEP the role of groundwater in reducing volatility and climate risk has been better factored. ADLI continued to be the drive of the growth. More than 15 project based multimillion birr budgeted groundwater resources evaluation has been initiated during PASDEP in different sectors of Ethiopia. With few exceptions, the synergy between the results provided by the groundwater investigation projects and overall PASDEP strategy has been weak. This is because the groundwater project mainly focuses on deep groundwater which cannot be available for rural community as it demands deep drilling and advanced technologies. Unlike the SDPRP which focus investment in water insecure areas PASDEP introduces a new concept of 'geographically differentiated strategy' (MoFED 2005). Accordingly, the strategy

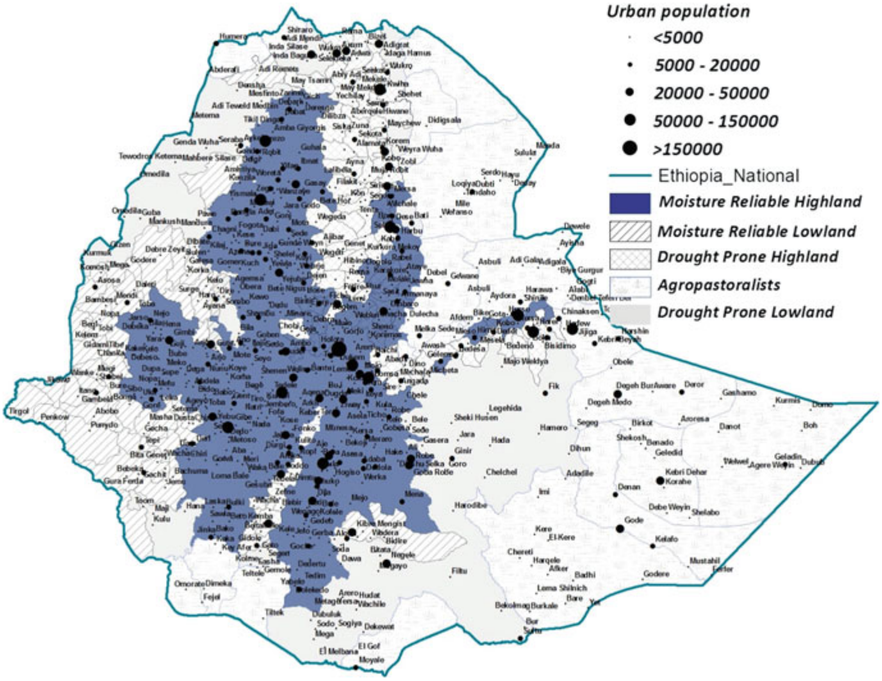


Fig. 9.4 The five agroecological zonation of Ethiopia, location and population sizes of urban centers and settlements

will take into consideration the varying geographical conditions in identifying development zones and to undertake appropriate activities suitable to the zones/areas. Five zones are recognized: moisture deficit highlands, moisture secure highlands, moisture deficit lowlands, moisture secure lowlands and agro pastoralist zones (see Fig. 9.4). As shall be shown later, some divergence exists between the surface water availability and groundwater resources availability in Ethiopia. For example the vast area of central sector of the rift valley, the Omo valley, the Gambela lowlands and the Afar zone etc. which are classified as moisture deficit lowland (or agro pastoralist zone) are underlain by high storage groundwater aquifers which could be exploited to reduce volatility associated with flood water harvesting and rainfalls.

Under PASDEP groundwater remains the basis of enhancing rural water supply. The plan for 5 years (2005–2010) targets the construction of 2,133 deep wells, 14,908 shallow wells, and 101,355 hand-dug wells, 404 ponds, 556 cisterns and 14 surface water sources and 11,065 spring development. Moreover, 48,510 schemes rehabilitation works had been planned to take place. These clearly show the recognition that role groundwater plays in growth endeavor. One of the success case stories ‘the floriculture industry’ in Ethiopia largely depend on groundwater exploitation.

Currently 1,500 ha of flower is grown (Ehpea 2011: http://www.ehpea.org) in central Ethiopia using groundwater as principal source of watering.

In the GTP the agriculture and water sectors fundamental strategy include the shift to produce high value crops, a special focus on high-potential areas, facilitating the commercialization of agriculture, supporting the development of large-scale commercial agriculture where it is feasible (MoFED 2010). Industrial sector is given particular emphasis. GTP recognizes well the role of groundwater plays in increasing agricultural productivity. Plans for pastoralist (pasture and water development) areas under GTP will largely depend on groundwater use.

In conclusion groundwater will play central role in growth strategies of the country. Groundwater now supplies more than 70 of domestic water use in rural Ethiopia. Large cities like Addis Ababa get up to 40 % of water supply and industrial water from groundwater. Groundwater exploitation is also the backbone of pastoral communities. The use of groundwater at household scale for small scale commercial irrigation is at its infancy (taking for example the Indian, Pakistan experience). Industrial expansion planned under GTP cannot be met without heavy reliance on groundwater exploitation. Thus a concerted effort is needed to continue mapping and describing the potential of aquifers to sustain the increasing demand. Investment in groundwater exploitation technologies and capacity building is imperative.

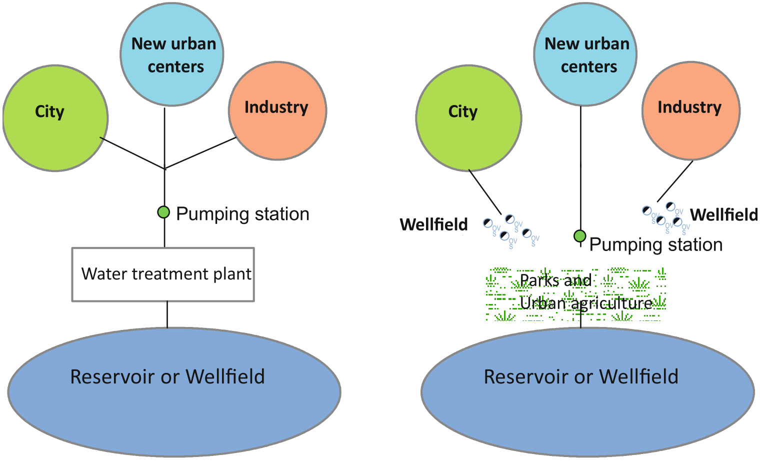
9.4 Groundwater and Urban Development

Many heavily populated areas can attribute their origins to groundwater which either emerged from the ground as cold springs of fresh, clear water or was drawn from shallow wells (Table 1.2). Role of groundwater in urban water supply in Ethiopia is increasing. Addis Ababa city draws more than 40 % of water supply from groundwater. Bahrdar, Diredawa, Mekelle, Derezeyit and several major towns in Ethiopia draw 100 % of domestic water supply from groundwater. The availability of water mainly as springs also was one of the prime drivers in the start of urbanization in Ethiopia. The level of dependence on groundwater is greater for smaller sized towns, which have lesser power to demand and have lesser economic strength to pay for surface water sources that are located at distant places.

Box 1: Some supply side measures to enhance Addis Ababa's water supply

Three measures are proposed among others for a better supply side measure to curb water supply challenges in Addis Ababa City. These are:-

Distributed waters sourcing: Modern views of urban development views distributed water sources or other service centers as a best option to increase foresight capability dealing with water scarcity and planning. In distributed water resources planning each sector of the socio economic activity rely on its own source from proximity. Groundwater use can be the best option in distributing water delivery to different sectors of the socio economic activity rather than relying on single water source from single place to all socio economic activity. The figure in the left show a centralized water sourcing where by all sectors of the urban area use water from centralized sources. Under this condition growth in any of the sub sector largely affect the other sector and this will complicate the foresight capability. The figure in the right shows more distributed water sourcing for different sub sectors of the urban area. Here change is demand-supply in one sector may not complicate the demand-supply issues in other sectors. Competition is reduced and foresight capability improved. Taking into account the various sources (three reservoirs, and two well fields) the distributing sourcing could be a possible alternative in Addis Ababa to improve foresight capability, better planning and management.



Reducing leakage and unaccounted water loss: Reducing water leakage: leakage loss account for more than 30 presence of water between its source and billing collected from the users

Sustainable city planning and urban agriculture: In Addis Ababa the surface waters are not widely used for industry or urban agriculture. Given appropriate restoration of the water quality and pollution status, the river waters could be used for industrial as well as urban water uses such as for fire fighting, cleaning, carwash, gardening and reducing pressure on existing water supply sources.

Figure 9.4 shows the population size of major settlements and their location with respect to the moisture scarcity and availability zonation. As can be seen from the figure, most of the settlements and large urban centers are located in moisture secure highland areas. An exception is the high urban population density in northern Ethiopia, and regions around Eastern plateau which occupy the moisture deficit highlands.

