SINET: Ethiop. J. Sci., 38(2):91-110, 2015 ISSN: 0379–2897 (Print)

2520–7997 (Online)

REVIEW OF HYDROGEOLOGY OF TEKEZE RIVER BASIN: IMPLICATIONS FOR RURAL AND URBAN WATER SUPPLY IN THE REGION

Ermias Hagos[1] , Tenalem Ayenew[2], Seifu Kebede[2] and Mulugeta Alene[2]

[1]Department of Geology, Addis Ababa Science and Technology University, PO Box 16417, Kilinto, Addis Ababa, Ethiopia. Email: ermiash2010@gmail.com
[2] School of Earth Sciences, Addis Ababa University, PO Box 1176, Addis Ababa, Ethiopia.

ABSTRACT: This paper reviews the available published and unpublished data on the geology, hydrology and hydrogeology of the Tekeze River Basin (TRB) with the aim to better conceptualize the hydrodynamics of the basin and its implications on the water resources potential for the development of rural and urban water supply system. The work also highlights some of the knowledge gaps to fully understand the hydrogeology of the basin and proposes better scientific approach that will lead to the understanding of the movement and occurrence of groundwater in the complex river basin. The TRB constitutes different rock types with ages ranging from Precambrian to Quaternary. These rocks are affected by different sets of faults, folds and lineaments with different orientations. The groundwater occurrence and flow is strongly controlled by the geomorphology, geological structures, type of rock and their hydraulic characteristics. The major aquifers in the basin are the Trap Basalts, the Antalo Limestone Formation, the Adigrat Sandstone and Quaternary sediments. An increase in permeability in shales and marls is observed due to the presence of dolerite dykes and sills. The Neoproterozoic basement rocks and associated intrusive bodies, and the Paleozoic sediments are characterised by shallow and localised aquifers. In many places the igneous intrusive bodies act as aquicludes. The major faults and associated drag folds in the basin form favourable conditions for groundwater recharge and groundwater localisation irrespective of lithology.

Keywords/ phrases: aquifer, groundwater, hydrostratigraphy, northern Ethiopia, Tekeze River Basin

INTRODUCTION

Approaches and methodology

In preparing this review article, pre-existing geological and hydrogeological maps and reports, structural data (more than 200), geophysical VES data (more than 150), borehole logs (more than 800) and pumping test data (more than 80), springs location and discharge data (more than 170) within the Tekeze River Basin (TRB) in Ethiopia were collected from various sources: MWR/Ministry of Water Resources Unpublished data, 1998; FWWDSE, 2007; WWDSE unpublished data, 2009; Tesfamichael Gebreyohannes *et al*., 2010; DH consult unpublished data, 2010; Ermias Hagos *et al*., 2015. These were used to synthesize the existing knowledge on the groundwater occurrence and flow pattern and their implications on the rural and urban water supply in the region. An attempt has been made to identify gaps and give recommendations for further study.

Location, physiography and climate

The TRB, which constitutes part of the Nile Basin in Ethiopia (NBE), is found in northern Ethiopia between 11^{0}40′ and 14^{0}51′ N latitude and 36^{0}40′ and 39^{0}50′ E longitude. It is bounded by the Blue Nile (Abay), Angereb and Mereb river basins and the Afar Rift (*Fig 1*) and has a catchment area of about 45694 km^2 within Ethiopia.

The basin has extremely variable topography (*Fig 2*). The altitude ranges from 500 m in most of the western lowlands to over 4000 m on the Ras Dashen Mountains. Broadly, the basin can be divided into three physiographic regions: the highlands, intermountain valleys and grabens and the western lowlands (Fig 2). A significant portion (70%) of the basin belongs to the highlands (over 1,500 m amsl) situated west of the Afar Rift (*Fig 2*). This region is characterised by flat-topped plateaus to undulating topography with intervening large volcanic mountains which form water divides and act as regional groundwater recharge zones. The highlands are deeply cut by major rivers and their tributaries which form deep canyons and gorges with steep and narrow river valleys. These areas have high surface runoff and are characterized by waterfalls and rapids.

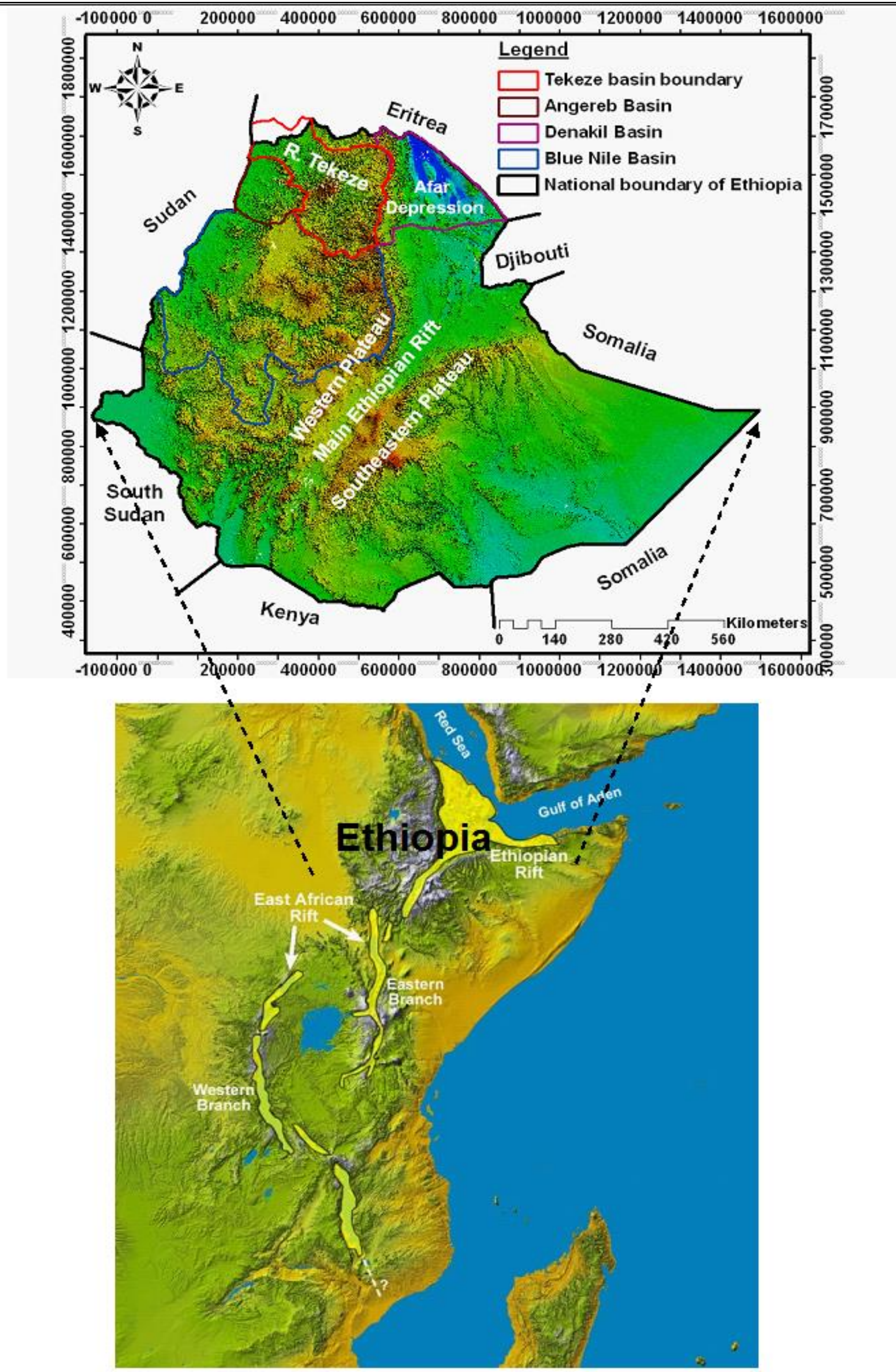

Figure 1. Location map, watershed boundary and major rivers of the TRB.

Along the course of these valleys, there are numerous springs that emanate along the contacts of the different rock units (mainly between the Mesozoic sedimentary rocks and the Trap series volcanics) and talus deposits and hence act as discharge areas. The western lowlands are found in a strip of about 150 km long and 30 to 100 km wide adjacent to the Sudanese border. Here, the elevation varies from 500 m to 1000 m with flat to slightly undulating topography.

The climate in TRB varies significantly in space and time. It is characterised by unimodal rainy season lasting from June to September when the Inter Tropical Convergence Zone (ITCZ) is located north of Ethiopia, with the exception of a small rainy season occurring in March-April, when the ITCZ is passing over Ethiopia northwards (Daniel Gemechu, 1977; WWDSE, 2009). The amount of rainfall decreases towards the northeast. However, local orographic effect results in high rainfall in mountainous areas. The annual rainfall varies from over 2000 mm in the Ras Dashen Mountains to less than 500 mm in the central and north-eastern parts of the TRB (WWDSE, 2009). The rainfall in the highlands gives rise to concomitant high discharge of rivers during the rainy season, whereas the dry season is characterized by low flows (*Fig 3*).

The temperature, wind speed and humidity are also highly variable with altitude and latitude. Mean annual temperature varies from over 30 ^{o}C in the tropical western lowlands to less than 10 ^{o}C at high mountain peaks. Based on the classification by Daniel Gemechu (1977) most of the highlands belong to *Kur* and *Weina Dega* while the lowlands are *Kola* and *Bereha* (Table 1.).

Table 1 Climate classification based on altitude and temperature (Daniel Gemechu, 1977)

Altitude (m.a.s.l)	Mean annual Temperature (^{o}C)	Description	Local name of climatic classes
3,300 and above	10 or less	Cool	*Kur*
2,300 - 3,300	10 - 15	Cool temperate	*Dega*
1,500 - 2,300	15 - 20	Temperate	*Weina Dega*
500 - 1,500	20 - 25	Warm temperate	*Kola*
Below 500	25 and above	Hot	*Bereha*

1.3. Hydrology

The rivers of the Abay basin contribute, on average, over 65% of the average Nile total at Aswan dam. Together with contributions from the Baro-Akobo and Tekeze rivers, Ethiopia accounts for 86 percent of the run-off at Aswan (EMA, 1999). The length of Tekeze River, from its source at springs near Lalibela downstream to the Ethio-Sudan border, is approximately 750 km. The river slope is quite steep in the mountainous stretch (>1.5%), but decreases gradually to 0.3%, and then to less than 0.1% in the lowlands. The mean annual flow of the Tekeze river at the Ethio-Sudan border is around 5600 MCM. The main tributaries of Tekeze, which originate from the eastern highlands, are Tsirare, Insia, Zamra, Giba, and Werii while those originating from Mount Ras Dashen are Zarima and Beleghes (*Fig 2*). The mean monthly stream hydrograph of some small rivers (Giba River and its tributaries) (*Fig 4*) that are found in the north eastern part of the basin have similar shape with that of the main Tekeze river (*Figs 3 and 4*) indicating similar seasonal fluctuations. The fact that high flows are recorded in the summer season and very low flows in the dry season (sharp recession curve) indicates that much of the rain water leaves the basin in the form of direct runoff and only a small proportion recharges the groundwater.

