Groundwater Development and Evaluation of the White Volta Basin (Ghana) using numerical Simulation

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Abstract: Increased exploitation of groundwater resources in recent years in northern Ghana has raised concerns about the natural limit of it, i.e. quantity of renewable resources. In addressing its sustainability, a three-dimensional transient and anisotropic groundwater flow model was developed to aid in the understanding of the groundwater system and the regional effects of groundwater development alternatives in the White Volta Basin. Mean annual data, available well data, general hydrogeological and geological information were used, and the predicted model results for several scenarios tested (i.e. increased population and decreased rainfall) indicated that the extraction rates will still be less than groundwater input. [The Journal of American Science. 2008;4(4):64-71]. (ISSN: 1545-1003).

Keywords: Ghana, Groundwater, Hydrogeology, Simulation, Model.

1. Introduction

The White Volta Basin is located in northern Ghana in the West African sub- region. Its total area is approximately 48800km^2 and is located between latitudes 8.5^{o}N and 11^{o}N, and longitude 0^o and 2.5^{o}W (Fig.1). Annual rainfall is (1000-1200 mm) with 75% of it occurring in July and September (Van de Sommen and Geinaert, 1988). Groundwater in recent years has become a premium source of portable water supply for most communities in Ghana. An improved economy in recent years coupled with campaigns on the imminent hazards of relying on sources of surface water, and factors such as: ease of developing hand pumps in remote communities, availability during protracted drought, superior chemical and biological quality (compared with surface water sources) and relatively low prices compared with methods of treating surface water (Dapaah-Siakwan and Gyau-Boakye, 2000; Gyau-Boakye, 2001) accounts for the increasing demand for safe water supply. The population growth rate in northern Ghana is 2.5% per year (Van de Giesen et al, 2001) (Gyau-Boakye, 2001), by March 1998, a total of 11,500 boreholes had been drilled, providing 52% of the rural population with potable water (up from 41% in 1984) (Gyau-Boakye, 2001).The White Volta Basin has low and unreliable rainfall pattern with protracted drought. Surface flow is usually ephemeral. Open well drying during dry season is a common feature whilst during the drought of the 1980s, reduced yield in deeper wells and drop in groundwater levels were experienced (Wardrop Engineering, 1987; Thiery, 1990). A phenomenon Gyau-Boakye and Tumbulto (2001) attributed to increasing abstraction and depletion of the groundwater resource.