Groundwater strategic role in initiating, growing and sustaining urbanization is clear. Nevertheless two main challenges are facing at least locally this role. The first relate to local over exploitation and the second is local pollution. Certain urban centers are growing rapidly (population or industry) beyond the point which locally available groundwater supply can no more support the ever increasing demand. Outstanding examples are: Harar, Gondar, Mekelle and Axum. Harar town initially depended on Lake Alemaya which is now dry because of excessive groundwater pumping from its catchment for crop production and town water supply. Harar town now will have to depend (if successful and at higher cost) on groundwater transfer from the lowlands of Shinile. In Mekelle pumping of groundwater from the Aynalem well field has resulted in depletion of the water table significantly and the town is facing sever water scarcity currently. The same applies to Axum town in northern Ethiopia which now competes with Adwa town to meet its increasing demand. In some of the urban centers located in water stressed areas there is no luxury of turning to alternative remote sources. A clear policy direction and management strategy is urgently needed to curb this challenging situation. Multiple measures are needed ranging from local water resources management, artificial recharge, water recycling, multiple sourcing, etc. Table vii proposes supply side measure that could be taken to enhance water coverage and better water resources management in Addis Ababa City.

9.5 Groundwater in Emergency Responses

Groundwater Availability During Drought

Rainfall across much of the country is exceptionally variable and unpredictable, both in time and space, with year-on-year variation often exceeds 35 % around the mean. One consequence of this variability is endemic and unpredictable drought and flood, with enormous direct impacts of availability of water for human consumption, agriculture economic activities, and the environment (erosion and desertification). Yet Ethiopia has only 40 m^3 per capita water in storage capacity (Table 7.3) compared to about 800 m^3 per capita in South Africa where the variability is much lower.

Emergency situation in water supply provision can come from a number of reasons. These include (a) Limited foresight capability, (b) Natural or manmade disasters such as earthquakes, flooding, landslides, drought, etc., (c) Foreseen or unforeseen increase in water demand while there is limited institutional, financial and technical capability to address the increasing demand. In Ethiopia, groundwater resources have proven to provide populations with timely replacement of vulnerable water supply systems and make rescue activities more rapid and effective. Emergency water need in Ethiopia over the last two decades shifted from merely addressing manmade and natural disasters to combination of natural disasters and emergency need related to limitations of foresight capability and accompanied financial and technical limitations to address the problems. Box 1 shows some of the common water related emergency situations in Ethiopia.

Box 2: Typical water related emergency situations in Ethiopia

1. Large scale flooding is a recent phenomenon in Ethiopia. Last year (2006), flood occurred in different parts of the country, mainly along the major riverbanks and more than 600,000 people were affected with more than 600 deaths and a significant loss of property. Urban dwellers, farmers, and pastorals were affected by the flood. Although flooding may not be as frequent as the other hazards in Ethiopia, when it occurs its effect is damaging. The majority of the flooding last year occurred in July–August in the western, southern, and northeastern parts of the country, and in October–November in the southeast (Somali region).
2. Conflict, especially in pastoral areas is a serious impediment to pastoral livelihoods.
3. Rapid population growth and environmental degradation, especially in the eastern half, drought prone, crop dependent areas. As population increases with subsistence farming, the existing fragmented small plots of land are no longer able to feed and accommodate and hence the existing food insecurity was further exacerbated.
4. Recurrent droughts, affecting the whole eastern half of the country. Even the most resilient communities in both eastern crop dependent highlands and pastoral communities find it difficult to cope with severe drought that extends to several seasons. These vulnerable communities are always constrained to feed their families for some part of the year, especially during the typical hunger period of June–August for crop dependent areas and the typical dry periods of June–October and January–April for the pastoral population.

A notable case where groundwater has been targeted as water supply source for the emergency situation was the drought of the year 1984–1986 where Ethiopian population faced the most widespread drought and famine. For example in northern Ethiopian town of Mekelle a total of 46 wells had been drilled around clinics, schools, and refugee camps in order to address the need (drinking, hygiene, sanitary and cooking) for the population coming to refugee camps and towns (Vernier and Giuliani 1989). Nevertheless in Ethiopia out of 100 drilled wells between the year 1990 and 2010 more than 50 % are meant to address emergency water requirements. In the drought and displacement event of the 1984–1986 in Tigray region for instance the number of people in new demand on water supply has been three fold higher than the normal case scenario (Vernier and Giuliani 1989). These will pose a significant threat of aquifer storage.

The key to selecting a strategy for resuscitating regular water supplies during or following catastrophic events is the knowledge of regional hydrogeological circumstances. In many areas it will be difficult or impossible to provide emergency supplies from completely separate groundwater systems. In such cases, the existing supply system and aquifer would have been thoroughly investigated in order to temporary increase exploitation to tide over the emergency.

Governmental and municipal authorities, civil defense and the army should know where such groundwater resources are available in the areas repeatedly affected by, and prone to, natural hazards. A timely investigation and community participation are essential in developing the emergency infra structure that will function successfully in case of emergency.

An approach to break the challenges associated with emergency water supply is to know local hydrogeology, not only in terms of where groundwater circulates but also where it stagnates and yet can produce adequate, short-term yields with acceptable quality; and adjust thinking beyond the traditional approach to hydrogeological investigation and the conventional appraisal of groundwater resources. Factoring emergency scenarios into water resources supply and sanitation planning can be a key step in managing risks associated with emergency situations.

Water Sector Disaster-Risk Intervention Indicators

In emergency water intervention or water development prioritization where and when to intervene (either policy wise or response wise) is the challenging question. A few methodologies or indicators of intervention exist though not complete enough to be practicable.

Water Economy for Livelihoods (WELS): WELS uses analytical framework to account for and assess water and livelihoods needs for different socio-economic groups within communities (Coulter et al. 2010). Identifying the water availability, access and use patterns within livelihood zones will help policy makers to identify areas to monitor and target for interventions. The method is very rigorous and accounts several parameters: seasonality of water sources, seasonal water demand and use, household income, etc. WELS can, combined with information on population and livelihood strategies that exert pressure on water sources, provide information that enhance our understanding of the linkages between how seasonal water availability affects water access at household level during different periods of the year, and how these impact livelihoods opportunities and constraints and vice versa. Seasonal variability in water sources is important to the ability of households to access adequate water because it impacts which sources of water are available, the time and labor required for collection, and water quality (Coulter et al. 2010).

Water Poverty Index (WPI): Is a tool for monitoring and prioritization in the water sector development intervention (Sullivan 2002). The purpose of the WPI is to express an interdisciplinary measure which links household welfare with water availability and indicates the degree to which water scarcity impacts on human populations. The idea of a WPI is to combine measures of water availability and access with measures of people's capacity to access water. People can be 'water poor' in the sense of not having sufficient water for their basic needs because it is not available. They may have to walk a long way to get it or even if they have access to water nearby, supplies may be limited for various reasons. People can also be 'water poor' because they are 'income poor'; although water is available, they cannot afford to pay for it. The underlying conceptual framework encompass water availability, access to water, capacity for sustaining access, the use of water and the environmental factors which impact on water quality and the ecology which water sustains.

WPI provides such an easy-to-use indicator for the water sector. It can be used by water managers and planners, but at the community level, people can also apply it to their own situations, to understand how water can best be managed to meet their own needs, and to lobby for action.

9.6 Groundwater and Carbon Dioxide Sequestration Media

Groundwater in basalts are known for their capacity to fix CO_2 (Broecker 2008) into carbonate mineral when groundwater and basaltic minerals undergo geochemical reactions. Table 9.1 shows the different water rock geochemical reactions that are responsible to change CO_2 into carbonate minerals. These examples are taken from typical processes taking place in the aquifers associated with volcanic terrain in Ethiopia. Such geochemical reaction takes place in volcanic rock aquifers of the Trap series basalts and in the rift valley volcanic.

The trap volcanic cover an area at least 6×10^5 km^2 (around two third surface of the country), and a total volume estimated to be at least 3.5×10^5 km^3 (Mohr 1983) and probably higher than 1.2×10^6 km^3 according to Rochette et al. (1988). Water charged with abundant CO_2 reacts with basalt, releasing Mg bound in pyroxene and olivine, which then combines with carbonate to form highly stable $MgCO_3$ (magnesite). Water with lower quantities of CO_2 reacts with plagioclase, releasing Ca which forms $CaCO_3$ (calcite). Such reactions are known to occur in nature elsewhere in the world where recharge water charged with CO_2 interact with basalts. A number of researches on investigating geochemistry of groundwater in volcanic terrain of Ethiopia show such process whereby CO_2 is involved

Table 9.1 Geochemical reaction involving silicate minerals, water and CO2

CO_2 fixing reactions	Aquifers for which such reaction is proposed	Source
Plagioclase + Olivene + Pyroxene + K-mica + CO2(g) → Na-Mg-HCO3 water + Illite + Calcite + Fluorite	Plateau basalt	Kebede et al. 2005
Plagioclase + Olivine + Pyroxene + K-mica + trace gypsum + CO2(g) → Na-Mg-HCO3 water + Calcite + Illite + trace fluorite	Plateau basalt	
Plagioclase + Pyroxene + K-mica + trace fluorite + CO_2(g) → Na-HCO3 water + Chalcedony + Ca montmorilonite + trace Gypsum		
Plagioclase + Pyroxene + K-feldespar + trace gypsum and fluorite → Na-HCO_3 water Chalcedony + Calcite + Illite	Plateau basalt	
Plagioclase + Pyroxene + K-mica + trace gypsum +CO_2(g) → Ca-Mg- HCO_3 water + illite	Quaternary plateau basalt	
$2NaAlSi_3O_8 + 11H_2O + 2CO_2 = Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SIO_4$	Rift Valley volcanic aquifers	Darling et al. 1996

The reactions are responsible for conversion of CO_2 in HCO_3 or permanently into carbonate minerals such as calcite, magnesite or aragonite in reaction and fixed to carbonates (Table 9.1). Taking into account the bulk volume of basalt rocks of Ethiopia and their oxide ratios a total of 500 G tones of CO2 can potentially be sequestered in the terrain.[1]

9.7 Opportunities Around Groundwater

Market Opportunity

If Ethiopia is to attain the millennium development goal (MDG) at least 80,000 more groundwater wells will have to be drilled over the coming five years (until 2015). The agriculture sector development also need as much as the water supply sector doubling the amount of water wells to be drilled in Ethiopia. This is a huge market opportunity in investment in drilling and water harvesting technologies.

