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GROUNDWATER FLOW MODELING IN THE AKYEM AREA, SOUTHEASTERN, GHANA

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Hydrogeological information from previous work and detailed geophysical analysis were used with a steady state groundwater flow simulation model to describe the hydrogeological conditions of aquifers in the Akyem area, southeastern Ghana. This series of investigations indicates that the groundwater resources of aquifers in this area are based on the intensity of secondary permeability resulting from weathering and fracturing. Aquifer transmissivity varies from 2.13 to 18 m^2/day with an average of 7.67 m^2/day, and relates strongly with specific capacity after twelve hours of pumping. Well yield correlates poorly with depth, which suggests that the water bearing structures are discrete entities which are not evenly distributed with depth. The flow simulation model reveals local, intermediate and regional flow systems. Groundwater contours follow the pattern of the topography, and range from 130 m to 180 m above sea level. There is a general flow from NE to SW. However, due to the heterogeneity of the aquifers and their dependence on secondary permeability, such as fractures and quartz veins among others, for groundwater storage and transmission, there are many barriers to continuous groundwater flow laterally as well as with depth and this is clearly displayed in the flow simulation model. The distribution of the hydraulic heads in the area, however, indicates significant opportunities for groundwater extraction for various uses.

INTRODUCTION

Groundwater resources management in Ghana constitutes one of the major aspects of sustainable development for rural communities. Sustainable delivery of groundwater of acceptable quality would satisfy growing domestic and irrigation needs. The success of groundwater resources management is based on the level of understanding of the hydrogeological conditions of the underlying aquifers and their general flow patterns. Groundwater flow simulation models have been used as decision support systems for management for sometime now, and have gained global acceptance as useful tools. They have been used effectively in such countries as India, China, Pakistan among others, to influence groundwater management paradigms (e.g. Shamir et al. 1984; Willis and Finney 1988; Finney et al. 1992; Emch and Yeh 1998; Ebraheem et al. 2003; Uddameri and Kuchanur 2007). McPhee and Yeh (2004) combined a flow simulation and optimization model to devise a decision support system for the management of groundwater resources under semiarid conditions in the Upper San Pedro River Basin in Arizona. Don et al. (2006) coupled a numerical simulation model with an optimization model to predict groundwater response to settlement and to determine the most optimal safe yield for groundwater without violating physical, environmental and socioeconomic constraints in the Shiroishi area in the Saga Plain in Japan.

The Akyem area (Figure 1) is located in southeastern Ghana and is underlain by rocks of the paleoproterozoic basement of the Birimian Supergroup. The Birimian in southwestern Ghana comprises northeast trending belts principally of volcanic and volcaniclastic material of tholeiitic and acidic composition. These are separated by broad sedimentary basins dominated by turbidites. The local geological setting is characterized by thinly foliated tuffaceous, phyllitic rocks, greywacke and metavolcanics intruded by quartz veins. In places, these rocks are highly sheared with zones swinging from a NE-SW direction to ENE-WSW. The local structural grain follows a NE-SW trend. However, joints which trend slightly discordant to the general structure are common and sometimes filled with quartz veins. Major lineaments in the area follow a NW-SE trend and these lineaments and joints were targeted during the siting of monitoring wells in the area. The degree of secondary permeability dictates the hydrogeological conditions of rocks in this part of the country.

This paper uses detailed information from geophysical investigations, well drilling surveys and general knowledge about the geology and hydrogeology, to build a groundwater flow simulation model in the area. The objective is to define groundwater flow pathways for the purpose of protecting the resource from surface pollution, and also manage it for productive uses in the area.

MATERIALS AND METHODS

Desktop study

This aspect of the study covered collection and collation of existing data on geology, structure, satellite images and airborne geophysical data; both digital and analogue topographical maps as well as geological maps covering the area were also collected and studied. Similarly, existing hydrogeological data which were available from 11 boreholes in the surrounding communities were collected and studied.

