Integrated Groundwater Modeling and Hydrochemical Study in Addis Ababa Area: Towards Developing Decision Support System for Wellhead Protection

Tenalem Ayenew[1], Stefan Wohnlich[2], Molla Demlie[3]

1. General Overview of the Area

The Akaki catchment is located in the central Ethiopian highlands at the western edge of the Main Ethiopian Rift (Figures 1 &2). The total surface area of the catchment is 1462 km^2. Large mountains and various volcanic rocks characterize the watershed boundary. The elevation varies from 2060 m.a.s.l in the south around the Akaki well field to 3200 m.a.s.l in the northern Intoto mountains. The south-eastern, central and eastern parts are flat and undulating lands covered with thick Quaternary alluvial and lacustrine deposits (AAWSA, 2000).

Major perennial rivers originate in the north and drains to the south. The main rivers are the Big Akaki, Small Akaki and Kebena rivers that drain through the city of Addis Ababa. The big dam, Legedadi, provide sustained flow to the Akaki river. The southern Aba Samuel reservoir was used for water supply and hydropower generation. Now it is a non-functional swamp, which retains highly-polluted surface and groundwater effluents from Addis Ababa.

The climate is warm temperate to humid. The dry season extends from October to May and the wet season from June to September, with intermittent rainfall in the rest of the months. The aerial average annual catchment rainfall and potential evapotranspiration are 1100 and 1226 mm respectively. The mean annual aerial groundwater recharge from rainfall over the catchment is estimated using semi-distributed soil-water balance model. It is 106 mm, accounting 10% of the mean annual aerial rainfall (Demlie, 2007; Ayenew et al., 2008).

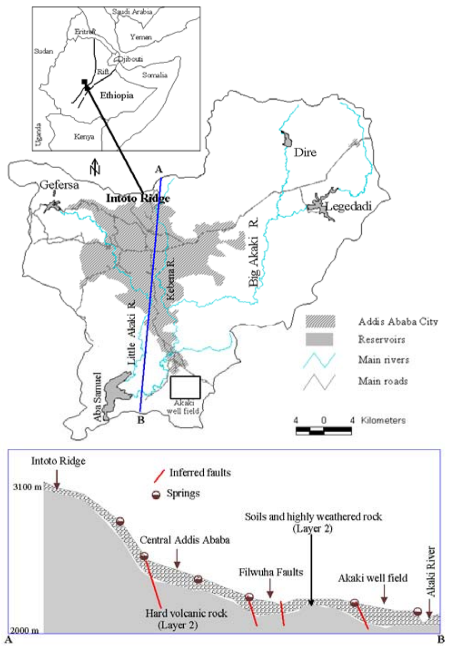

Fig. 1. Location map with N-S cross-section

2. Objective and Methodology

The general objective is to understand the groundwater flow system and its relation with surface waters using numerical groundwater flow model and hydrochemistry along with conventional hydrogeological mapping with particular emphasis to identifying the most susceptible areas which are likely to be polluted from different effluents (identification of wellhead protection areas).

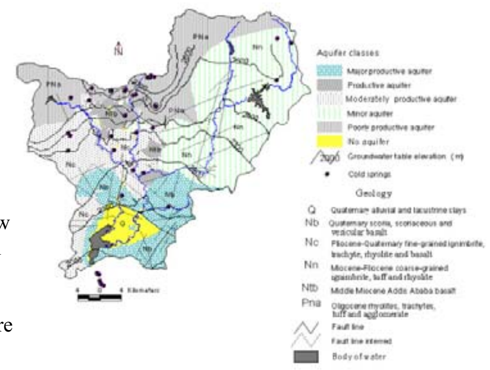

Fig. 2. Geological map

The popular three-dimensional finite difference groundwater flow model called MODFLOW (MacDonald and Harbaugh, 1988) is used. Extensive hydrochemical analysis was carried out. Ancillary environmental isotope data was also used. Converging evidence approach was employed to integrate the model simulation results with the water quality data. The groundwater recharge was estimated using a semi-distributed soil-water balance model and checked independently using chloride mass balance approach (Demlie, 2007). The recharge estimation process accounted all pertinent hydrometeorological data, soil types, slope and land use aspects. The aerial extent of the aquifers was delineated from well lithological logs and existing hydrogeological maps. Static groundwater levels were recorded from 131 wells and used for calibration. Water level was measured in few wells periodically since the year 2000.

3. Model Boundary Conditions

The catchment boundary is assumed to be no flow boundary. Major reservoirs are treated as constant head cells. Small reservoirs and rivers are treated with the drain and river package respectively. In the southern tip groundwater outflow is evident and treated as general head boundary (Fig. 3). The basin is treated as a two layer unconfined aquifer system.

One of the most important model input and calibration parameters is hydraulic conductivity. The limited hydraulic conductivity value available indicate that it ranges from 0.09 m/day in the homogeneous less fractured highland volcanics to around 550 m/day in the highly fractured volcanics and permeable alluvial and lacustrine deposits. The aquifer thickness ranges from around 80 m in the highlands to a maximum of around 230 m in the low-lying areas. Table 2 summarizes the transmissivity and depth to static water level from 120 wells.