Investment Opportunities

Bottled water production is a profitable industry that is currently underdeveloped in Ethiopia. The most attractive groundwater types for bottled water production are naturally sparkling waters with high natural CO_2. These kinds of waters are rare worldwide. Often groundwater which are naturally carbonated, sparkling, warm at point of emergence, contain balanced constituents of mineral species, and contain appreciable amount of trace elements are considered as mineral waters (Table 8.2). Generally mineral waters contain higher total dissolved solids. Unlike ordinary groundwater naturally sparkling mineral waters contain most of the dissolved constituents at balanced and similar proportions. This is the result of CO_2 joining the waters and keeping the mineral constituents in dissolved forms.

Certain regions of Ethiopia contain naturally sparkling, soda springs rich in minerals and balanced chemical constituents (Fig. 4.4). The occurrence of naturally sparkling waters is rare because of the complex processes that are required to form them. A natural source of CO_2 gas, heat, and shallow circulating groundwater is needed. A number of places discharge naturally sparkling soda waters in Ethiopia. These include Senkele at Ambo, the flanks and Wonchi Volcano, the Didessa Valley, Bure Baguna, and the Lake Tana basin. Some of the Ethiopian mineral waters are equivalent in origin and composition to the globally acclaimed mineral waters such as San Pellegrino bottled water in Italy. It should be noted that there is a distinction between ordinary bottled waters and bottled mineral waters. Bottled mineral water is distinguished from other types of bottled water by its constant level and relative proportions of mineral and trace elements at

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[1] It should be noted that this refers to the total amount of CO_2 that can be sequestered given that the entire silicate minerals in the basalt converts to carbonate mineral by taking in CO_2.

the point of emergence from the source. Figure 4.4 show location of emergence of naturally sparkling mineral waters and potential sites for future investment. Currently the bottling water industry created more than 7,000 jobs. Given the uniqueness of certain types of groundwater particularly those indicated in Table 4.4 further investments can be made. Box 3 shows some facts about bottled water industry.

Bottled water

The problem of poor water quality in many urban centers has been one of the factors that have lead those who can afford it to turn to bottled water. Bottled water sales worldwide have increased rapidly with global consumption now at more than 200,000 M L a year. While the USA is the biggest consumer of bottled water, China has shown the strongest growth, increasing consumption by more than 15 % since 2003 (Beverage Marketing Corporation). The cost of producing bottled water is a serious concern. In the United States it is estimated that the production of bottles alone requires 17 M barrels of oil a year and it takes three liters of water to produce one liter of bottled water.

Source:http://www.pacinst.org/topics/waterand_sustainability/botled_water/bottled_water_and_energy.html

9.8 Groundwater-Energy Nexus

Water resources development and energy development are two strongly linked domains of development. Energy production and generation require water. Water pumping, treatment and transportation require energy. The way out of such nexus is through reduction of water conveyance or hauling distance and or through lowering of water treatment costs. No research has been done in Ethiopia in this line but it is apparent that groundwater use using manually operated wells, spring development and drilled wells can reduce significantly the energy requirement for water resources development by investing on surface water development. Increase in energy production wills also enhance groundwater pumping in rural Ethiopia.

9.9 Military Hydrogeology

Military activities have known to be driver of development of groundwater science. As indicated in chapter one, the first machine drilling ever was conducted in Ethiopia. This was operated by the British military led by the Napier while invading Gondar back in early nineteenth century.

Geological studies in Ethiopia started in the second half of the nineteenth century with the first Military expedition called the ‘Napier Expedition’ conducted between 1867 and 1868 by W.T. Bradford and his team. The team established the well known fivefold subdivision of the geology of northern Ethiopia into Basement, Adigrat sandstone, Antalo Limestone, Upper Sandstone and Trap series.

Several wells have been drilled in Ogaden and Borena lowlands by the Italian forces in 1930s. The wells drilled in Borena were later used as indicators of groundwater availability in the region and several other wells were later drilled around the vicinity of the Italian wells. The Italians (1939–1944) have also developed Gerbi spring, a water supply point of Yabelo town in southern Ethiopia. The spring emanates from fractured gneisses north of the town at elevation of 1,900 masl.

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Chapter 10
Groundwater Management

Groundwater management or managed groundwater development deals with legal, institutional, financial and technical aspects. Here more technical aspect of groundwater management with a brief touch to legal aspect is addressed. Groundwater management deals with managing uncertainty. Better groundwater management practice is that which factors uncertainty. Better management increases success of water schemes and increase efficiently. Management of groundwater operates within the national and international laws. Having appropriate institutional framework (e.g. linkage across institution in dealing with data, information and knowledge) is key to water resources management.

10.1 The Nature of Hydrogeological and Geological Sciences

Hydrogeology is science of uncertainty. The uncertainty partly arises from the fact that aquifers are hidden materials below the surface of the earth. Geology particularly volcanic geology and stratigraphy is complex. Groundwater flows are normally described by partial differential equations. Partial differential equations are solved if boundaries conditions are known. The goodness of the partial differential equation of groundwater flow is directly dependent upon accuracy of the boundary conditions used. Boundary conditions are geologic in nature and are only accurate if knowledge of the geology of the area is investigated in the highest detail, which is often difficult to achieve.

Over striving to unearth uncertainty or to have the right answer is costly and unnecessary. Uncertainty is normal in hydrogeology, the danger however is when practicing professionals forget this fact and feel or think they have got the answer. Table 9.1 shows the various responses to uncertainties and ways of dealing with them (Table 10.1).

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Table 10.1 Response to uncertainties in hydrogeoloigical analysis and various outcomes related to the responses made

Response	Outcome
Over striving to have the answer	Time taking, unachievable end, costly
Peer review	Input from new eye, input from new experience, lowers cost
Learning from doing	Saves cost but requires experience
Integrating methodologies to reduce uncertainty	Factual outcome, acceptable result, scientific approach and result may not be challenged unless new methods are used, working output, incur cost, shifting problem

Table 10.2 Water scheme failure rate by region (a) and by specific location (b)

Region	All surveyed		Developed springs		Hand pumps		Boreholes	
	Total	NF (%)	Total	NF	Total	NF (%)	Total	NF (%)
Benshangul	125	67	9	0	116	72	0	
Gambela	102	48	10	0	14	0	78	63
Somali	56	34	0		0		56	34
SNNPRS	830	32	155	10	208	37	467	38
Oromia	2571	24	1305	16	856	27	410	42
Amhara	634	22	359	27	248	17	27	0
Tigray	686	18	45	27	208	24	433	14
Total	5004	26	1883	18	1650	29	1471	33

Data source	Region/Basin	Total schemes	FN	NF	% Failed schemes
Genale Dawa Master Plan Study, 2007	Genale River Basin	1,159	433	294	40
Netsanet Kassa, 2007	Ziway Shalla				75
Desta Horecha	Mekelle Outlier	1,262	1,076	174	14
SNNRP	South Omo	5,445	3,895	1,560	26

10.2 Failed Groundwater Schemes in Ethiopia and Drilling Success Rate

In Ethiopia little documented evidence is available as to the causes of water scheme failures. Among professionals is the field it is believed that up to 70 % of developed water wells fail to deliver water after construction in some areas (Table 10.2). However at the time of drilling, success rate is generally higher and is estimated at 75–85 % (MWR 2006). Water scheme failure is significantly undermining return on investment and sustains the situation of water supply emergency. Among the major reasons of water scheme failures the following are documented in various reports

1. Decline in water table linked to seasonal change in water levels
2. Long-term decline in recharge
3. Discharge of poor quality water during drilling or after construction
4. Flooding of water points after construction
5. Poor design of water wells or water schemes
6. Corruption
7. Aging of water schemes and facilities
8. Corrosion (common problem around specific areas such as acid water and CO_2 rich groundwater regions

Lack of sustainability and reliability of water supply services are key problems in rural Ethiopia. The major causes of these problems include, but not limited to, the following:

- Dependency of users on support agencies (including the government) for covering both the investment and operation and management costs;
- Severely limited capacity of regional water bureaus to provide maintenance services;
- Poor sense of ownership of users towards the scheme;
- Lack of accountability and transparency of water committees;
- Political interference by kebele (sometimes woreda) administration;
- Passive participation of women in the management of water schemes due to cultural barriers;
- Unavailability of spare parts and maintenance service providers close to the user community;
- Lack of standardization of equipment used in water supply schemes;
- Inadequate community contribution to cover even the operation and management costs; and
- Poor financial management, including misappropriation, and absence of auditing.