These data provided an insight into the geological and hydrogeological conditions of the area and the surrounding communities.

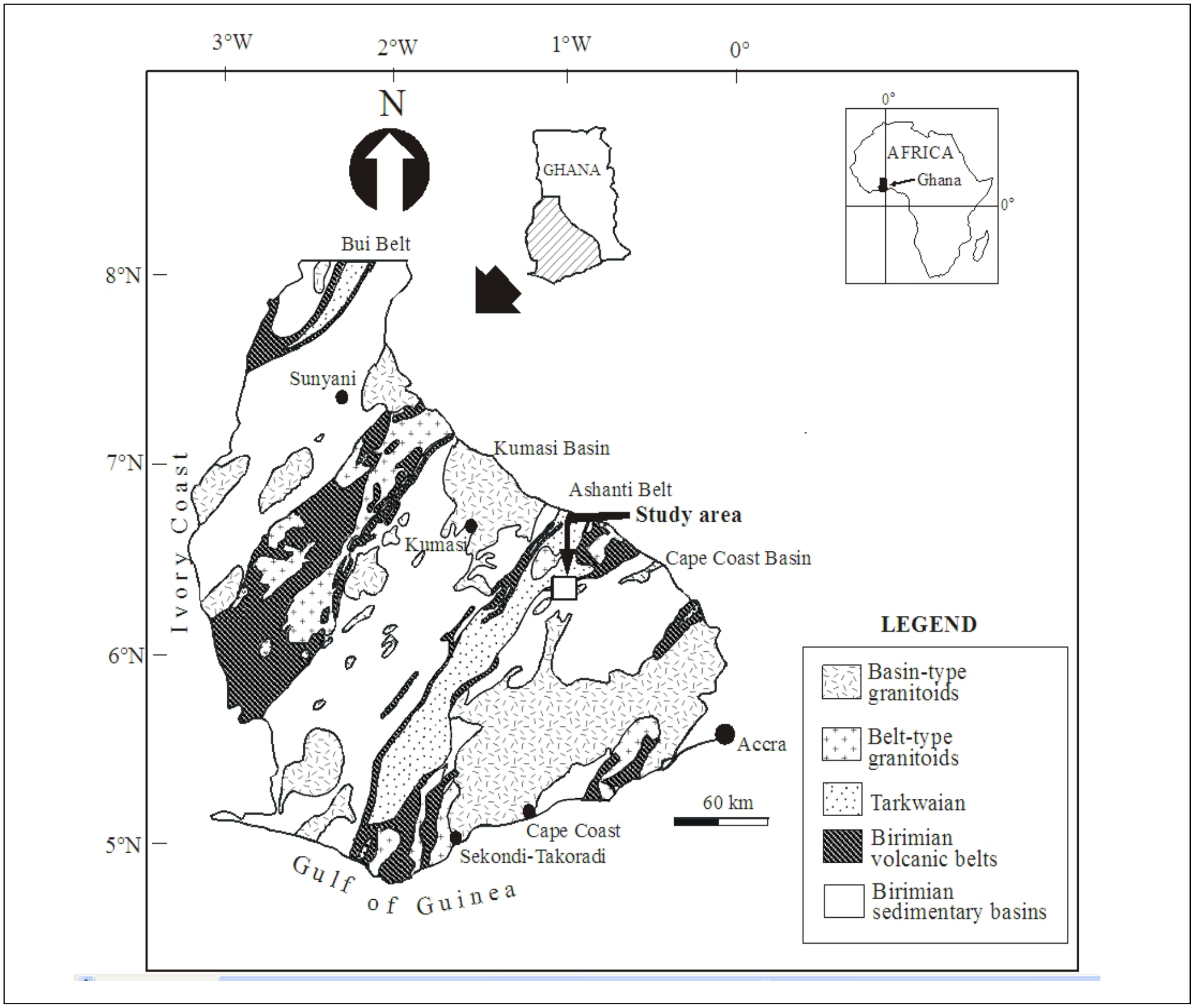

Figure 1. Simplified geological map of southwestern Ghana showing the study area. Modified after Taylor et al. (1992).