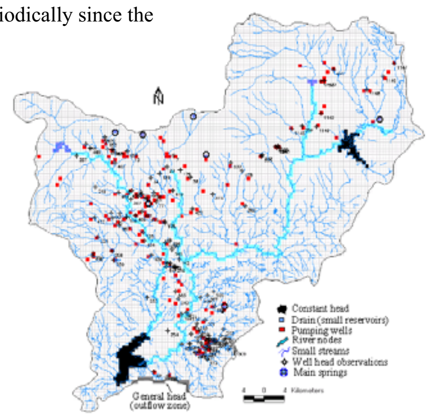

Figure 3. Boundary conditions

4. Recharge and High Risk Zones

The groundwater recharge varies in a wide range governed by the rainfall distribution, topography, land use and geology. The major recharge to the aquifer comes from precipitation and river channel losses. Main direct recharge is assumed to take place in all areas except where low permeable lacustrine soils exist. The recharge has been assigned in the model in a distributed manner by varying in a wide range from 0.00007 to 0.0005 m/day. The least recharge is within the city of Addis Ababa and in areas where less permeable clay and lacustrine soils exist. Much of the watershed boundaries and the permeable volcanics in the southern flat areas get the maximum recharge.

Extensive hydrochemical surveying of groundwater and surface water sources allowed to identify major areas susceptible to groundwater pollution. Figure 4 shows the most important sites to be considered from groundwater pollution control point of view or well head protection areas. Heavy metal and nitrate pollution have been detected in samples collected from rivers, springs and shallow hand dug wells (Alemayehu, 2000). Coli bacteria has also been detected in some water samples. The most important zones that have to be given utmost priority from pollution protection point of view is indicated on Fig. 4. Most of these sites are close to water supply wells within the city of Addis Ababa and in the Akaki well field in the south.

Stat. variables	Depth to static water level (m)	Transmissivity (m^2/day)
Minimum	1782	0.3
Maximum	2615	105408
Mode	2019	5
Average	2153.9	6818.1
Variance	29127	364031044.8
Standard deviation	170.7	19079.6

Table 1. Summary of hydraulic parameters

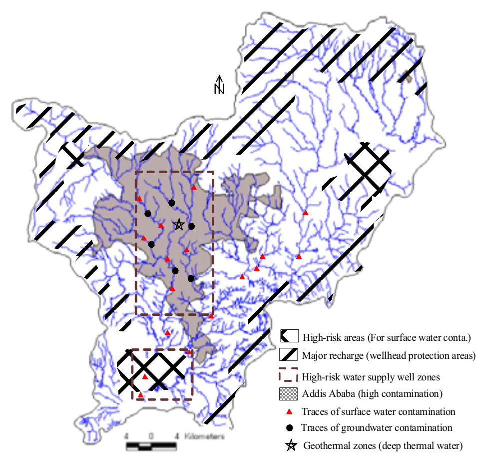

Figure 4. Recharge and risk zones

4. Groundwater Movement and Occurrence

Figure 5 shows the model-predicted groundwater contours. The water level contour is the subdued replica of the topographic contours. Flow converges from all sides towards the Akaki well field and its surrounding plains. The large hydraulic gradient and the presence of highly permeable rocks resulted in the emergence of springs and seepage zones at different elevations, mainly in the foothills of Intoto ridge and along the major regional faults. The high elevation difference between the northern mountainous areas and the flat southern plain favour occurrence of local and intermediate flow systems (Fig. 1). Channel losses are common along main river courses. Large flow from the rivers into aquifers is dominant along the course of the Big and Small Akaki rivers. The major recharge from the surrounding mountains contribute to the aquifers in the southern and central part of at an altitude below 2500 m.a.s.l. In places the lateral flow of groundwater is manifested as springs where there are large topographic and hydraulic gradients. The north-south cross-sectional model simulation indicates that the southern springs have direct connections with the high recharge in the northern wellhead protection areas. Despite previous assertions from hydrochemical and isotopic evidences indicating the presence of local subsurface groundwater barrier between the Akaki well field and northern Intoto ridge, all the aerial and cross-sectional model simulation revealed the continuity of flow in the north-south direction. This has important implications for wellhead protection. The location of the major well field downstream of the polluted urban centre may lead to future contamination if excessive pumping continues.