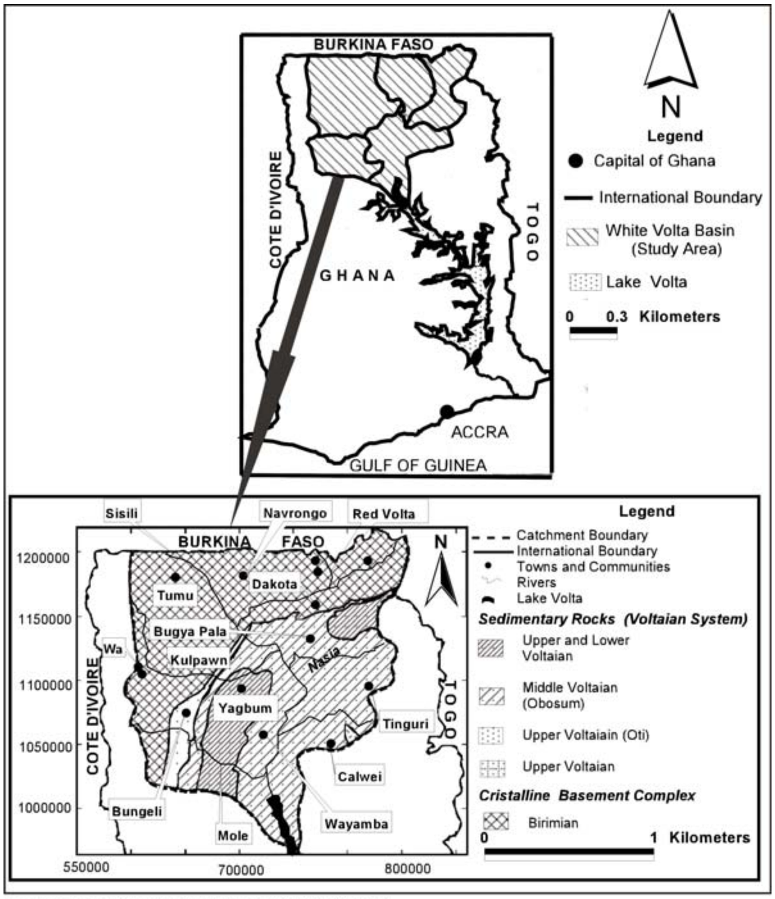
2. Purpose and Scope

(1) The aim is to simulate the groundwater flow in the weathered rock and sandstone aquifers of the White Volta Basin.

(2) Evaluating potential groundwater recharge and discharge rates.

(3) estimating source and quantity of groundwater and ascertaining the effects of current pumping on groundwater resources applying a three-dimensional numerical groundwater flow model taking into consideration population change and drought.

The presence of fluoride, iron and nitrate concentrations exceeding the World Health Organization (WHO) recommended level of 1.5 mg/l, 0.3 mg/l and 10 mg/l respectively are worth mentioning in this paper. A data base of 14 monitoring wells analyzed for various water quality constituents (WRI, 2006) revealed high fluoride concentrations in communities around Tumu, Bongo-Nayare and Tinguri. High concentrations of iron exceeding 0.3 mg/l were recorded in wells at Bongo-Nayire, Bungeli and Galiwei, whilst nitrate concentrations higher than 10mg/l were recorded at Bugya-Pala due to the application of organic manure for farming activities. Groundwater quality in the basin is generally considered acceptable by World Health Organization standards (WRI, 2006).

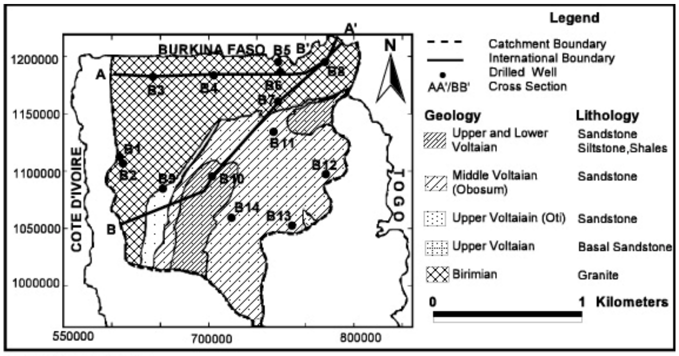


Source:Water Resources Institute (WRI)
Fig.1:Location Of the White Volta Basin(WVB)

3. Materials and methods

3.1. Geology and Hydrogeology

The White Volta Basin is partly underlain by aquifers of the crystalline basement complex (weathered rocks) and aquifers of the consolidated sedimentary (sandstone) rocks. The crystalline basement complex is composed of gneiss, phyllite, schist, granite-gneiss and quartzite which occupy an area of 21,960km^2 with the consolidated sedimentary formation which consists mainly of sandstone, shale, arkose, mudstone, sandy and pebbly beds and limestone occupying 26,840 km^2. Detailed geology and hydrogeology is contained in reports by (Junner and service 1936; Junner and Hist, 1964), (Acheampong; 1969) and (Kesse; 1985). Drilling projects and hydrological investigations indicate that shallow potential aquifers capable of delivering water of sustainable quantities for domestic consumption and for industrial use exist in the basin (Kortatsi; 1984) and (Dapaah-Siakwan; 2006). Previous studies indicate that primary porosities are very low due to the impervious nature of the rocks. However, where secondary porosity imposed by the fracturing and weathering of rocks occurs, the hydrogeological properties of these rocks are very much enhanced. Therefore, the hydrogeological parameters are based on secondary permeabilities in the form of joints developed after the primary porosities had been destroyed in the wake of rock compaction and slight metamorphism (Acheampong and Hess; 1988: Yidana et al; 2007). When secondary porosities have not been imposed to provide ingresses for infiltration and recharge, the aquifer properties are very poor. Where weathering of rocks is intense, secondary permeability is enhanced and they serve as better aquifers. Recharge ranges between 3.8 and 5 % of annual precipitation (Ricolvi, 1999; Ampambire, 200; Martin and van de Giesen, 2005). There has not been any known recharge from surface water bodies but water from aquifers in this basin has been noted as a source of recharge of the Volta Lake.