Field Reconnaissance

Field reconnaissance was carried out to verify and confirm some of the information gathered during the desk study. This included field visits to familiarize the team with the area. In the field office, an orientation of the geology of the area from drill-holes and field mapping was conducted by the project geologist, and later details of the geological nomenclature and setting were confirmed in the field by other geologists.

Lineaments and other structural entities identified from the satellite image and aeromagnetic and digital elevation models were ground-truthed to determine, along with other data obtained from the desk-study, the various fracture systems and their orientations. Similarly, field reconnaissance studies of the geology and structure of the area was conducted along outcrops through road cuttings and embankments.

During this period, the locations of the various zones for geophysical surveys to locate monitoring wells were determined in eight locations around the southern, northeastern and the south central portions of the area. The locations of these monitoring wells are shown in Figure 2.

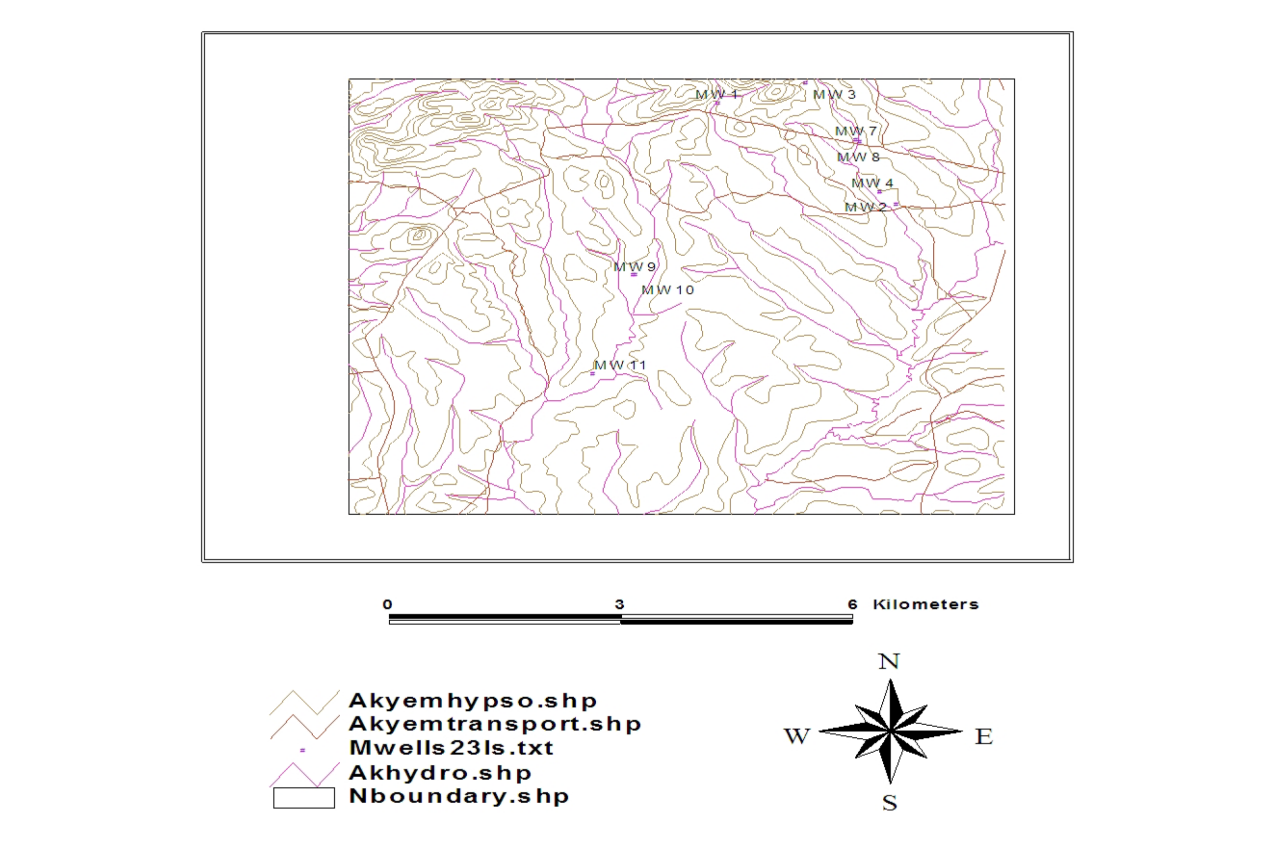

Figure 2. Location of the wells/boreholes drilled in the Akyem area.

Geophysical Investigations

Comprehensive geophysical investigations were carried out at six sites to locate the weathered zone, identify and delineate the various fracture systems, their orientations, depths, thicknesses and areal extent. Extensive resistivity profiling and soundings were carried out during this phase which generated a total of about 2600 m of profiles, from which 11 sounding points were located for drilling.

The use of appropriate geophysical techniques to show the location of prolific aquifers for monitoring purposes in the Akyem area was aimed at the detection of fracture systems and faults both laterally and at depth, as well as the mapping of the weathered zone in the proposed sites of the monitoring wells. In a fractured crystalline lithological setting as found in the Akyem area, which has high rainfall and humid conditions, the development of weathered zones is expected to be deep since the processes of weathering are strongly influenced by temperature and the amount and distribution of rainfall. Infiltration and subsequent percolation of groundwater is essentially enhanced in the subsurface.