Consequently, as several studies found it, a large percentage of rural schemes are not functional at any given time (Table 10.2).

To curb this problem the following action research may be needed, (a) investigate the root cause of water scheme failures factoring all geophysical and political/administrative causes and (b) screening the robustness of existing water schemes to deliver water under future water demand and climate change.

10.3 Appropriateness of Water Schemes

Table 10.2 show that nearly half of water schemes developed in Ethiopia for community water supply, irrigation or supplying urban centers fail or have at least substantially failed prior to delivering the desired objective. A number of reasons have been given as to the major causes of water scheme failures in Sect. 10.2. Principally though any water development planning should take into account the appropriateness of a given scheme prior to implementing it. Apparently no guideline exists in the literature on methods of determining or selecting the most appropriate scheme. Appropriateness of scheme is the determinant of schemes sustainability and effectiveness. It is a common practice to see in Ethiopia of selecting a scheme and over advocating it until it is realized that it does not work. Example includes the push towards small scale micro dam development and water harvesting scheme to enhance food security under the growth plan of Ethiopia called Sustainable Development and Poverty Reduction Program2000-005-SDPRP (see Sect. 9.3). Final evaluation of the schemes effectiveness reveal mixed result at the best or have failed in the majority of cases to bring about the desired objectives.

On the other hand many efforts have been excreted as to determine effectiveness of water schemes (e.g. MWR 2006) with little emphasis on comparison among different schemes or whether a given scheme is appropriate for a given hydroclimatic or geophysical setting. Here attempt is made to give a border perspective of determining schemes appropriateness for a given physical, environmental and hydroclimatic setting. Appropriateness is measured by the consideration of the physical, environmental, ethical, cultural, social, political, and economical aspects of the proposed scheme.

Determining Schemes Appropriateness

A number of schemes exist in order to exploit or store water for water supply. Schemes include Subsurface dams, rainwater harvesting and associated technologies, shallow wells, ponds, micro dams, large dams, hand dug wells, shallow boreholes, deep boreholes, springs or gravity schemes, river diversion, large diameters dug wells, solar powered wells, wind powered wells, interbasin water transport, 3R (recharge, recycle, reuse), fog collection, artificial rains, air well, hand pumps and treadle pumps, condensation bags, hippo water roller, roundabout play pump etc.

Subsurface dam: Unlike a conventional dam that stores water above the surface, a sand dam is a subsurface structure. The dam in constructed underneath the riverbed and traps and stores water between the pores of the riverbed's sand (Fig. 10.1). The benefits of this are great since the water does not evaporate from storage as it would in a conventional dam. Additionally, the sand acts as a natural filtration system making this subsurface water safe to drink. This type of dam is especially useful in seasonal rivers (rivers that only flow during the rainy season). Seasonal rivers appear to be dry when in fact the riverbed's sand contains water. A sand dam's components are subsurface dam walls and PVC (plastic) slotted pipes that are buried beneath the sand at a level equivalent to the bottom of the dam wall. The slots are covered with gravel before being buried in the riverbed's sand to prevent clogging. Water trickles down through the riverbed sand and gravel, into slotted pipes, where it is captured and piped to a storage reservoir tank.

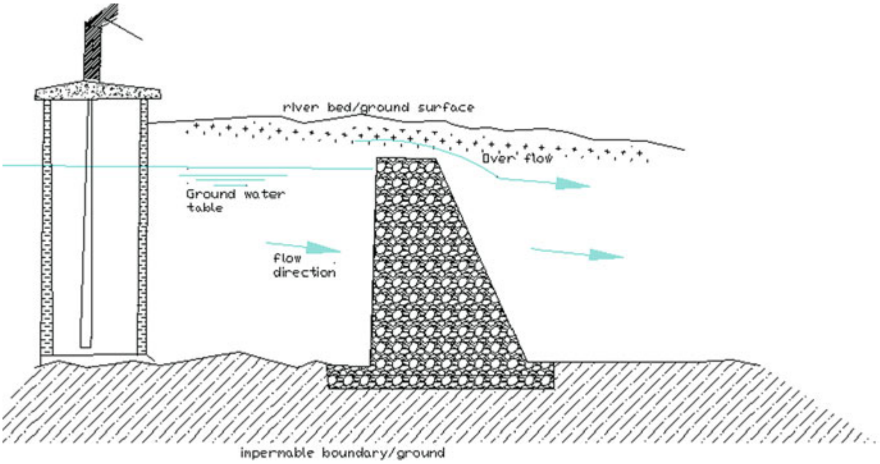


Fig. 10.1 Schematic figure showing a shape of a sand dam

From the storage tank it can be piped to various water points. The water will not need any treatment because of the natural filtration that it went through and will be safer than the local groundwater.

The most suitable site for locating sand dams is that which is covered by basement and sedimentary rocks which upon erosion give rise to sand and gravel materials to be deposited in the wadi beds, In this regard volcanic rocks whose weathering product normally leads to clay and silt materials may not contain suitable sand beds or gravels in the wadi beds. The advantage about the wadi beds in Ethiopian terrain is the fact that the head waters of the wadis are located in relatively high rainfall areas which would lead to availability of flood waters to recharge the wadi sediments even in the failure of rains in the lowlands (Fig. 3.16). Consideration in design of the sand dams include volume of flow generated from flash floods, permeability of bedrocks and abutment at dam site, the volume of flood generated with respect to the storage volume of the subsurface dam, stability of the wadi channel and its susceptibility to erosion, etc.

Sand dams are not appropriate for all locations (see Sect. 3.16, Fig. 3.16 and Box 1 for further reference). They require fresh and relatively impermeable bedrock at shallow depth; the dominant rock formation in the area should weather to coarse, sandy sediments; sufficient overflow is required for fine sediments to be washed away; and risk of buildup of soil and groundwater salinity needs to be low. Cooperative effort, ownership and ongoing maintenance by the local community are also necessary for the success of these schemes (Foster and Tuinhof 2004).

In Ethiopia, total wadi bed length is greater than 30,000 km. Assuming a five meter average wadi bed width, two meters effective wadi bed storage and 0.1 % porosity of wadi bed sediments the total groundwater that can be stored in the wadi bed sediments is estimated at 3 billion m^3. Sand dams are much widely used in Kenya and waters can be used for irrigation and household water supply and local cottage industries. The larger part of the flash floods volume will pass over the dam, but a small part of one single and short-lived flash flood may completely fill a reservoir with water.

Water harvesting using rock catchment: In arid and semi-arid lands, with large rock outcrops a lot of runoff is generated after rains. Through development of rock surface into a catchment, the runoff can be harvested and stored for domestic and livestock use to alleviate water shortages. In order to construct these schemes seven steps can be followed (Box 1).

Box 1: Steps in constructing water harvesting in rocky catchment

Step 1: Determine a suitable site with an expansive, impermeable rock out crop;
Step 2: Clear and clean the site off vegetation,
Step 3: Mark out the effective catchment area of the rock surface,
Step 4: Estimate the amount of runoff volume (m^3) anticipated = rainfall (m) × catchment area (m2) × runoff coefficient (normally 0.9 for rock surfaces). As a guide to the design of storage structure,
Step 5: Site the water storage structure or masonry gravity dam on the outer edge of a hollow or depression on the rock surface,
Step 6: Design the water storage structure or masonry gravity dam with capacity as in step 4,
Step 7: Estimate the material requirements for both the rock catchment and the water storage structure or dam.

Rainwater harvesting: An effective rainwater harvesting system requires a synergetic combination of different technological components, including a rainwater collection and storage system, and water saving irrigation system. The later will enhance the economical and effective use of water, while the former provides the required water. Three types of rainwater harvesting structures are commonly used in Ethiopia. This includes trapezoidal plastic lined ponds, hemispherical concrete tanks and dome shaped concrete structures.

The household level rainwater harvesting has many advantages compared to conventional small scale or large scale irrigation schemes, which are the conventional solution to rainfall variability and droughts. Firstly, it is suitable to the mountainous and rugged terrain of the country, where development of conventional irrigation schemes can be difficult or very costly. Secondly, construction, maintenance and management of the rainwater harvesting structures will be easy as it is a micro scale and household level enterprise; it does not require cooperation of, and collective action by, many households, which are normally the case with community ponds and irrigation schemes. The ownership of the rainwater harvesting facilities by individual farming households can be an incentive for the farmers to maintain and use the technologies. Thirdly, the cost of construction of the rainwater harvesting structures is minimal as compared to the conventional irrigation schemes, as it largely requires efforts of individual households. Fourthly, the household level rainwater harvesting technologies start to provide benefits within a short period of time as they do not require long construction delays, unlike the conventional small or large scale irrigation schemes. Fifthly, it is possible to disseminate the technology to many households in a few years.