GEOLOGICAL SETTING

The geology of Ethiopia can be divided into three major age categories: the Neoproterozoic basement, Late Paleozoic to Early Tertiary sediments, the Cenozoic volcanics and associated sedimentary rocks. Large parts of the stratigraphic succession have been affected by Cenozoic rifting (EIGS, 1996). The TRB constitutes diversified rock types ranging from Neoproterozoic basement rocks to Quaternary sediments (*Fig 5*) and is characterized by complex tectonic structures.

Neoproterozoic basement

The Neoproterozoic basement is exposed in TRB where all the younger rocks have been removed by erosion. It is composed of low grade metavolcanics, metagraywackes, slates, schists, carbonates and plutonic rocks (Arkin *et al*., 1971;

Beyth, 1971; Garland, 1980; Tarekegn Tadesse, 1997; Mulugeta Alene, 1998; Mulugeta Alene *et al*., 2000, 2006). The rocks are categorized into the older, largely metavolcanic unit (the Tsaliet Group) and the younger dominantly metasedimentary unit (the Tambien Group) (*Fig 5*). These rocks along with associated intrusive rocks belong to the Arabian-Nubian Shield (ANS) that developed during the East African Orogeny (Stern, 1994; Mulugeta Alene, 1998; Mulugeta Alene *et al*., 2000, 2006). The ANS is considered to have evolved through the opening and closure of oceanic basins, formation and accretion of island arcs, followed by terrain amalgamation and collision processes (Stern, 1994; Meert, 2003). As a result, the basement rocks of TRB possess tectonic fabric as well as low grade metamorphic features typical of ANS rocks. The rocks have been subjected to two major, N-S and E-W regional compressions producing various folding phases and pervasive foliations and associated lower greenschist facies metamorphism (Mulugeta Alene, 1998; Mulugeta Alene *et al*., 2000, 2006).

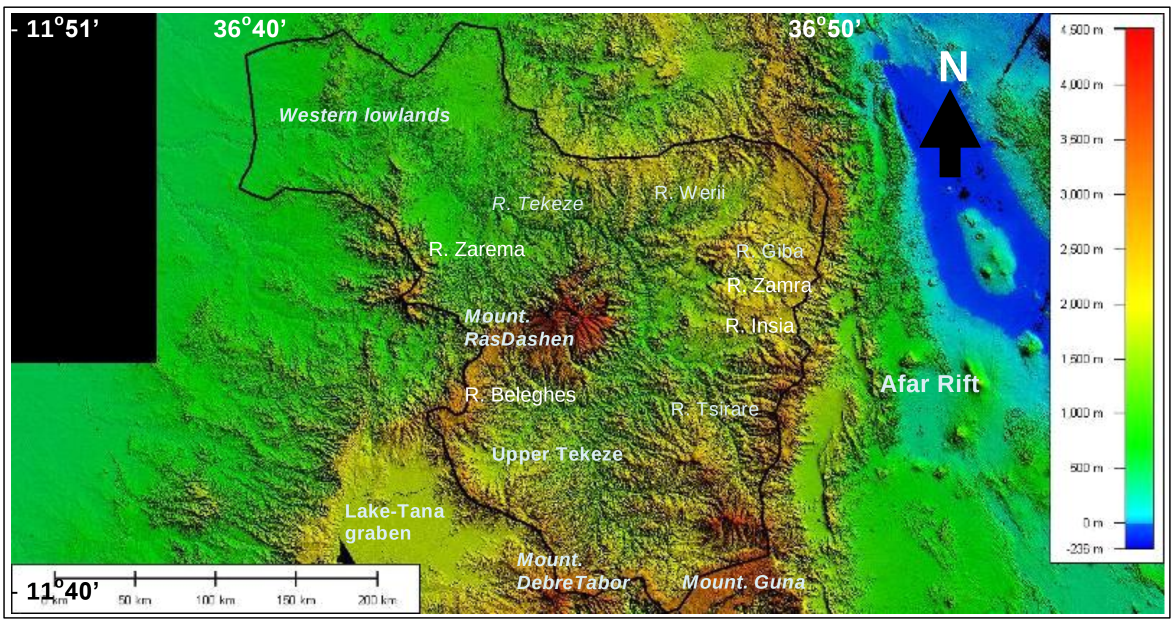

Figure 2. Digital Elevation Model of the TRB (elevation legend expressed in metres) Note: data derived from the Shuttle Radar Terrain Mission (SRTM).

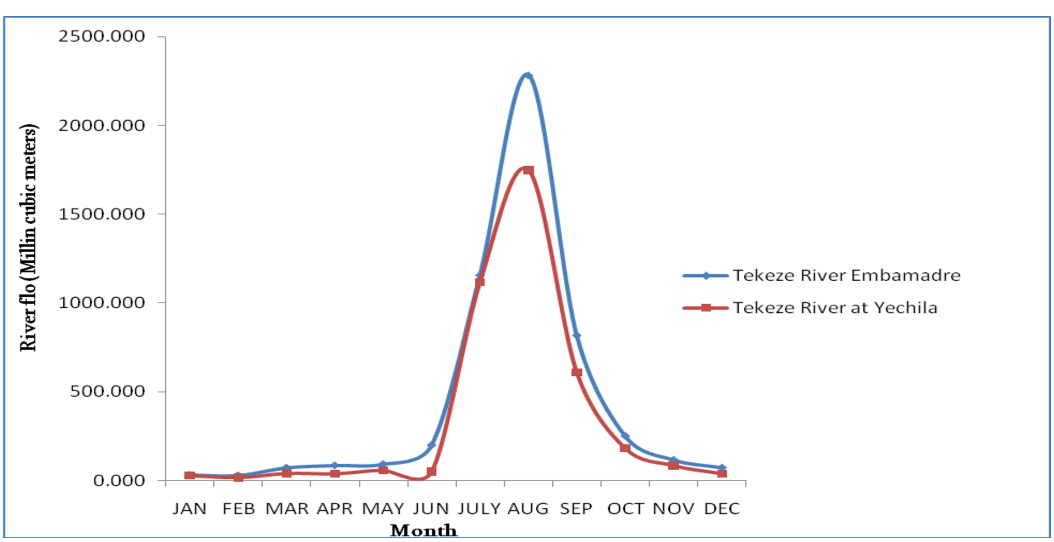

Figure 3. Hydrograph of the mean monthly river flow of Tekeze River.

The most prominent ductile structures are the older NNE-trending pervasive regional foliations associated with tight minor folds. This is followed by younger deformation in the area which produced major synclinoria such as the Negash, Chehmit, Tsedia and Mai Kinetal (Beyth, 1971, 1972; Mulugeta Alene, 1998). The synclinoria are open and upright with NNE axial trend and contain slate and metacarbonate sequences of the Tambien Group. In addition to the pervasive cleavage, the Tambien Group rocks display primary features such as bedding, graded bedding, cross-bedding, mud cracks, channel-fill structures and ripple marks. In between the synclinoria, there are metavolcanic and metavolcanoclastic units of the Tsaliet Group forming anticlinoria that show deformation fabric varying from massive to fracture- and phyllitic-cleavages (Beyth, 1971; Mulugeta Alene, 1998; Mulugeta Alene and Sacchi, 2000). There are also Precambrian and younger normal and strike-slip faults within or bounding the main synclinoria (Beyth *et al*., 2003).

Paleozoic - Mesozoic Sedimentary Formations

The nearly flat-lying Phanerozoic sedimentary rocks of the TRB fall under two major episodes of deposition: Paleozoic and Mesozoic eras (Danielli, 1943; Bosellini *et al*., 1997). The Paleozoic formations are localized within the Tekeze basin and are rarely mapped in other parts of Ethiopia. They are essentially constituted of Enticho Sandstone and Edaga Arbi Tillite (glacial deposits) with an overall measured thickness of 150 to 180 m (Beyth, 1972). The Enticho Sandstone is the lowermost unmetamorphosed sedimentary unit in the TRB, unconformably overlying the Proterozoic basement and generally forms flat-topped plateaus and sometimes mesas. It is characterised by white, medium to coarse grained sandstone, coarsely cross-bedded with silty beds and some ferruginous layers. It also exhibits calcareous sandstone, with lenses of polymicritic conglomerates, pebbles and large granite boulders. The Edaga Arbi Tillite consists of poorly sorted, unstratified and poorly consolidated sediments forming small conical hills or irregular slopes. It is exposed in the western and northern margins of the Mekelle Outlier (*Fig 5*). In most cases, the Enticho Sandstone is found interfingered with Edaga Arbi Tillite beds. Hence these rocks are not considered as separate stratigraphic horizons, rather as two different facies of the same age (Tesfamichael Gebreyohannes *et al*., 2010).

Overlying the Paleozoic rocks is a Mesozoic sedimentary sequence of marine and continental facies (*Fig 6*). These rocks outcrop dominantly in the Mekelle Outlier and in the incised valleys of the Upper Tekeze river and its major tributaries. The Mesozoic succession includes the Adigrat Sandstone, the Antalo Limestone, the Agula Shale and the Amba Aradem Formation (Fig 5 and 6) (Merla and Minucci, 1938; Danielli, 1943; Bosellini *et al*., 1997).

The Adigrat Sandstone in TRB is described as Triassic to Collovian in age and fluviatile in origin (Bosellini *et al*., 1997). It has variable thickness ranging from about 80 to 700 m (Beyth, 1972). It is mostly massive and thickly bedded with frequently observed cross-bedding. It is mostly white or grey to red, fine- to medium-grained and well sorted. It generally shows an intercalation of conglomerate, silt-shale, laterite and carbonate beds (Worash Getaneh, 2002).

The Antalo Limestone is largely comprised of limestone, marls and variegated shale showing a classical depositional sequence on a gently sloping ramp of Neoproterozoic basement during Jurassic transgression which was punctuated by periodic regression. The boundary between the Antalo Limestone and the underlying Adigrat Sandstone is transitional, marked by the occurrence of 20 to 30 m thick shale, calcarenite and sandstone (Bosellini *et al*., 1997). The Antalo Limestone has been subdivided into several depositional sequences and parasequences, i.e. thickening and shallowing up cycle, showing systematic vertical and lateral changes. Its thickness is well over 800 m (Bosellini *et al*., 1997). Based on its abundant foraminiferal fauna, the age of the Antalo Limestone is considered to be Late Oxfordian – Early Kimmeridgian (Bosellini *et al*., 1997). The Agula Shale is the upper marly part of the carbonate succession which includes some shale but mostly marlstone, coquinoid limestone, quartz sandstone and gypsum. The boundary between Antalo and Agula formations is transitional and arbitrary. The thickness of Agula Shale is estimated to be up to 300 m and its deposition is attributed to a regional regression towards the end of Jurassic and beginning of Cretaceous (Bosellini *et al*., 1997).