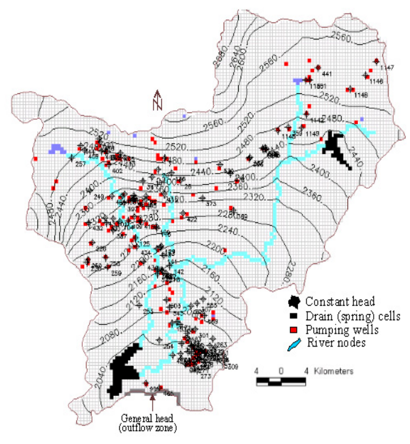

Fig. 5. Groundwater movement

5. Hydrochemistry and Vulnerability to Pollution

Accounting six different parameters, the aquifer vulnerability map (Fig. 6) was established using what is know as DRASTIC approach (Civita & De Maio, 2000. This approach coincides with the results obtained from flow model simulation, The Hydrochemical and isotopic signatures clearly demonstrates the existence of different water types with indications of groundwater pollution in few places (Figures 7 & 8). Conventional hydrochemical analysis indicated a very dilute Ca-HCO_3, Ca-Na-HCO_3 type water in the north (Intoto range) draining the Intoto silicics; Ca-Mg-HCO_3, Mg-Ca-HCO_3 type water draining the Addis Ababa basalt in the central sector and the Bischoftu basalt aquifers in the south and Na-HCO_3 type water of the 'Filwuha' thermal system, which have rock dominated hydrochemistry. While a Ca-NO_3 and Ca-Cl type water circulating in the central sector of the catchment is a result of anthropogenic influences, demonstrating pollution.

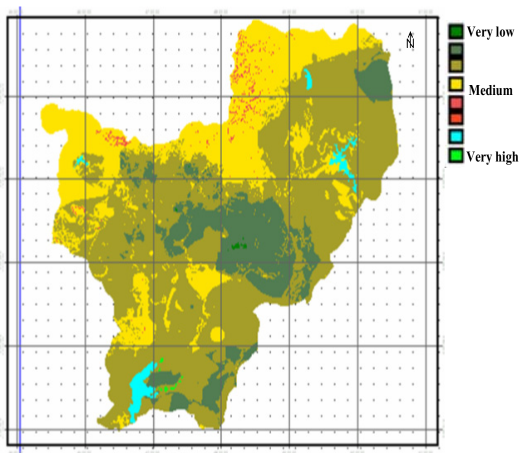

Fig. 6. Groundwater movement

(Modified from Nigussa, 2003)

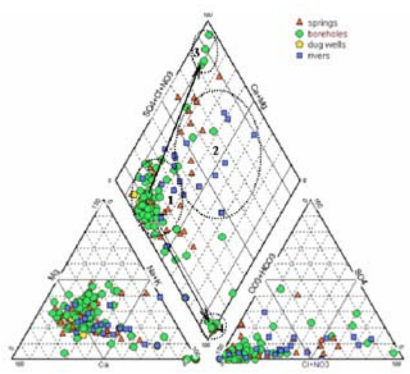

Fig. 7. Piper diagram

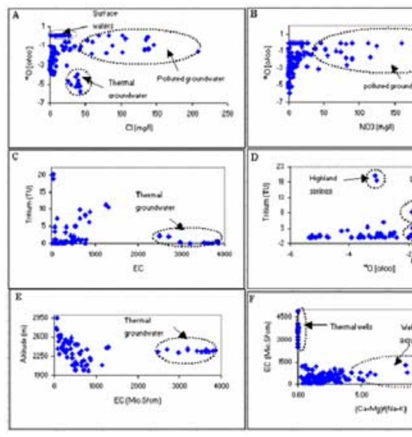

Fig. 6. Scatter plots

6. Conclusions

By converging the groundwater flow simulation results and hydrochemical analysis the groundwater flow system and focal areas to be protected from likely groundwater pollution were identified. Reservoirs and rivers play important role in recharging the fractured volcanic aquifers. Model simulations made under different pumping scenarios revealed that an increase in pumping rate results in substantial regional groundwater level decline, which will lead to the drying up of springs and shallow hand dug wells. This causes reversal of flow from contaminated rivers in to productive shallow aquifers close to highly polluted rivers draining through the city of Addis Ababa. The comprehensive hydrochemical survey signify that most of shallow wells, springs and rivers are polluted by heavy metals and nitrate. In places coli bacteria has been detected. Excessive pumping and luck of considerations on issues of wellhead (recharge area) protection will likely lead to large-scale groundwater pollution. The vulnerable areas are close to major aquifers. The study clearly indicates the importance of numerical groundwater flow models in identifying the most susceptible areas, groundwater and surface water interactions. This work is believed to have far-reaching impactions for many urbanized areas established on fractured volcanic aquifers that can easily be polluted by contaminated rivers and springs elsewhere in the East African rift system.

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[1]Tenalem Ayenew
Addis Ababa University
Dep;artment of Earth Sciences
P.O.Box 1176
E-Mail: Tenalema@yahoo.com

[2]Stefan Wohnlich
Ruhr University Bochum,
Department of Applied Hydrogeology, D-44801
Bochum, Germany.
E-mail: Stefan.wohnlich@rub.de

[3]Molla Demlie
School of Geological Sciences
University of Kwazulu-Natal. Durban
South Africa.
E-mail: demlie@ukzn.ac.za