The movement and occurrence of groundwater in the Ethiopian volcanic terrain

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1. General overview of the region

Ethiopia is characterized by high-altitude volcanic plateaux tapering into Rift valley and peripheral lowlands. The country has huge groundwater potential, mostly localized in the volcanic terrain covered with Quaternary deposits.

This comprehensive hydrogeological study focuses on the volcanic province of central Ethiopia which includes the Rift Valley (Fig. 1). The geology is quite complex (Fig. 2).Except patchy Precambrian rocks, the rift is covered with Cenozoic volcanics and recent sediments (Mohr, 1967; Woldegebriel et al., 1990). The volcanics are dominantly fissural basaltic lava flows, rhyolites and ignimbrites alternated with volcano-clastic deposits derived from tuff and volcanic ash. In the rift recent continental type volcanism has developed, giving rise to large sialic rocks fissural basic lava flows covered with alluvial and lacustrine deposits (Zanettin et al., 1980). The alluvial deposits filled troughs in the lowlands and along river valleys. Most of the rocks are are extremely faulted (Woldegebriel et al., 1990). There are at least three sets of faults in the Afar associated with the triple junction representing the Ethiopian Rift, Red Sea and the Gulf of Aden. The rift is distinctly separated from the plateaux by a series of normal faults. Numerous geothermal fields and caldera volcanoes characterize the rift floor. Volcanism has persisted up to the present day in the Afar within small eruptive centres.

The climate is extremely variable. Mean annual temperature varies from over 30^{0}C in the tropical lowlands to less than 10 ^{0}C in the high altitude plateaux. Annual rainfall varies from less than 100 mm in much of the rift to more than 2000 mm in the southwestern and western highlands. The national annual average is 744 mm/yr (FAO, 1995).

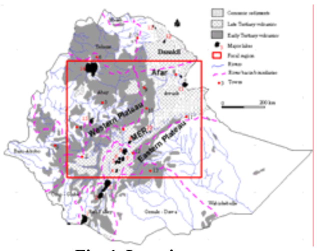

Fig. 1. Location map

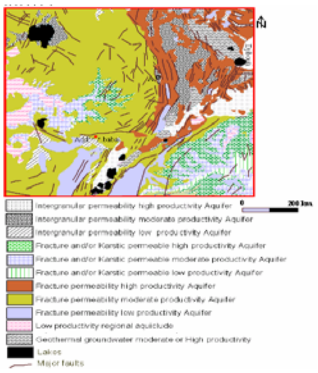

Fig. 2. Geological map

Approach and Methodology

Integrated conventional and up to date hydrogeological investigation techniques have been applied including field mapping, structural analysis, remote sensing and GIS, hydrometeorological, hydrochemical and isotope data analysis. These enable to conceptualize the movement and occurrence of groundwater in the Ethiopian volcanic terrain. The study starts from regional conceptualisation to a more focussed analysis of four selected regions with distinct hydrogeological setting. The sleeted areas represent highland Trap volcanic sequence characterized by multi-layer aquifers, intermountain sedimentary grabens, fractured rift floor volcanics boarded by steep high altitude plateau, and vast flood plain covered with alluvial sediment with adjoining pediments.

Groundwater Recharge

For selected basins groundwater recharge has been estimated based on conventional water balance approaches and systematic river discharge measurements. Generally, the main source of groundwater recharge is rainfall and river channel losses. The average yearly groundwater recharge for the entire country is around 2.8 billion cubic meters (Tadesse, 2004). With the exception of the Afar and Danakil Depressions where rainfall is very low, the recharge for the different river basins has been estimated (Table 1). The major recharge occurs in the highlands where annual rainfall is more than 1000 mm (Fig. 3). The rift floor acts as regional discharge zone, which contains perennial rivers, springs and lakes. There is strong spatial and temporal variation of groundwater recharge. Especially, this is apparent when the lowlands, the rift and highland recharges are compared. In the central and northwestern highlands direct recharge ranges from 90 to 150 mm annually. This accounts 10 to 20 percent of the annual rainfall of the region. In southwestern highlands recharge my reach as high as 400 mm. In the Ziway-Shala basin (ZSB) direct annual recharge in the rift floor, escarpment and highlands is around 10, 90 and 100 mm respectively.

Aquifer systems	*Common depth to water (m)*	*Specific yield range (lps)*	*Location*
Tertiary volcanic rocks	30-250	2 - 6	Central, eastern and western highlands
Quaternary volcanic rocks	50-250	2 - 5	Rift valley floor
Unconsolidated sediments	20-80	1 - 5	Mostly in the rift and intermountain valleys
In situ developed soils and river gravels	5-20	0.1 - 1	Highland/escarpment

Table 1. Regional groundwater recharge

Figure 3. Recharge zones

Aquifer hydraulic parameters

Erratic data from over 1200 wells indicate that the productivity of the multilayer aquifers considerably varies. The yield of the aquifers from the northwestern plateau basalts ranges from 1 to 12.3 l/s. The range of the well yields for the Lake Tana basin the southeastern plateau and the northern intermountain grabens is 0.4-12,1.2-15 and 2-12 l/s respectively. The highly permeable volcano-clastic deposits and fractured basalts of Addis Ababa area yield as high as 20 and 27 l/s respectively.