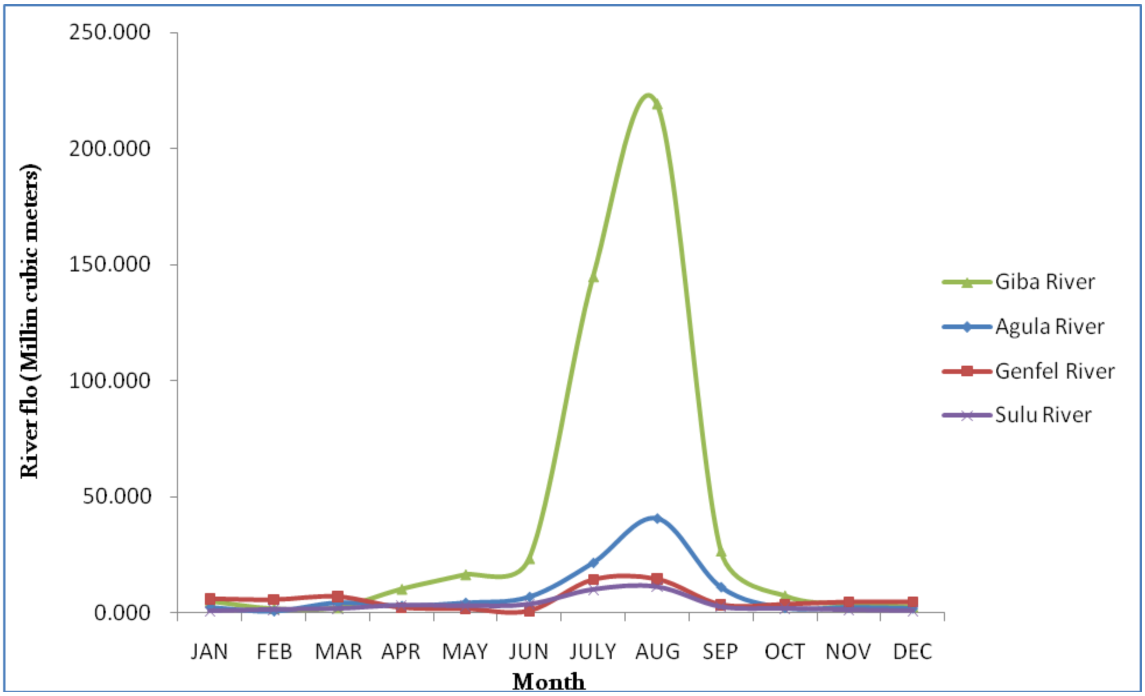

Figure 4. Hydrograph of the mean monthly river flow of Giba Rivers and its tributaries.

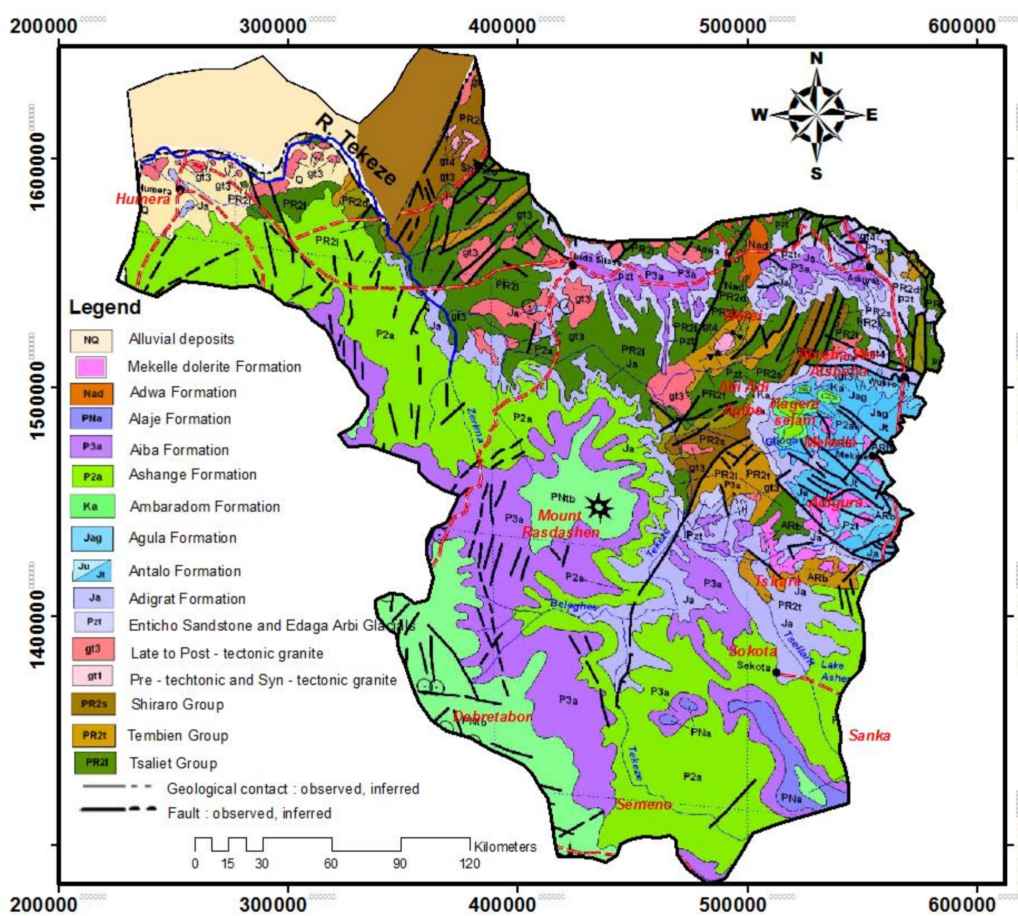

Figure 5. Simplified geological map of the TRB (Modified from EIGS, 1993).

The Amba Aradem Formation (also called 'Upper Sandstone') unconformably overlies the Agula Shale and is overlain by Tertiary Trap basalts (Danielli, 1943). Its age is deduced to be Late Cretaceous. Within the TRB, the Amba Aradem Formation is 100 to 200 m thick and consists of fluviatile sandstone and shale. It shows fining-upward cycles and coarsens to the southern margin of the Mekelle Outlier (Bosellini *et al.*, 1997).

Cenozoic Volcanics

In Ethiopia, the earliest and most extensive volcanic rocks are the Trap Series, erupted from fissures during the Early and Middle Tertiary (Pik *et al.*, 1998). Shield volcanoes consisting mainly of basalt lavas also developed on the Ethiopian plateau during the Miocene and Pliocene (Kazmin, 1979) forming prominent mountains such as Ras Dashen, Choke and Guna. According to Mohr (1983) and Mohr and Zanettin (1988), the Trap Series consists, from bottom to top, of the Ashange basalt (Eocene), Aiba basalt (32-25 Ma), Alaji volcanics (32-15 Ma) and Tarmaber basalt (30-13 Ma) formations (*Figs. 5 and 6*).

The Ashange basalt formation is marked by its tilted appearance, more brecciation, deep weathering, thin layering (< 10 m), smooth topography and cross-cutting sets of dykes. In contrast, the Aiba and Alaje formations are marked by their low degree of weathering, thick layering and cliff forming topography. The Tarmaber formation is marked by its jointing, thick layering and cliff-forming topography with flat tops.

Kieffer *et al*. (2004), on the other hand, have classified the Ethiopian Flood Basalt pile into two stratigraphic sequences: the basal (mainly the Ashange basalt) and upper (the plateau-forming volcanic units overlying the Ashange basalt). These authors have shown that both the basal and upper sequences were erupted rapidly during the period of 29 to 31 Ma, with no major differences in their chemistries. The flood basalts were later capped with large basaltic shield volcanoes (< 20 Ma in age) and Quaternary basalts (Kieffer *et al*., 2004).

The southern and south-eastern parts of the TRB are covered with these Tertiary flood and shield volcanics (*Fig 5*). Numerous dykes, sills and other hypabyssal intrusions composed of dolerite, trachyte, phonolite, microsyenite and microgranite also occur within TRB (Arkin *et al.*, 1971; Kazmin, 1975; Davidson, 1983).

Quaternary Sediments

In the TRB , the Quaternary era is represented by a great variety of loose unconsoldiated sediments. The main deposits are alluvial and colluvial. The alluvial deposits are of two types: those spread out in alluvial plains and paleo-lake basins and those strips along rivers and streams. The troughs in the lowlands trap large amount of sediments which were carried down from the highlands during the fluvial period. Thin strips of alluvium along river basins occur both on the highlands and the lowlands. In the alluvial plains, alternating layers of fine and coarse sediments are characteristic. Particularly, those plains in the western lowlands around Humera (*Fig 5)* have relatively thick (15 m – 30 m) sediment deposits with coarse grain sizes; colluvium are also common on hill sides and feet of hills. In general, only less than 20% of the TRB is covered by these Quaternary deposits which are mostly thin (0.5 m – 6 m thick).

Fault Structures

The TRB is prominently dissected by belts of WNW-oriented normal faults (Wukro, Mekelle, Chelekot, Fucea Mariam, Adi-shihu and Tsirare faults; Fig. 7), probably originating from pre-flood basalt extensional tectonics. Cross-cutting relationships indicate that these faults are pre-rift structures, oriented obliquely to the NNE-trending marginal faults of the Afar Rift (*Figs 5 and 7*). Up to 100 m vertical displacements have occurred along the WNW-trending faults. These faults have created major elongate blocks between them. A major curved valley also dissects the Simien massif (Mount Ras Dashen) which could be the result of a regional slump associated with the Tsirare fault. A number of NW-SE running faults are also observed in the Sekota area. In general, the WNW-trending faults are responsible for block rotation, lateral disruption of lithologies and emergence of springs in the area (WWDSE, 2009). The geometries of the WNW-trending normal faults show that the maximum vertical displacements occurred at the middle of the fault segments, and only minor downthrows at the fault terminations to the east and west.

The density of other WNW-striking lineaments (traced from satellite images) is higher closer to these major fault zones than within the respective hanging and foot blocks (*Fig 8*).