Nevertheless, a number of negative consequences have been recorded in the implementation of this technology. Among this:

1. Loss of stored water because of development of cracks on the hemispherical concrete tanks and puncturing of the plastic lined ponds
2. Poor quality of water in ponds, and ponds can be sites of malaria and pathogen spreading with significant health risks
3. The storage capacity of rainwater harvesting structures sometime is far lower than the need

Combination of spate irrigation and shallow groundwaters: FAO-UNDP (1987) have defined spate irrigation as an ancient irrigation practice that involves the diversion of flashy spate floods running off from mountainous catchments where flood flows, usually flowing for only a few hours with appreciable discharges and with recession flows lasting for only one to a few days, are channeled through short steep canals to bunded basins, which are flooded to a certain depth.

The uncertainty stems from the unpredictable numbers, timing and volumes of floods, the occasional very large floods that wash out diversion structures, and the frequent changes to the wadi channel geometry from which the water is diverted. Substantial local wisdom has developed in setting up and constructing intakes, organizing water distribution and managing the flood waters and their heavy sediment loads.

According to Van Stenbergen et al. (2010) and references therein potentially a total of 140,000 ha of land can be irrigated in Ethiopia using spate irrigation. Where possible, access to groundwater substantially reduces the uncertainty inherent in spate irrigation and allows cropping of cash crops that cannot survive for long periods between watering. Spate flows enhance the recharge of the shallow aquifers. The same author describes the water resources issues associated with spate systems as follows.

The relation between spate irrigation and groundwater is complex. Spate irrigation offers opportunity for in situ groundwater recharge but, at the same time, reduces possible recharge downstream. The balance of opportunities and costs is site specific, and a careful assessment of potential and constraints of groundwater use and recharge needs to be done to understand the implications of proposed spate-related interventions. In particular, most of the water diverted onto the land by spate irrigation is accounted for by evapotranspiration, and the proportion of groundwater recharge is less. When designing spate irrigation systems, a careful assessment of the changes in water balance must therefore be performed at the level of the river basin to understand the implications on the overall hydrology of the wadi.

On the other hand, groundwater development in spate systems has the potential to considerably modify agricultural practices and can sustain highly productive farming. Where groundwater is available, the unpredictability associated with spate irrigation disappears, and farmers can rely on a safe supply of water for their production. Wherever groundwater development has been possible, farmers have taken advantage of it and harnessed water in a more productive way than that expected from traditional spate systems. Some estimates show that groundwater based irrigation is six times more productive than spate irrigation. Where recharge is possible, according to local aquifer and terrain conditions, it should therefore be considered as an integral part of the design of spate projects.

Gravity schemes (*springs*): Gravity can be used to exploit groundwater and surface water resources. Gravity schemes use cold springs emerging naturally in depressions, as karst groundwater discharge or at contact zone of lithologies. The highlands of Ethiopia underline by the volcanic cover and the Mesozoic sediments occupying the faulted and fractured highlands of Ethiopia are characterized by the densest spring water points (Fig. 2.36). The requirement of energy for their use is nearly zero as most can be developed and used only using natural force of gravity.

The suitability of spring for development above all depends on the variation in discharge (sustainability) of the spring across seasons and across drought cycles. Sustainability is rather dependent on their storage capacities. This means that high discharge does not necessarily imply a sustained flow. If springs of low reserve are compensated by high renewal rate, they can sustainably flow for long time. On the contrary, if springs of low renewal rate are compensated by big reserves, a sustained flow can be ensured. Identification of springs with sustainable flow has been a pre requisite prior to developing the spring for water use. At least two approaches exist to identify the suitability of springs. These are the Meinzer Spring discharge index and a more rigorous analytical method of Mangin (1970).

The Meinzer Spring Discharge Index (Vi) is the easiest and rapid method to determine the spring suitability and uses the maximum minimum and median discharge values and it is given by the relation

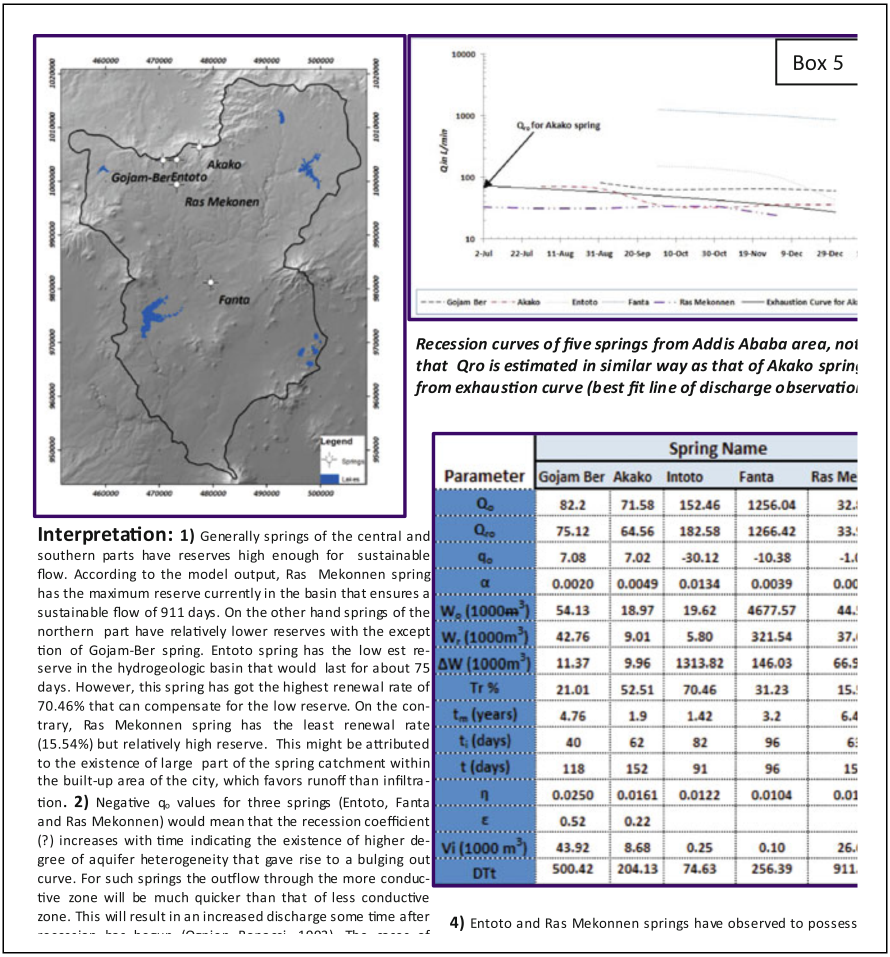
$$\mathrm{Vi} = [(Q_{max} - Q_{min})/ Q_{md}] \times 100$$

Vi is the percentage of variability, Q_{max} is the maximum discharge; Q_{min} is the minimum discharge, Q_{md} is the median discharge. Springs with $\mathrm{Vi} < 25\ \%$ can be considered constant discharge spring, while when $25\ \% < \mathrm{Vi} < 100\ \%$ is sub variable and variable springs when $\mathrm{Vi} > 100\ \%$. Investigation in several sector of highland-lowland transect across Ethiopia rift prove that springs in the highlands show the most variable discharge while in the mid section of the slope discharge is sub variable to constant (Kebede and Zeleke 2010; Debebe 2006). Highest discharge springs are noted in the limestone terrains of highlands of SE Ethiopia while in the volcanic terrain the discharge vary between less than 0.001 and over 500 l/s.

