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

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1. General Overview of the Area

The Akaki catchment is located in the central Ethiopian highlands at the western end of the Main Ethiopian Rift (Figures 1 & 2). The total surface area of the catchment is 1462 km². Large mountains and various volcanic rock exposures 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 intrusive mountains. The south-eastern, central and eastern parts are flat with large alluvial deposits and undulating lands covered with thick Quaternary alluvial and lacustrine deposits (A.AWSA, 2000).

Major perennial rivers originate in the north and drain 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 Akaki drains the Addis Ababa city and provides sustained flow to the river. The southern Aba Samuel reservoir was used for water supply and hydropower generation. Now it is a non-functional reservoir, which contains 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 rainfall catchment rainfall and potential evapotranspiration are 1180 and 1220 mm respectively. The mean annual aerial groundwater recharge from rainfall over the catchment is estimated using semi-distributed rainfall-runoff models. It is 110 mm, accounting 10% of the mean annual aerial rainfall (Demlie, 2007; Ayenew et al., 2008).

2. Objective and Methodology

The general objective is to understand the groundwater flow system and to relate it with surface water. The popular three-dimensional finite difference groundwater flow model called MODFLOW (MacDonald and Harbaugh, 1988) is used. Extensive hydrochemical surveying of groundwater and lacustrine soils exist. Much of the watershed boundaries are characterized by flat and semi-distributed soil-water balance model and checked independently using chloride (Figures 1 & 2). The total surface area of the catchment is 1462 km². Large mountains and various volcanic rock exposures 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 intrusive mountains. The south-eastern, central and eastern parts are flat with large alluvial deposits and undulating lands covered with thick Quaternary alluvial and lacustrine deposits (A.AWSA, 2000).

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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 0.01 m/day in the homogenous low fractured highland volcanics to around 500 m/day in the highly fractured volcanics and paramagnetic alluvial and lacustrine sediments. The aquifer thickness ranges from around 80 m in the highlands to a maximum of around 210 m in the low-lying areas, which ensures the continuity and depth to static water level from 120 m.

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 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 0.0000 to 0.0002 m/day. The least recharge is within the city of Addis Ababa and in areas where low 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 the most important areas susceptible to groundwater pollution. Figure 4 shows the most important sites to be considered. Three groundwater pollution control point of view of well head protection areas. Heavy metal and nitrate pollution have been detected in all samples collected from 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 are the following: 1. Areas close to water supply wells within the city of Addis Ababa, 2. Areas close to the lakes and reservoirs, 3. Areas close to major aquifers. The study clearly indicates the importance of numerical groundwater models in identifying the most important areas susceptible to surface water and groundwater interactions. This work with the central sector of the catchment result of anthropogenic influences, demonstrating pollution.

5. Hydrochemistry and Vulnerability to Pollution

Accounting six different parameters, the aquifer vulnerability map (Fig. 6) was established using what is known as DRASTIC approach (Civco & Do Dac, 2004). This approach coincides with the results obtained from model flow simulation, The Hydrochemical and Hydroisotope signatures clearly demonstrate the existence of different water types with indications of groundwater pollution and recharge and evapotranspiration. The north-south cross-sectional model simulation indicates that the south-eastern, central and eastern parts are flat characterized by high recharge in the northern wellhead protection areas. Despite prevailing rose types from hydrochemical and isotopic evidences indicating the presence of local subsurface groundwater barrier between the Addis Ababa well field and northern intrusive mountains, all the aerial and cross-sectional model simulation revealed the continuity of flows in the north-south direction. This has important implications for wellhead protection. The location of the major well field downstream of the urban political centre may lead to future contamination if excessive pumping continues.

6. Conclusions

By conveying the groundwater flow simulation results and hydrochemical analysis the groundwater flow system and local areas to be protected from likely groundwater pollution were identified. Reservoirs and rivers play important role in recharging the fractured volcanic aquifers. Models simulations made under different pumping scenarios identifies that an increase in pumping intensity in substantial regional groundwater level, which will lead to the drying up of springs and shallow hand dug wells. This causes reversal of flow from contaminated rivers to recharge 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 lack of considerations on rates 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 important areas susceptible to surface water and groundwater interactions. This work with the central sector of the catchment result of anthropogenic influences, demonstrating pollution.

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References


Fig. 6. Groundwater movement (Modified from Negussie, 2003)