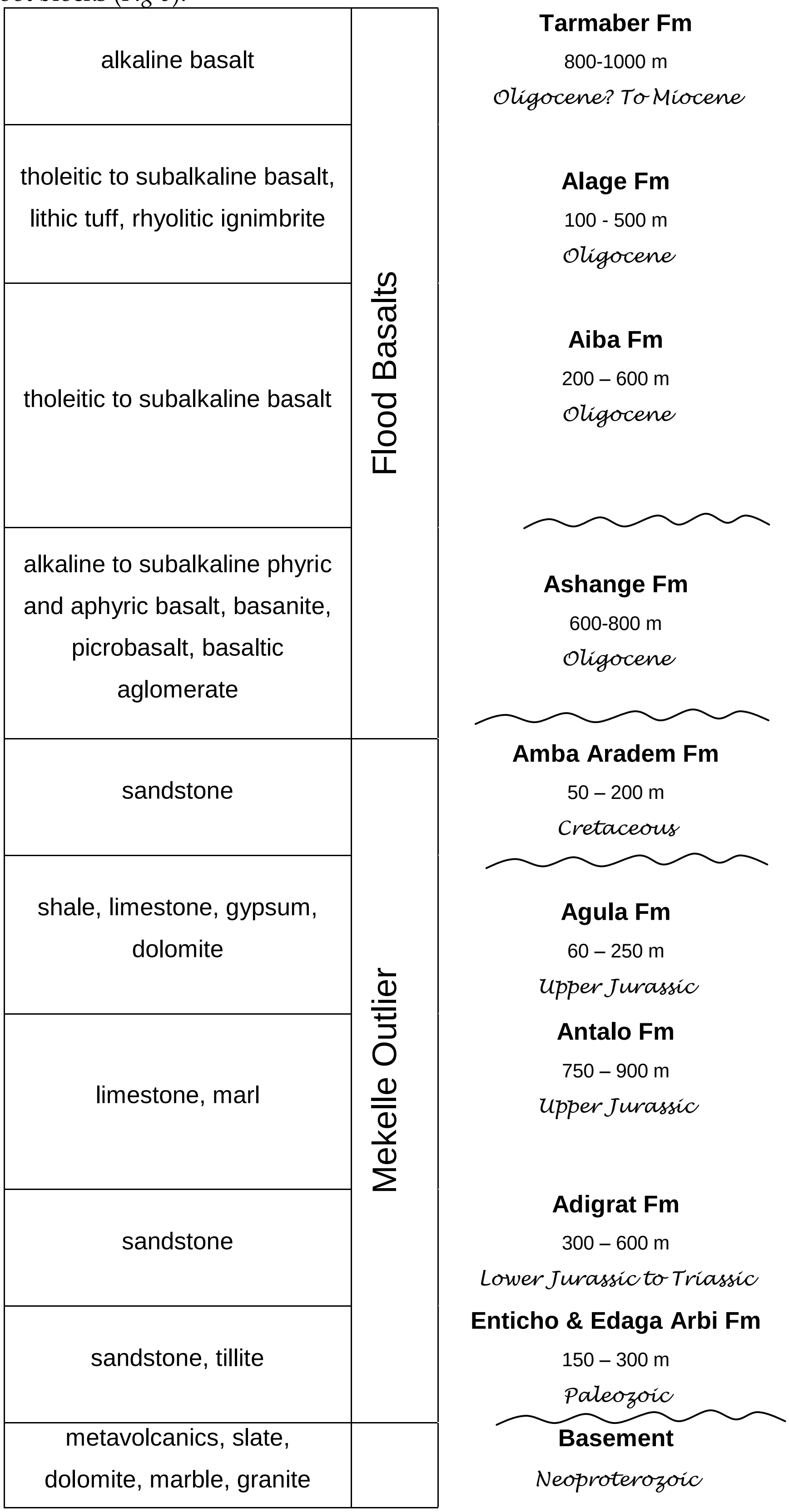

Figure 6. Simplified stratigraphy of the Mekelle Outlier and northern Ethiopia flood basalt province (after Arkin et al. 1971; Beyth 1972; Merla et al. 1979).

Close to the fault scarps, sedimentary beds on hanging walls are usually gently dipping away from the fault scarps. This has resulted in gentle drag folds having axes parallel to the strike of the fault scarps. These folds are responsible for the development of local basins parallel to the fault orientation (Beyth, 1972). Otherwise, the sedimentary strata in the basin are generally flat-lying or slightly tilted eastward (Kuster *et al*., 2005).

Another group of faults is the N-S to NNE-SSW-trending faults associated with the rifting in Afar (*Fig 8*). These are confined to the eastern boundary of the TRB along the great escarpment of the Afar Rift (*Fig 8*). The western and southern boundaries of the TRB are marked by the Chilga-Gondar sub-rift and the Debre Tabor sub-graben, respectively. The two sub-rifts are parts of the Quaternary Lake Tana Rift. The northern boundary of the basin is not marked by any apparent geomorphologic or structural feature.

GROUNDWATER HYDROLOGY

Aquifer Characteristics

Various rock types of Precambrian, Mesozoic, and Tertiary ages exist in the TRB. These rocks are affected by several episodes of deformation and intrusion. This gave rise to quite complex hydrogeological setting which requires a lot of scientific research to fully understand the system. In this study, a wide range of patchy previous hydrogeological studies has been reviewed to conceptualize the hydrogeological system.

Pertinent data from different sources including pumping test data, well lithological logs and geophysical survey results have been evaluated to characterise the aquifers, including groundwater recharge and discharge conditions in different parts of the basin. The result revealed that different aquifer types exist (confined including artesian, semi-confined and unconfined). The most dominant aquifers are of unconfined and semi-confined types forming the shallow and most used aquifers in all kinds of rocks localized in different physiographic regions. Figure 9 shows the simplified hydrogeological map of the basin (extracted from the hydrogeological map of Ethiopia at the scale of 1:2,000,000).

Aquifers in the Neoproterozoic basement complex rocks

In these metamorphic and intrusive rocks, which cover the north-eastern and central parts of the study area (*Fig 5)*, a complicated hydrogeological environment is evident owing to the geological history of the rocks. Most of the rocks have low primary porosity and permeability. However, weathering and fracturing have created significant secondary porosity and permeability which is highly variable both spatially and with depth. The absence of uniform permeable lithologic units extending over large areas indicates absence of extensive aquifers. Instead, limited exploitable groundwater exists in large fracture zones and associated depressions where yield of wells ranges from 0.5 to 5 L/s. These wells supply many rural villages and small towns.

The massive to weakly foliated metavolcanic rocks on either side of the synformal folds often form hilly landforms. Because of their geomorphologic setting and their hard and compact nature, these rocks mostly act as runoff zones. Groundwater occurrence is restricted along faults, fractures and joints in these rock units and in contact zones with the apilitic dykes and granitic plutons. In the open synformal folds of the basement rocks, groundwater flow is more controlled by the dip of metasedimentary strata and plunging of the folds. Narrow valleys along the core of these folds, which contain slates and phyllites and are covered with thin alluvial sediments, are found to be more productive. Most of the productive hand-dug wells and shallow boreholes in the metamorphic terrains are found along these narrow valleys. In between these valleys, metadolomites and metalimestons form elongated ridges similar to the metavolcanic hills. These ridges have negligible groundwater storage due to the small recharge area, steep slopes and low permeability of the rocks.

The metamorphic rocks are also affected by sub-horizontal sheet jointing formed by erosional unloading and are dissected by tensile sub-vertical joints. These are sources of secondary porosity and significantly contributing to the occurrence and flow of shallow groundwater in the basement rocks. However the frequency and aperture of the joints decreases with depth. The thickness of the fractured zones mostly ranges from 12 to 60 m. Therefore, the storage capacity and transmission of the groundwater in basement rocks is restricted to the shallow weathered zones, joints, fractures, faults, contact zones with intrusive rocks and other related discontinuities. Therefore, it is very unlikely to get extensive highly productive aquifers in these rocks.

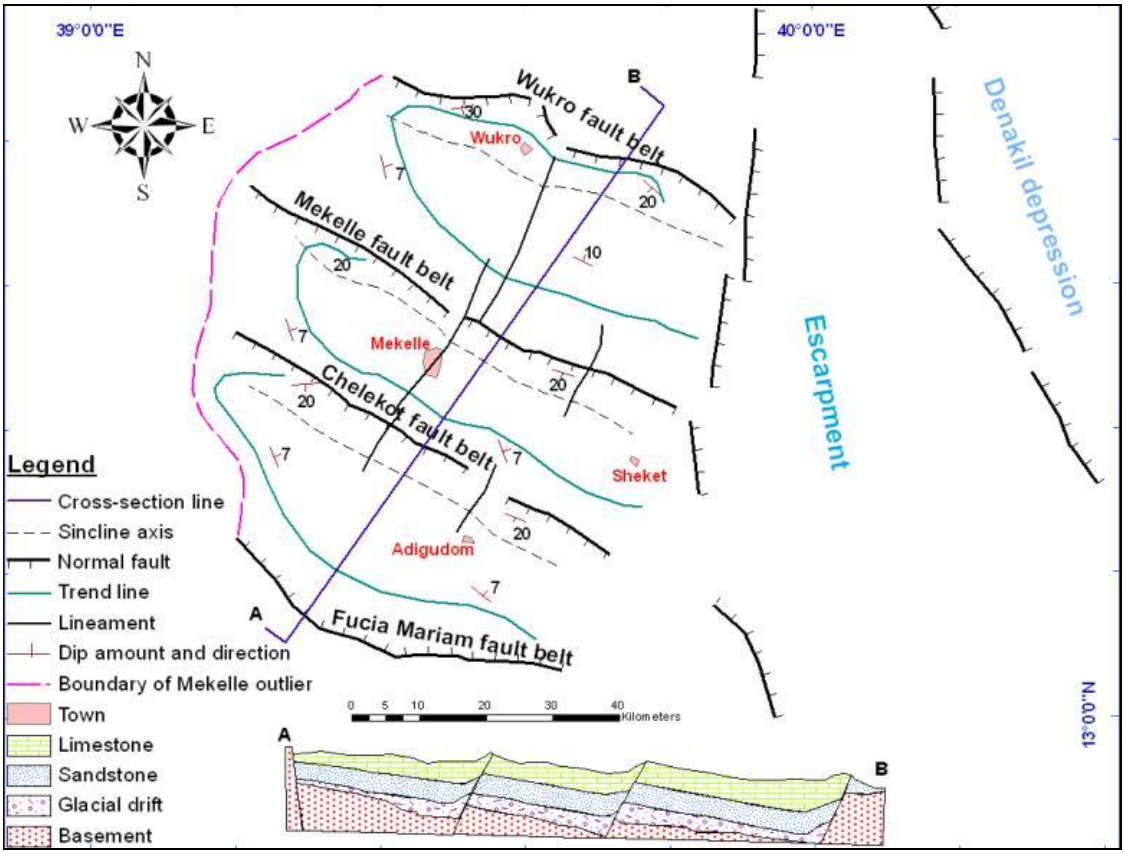

Figure 7. Structural sketch map of Mekelle Outlier (Beyth, 1972).

Aquifers in the Paleozoic Sedimentary rocks

Groundwater occurence and flow in the Edaga Arbi tillite is very localised and is limited to the thin (< 15 m) upper weathered and fractured zone along stream channels and occasionally as perched aquifers in more permeable horizones at depth that pinches out in a short distance. Joints and fractures are discontineous both laterally and vertically due to high variation in lithilogy. The poorly sorted and unstratified nature of this unit results in only local accumulation and slow rate of groundwater flow and recharge. Springs from this unit have less discharges hardly exceeding 2 L/s. Hand dug wells and shallow tube wells (8 – 70 m depth) have seasonaly fluctuating discharges. During the rainy months they discharge as high as 3 – 8 L/s but they may even get dry during the dry season.

The Enticho Sandstone unit generally forms dome-shaped hills and flat-topped plateaus, mesas, unconformably overlying the basement rocks north of Mekelle town. Its thickness reaches up to 100 m. This sandstone unit is characterized in the lower part by white, medium to coarse grained sandstone, coarsely cross-bedded with silty beds and some ferruginous layers. In the upper part, it exhibits calcareous sandstone, with lenses of polymicritic conglomerates, pebbles and large granite boulders.