The electrical resistivity methods consisted of resistivity profiling and vertical electrical sounding (VES). Resistivity profiling was conducted to map out the lateral inhomogeneities in the terrain to establish a basis for selecting appropriate points for vertical electrical sounding. The vertical electrical sounding was then used to locate various fractures at depth. The Abem Terrameter SAS 4000 was used for the resistivity measurements.

Resistivity profiling was carried out along all the traverses using a Schlumberger configuration with two current and potential electrode separations of (L/2, a/2) given by (19m, 0.5m) and (40m, 5m) at 10m intervals. The chosen half current electrode spacing corresponds to depth investigations of approximately 25 and 50m respectively. The electrode arrays (19m, 0.5m) and (40m, 5m) were assumed to probe the weathered layer and bedrock respectively.

Flow simulation modeling

A conceptual framework for the hydrogeological situation in the area was developed based on the information on the local geology, hydrogeology, the geophysical profiling and the drilling projects in the area. A good understanding of the local hydrogeology is needed to build a conceptual model for a good numerical flow simulation model. In order to obtain as much detail about the flow patterns in the area as possible, a ten layer model was constructed. All vertical boundaries were modeled as no flow boundaries because they were far enough from the central areas of interest. The bottom layer was also modeled as a no flow boundary since hydraulic conductivities were observed to generally decrease downwards. The static water levels were used with the topography to calculate the approximate piezometric levels in the eleven wells drilled in the area. Average annual rainfall in the area is 1389 mm. Annual recharge of 10% of this precipitation was assumed for the purpose of this model.

The three dimensional flow of groundwater of constant density through a porous material under equilibrium conditions is defined by Equation 1 (Don et al. 2006):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{dz}\right)=0 \qquad (1)$$

where K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivities in the x, y and z directions respectively which are assumed to be parallel to the axes of hydraulic conductivity (LT^{-1}), h is the potentiometric head (L). Equation 1 is derived from the law of conservation of mass and the Darcy equation under steady state conditions.

The three dimensional finite difference code, MODFLOW (McDonald and Harbaugh 1988) contained in the Groundwater Modeling Software, GMS, (EMRL 2004) was used to solve Equation 1 for hydraulic heads in the area under steady state conditions.