The majority of the rural community depends on hand-dug wells dug in alluvial and lacustrine deposits forming unconfined aquifers. The well yield and depth to water is less than 2.5 l/s and 10 m respectively. Permeable alluvial and colluvial deposits associated with lacustrine soils form the main shallow aquifers in much of the lowlands of central Ethiopia. The lacustrine deposits are known to provide more than 10 l/s (Chernet, 1993).

Groundwater localization in representative basins

The major groundwater reserves is localized in selected basins. The localization is controlled mainly by faults and intricate relation of the volcanic and overlying Quaternary deposits. Four representative basins are selected (Fig. 5). These are highland thick Trap volcanic sequence, intermountain graben field with thick sediments, fractured rift boarded by steep high altitude plateau, and vast flood plain covered with alluvial sediment with adjoining pediments in a tectonically active rift.

Region	*Stat.*	*Ground Altitude (masl)*	*Depth (m)*	*Depth To SWL (m)*	*Specific Capacity (l/s/m)*	*Yield (lps)*	*Hydraulic conductivity (m/d)*	*Transmissivity (m^2/d)*
Central hi	Min	1630	60	Artesian	0	0	1	30.7
	Max	23400	252	137.6	18.6	2.5	89.8	2156.6
	Mean	2303	129.9	40.6	2.4	35	19.8	378.6
Raya-Kob	Min		65	2	0.2	2	-	0.7
	Max		250	97	10.3	25	-	3765
	Mean		98	33.4	2.4	4.2	-	327.9
Northwes	Min	1937	56	0.8	-	0.8	0	1
	Max	373354	182	73	-	30	85.4	2630
	Mean	160924	123.3	15.5	-	5.2	23.2	468.1
MER/ (do	Min	1440	13	2	-	0	0.1	132
	Max	3044	293	207.6	-	5.8	138	1430
	Mean	2037	111.8	51.9	-	0.9	6	290
Eastern hi	Min	1659	51	31.5	-	0	0.1	32
	Max	2705	180	168	-	2.5	18	240
	Mean	2248	132	82.8	-	1.8	3.2	18

Table 2. Aquifer hydraulic parameters

Movement and Occurrence

The groundwater movement is strongly controlled by geological structures; mainly faults. Figure 4-6 illustrate the movement and occurrence of groundwater across and along the rift valley in selected areas. Fig. 4 represent active symmetrical rift bordered by high-altitude plateau. In this case the groundwater flow direction is parallel to the rift axis along major faults against the regional topographic slope. The image shows large faults.Fig. 5 represent three basins. In section A; groundwater occurs at different elevations based on the extent orientation of the normal step faults in the escarpment and rift zones.In section B, wide rift faulted volcanics is covered with thick sediments forming highly productive aquifers. The undryling fractured volcanics also forms deep aquifers.Section C represents high-alitiude intermountain valleys (grabens) filled with thick sediments) forming unconfined and locally semi-confined aquifers feed by high-overland flow from the adjacent highlands. Figure 6 represents the conceptual groundwater flow from the central highlands to the north-eastern highlands. It shows the existence of deep, intermediate and shallow flows. The deep system is associated with geothermal fields represented by hot-springs at different elevations, often controlled by faults.

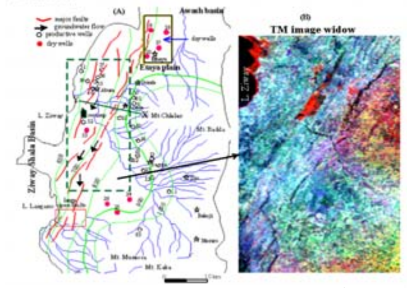

Fig. 4. Groundwater movement in the central rift

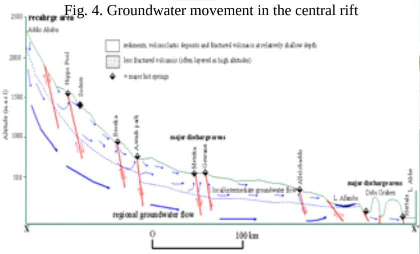

Fig. 6. Conceptual groundwater flow model along the highland rift transect

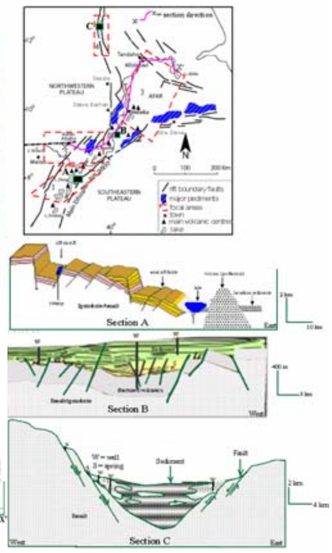

Fig. 5. Selected groundwater basins (A = Faulted basin; B = alluvial plain in the rift; C= intermountain highland valley)

Conclusion

The Ethiopian volcanic terrain and associated Quaternary deposits represent complex aquifer systems where groundwater occurrence and distribution is strongly controlled by the geomorphological architecture of the plateaux, escarpments and the rift valley. The complex spatial and temporal distribution of the volcanic rocks, their different intricate stratigraphic and structural relationships, wide compositional variability, different level of weathering and topographic position complicate the hydrogeological behaviour of the volcanic aquifers and the hydrochemical signature. Any groundwater exploration and development requires mapping of the important structures and evaluation of their role in the recharge, movement and occurrence of groundwater.

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