This unit is more permeable and it has relatively extended aquifers that intercalate with aquicludes (silt beds). Joints and fractures are continuous eventhough they are mostly filled with silica and calcite precipitates. But in places where it is exposed to the surface, it is discontinued by faults and recent weathering and erosion. Therefore, it usualy forms Mesa structures. There are points of higher discharge (2 – 5 L/s) and perennial contact/fault springs at the feet of these Mesa structures. Tube wells (35 – 90 m depth) drilled into this unit show discharges of 3 – 7 L/s. But its storage capacity is low because of the high permebility and limited lateral extent of the aquifer. It is also noted that the Enticho sandstone is sometimes found interfinged with Tillite beds; this results in the occurrence of perched aquifers.

Aquifers in the Mesozoic sedimentary rocks

Adigrat Sandstone aquifers

Double porosity (both intergranular and fracture porosity) is characteristic of the Adigrat Sandstone formation. It hosts regional aquifers of mostly confined type. The confinement is due to the inter-beds of the less permeable siltstones and mudstones between the sandstone aquifers. Most deep wells (>100 m) drilled into this sandstone formation are found to be artesian or the water level rises close to the surface. Deep wells drilled around Wukro and Chinferes near Mekelle, where the sandstone is found on the surface due to the regional faults of the area, indicate the existence of highly productive aquifer with a yield that ranges from 40 L/s to 60 L/s and insignificant draw-downs during pumping tests. There are also high discharge (>30 L/s) springs at the western margins of this sandstone formation around Agibe and Abi Adi. But many deep wells (350 – 600 m) drilled around Mekelle with the intension to penetrate into the Adigrat Sandstone aquifers were not successful because of the thick pile of the Antalo Supersequence.

Antalo Limestone and Agula Shale aquifers

Within the Antalo Supersequence, groundwater flow is generally restricted to fractures, dissolution cavities and along bedding planes in thinly bedded horizons. The intensity of fracturing is higher within the marl units than in the limestone beds while the fracture openings are wider within the limestone beds. Therefore, flow rates of the groundwater vary accordingly.

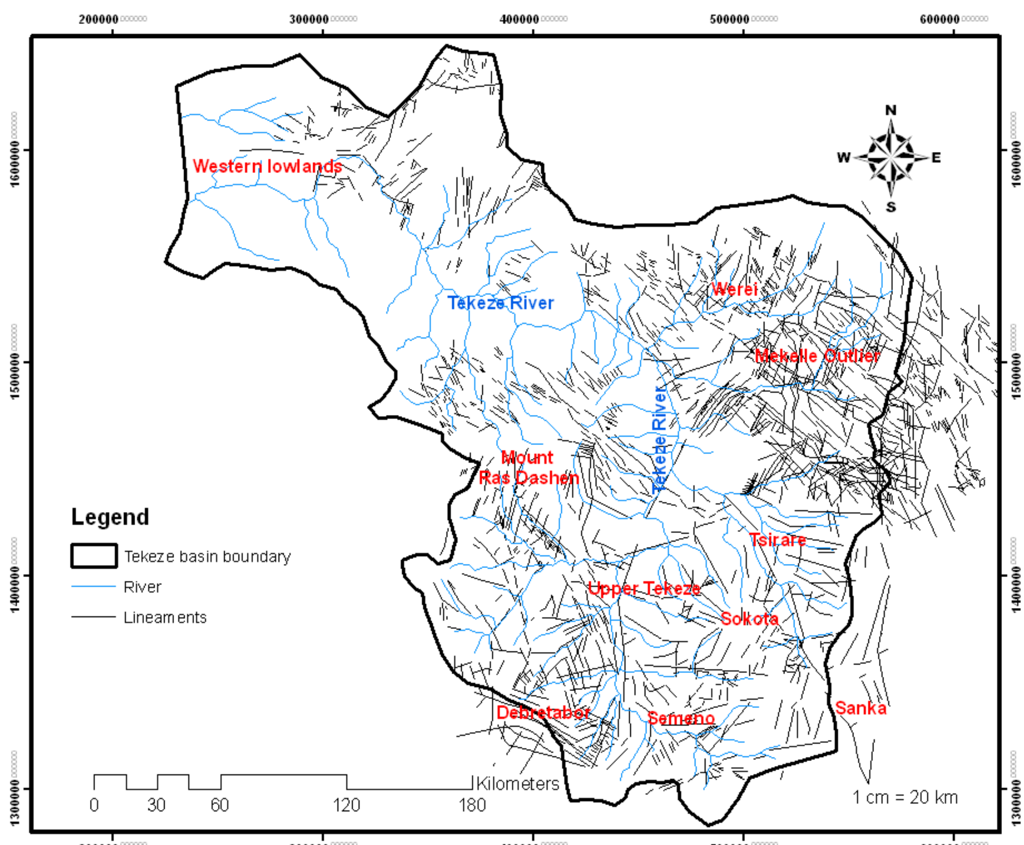

Figure 8. Lineament map of the Tekeze River Basin.

When water passes though the wider fractures within limestone units to the marl units, its vertical flow is hindered because of the more tight fractures within the marl and hence hydrostatic pressure builds at the contacts between the limestone and marl units. This results in the accumulation and horizontal flow of groundwater along these contact zones. Many springs within the Antalo and Agula formations are observed to emerge at the contacts between limestone and marl or shale. Superficial Solution cavities within limestone are also common in these contact zones. The development of deep and interconnected karsts in the limestones of the Mekelle outlier is sometimes hindered by the frequent intercalations of marl and shale beds. When the potential of dissolution is low, erosional processes are dominant resulting in the formation of cliffs instead of karst (Singhal and Gupta, 2010). Such a case is observed in the study area where narrow valleys bordered by steep cliffs of intercalated limestone-marl-shale are common.

The deeper aquifers in the Antalo Limestone formation are confined type and artesian wells that penetrate into these aquifers are encountered. The extents of the aquifers in this formation are also semi-regional. In localities where the marl beds are brought closer to the surface, as a result of faulting and subsequent erosion of overlying material, the fractures are observed to be locally widened because of pressure relief. In such cases the marl units also serve as aquifers although they mostly act as aquicludes at depth. Except close to faults and along axes of associated drag folds, the intensity of fracturing within these carbonate sequence decreases with depth and become tight below 200 m.

At the transitional contact zones between the Antalo Limestone formation and the Agula Shale formation, thin layering of sedimentary beds result to increase the amount of primary porosity along bedding planes. In localities that are close to stream valley and fault zone, this transitional intercalation unit is observed to accommodate significant amount of shallow groundwater. Many productive hand-dug-wells and shallow boreholes are encountered in Mekelle area.

The upper most part of this Mesozoic sedimentary sequence (Agula Shale formation) is characterized by thick shale beds intercalated with thin horizons of limestone, marl and gypsum. Even though this formation is also affected by diverse sets of joints, its dominantly clayey composition results in the swelling of rock blocks when saturated by infiltrating water. This minimizes their secondary permeability. Therefore, although significant amount of moisture is found in these shale beds and their intercalated limestone and marl, the flow rate of groundwater is so slow that they should be considered as aquiclides. Wells and springs have low discharge hardly exceeding 2 L/s. The shale dominated units are therefore considered as recharging horizons to the underlying limestone and marl units of the Antalo Limestone formation even though recharge rates can also be low. Whereas the lower part of the Antalo Limestone are characterized by extensive/semi-regional aquifers with boreholes' yield mostly ranging between 10 and 60 L/s.

In the locality around and south of Mekelle town, the dolerite intrusions have created baking effect (contact metamorphism) and recrystalized zones on the carbonate layers within the Agula Shale Formation. However, fractures and joints in the dolerite resulted in higher levels of secondary porosity and permeability within these rocks. From field observations and drilling data, it has been observed that the contact zones between the dolerite intrusions and the host sedimentary rocks are more fractured and show faster groundwater flow. Many intermittent and semi-perennial springs with discharges ranging from 0.2 L/s to 3 L/s and high discharge tube wells (10 L/s – 40 L/s) are common from such horizons in the vicinities of Mekelle town. However, the geometry and emplacement mechanism of these Mekelle dolerites is complex and their roles in controlling the groundwater occurrence and flow are not well understood.

According to FWWDSE (2007), the aquifer in the lower part of the Agula Shale (~54 m thick) which is found on top of the dolerite sill in the Aynalem well field, a well field in the Mekelle town, has transmissivity ranging from 100 m^2/day to 4750 m^2/day and for the upper part of the Antalo Limestone (~200 m thick), found below the dolerite sill, it ranges from 100 to 3500 m^2/day. In this study, significantly lower transmissivity values that range between 1.02 and 5.5 m^2/day are recorded for the dolerite sill. DH Consult (2010) has estimated an average transmissivity of 412 m^2/day for the lower section of Agula Shale. Pumping test analysis of two recently drilled wells into the Upper part of the Antalo Limestone (350 m and 375 m deep) gave rise to similar transmissivity value of 432 m^2/day. Nearly equal transmissivity (421 m^2/day) is estimated for the Adigrat Sandstone from a well drilled (180 m) into the formation at Chinferes near Mekelle town.

The Paleozoic-Mesozoic sedimentary rocks within TRB, as mentioned above, are affected by numerous normal faults and associated drag folds. The gently dipping and highly fractured parts of the hanging blocks of these faults create preferential recharge and flow of groundwater. The encounter of artesian wells along the fold axes both in the Adigrat Sandstone and Antalo Limestone formations can be due to higher hydraulic heads with confined groundwater flow through the tilted bedding planes towards the fold axes. In the inner parts of the blocks away from the major faults, sedimentary strata are nearly flat-lying and undisturbed resulting in lower intensity of fracture.

Karst features in limestones of the Antalo Limestone formation are frequently observed close to the major fault zones and along the axes of the drag folds where concentrated groundwater flow occurs along the dense and more open joints, fractures and bedding planes. Highly discharging perennial springs (like the Michael Tselamo and Mai Ambesa near Mekelle town, Birki Gebriel near Agula and Endaba Hadera, Endaba Noh and Ruwakisa near Hagereselam, Aini-mai-shugala near Shiket and many other springs aligned along the foot of the Afar rift escarpment) emerge through such dissolution cavities. In general, the major fault zones in the sedimentary terrain are the main source of localized recharge particularly to the deeper aquifers. The groundwater in the shallow aquifers is discharged in the form of springs and base flow in the upper steam of TRB where the rock mass is truncated by the major faults.

But there are also cases where adjacent deep wells (<1.5 Km apart) drilled into the Adigrat Sandstone and both Antalo and Agula formations on opposite sides of faults close to the Wukro and Mekelle fault belts show significantly different hydraulic properties (table 5). These faults brought the Adigrat Sandstone adjacent to Agula Shale particularly around Abreha-we-atsbeha and Chinferes localities. As a result the wells drilled into the Adigrat formation are characterized by higher well yields (>50 L/s) and transmissivity values (around 400 m^2/day) while those on the Agula Shale indicate much lower well yields (< 3 L/s) and transmissivity values (< 3 m^2/day) regardless of their close proximity to the major faults (table 2).