RESULTS AND DISCUSSION

Resistivity profiling interpretation was conducted for the identification and selection of anomalous points or zones in the terrain, and at the same time to map the terrain to a particular depth. In this research, the resistivity profiling and the subsequent vertical electrical sounding showed the location of fracture zones and zones of weathering for the siting and drilling of eleven wells. Results from pumping tests conducted in the eleven wells suggest that aquifer hydraulic conductivity and transmissivity respectively ranges from 0.07 m/d to 1.92 m/d, and 2.13 m^2/d to 18 m^2/d. Table 1 provides more information about the lithology and general hydrogeology shown by the eleven wells and boreholes in the area. Well yield ranges between 6 m^3/d and 20.4 m^3/d. Although aquifer transmissivity plays a vital role in well yield, other factors such as the location of the well in the hydrogeological system, the nature of the fracture systems intercepted, the width of the well and the drilling technique, play equally significant roles.

Well yield might not necessarily be high where transmissivity is high. A pattern has been observed in the study area and most terrains in Ghana where wells drilled in recharge areas either dry out quickly or are poorly yielding. The reasons for this are not clear. Flow simulation modelling

Table 1. The hydrogeological properties of the aquifers exposed by wells and boreholes in the Akyem area.

BHID	SGS BH ID	Formation Constant, B	Well Loss, C	Top of screen (m)	Borehole depth (m)	Static Water level (m)	Rock type(s)	Measured Yield (m^3/h)	Measured Yield (l/min)
BH13/A150	MW1	0.749	0.0137	25	41	6.17	Greywacke	9	150
BH1/C116	MW2	4.4	2.368	33	61	20.14	Greywacke/ Metavolcanics	20.4	340
BH2/C138	MW3	4.95	3.571	30	61	11.76	Greywacke /Schist	8.52	142
BH10/A140	MW4	4.62	0.341	30	43	1.17	Schist	3.84	64
BH8/A50	MW6	5.9	0.418	27	40	0.52	Schist	3.24	54
BH3/A110	MW7	0.942	0.003	28	45	0.5	Greywacke/ Phyllites	18	300
BH4/A60	MW8	2.35	0.091	17.5	31	1.74	Greywacke/ Phyllites	6	100
BH14(TDCD)	MW9	0.564	-0.008	33	55	2.02	Greywacke /Schist	30	500
BH16(TDCS)	MW10	2.77	0.0775	27	34	3.61	Schist		
BH16(TDED)	MW11	0.54	0.022	41	60	2	Greywacke	12.6	210

was carried out to better understand this phenomenon and to identify areas where there is significant potential for groundwater extraction for various purposes.

Fortunately, the detailed geological and geophysical work provided enough data for a good flow simulation model. A plot of aquifer transmissivity against specific capacity for 12 hour discharge from the 11 wells revealed a very strong relationship (Figure 3). However there appears to be a poor relationship between well depth and yield (Figure 4), which reinforces the belief that the water bearing structures in the area are discrete entities with highly variable capacities, and are not necessarily related to depth of wells and/or boreholes.

A piezometric surface shown by the groundwater flow simulation model is presented in Figure 5. Water levels in the 11 wells and boreholes in the area were used as part of the initial conditions in constructing the model for steady state conditions. Due to the absence of historical data on water levels because of the relatively undeveloped nature of the groundwater delivery system in the area, the model could not be verified.

The pattern and distribution of the groundwater contours generally follow the pattern of the topography and tie in with the generally knowledge of the flow system as shown by previous

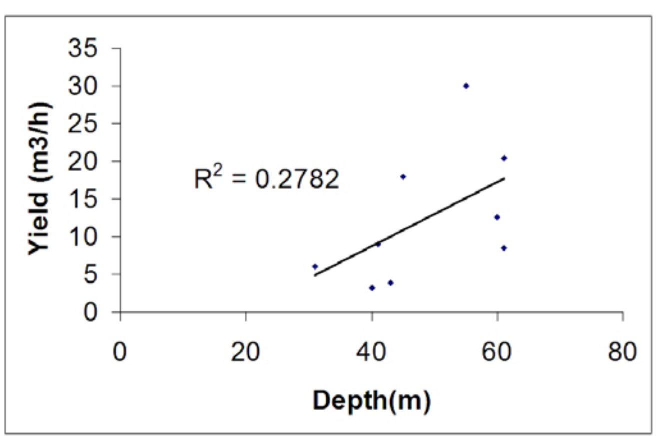

Figure 3. The relationship between well yield and depth in the Akyem area.