The Mangin (1970) method is based on rigorous mathematical analytical flow modeling of springs (Box 2). Here, first the emptying curves of springs are constructed from monthly discharge monitoring of the springs for one year. Water physico-chemical properties can also be measured for the determination of seasonal water quality changes. The recession curves drawn from spring discharge data will then be used to extract information such as the contribution of rainfall to the spring discharge, storage conditions of the spring reservoir, the recharge conditions (rate of recharge) and the current reserve for sustainable flow etc. The method is applicable even to very small discharge springs. Box 5 shows Mangin

Box 2: Steps in estimating spring hydraulic parameters using the Mangin (1970) analytical model

Springs parameters	Estimation
Q_t: Discharge of spring at end of exhaustion time t Q_{ro} is discharge at beginning of exhaustion η = coefficient of infiltration ε = coefficient of flow heterogeneity q_o = Initial contribution of infiltration t = total time of exhaustion	$Q_t = Q_{ro}\ e^{-\alpha t} + q_o \frac{(1-\eta t)}{(1+\varepsilon t)}$
W_r: The annual volume of water that regularly remains in the aquifer	$W_r = \int_0^\infty Q_{ro}\ e^{-\alpha t} dt$
V_i: Infiltration volume starting from maximum peak of the year	$V_i = \int_0^{t_i} q_o \frac{(1-\eta t)}{(1+\varepsilon t)} dt$
α: decay rate. Once Q_{ro} is estimated from the recession curve (semi log) of time vs discharge then determine α	$\alpha = \frac{(LNQ_{ro} - LNQ_t)}{t}$
q_t: total discharge from infiltration (In order to calculate q_t it is necessary to subtract, for every value of t (starting from t = 0), the value of Q on the curve from that of the straight line of the best fit. In doing so, a new curve labeled as q_o is generated. The curve is called curve of decrement	$q_t = q_o \frac{(1-\eta t)}{(1+\varepsilon t)}$
ε: coefficient of flow heterogeneity, can be estimated once V_i is obtained by iterative method t_i = duration of infiltration	$V_i = q_o \left[\frac{1}{\varepsilon}(1 + \frac{\eta}{\varepsilon}) LN(1 + \varepsilon t_i) - \frac{\eta t_i}{\varepsilon}\right]$
W_o: Dynamic Storage W_o is the reserve of the sources to the maximum piezometric height of the reservoir during the period of exhaustion ($t = t_o$)	$W_0 = \frac{Q_{ro}\ 1440}{\alpha}$
W_r: Regular reserve W_r is the volume of water stored between the minimal piezometric level and the measured level at the end of the time of exhaustion	$W_r = \frac{Q_{ro}\ 1440}{\alpha\ e^{\alpha t}}$
ΔW: Ability of emptying is the volume of water freed during the time of exhaustion (this is the dynamic resources at the time $t = 0$)	$\Delta W = W_0 - W_r$
T_r: Rate of renewal represent the quantity of water that has infiltrated from the total amount that was available to renew the aquifer storage in the course of the hydrologic year	$T_r = (\Delta W / W_0)100$
t_m: the minimum time of renewal expresses the minimum time necessary to replenish the water volumes of dynamic storage	



Recession curves of five springs from Addis Ababa area, not that Qro is estimated in similar way as that of Akako sprin from exhaustion curve (best fit line of discharge observatio

Parameter	Spring Name				
	Gojam Ber	Akako	Intoto	Fanta	Ras Me
Q_o	82.2	71.58	152.46	1256.04	32.
Q_{ro}	75.12	64.56	182.58	1266.42	33.
q_o	7.08	7.02	-30.12	-10.38	-1.
α	0.0020	0.0049	0.0134	0.0039	0.00
W_o (~~1000m~~^{3})	54.13	18.97	19.62	4677.57	44.
W_r (1000m^3)	42.76	9.01	5.80	321.54	37.
ΔW (1000m^3)	11.37	9.96	1313.82	146.03	66.9
Tr %	21.01	52.51	70.46	31.23	15.
t_m (years)	4.76	1.9	1.42	3.2	6.4
t_i (days)	40	62	82	96	6
t (days)	118	152	91	96	15
η	0.0250	0.0161	0.0122	0.0104	0.01
ε	0.52	0.22			
Vi (1000 m^3)	43.92	8.68	0.25	0.10	26.
DTt	500.42	204.13	74.63	256.39	911.

Interpretation: 1) Generally springs of the central and southern parts have reserves high enough for sustainable flow. According to the model output, Ras Mekonnen spring has the maximum reserve currently in the basin that ensures a sustainable flow of 911 days. On the other hand springs of the northern part have relatively lower reserves with the excepttion of Gojam-Ber spring. Entoto spring has the low est reserve in the hydrogeologic basin that would last for about 75 days. However, this spring has got the highest renewal rate of 70.46% that can compensate for the low reserve. On the contrary, Ras Mekonnen spring has the least renewal rate (15.54%) but relatively high reserve. This might be attributed to the existence of large part of the spring catchment within the built-up area of the city, which favors runoff than infiltration. **2)** Negative q_o values for three springs (Entoto, Fanta and Ras Mekonnen) would mean that the recession coefficient (?) increases with time indicating the existence of higher degree of aquifer heterogeneity that gave rise to a bulging out curve. For such springs the outflow through the more conductive zone will be much quicker than that of less conductive zone. This will result in an increased discharge some time after

4) Entoto and Ras Mekonnen springs have observed to possess

Box 3: Discharge Characteristics of Cold Springs

As can be noted from Fig. 3.36 in volcanic aquifers of Ethiopia the mean discharge of springs is close around 0.25 l/s, in several extreme cases discharge can go up to 500 l/s. The low discharge of the springs could be indicators of the nature of the aquifers. It may indicate that groundwater discharge is in the form of diffuse discharge as low discharge springs in depressions. Regardless of the faulting and fracturing in the aquifers still the porous flow type dominates the flow in the volcanic terrain. There is a notable difference in discharge characteristics of the springs from the Antalo Limestone sequence in Ethiopia. Generally the springs from limestones show higher discharge value compared to springs from volcanic terrains. This could probably indicate the fact that flow and storage in the limestone aquifers is dominated by fractures and karst features. There is a notable difference between the Antalo Limestone Sequence of Mekelle Outlier and that of the Harar-Bale Plateau, whereby the later show high discharge variability and relatively higher discharge springs. This reflects the differences in degree of fracturing and karstification. In Mekelle outlier the intercalation of marl within the Antalo super sequence leads to flows dominantly controlled by both fracture and porous medium while in the Harar plateau owing to low among of intercalated marl and shale in the Limestones high fracturing and karstification lead to karst and fracture related springs. Another notable feature is the least variable discharge of springs from basement aquifers of western Ethiopia. This low variability around a mean value of 0.25 l/s is indicative of principal flows taking place within the regolith layers with minimum contribution from fracture media flows, a process which could have resulted in strong discharge differences across the terrain. Springs from Marble also show high discharge values probably indicating flow and discharge controlled by fractures in marbles of Ethiopian basement.

(1970) based analysis of emptying curves of five springs from Addis Ababa. The method has been used to draw hydraulic and storage information about the springs. Box 3 summarizes major discharge characteristics of springs in Ethiopia.

Drilled wells: In drilled wells development, the most important question may be when to stop drilling once the water table is struck. At least two logical answers follow one ‘stop when you get enough water for the purpose’ two ‘stop when the full thickness of the aquifer is penetrated’. Other consideration[1] can be used to choose between these two options.

But the choice to be made between drilling multiple shallow wells of lower individual discharge vs. few deep wells of higher individual discharge can be addressed using a complex analytical modeling or pumping test approaches. Like the spring variability index one can determine aquifer specific capacity index. Specific capacity index (Si) can be calculated by segregating the wells into categories based on the formation penetrated depth, and comparing the distribution of the specific capacity index for each depth category. This calculation is important because often times in fractured volcanic aquifers specific yield, transmissivity and storage properties of aquifer decline with depth. Gebreslassie (2010) based on this approach compared specific index of wells with depth and age categories.

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[1] Do not drill unnecessarily deep; drill at the smallest diameter appropriate to the required discharge, pump and casing sizes; wherever possible use plastics rather than steel casings and screens; in appropriate geological formations, leave the hole open (uncased); use small, lightweight rigs wherever possible; carry out only the appropriate duration and specification of test pumping; package and cluster contracts whenever possible in order to reduce mobilisation costs.

The Termaber basalts (upper plateau basalt sequence) have mean specific capacity index that varies from 1.5 m/day for the shallow wells, 1.1 m/day for the intermediate depth wells and 0.29 m/day for the deeper drilled wells. The mean specific capacity of the Younger Termaber Megezez basalt is 0.55 m/day and the mean specific capacity of the relatively older Termaber Gugessa basalt is 0.06 m/day which implies the decrease of aquifer productivity of the Termaber formations with increasing age of the formation. The specific capacity index value also shows a decreasing trend with increasing boreholes drilled depth which indirectly implies that, shallow to intermediate depth have a better aquifer productivity than the deeply buried Termaber basalts. Therefore, drilling several shallow wells could be more appropriate than drilling deeper wells in Termaber formation. As assertion is based on few spot studies a detailed characterization of depth segregated aquifer

Box 4: The sunk cost fallacy of deeper drilling from Maréchal 2009

One can observe a gap between hydrogeological practice and science. The most probable reason to explain this gap is called, in psychological sciences, the escalation of commitment. This phenomenon is where people justify increased investment in a decision, based on the cumulative prior investment, despite new evidence suggesting that the decision was probably wrong (Staw 1976). In economics and business management, it is well known as the sunk cost fallacy: increasing the resources available to an unsuccessful venture in the hope of recovering past losses. More generally, the sunk cost effect is manifested in a greater tendency to continue an endeavor once an investment in money, effort, or time has been made. In water exploration, the escalation of commitment consists of drilling a borehole deeper in the hope of recovering the money wasted to drill the first dry meters. Once started, it is difficult to decide to stop drilling if the well is dry because the driller thinks that expected water-bearing structure could be a few meters away. This is similar to the compulsive gambler who needs, after losing, to gamble again to recover his losses. Of course, it can sometimes happen that a dry well becomes productive after deepening but, as suggested by the limited thickness of the active zone, it becomes a matter of luck.