Most of the NNE trending faults and lineaments (*Fig 8*) have not lead to visible displacements. However, few of them are observed to have significant displacements (100 m to 500 m) giving rise to the existence of the Tekeze, Werei and Giba River valleys. The regional groundwater flow from the east and west of these rivers is therefore structurally controlled and converges towards these valleys and ultimately flow parallel to their respective river flow directions (Fig 10). Significant part of this regional flow is discharged at the contacts between the Adigrat Sandstone and the Paleozoic sediments/Proterozoic basement rocks contributing to the perennial flow of the rivers. Small proportion of the regional groundwater flow percolates down to recharge the fractured basement aquifers and/or the narrow and thin (< 20 m) alluvial aquifers in the lower reaches of the Giba River.

In general, the Adigrat Sandstone and Antalo Limestone formations are the most productive semi-regional aquifers in TRB. On the other hand, the Amba Aradem Sandstone, Agula Shale, Paleozoic sediments and Proterozoic basement rocks are characterised by shallow and local groundwater systems and mostly serve as recharge to the underlying formations.

Aquifers in the Cenozoic volcanic rocks

Semi-regional aquifers are found in the fractured and weathered volcanics that form elevated plateaus and alluvio-colluvial sediments filling intermountain depressions, river valleys and lowland plains. Alluvial deposits dominated by volcano-clastics and river gravels and paleosoils are present within the Trap Series (Tesfaye Chernet, 1993; Tenalem Ayenew *et al.*, 2007; Seifu Kebede, 2013). Thick pyroclastic deposits, buried paleo-valleys and volcanic rocks within structural discontinuities in the highlands are known to provide one of the best aquifers in the country (Tesfaye Chernet, 1993; EIGS, 1993; Bayessa Asfaw Unpublished data, 2003; Ermias Hagos *et al.*, 2015). Due to the presence of different interbedded layers of river gravels and paleosoils, the north-western highland volcanics of Ethiopia form multi-layer aquifers. Good examples of multilayer aquifers in the highlands are located around Dessie, Mekelle, Ambo and Addis Ababa areas with yields as high as 40 L/s (Mola Demelie *et al.*, 2008; Ermias Hagos *et al.*, 2015).

In the Upper Tekeze sub-basin, the volcanic rocks particularly the Ashange basalts are important aquifers. These rocks, which form the western and eastern highlands of the sub-basin, bear considerable amount of secondary porosities that result from the effects of extensive weathering, jointing, faulting and fracturing. Emergence of springs of significant discharge from the Ashange basalts suggests the productivity of these aquifers (e.g. > 50 L/s at Sanka and Adigura springs). Field evidence suggests that most of these springs emerge at the contact between the Ashange sequences and the underlying Mesozoic sediment; these contacts are mostly highly indurated and thermally compacted (Seifu Kebede, 2013). Transmisivity values estimated from shallow wells indicate that in the Ashange basalt transmisivity ranges from 0.66 to 81.25 m^2/day with wells having discharges of 0.7 to 5.6 L/s.

Aquifers in the Quaternary alluvium

With regard to the Quaternary deposits in the western lowlands of the TRB (Fig 9), a well drilling report at the centre of Humera town revealed that the alluvial deposit which is composed of clay, sand and gravel extended to a depth of 42m. At a depth of 42 m the drilling stopped because granite had been reached. Some other drilling reports indicate that the drilling of several boreholes had to be stopped because granite was encountered at shallower depth and the wells remain dry. Many other productive wells near Humera are drilled into the Mesozoic sandstone, weathered basalt and the alluvium.

The groundwater table in this area dips away from the Tekeze River, indicating that the (influent) river recharges the groundwater. This appears to be the only recharge of the alluvium, and weathered and/or fractured rocks underlying the alluvium, because the top part of the alluvium is dominantly covered with clay deposits which are characterised by low infiltration rates and low permeability. This means that, near Humera, pumped groundwater represents induced-recharge from the Tekeze River (MWR/Ministry of Water Resources, 1998). In fact in some intermountain valleys with thicker sand alluvial deposits many productive wells have been reported

Table 2. Summary of some hydrodynamic characteristics of the various geological formations in the TRB (Source: MWR Unpublished data, 1998).

Formation	Yield (l/s)			Specific Well Capacity (l/s/m)				Transmissivity (m^2/day)		
	average	max	min	count	average	max	min	average	Max	Min
Quaternary alluvium	3.6	6	0.5	5	4.6	10.8	0.06	482	1005	12
Ashange basalt	1.8	5	0.2	6	0.033	0.065	0.01	16	32	1
Amba-Aiba basalt	2.6	6.2	0.3	14	0.33	0.74	0.05	20	40	6
Welega basalt				5	1.16	11.43	0.9			
Agula Shale	2.4	5	0.6	2	0.23	0.45	0.01	20	20	20
Agula Shale & Antalo Limestone	0.9	1.5	0.3							
Antalo Limestone				4	1.26	2.63	0.22	76	146	7
Antallo limestone & dolerite	3.1	7	0.3					125	140	110
Tertiary dolerite	3.6	6	0.5	6	1.8	3	0.24	178	351	8
Amba Aradem Sandstone	2.2	6	0.2	3	1.53	4.54	0.02			
Enticho Sandstone	2.7	5.5	0.4	5	0.21	0.7	0.01	35	123	1
Adigrat Sandstone	2.8	6.9	0.2	9	0.25	0.92	0.01	229	261	196
Edaga-arbi glacials	0.7	1	0.5							
Precambrian metamorphic	1.6	8	0.1	11	0.18	0.36	0.03	20	57	3
Alluvial & Ashange basalt	0.7	1.4	0.1	2	0.03	0.06	0.01			
All formations	2.7	10	0.1	87	1.02	11.43	0.01	84	1005	1

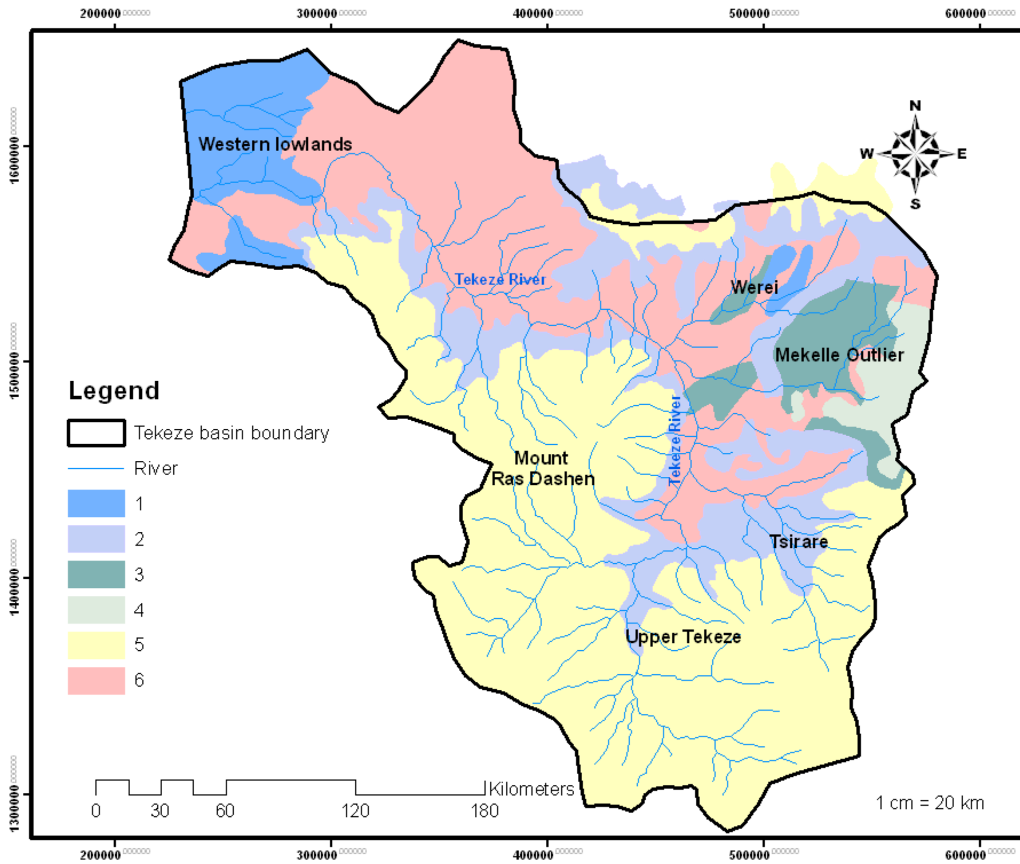

Figure 9. Simplified hydrogeological map of the TRB (modified from Tesfaye Chernet 1988).

Note: The intensity of the colour tone represents the degree of productivity of aquifers). Numbers on the legend represent aquifer classes: 1 = mainly shallow unconfined aquifers in the Quaternary sediments; 2, 3 and 4 = aquifers in the Mesozoic sedimentary rocks mainly existing along river valleys, 5 = diverse productive aquifers in the Cenozoic volcanics; 6 = shallow, less productive aquifers in the Neoproterozoic basement rocks.

Groundwater Flow Pattern

The groundwater flow in the TRB is an intricate interaction of recharge and discharge under local and regional groundwater flow systems. The groundwater level records are patchy to reconstruct the local and intermediate (sub-regional) flow systems and the groundwater and surface water interactions. However, from the distribution of springs, seepage zones, shallow wells and the existing geological and geomorphological maps, a semi-quantitative analysis of groundwater flow system of the basin can be made. In many places since the wells are screened across various intervals, the water level recorded does not necessarily accurately represent the piezometric surface in particular in aquifers within the multi-aquifer geological profile, mainly in the volcanic plateau. In this work the water level is referred to as the groundwater surface rather than the potentiometric surface as it is recognized that under different recharge and discharge conditions in shallow and deeper aquifer intervals, the potentiometric surface of individual aquifers may vary vertically with depth. In such complex aquifer systems groundwater elevations of different aquifers can only be established with systematic drilling in different formations. However, from the existing information the general regional flow can be deduced.

In the TRB the groundwater contour maps are often subdued replica of the topographic contours. In other words, the regional groundwater flows generally sub-parallel to the surface water flow direction at regional and sub-regional scale (Fig 10).