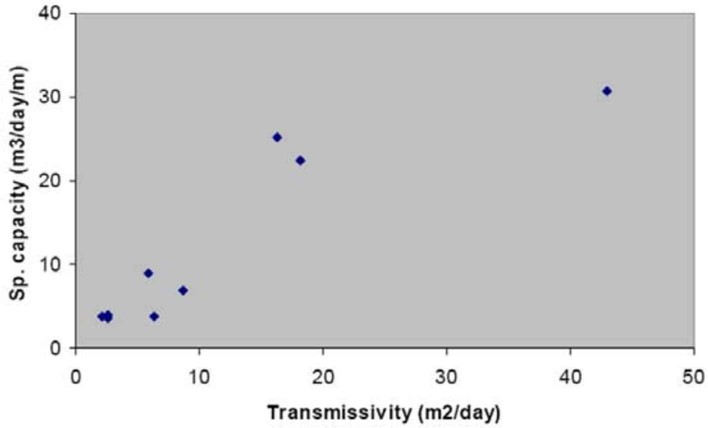

Figure 4. The relationship between aquifer transmissivity and specific capacity in the Akyem area.

investigations. The simulation reveals a general tendency towards a NE – SW flow, with some cases of local flow systems. The local flow systems are probably caused by the nature of the local topography. Hydraulic heads generally range from 130 m to 180 m, suggesting good groundwater potential in the area.

Toth (1963) has discussed the basis upon which local, intermediate and regional groundwater flow systems occur under water table conditions. Local groundwater flow systems occur where the surface topography has a well-defined local relief. With an increase in depth-to-width ratio, intermediate flow systems can occur, in which at least one local flow system exists between their recharge and discharge areas. Regional flow systems normally have their recharge area in the basin