This escalation of commitment for drilling deeper and deeper may be encouraged by drilling companies as the potential money gains are increased. In India, the cost of dry deep wells becomes unaffordable for most of the farmers. The rate of farmer suicides has reached high levels as they cannot reimburse loans undertaken for increased expenses, among which are well drilling costs. As water engineers and water experts, our duty is to contribute to end this unreasonable trend of well-deepening in hard rocks. This could be done by planning drilling better, and includes the a priori definition of a maximum drilling depth according to local hydrogeological knowledge and statistical information on the local relationship between yield and depth. After reaching that depth, instead of drilling deeper, the borehole should be closed.

productivity index of major aquifers in Ethiopia could be a helpful approach in groundwater resources exploitation and management.

An easier decision can be made in drilling of basement aquifers because a clear and now accepted conceptual model of groundwater productivity vs. depth is available from practices across the world. In drilling in basement rock terrains, hydrogeologists encounter the dilemma between investing more in drilling deeper hoping to strike water and abandoning the exercise of drilling. This dilemma in economics is widely studied and in water sciences is called the sunk cost fallacy (Maréchal 2009). It is described in Box 4. The conceptual model states the most productive zones are located at the base of regolith and the top of the fractured-weathered bedrock (Foster 1984; Acworth 1987; Taylor and Howard 2000). As a general rule, fractures near the bedrock surface are most numerous and have the largest openings, so that the yield of most wells is not increased by drilling to depths greater than the bottom of this active zone. Exceptions to this can occur where water-bearing faults or fractured zones, due to tectonic activity, are present at depths as great as 200–300 m. Nevertheless, statistically, it is clear that beyond the active zone, the probability of increasing the yield of a given well in basement rocks is very low. For the Ethiopian terrain maximum drilling depth in basement aquifers should not exceed 100 meters according to experience.

10.4 International Practices, Laws and Regulations on Groundwater

Regulatory issues are one of the major prerequisite to enforce certain groundwater management practices. The purpose of this section is to highlight some international and national laws pertaining to water in general and groundwater in particular.

Ethiopian 1960 Law on Ownership and Use of Water

Ethiopian Civil Code codifies a few articles (from Art. 1228 to Art 1256) pertaining to surface water, groundwater, rainwater use, sharing, ownership etc. Some of the selected articles are given in Table 10.3.

The Law of Trans-Boundary Aquifers

Trans-boundary aquifers have recently gained increasing recognition from monitoring and management point of view. This is because the vast majority of

Table 10.3 Excerpt from the Ethiopia's 1960 civil code on ownership and use of water and collective expropriation of property

Excerpt from Ethiopia's 1960 Civil Code on Ownership and Use of Water and Collective expropriation of property
Article 1255: *Under-groundwater*
1. Underground accumulation of water and rivers shall form part of the public domain
2. No person may without permission construct on his land a drilling exceeding one hundred meters of depth
Article 1235: *Prohibited works*
1. Whoever is entitled to use a well, spring or other water, whether running or still, may object to the construction of any work such as a sewer or latrine, capable of polluting the water used by him
2. He may require that any such work done in disregard of his rights be destroyed
Article 1248: *New springs*
1. The provision of article 1247 shall apply where an owner creates springs on his land by boring or underground works
Article 1447: *Water*
1. Waterways, lakes and underground accumulation of water shall be deemed to form part of the public domain
Article 1209: *Ownership of subsoil*
1. Ownership of land shall extend below the surface of the land to the extent necessary for the use of the land

countries shares aquifers with their neighbors. Political, socio-economical, cultural and other differences among the countries make the assessment and the management of internationally shared aquifers difficult, comparing with national ones. Table 10.4 shows excerpts from the International law of transboundary aquifers.

10.5 Transboundary Aquifers

Ethiopia-Kenya

Prominent geologic and geomorphic features of Ethiopia and Kenya and the east African regions in general are domal uplifting centered over Ethiopia and Kenya, rift valley traversing the Ethiopian and Kenya domes, and accompanied volcanism and sedimentation. These prominent tectono-geomorphic features are responsible for the regional drainage pattern. The border between Ethiopia and Kenya is approximately located at the intersection of the Ethiopian and Kenyan domes. These make the border region generally site of drainage convergence from the Kenyan and Ethiopian highlands to the border regions. The hydrography of the basins is a direct reflection of the geology and structures and is characterized by

Table 10.4 Table showing excerpts from the draft law of the transboundary aquifers

Excerpt from the Draft UN resolution on Trans-boundary aquifers
Obligation not to cause significant harm
Aquifer States shall, in utilizing transboundary aquifers or aquifer systems in their territories, take all appropriate measures to prevent the causing of significant harm to other aquifer States or other States in whose territory a discharge zone is located
Protection and preservation of ecosystems
Aquifer States shall take all appropriate measures to protect and preserve ecosystems within, or dependent upon, their transboundary aquifers or aquifer systems, including measures to ensure the quality and quantity of water retained in an aquifer or aquifer system, as well as that released through its discharge zones, are sufficient to protect and preserve such ecosystems
Recharge and Discharge zones
Aquifer States shall identify the recharge and discharge zones of transboundary aquifers or aquifer systems that exist within their territory. They shall take appropriate measures to prevent and minimize detrimental impacts on the recharge and discharge processes
All states in whose territory a recharge or discharge zone is located, in whole or in part, and which are not aquifer States with regard to that aquifer or aquifer system, shall cooperate with the aquifer States to protect the aquifer or aquifer system and related ecosystem
Planned activities
When a State has reasonable grounds for believing that a particular planned activity in its territory may affect a transboundary aquifer or aquifer system and thereby may have a significant adverse effect upon another State, it shall, as far as practicable, assess the possible effects of such activity
Before a State implements or permits the implementation of planned activities which may affect a transboundary aquifer or aquifer system and thereby may have a significant adverse effect upon another State, it shall provide that State with timely notification thereof. Such notification shall be accompanied by available technical data and information, including any environmental impact assessment, in order to enable the notified State to evaluate the possible effects of the planned activities
If the notifying and the notified States disagree on the possible effect of the planned activities, they shall enter into consultations and, if necessary, negotiations with a view to arriving at an equitable resolution of the situation. They may utilize an independent fact-finding body to make an impartial assessment of the effect of the planned activities
Protection in time of armed conflict
Transboundary aquifers or aquifer systems and related installations, facilities and other works shall enjoy the protection accord by the principles and rules of international law applicable in international and non-international armed conflict and shall not be used in violation of those principles and rules

complex networks of primary and captured drainages. Though localized in the great East African rift which is otherwise the site of volcanism and tectonism the major parts of the region straddling Ethiopia and Kenya are underlain by Precambrian metamorphic rocks, Mesozoic sediments, Tertiary volcanics, and thick Miocene to Quaternary sediments. In the shared basins of Ethiopia and Kenya the basement rocks are characterized by the lowest storage potential. Unlike many parts of central Africa where the basement rocks are overlain by up to a few tens of meter thick regolith (Chilton and Foster 1995) the basement aquifers of