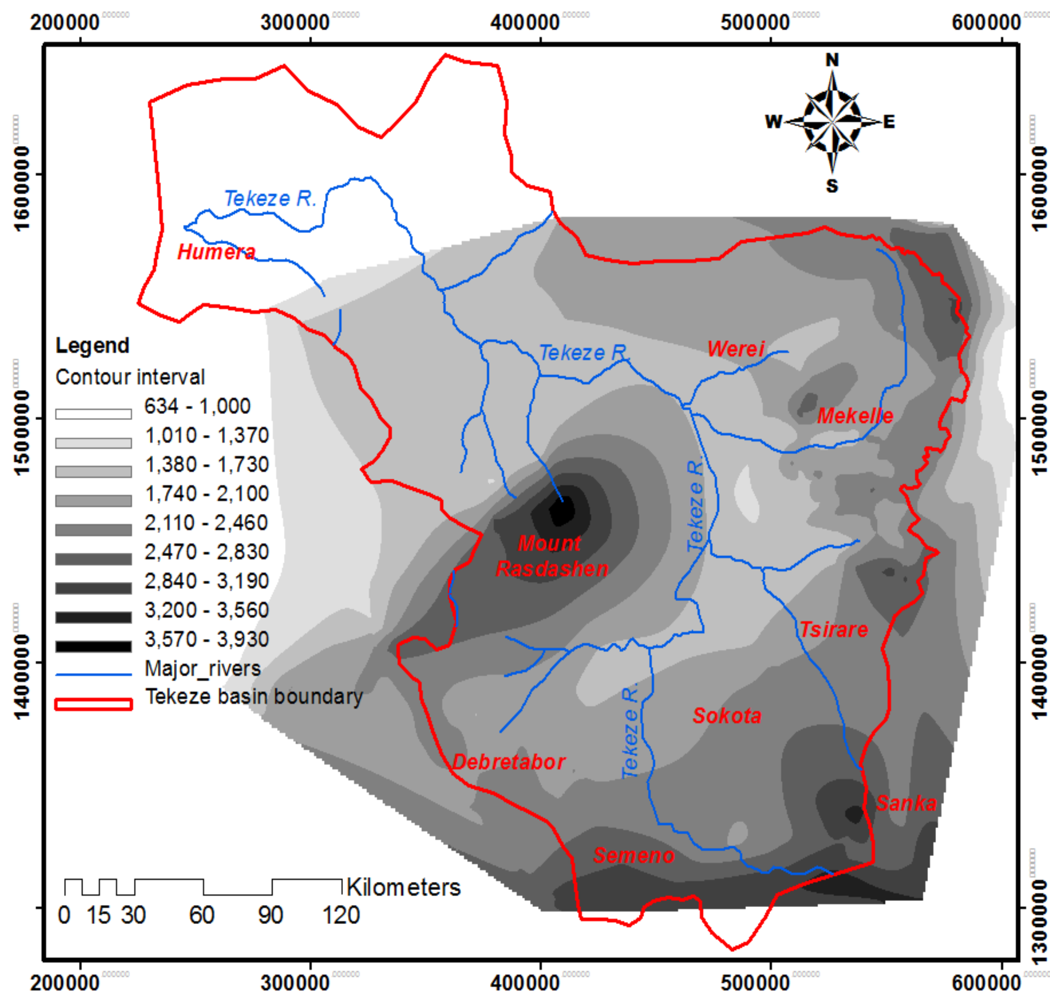

Figure 10 Groundwater level contour map based on springs location in the TRB.

This general flow pattern indicates that most intermountain depressions and lowlands are discharge areas characterized by a number of springs and seepage zones. In these discharge areas depth to groundwater is very shallow (MWR Unpublished data, 1998; Tesfamichael Gebreyohannes, 2009; DH Consult, unpublished data, 2010).

The abundance of springs at different elevations, and the overall relation of groundwater level with topography, particularly in steep landscapes, suggests that the shallow groundwater flows in local flow systems controlled by ground elevation. However, the thickness and lateral extent of the aquifers indicates that deeper, regional flow systems operate mainly in the volcanic and sedimentary rocks. Most of the Precambrian rocks have shallow aquifers. In these aquifers depth to groundwater level is not more than a few tens of meters (Tesfamichael Gebreyohannes, 2009; DH Consult, unpublished data, 2010).

CONCLUSIONS

The study revealed that the Tekeze river basin is characterized by different rock types ranging in age from Precambrian to Quaternary with associated complex tectonic structures. The area south of the Tekeze River is mainly covered by the Cenozoic volcanics. In northern half of the basin, central and western part is dominantly covered with the Neoproterozoic metamorphic and intrusive rocks. Mesozoic sedimentary rocks, belonging to marine and continental facies, cover significant portion of the basin to east, particularly in the Mekelle Outlier. Quaternary sediments cover small area in the western lowlands and narrow stretches along major river valleys in the highlands. The WNW-ESE oriented fault systems, NNE-SSW directed lineaments and the N-S trending foliations and lineations associated with synclinoria structures in the metamorphic rocks are prominent structures in the basin. These structures strongly control the movement and occurrence of groundwater.

The highlands are deeply incised by the major rivers and their tributaries which form deep canyons and gorges with steep and narrow river valleys. Along the course of these valleys there are many springs that emanate along the contacts of the different rock units (mainly between the Mesozoic sedimentary rocks and the Trap series volcanics) and talus deposits and hence act as discharge areas. These areas have high surface runoff and are characterized by waterfalls. The fact that high river flows are recorded in the summer season and very low flows in the dry season (sharp recession curve) indicates that much of the rain water leaves the basin in the form of direct runoff and only a small proportion recharges the groundwater. This indicates that the low storage is controlled by the physiographic setting (rugged terrain with deep canyons).

The aquifers in the TRB can be regionally classified as fractured (mainly volcanics, hard sedimentary rocks and basement complex rocks), intergranular (mainly Quaternary sediments) and karastic limestones. Exploitable groundwater occurrence in the basement rocks is limited to large fracture zones and associated depressions and grabens where drilled wells are in many cases found with a yield that range between 0.5 L/s to 5 L/s. The absence of uniform permeable sediments (fracture zones) extending over large areas implicates that extensive aquifers are unlikely to exist. Similarly, the poorly sorted and unstratified nature of the Edaga Arbi tillite results in only local accumulation and slow rate of groundwater flow and recharge. Springs from this unit has less discharges hardly exceeding 2 L/s. Hand-dug wells and shallow tube wells (8 – 70 m depth) have seasonaly fluctuating discharges. During the rainy months they discharge as high as 3 – 8 L/s but they may even get dry during the dry season. Whereas the Enticho sandstone is more permeable and it has relatively extended aquifers that intercalate with aquicludes (silt beds). It usualy forms Mesa structures where higher discharge (2 – 5 L/s) and perennial contact/fault-controlled springs are encountered. Tube wells (35 – 90 m depth) drilled into this fomation has discharges of 3 – 7 L/s. Owing to its high permebility the storage capacity of the Enticho sandstone is low and therefore, it bears groundwater with less residence time.

Double porosity (both intergranular and fracture porosity) is characteristic of the Adigrat/Tekeze sandstone formation. It hosts regional aquifers of mostly confined type. In most parts of the basin this formation is covered with thick pile of the Antallo supersequence and overlying volcanic rocks (> 700 m). But in some localities (like around Wukro and Mekelle towns) where it is found on the surface due to the regional faults of the area, highly productive (40 – 60 L/s) artesian wells are encountered with insignificant draw-downs. There are also high discharge (>30 L/s) springs at the margins of this sandstone formation around Agibe, Abi Adi and Sokota.

Within the Antalo Limestone and Agula Shale formations groundwater flow is generally restricted to major fracture zones and associated drag folds, dissolution cavities and along bedding planes in thinly bedded horizons. The intensity of fracturing is higher within the marl units than in the limestone beds while the fracture openings are wider within the limestone beds. Therefore, flow rates of the groundwater vary accordingly. When water passes though the wider fractures within limestone units to the marl units, its vertical flow is hindered because of the more tight fractures within the marl and hence hydrostatic pressure builds at the contacts between the limestone and marl units. This results in the accumulation and horizontal flow of groundwater along contact zones. Many contact springs within the Antalo Limestone and Agula Shale formations are observed to emerge through solution cavities in limestones usually at their contact with marl/shale units. Confined aquifers giving rise to artesian wells are encountered within the Antalo Limestone formation. The lateral extent of the aquifers is semi-regional. In the transitional contact between the Antalo Limestone and the Agula Shale, thin layering of sedimentary beds result to increased primary porosity along bedding planes. Particularly close to stream valley and fault zones, this transitional contact forms significant amount of shallow groundwater system. Many productive hand-dug-wells and shallow boreholes are encountered in such localities as in the case of Mekelle area.

The upper most part of this Mesozoic sedimentary sequence (Agula Shale formation) is characterized by thick shale beds intercalated with thin horizons of limestone, marl and gypsum. Even though this formation is also affected by diverse sets of joints, its dominantly clayey composition results in swelling of rock blocks when saturated. This minimizes their secondary permeability and hence wells and springs have low discharge (hardly exceeding 2 L/s). The shale-dominated units are often considered as recharging horizons to the underlying limestone and marl units of the Antalo formation even though recharge rates can also be low whereas the Adigrat Sandstone and the lower part of Antalo Limestone are characterized by extensive/semi-regional aquifers with borehole yields mostly ranging from 10 to 60 L/s. But in southern Mekelle area, the dolerite intrusions have created cooling fractures and joints which increased secondary porosity and permeability at contact zones with the Agula shale. In this area, many intermittent and semi-perennial springs with discharges ranging from 0.2 to 3 L/s and high discharge tube wells (10 – 40 L/s) are common. The geometry and emplacement mechanism of the Mekelle dolerites is complex and less understood; their roles in controlling the groundwater occurrence and flow are also meagerly studied.

In the Cenozoic volcanics of the Tekeze basin, the Ashange basalt, which is characterised by extensive weathering, jointing, faulting and fracturing, form important aquifers. Shallow wells drilled in this formation have discharges ranging from 0.7 to 5.6 L/s. Many high discharge springs are encountered at the contacts between Ashange sequences and the underlying Mesozoic sediment. But deep borehole data is scarce to characterise the deep aquifers in this formation.

In the TRB the groundwater contour maps are often subdued replica of the topographic contours. The abundance of springs at different elevations, and the overall relation of groundwater level with topography, particularly in steep landscapes, suggests that the shallow groundwater flows in local flow systems is controlled by ground elevation. However, the thickness and lateral extent of the aquifers indicates that deeper, regional flow systems are controlled mainly by the volcanic and sedimentary rocks. In general, the hydrodynamics of the TRB are strongly controlled by the geomorphology, type of rocks, their respective permeability and associated geological structures. Further studies that integrate hydrogeochemical and isotope approaches with other conventional hydrogeological techniques are highly recommended to better understand the hydrogeology of this complex basin.

ACKNOWLEDGEMENTS

The authors appreciate the support from the Addis Ababa University (School of Earth Sciences) during the preparation of this review article. The anonymous reviewers and the Associate Editor of SINET are gratefully acknowledged for their highly valuable inputs during the review process. All of the institutions and individuals, whose works are cited in this article, are acknowledged for making their published and unpublished materials available to the authors.