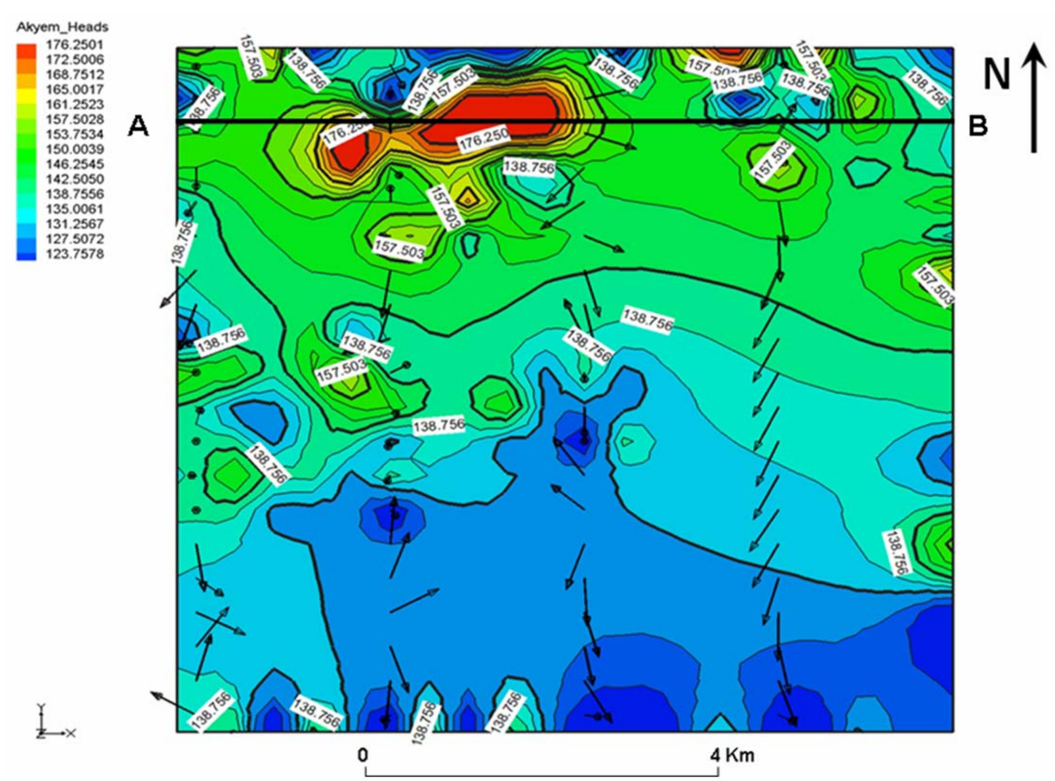

Figure 5. Groundwater levels and general flow pattern in the Akyem area.

divide and the discharge area at the valley bottom. Figure 6 provides details of the flow system across the mid section in the east-west direction (line A-B) in Figure 4. In the study area, due to the heterogeneity of the aquifers and their dependence on secondary permeability, such as fractures and quartz veins among others, for groundwater storage and transmission, there are many barriers to continuous groundwater flow laterally as well as with depth. The rock types are varied and as such, weather to different depths. Weathering depths to beyond 50 m were recorded in the area and the tramsmissivities of the aquifers and the degree of weathering also vary spatially. Due to high rainfall in the highly fractured terrain, weathering is deep and intermediate groundwater conditions exist. Similarly, as a result of topographic barriers, localized groundwater flow exists in the saprolite. This is well captured by Figures 5 and 6.

Toth (1963) showed that the more pronounced the relief of the water table, the deeper the local flow system. Thus it is possible to have deeper local flow systems developing in an area as a result of the pronounced water table relief. However, the aquifers in the area are mainly the leaky type, with the leakage assuming different extents. The local flow appears to take the pattern of the relief, with a few local flow systems.

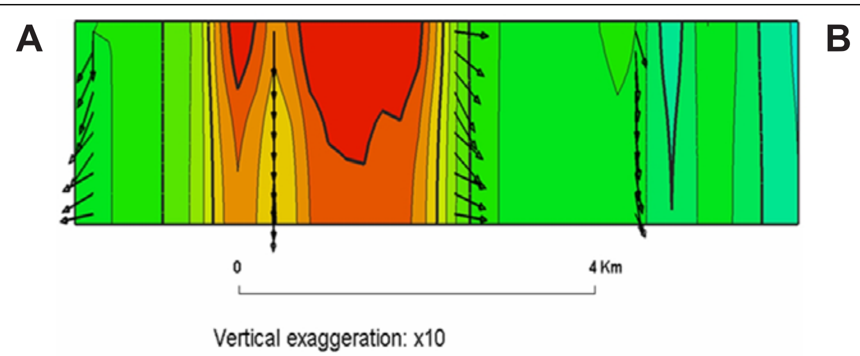

Figure 6. A section through line A-B in Figure 5, showing details of the flow pattern in the northern section of the area.

CONCLUSION

The hydrogeological conditions of aquifers in the Akyem area are controlled by the degree of weathering and fracturing of the aquifers. Aquifer transmissivity varies from 2.13 to 18 m^2/day with an average of 7.67 m^2/day. There is a strong relationship between specific capacity and transmissivity. Well yield is poorly correlated with well depth, which suggests that the water bearing structures in the area are discrete entities with highly variable capacities, which are not necessarily related to depth of wells and/or boreholes. Groundwater flow follows the orientation of the fracture systems in the area. A flow simulation model suggests that groundwater contour lines generally take the form of the local topography. Hydraulic heads range between 130 m and 180 m above sea level, and if these levels are sustained through continuous recharge, there is significant promise for groundwater development for most uses in the surrounding communities.

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