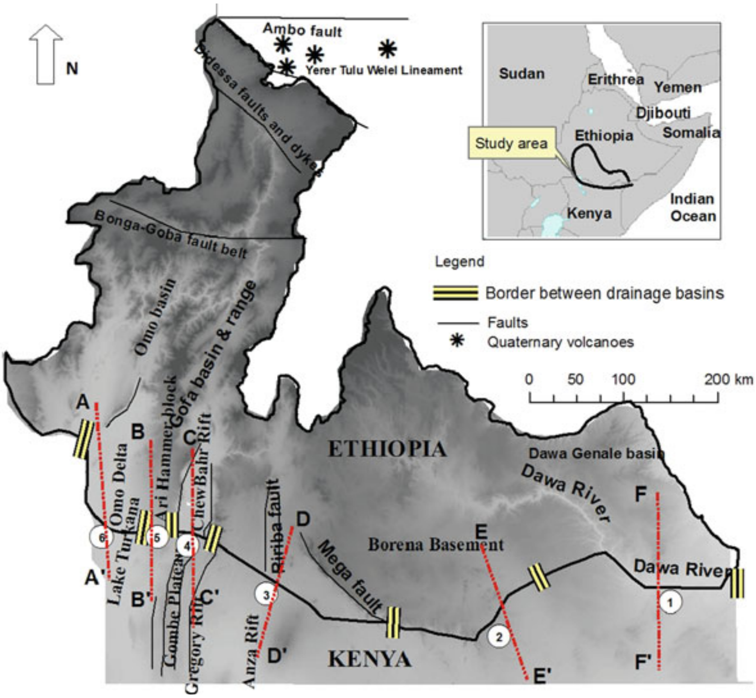
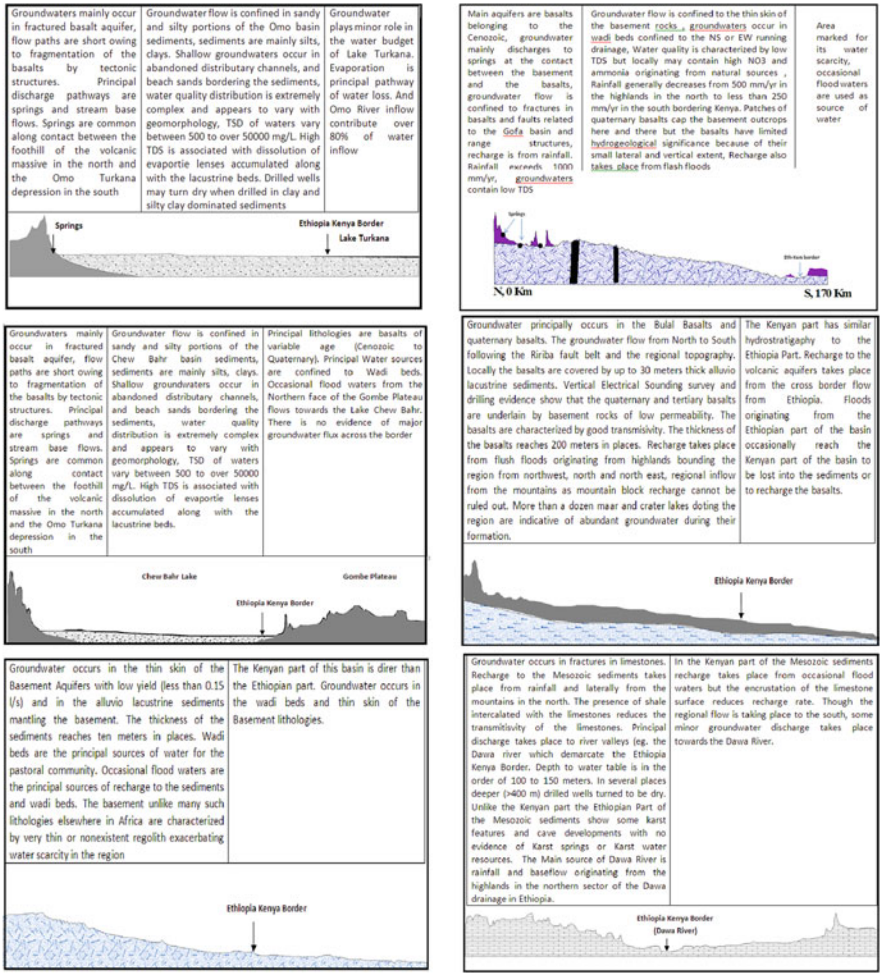


Fig. 10.2 Hydrographic, and topographic features of shared basin of Ethiopian and Kenya (Ethiopian part), *red* lines are profile lines along with hydrogeologic sections in Fig. 10.3 are constructed

southern Ethiopia and northern Kenya are characterized by only thin (in the order of 2–3 m) regolith thereby hampering groundwater flow and storage. Wadi bed sediments are the most prominent sources of groundwaters. Figure 10.2 shows hydrographic, topographic features of the shared basin. Figure 10.3 shows detailed hydrogeologic features (cross boundary flow, recharge and discharge conditions and water quality issues) along the shared hydrologic basin of Ethiopia and Kenya.

Ethiopia–Sudan

Ethiopia and Sudan share close to 1,600 km of boundary and three principal drainage basins including the Baro-Akobo, The Abay, Angreb, Rhad and the



Groundwaters mainly occur in fractured basalt aquifer, flow paths are short owing to fragmentation of the basalts by tectonic structures. Principal discharge pathways are springs and stream base flows. Springs are common along contact between the foothill of the volcanic massive in the north and the Omo Turkana depression in the south	Groundwater flow is confined in sandy and silty portions of the Omo basin sediments, sediments are mainly silts, clays. Shallow groundwaters occur in abandoned distributary channels, and beach sands bordering the sediments, water quality distribution is extremely complex and appears to vary with geomorphology, TSD of waters vary between 500 to over 50000 mg/L. High TDS is associated with dissolution of evaportie lenses accumulated along with the lacustrine beds. Drilled wells may turn dry when drilled in clay and silty clay dominated sediments	Groundwater plays minor role in the water budget of Lake Turkana. Evaporation is principal pathway of water loss. And Omo River inflow contribute over 80% of water inflow

Main aquifers are basalts belonging to the Cenozoic, groundwater mainly discharges to springs at the contact between the basement and the basalts, groundwater flow is confined to fractures in basalts and faults related to the Gofa basin and range structures, recharge is from rainfall. Rainfall exceeds 1000 mm/yr, groundwaters contain low TDS	Groundwater flow is confined to the thin skin of the basement rocks , groundwaters occur in wadi beds confined to the NS or EW running drainage, Water quality is characterized by low TDS but locally may contain high NO3 and ammonia originating from natural sources , Rainfall generally decreases from 500 mm/yr in the highlands in the north to less than 250 mm/yr in the south bordering Kenya. Patches of quaternary basalts cap the basement outcrops here and there but the basalts have limited hydrogeological significance because of their small lateral and vertical extent, Recharge also takes place from flash floods	Area marked for its water scarcity, occasional flood waters are used as source of water

Groundwaters mainly occur in fractured basalt aquifer, flow paths are short owing to fragmentation of the basalts by tectonic structures. Principal discharge pathways are springs and stream base flows. Springs are common along contact between the foothill of the volcanic massive in the north and the Omo Turkana depression in the south	Groundwater flow is confined in sandy and silty portions of the Chew Bahr basin sediments, sediments are mainly silts, clays. Shallow groundwaters occur in abandoned distributary channels, and beach sands bordering the sediments, water quality distribution is extremely complex and appears to vary with geomorphology, TSD of waters vary between 500 to over 50000 mg/L. High TDS is associated with dissolution of evaportie lenses accumulated along with the lacustrine beds.	Principal lithologies are basalts of variable age (Cenozoic to Quaternary). Principal Water sources are confined to Wadi beds. Occasional flood waters from the Northern face of the Gombe Plateau flows towards the Lake Chew Bahr. There is no evidence of major groundwater flux across the border

Groundwater principally occurs in the Bulal Basalts and quaternary basalts. The groundwater flow from North to South following the Ririba fault belt and the regional topography. Locally the basalts are covered by up to 30 meters thick alluvio lacustrine sediments. Vertical Electrical Sounding survey and drilling evidence show that the quaternary and tertiary basalts are underlain by basement rocks of low permeability. The basalts are characterized by good transmisivity. The thickness of the basalts reaches 200 meters in places. Recharge takes place from flush floods originating from highlands bounding the region from northwest, north and north east, regional inflow from the mountains as mountain block recharge cannot be ruled out. More than a dozen maar and crater lakes doting the region are indicative of abundant groundwater during their formation.	The Kenyan part has similar hydrostratigaphy to the Ethiopia Part. Recharge to the volcanic aquifers takes place from the cross border flow from Ethiopia. Floods originating from the Ethiopian part of the basin occasionally reach the Kenyan part of the basin to be lost into the sediments or to recharge the basalts.

Groundwater occurs in the thin skin of the Basement Aquifers with low yield (less than 0.15 l/s) and in the alluvio lacustrine sediments mantling the basement. The thickness of the sediments reaches ten meters in places. Wadi beds are the principal sources of water for the pastoral community. Occasional flood waters are the principal sources of recharge to the sediments and wadi beds. The basement unlike many such lithologies elsewhere in Africa are characterized by very thin or nonexistent regolith exacerbating water scarcity in the region	The Kenyan part of this basin is direr than the Ethiopian part. Groundwater occurs in the wadi beds and thin skin of the Basement lithologies.

Groundwater occurs in fractures in limestones. Recharge to the Mesozoic sediments takes place from rainfall and laterally from the mountains in the north. The presence of shale intercalated with the limestones reduces the transmitisvity of the limestones. Principal discharge takes place to river valleys (eg. the Dawa river which demarcate the Ethiopia Kenya Border. Depth to water table is in the order of 100 to 150 meters. In several places deeper (>400 m) drilled wells turned to be dry. Unlike the Kenyan part the Ethiopian Part of the Mesozoic sediments show some karst features and cave developments with no evidence of Karst springs or Karst water resources. The Main source of Dawa River is rainfall and baseflow originating from the highlands in the northern sector of the Dawa drainage in Ethiopia.	In the Kenyan part of the Mesozoic sediments recharge takes place from occasional flood waters but the encrustation of the limestone surface reduces recharge rate. Though the regional flow is taking place to the south, some minor groundwater discharge takes place towards the Dawa River.

Fig. 10.3 Hydrogeologic section along profile lines (Fig. 10.2) describing groundwater recharge, flow and discharge conditions in shared basins of Kenya and Ethiopia (Ethiopian part)

Tekeze. Along this line the two countries share one principal aquifer called the Alwero sandstone aquifer underlying much of the Baro Akobo basin (see Figs. 3.4, 3.5 and Sect. 3.4 for details about Alwero sandstone aquifer).

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