REFERENCES

1. Andarge Yitbarek (2002). Hydrogeological investigation of the Megech river basin. Unpublished M.Sc. Thesis. Addis Ababa University. Addis Ababa, Ethiopia.
2. Arkin, V., Beyth, M., Dow, D.B., Levitte, D., and Tsegaye Haile (1971). Geological Map of Mekele Sheet (ND 37-11). Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.
3. Bayessa Asfaw (2003). Hydrogeology of Northern Ethiopia, Geological Survey of Ethiopia.
4. Beyth, M. (1971). The Geology of central and western Tigray. Draft report, Ministry of Mines, EIGS, Addis Ababa, Ethiopia.
5. Beyth, M. (1972). The Geology of central and western Tigre. PhD Thesis, University of Bonn, Germany, 155 pp.
6. Beyth, M., Avigad, D., Wetzel, H., Matthews, A., and Seifemichael Berhe (2003). Crustal exhumation and indications for Snowball Earth in the East African Orogen: north Ethiopia and east Eritrea. *Precambrian Research,* **123:** 187–201.
7. Bosellini, A., Russo, A., Fantozzi, P.L., Getaneh Assefa and Solomon Tadesse (1997). The Mesozoic succession of Mekelle Outlier (Tigre Province, Ethiopia). *Mem. Sci. Geol.,* **49:**95-116.
8. Chorowicz, J., Collet, B., Bonovia, F.F., Mohr, P.A., Parrot, J.F. and Tesfaye Korme (1998). The

Tana basin, Ethiopia: Inter-plateau uplift, rifting and subsidence. *Tectonophysics,* 295:351-367.

9. Davidson, A. (1983). Reconnaissance Geology and Geochemistry of parts of Illubabor, Kafa, Gemu Gofa and Sidamo, Ethiopia. EIGS, Bull No.2, Addis Ababa, Ethiopia.

10. Daniel Gemechu (1977). *Aspects of climate and water budget in Ethiopia*. Addis Ababa University Press, Addis Ababa, 71 pp.

11. Danielli, G. (1943). *Geologia dell'Africa Orientale*, Vol.4,. Reale Acc, Italia, Roma.

12. DH Consult (2010). Groundwater resources potential assessment of the Mekelle Outlier. Phase II Report. Ministry of Water Resources, Addis Ababa, Ethiopia, 153 pp.

13. EIGS (1993). Hydrogeological map of Ethiopia, 1:2,000,000 scale. Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia.

14. EIGS (1996). Explanation of the Geological map of Ethiopia (Scale 1:2,000,000), 2nd edition. Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia, 78 pp.

15. EMA (1999). National Atlas of Ethiopia. Ethiopian Mapping Agency (EMA), Addis Ababa, Ethiopia.

16. Ermias Hagos, Tenalem Ayenew, Seifu Kebede, Mulugeta Alene, Wohnlich, S., and Wisotzki, F. (2015). Conceptual groundwater flow model of the Mekelle Paleozoic-Mesozoic sedimentary outlier and surroundings Northern Ethiopia using environmental isotopes and dissolved ions. *Hydrogeology Journal,*. DIO 10.1007/s 10040-015-1243-4.

17. FWWDSE/Federal Water Works Design and Supervision Enterprise (2007). Evaluation of Aynalem Well Fields around Mekelle Town for Water Supply Source, Unpublished Final Report, Volume II. Addis Ababa, Ethiopia, 147 pp.

18. Garland, C.R. (1980). Geology of the Adigrat area. Min, Mines Memoir, No. 1, Addis Ababa.

19. Griffiths, J. F. (1972). Climates of Africa. In: *World Survey of Climatology, (*Griffiths, J.F., ed.). Elsevier, Amsterdam.

20. Kazmin, V. (1975). Explanatory Note to the Geology of Ethiopia. EIGS, *Bull No.2*, Addis Ababa, Ethiopia.

21. Kazmin, V. (1979). Stratigraphy and correlation of volcanic rocks of Ethiopia. EIGS, Note number 106, pp 1-26.

22. Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Gezahegn Yirgu, Dereje Ayalew, Weis, D., Jerram, D.A., Keller, F., and Meugniot, C. (2004). Flood and shield basalts from Ethiopia: Magmas from the African Superswell. *J. Petrol.*, **45:**793–834.

23. Kuster, D., Dwivedi, S.B., Kurkura Kabeto, Kassa Mehari, and Matheis, G. (2005). Petrograhic reconnaisance investigation of mafic sills associated with flood basalts, Mekelle basin, Northern Ethiopia: Implications for Ni-Cu Exploration. *J. Geochem. Exp*., **85:**63-79.

24. Meert, J.G. (2003). A synopsis of events related to the assembly of eastern Gondwana. *Tectonophysics*, **362:** 1-40.

25. Merla, J.G. and Munucci, E. (1938). Missione geologica nel Tigrai, *Reale Accademia d'Italia*, Rome.

26. Merla, G., Abate, E., Azzaroli, A., Bruni, P., Fazzuoli, M. and Sagri, M. (1979). Comments to the Geological map of Ethiopia and Somalia. *Consiglio Nazionale delle Ricerche*. Frenze, 95 pp.

27. Mohr, P.A. (1983). Ethiopian flood basalt province, *Nature,* **303:**577-585.

28. Mohr, P.A. and Zanettin, B. (1988). The Ethiopian flood basalt province. In: *Continental Flood Basalts*, pp 63-110, (Macdougall J. D. ed.), Kluwer, Dordrecht.

29. Mola Demlie, Wohnlich, S. and Tenalem Ayenew (2008). Major ion hydrochemistry and environmental isotope signatures as a tool in assessing groundwater occurrence and its dynamics in a fractured volcanic aquifer system located within a heavily urbanized catchment, central Ethiopia. *J. Hydrol.*, 353:175-88.

30. Molla Fetene (2004). Water resource evaluation of Ribb river basin, North-western Ethiopia, South Gonder. Unpublished M.Sc. Thesis, Addis Ababa University, Addis Ababa, 150 pp.

31. Mulugeta Alene (1998). Tectonomagmantic evolution of the Neoproterozoic rocks of the Mai Kenetal-Negash area, northern Ethiopia. Unpublished PhD Thesis, University of Turin, Italy.

32. Mulugeta Alene, Jenkin, G.R.T., Leng, M.J. and Darbyshire, D.P.F. (2006). The Tambien Group, Ethiopia: An early Cryogenian (ca. 800-735 Ma) Neoproterozoic sequence in the Arabian-Nubian Shield. *Precambrian Research*, **147:**79-99.

33. Mulugeta Alene, Ruffini, R., and Sacchi, R. (2000). Geochemistry and Geotectonic setting of Neoproterozoic rocks from northern Ethiopia (Arabian-Nubian Shield). *Gondwana Res.,* **3:**333-347.

34. Mulugeta Alene and Sacchi, R. (2000). The Neoproterozoic low-grade basement of Tigrai, northern Ethiopia.. Abstract: 18th

Colloquium of African Geology, Graz. *J. Afr. Earth Sci.,* **30(4):** 5-6.

35. MWR (1998). Tekeze River Basin integrated development master plan project. Sectoral Reports. Ministry of Water Resources (MWR),– Netherlands Engineering Consultants, Addis Ababa, Ethiopia.

36. Nata Tadesse (2003). Hydrogeological investigation and environmentally-sound plans for the development of groundwater in the Werei River basin, Tigray, Ethiopia.. Unpublished Ph.D. Thesis, University of Natural Resources and Applied Life Sciences, Department of Applied Geology, Vienna, Austria.

37. Pik, R., Deniel, C., Coulon, C., Gezahegn Yirgu, Hoffman, C. and Dereje Ayalew (1998). The northwestern Ethiopian plateau flood basalts:Classification and spatial distribution of magma types. *J. Volc. and Geotherm. Res.* **81:**91-111.

38. Rochette, P., Tamirat Endale, Feraud, G., Pik, R., Courtillot, V., Endale Ketefo, Coulon, C., Hoffmann, C., Vandamme, D. and Gezahegn Yirgu (1998). Stratigraphy and timing of the Oligocene Ethiopian traps. *Earth and Planetary Science Letters,* 164:497–510.

39. Samuel Yihdego (2003). Hydrogeological Assessment of the Ellala-Aynalem Catchments with Particular Reference to the Chemical Variation and Aquifer Characterization, Northern Ethiopia. Unpublished M.sc thesis, Addis Ababa University, Addis Ababa, Ethiopia, 183 pp.

40. Seifu Kebede (2004). Vertical electrical sounding for groundwater exploration in volcanic terrain of central and North-Western Ethiopia. International conference and exhibition on groundwater, Addis Ababa, Ethiopia.

41. Seifu Kebede (2013). *Groundwater in Ethiopia features, numbers and opportunities*. *Springer Hydrogeology*. 121 pp.

42. Singhal, B. and Gupta, R. (2010). *Applied hydrogeology of fractured rocks: Second edition*. Springer, 408 pp.

43. Stern, R.J. (1994). Arc assembly and continental collision in the Neoproterozoic East African Orogen: Implication for the consolidation of Gondwana. *Anual Reviews Earth Sciences,* **22:** 319-351.

44. Tarekegn Tadesse (1997). Geology of the Axum area. Ethiopian Institute of Geological Survey. *Memoir No.9*. Addis Ababa.

45. Telford, R.J. (1998). The paleo-environmental record of Holocene environmental change in the Ethiopian rift valley. Unpublished Ph.D.thesis, University of Wales, U.K..

46. Tenalem Ayenew, Seifu Kebede and Tamiru Alemyahu (2007). Environmental isotopes and hydrochemical study as applied to surface water and groundwater interaction in the Awash River basin. *J. Hydrol. Processes,* **22(10):**1548-1563.

47. Tenalem Ayenew (2009). Hydrogeological and geophysical investigation for water well drilling site selection in Werei Leke wereda of central Tigray zone, Northern Ethiopia. Tigray Bureau of Water, Mines and Energy, Mekelle, Ethiopia. 76 pp.

48. Tesfamichael Gebreyohannes (2009). Regional groundwater flow model of Giba Basin, Northern Ethiopia. PhD Thesis, Vrije Universiteit Brussel, Belgium, 265 pp.

49. Tesfamichael Gebreyohannes, Smedt, F.D., Miruts Hagos, Kassa Amare, Kurkura Kabeto, Abdelwassie Hussein, Nyssen, J., Bauer, H., Moeyersons, J., Deckers, J., and Nurhussen Taha (2010). Large-scale Geological mapping of the Geba basin, Northern Ethiopia. VLIR – Mekelle University IUC program. *Tigray Livelihood Papers 9,* 46 pp. ISBN 978-90-8826-134-3.

50. Tesfaye Chernet (1993). Hydrogeology of Ethiopia and water resources development. Unpublished report. EIGS, Addis Aaba, Ethiopia, 222 pp.

51. Tesfaye Chernet (1988). Hydrogeological map of Ethiopia, 1:2,000,000 scale. Ethiopian Institute of Geologycal Surveys, Addis Ababa, Ethiopia.

52. WWDSE, Water Works Design and Supervision Enterprise (2007). Evaluation of Aynalem well field and selection of prospective well fields around Mekelle town for water supply source. Final report. Volume II: Evaluation of groundwater potential. Tigray Bureau of Water Resources Development, Mekelle, Ethiopia. 147 pp.

53. WWDSE, Water Works Design and Supervision Enterprise (2009). Groundwater resources of the upper Tekeze basin: Resource description, assessment and model. Phase one report (Hydrogeology). Addis Ababa, Ethiopia. 62pp.

54. Worash Getaneh (2002). Geochemistry province and depositional tectonic setting of the Adigrat Sandstone, Northern Ethiopia. *J. Afr. Earth Sci.,* **35:**185-198.