Source : Kesse (1985)
Fig.2 : Map Showing Geology and Cross Sections Of the White Volta Bassin

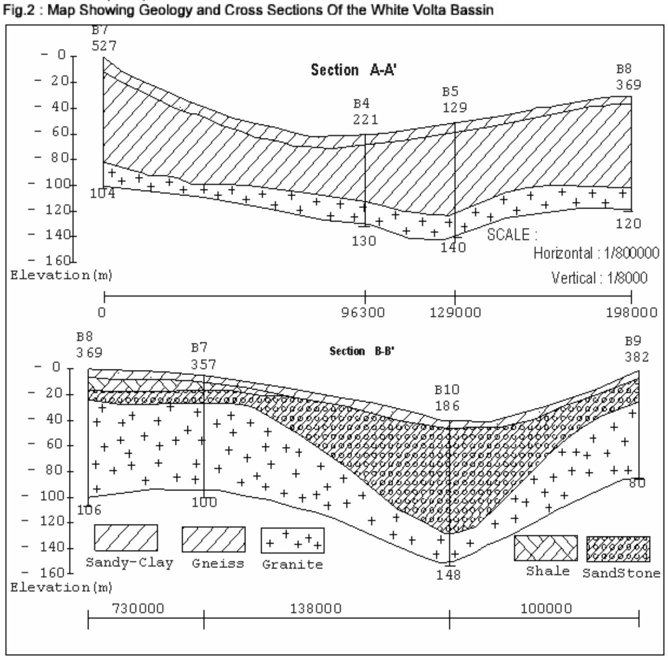


Fig.3: Cross Sections of the Crystalline Basement Complex and the Weathered Sedimentary Rocks

4. Data collection and analysis

The data used for this research was collected during drilling projects conducted during the periods of 1984 and 2006 by World Vision International and the Water Resources Institute, Ghana. The hydrogeological data used in the study include information on aquifer hydraulic conductivity, well yield and depths, specific capacity and the general geology of the hydrostratigraphic units. Well log data was used to help determine the thickness of the hydrostratigrahic units at several locations in the area.

5. Conceptual Model

There are no obvious physical and geographical boundaries in any direction of the model domain, except the White Volta River which traverse the model. The basin is predominantly underlain by granite, granitic gneiss, hard sandstone, shale, siltstone and mudstone as revealed by shallow high and moderate yielding wells in the area. These lithologies can be separated into distinct hydrostratigraphic units on the basis of the hydraulic conductivity (fig.3). The wells in the study area do not expose all the hydrostratigraphic units and information from literature was used to cover the entire stratigraphy. The upper 20-100 m of materials reveals various materials with different hydraulic properties. There is also a mixture of different lithologies with the hydraulic conductivities ranging from 0.057-4.38 m/day.

The conceptual model (fig.4) was converted to a numerical model using Groundwater Modeling Software (GMS) (EMRL 2004). The study area was discretized into 80 cells in the x- direction by 80 cells in the y- direction. The hydrostratigraphic units were converted to three layers on the basis of available hydraulic conductivities. All the vertical boundaries of the model were assumed to be no- flow boundaries because they either coincided with flow symmetry below the major water bodies of the basin or were far enough from the main recharge areas of interest of the model domain.

The bottom boundary was also assumed to be a no-flow boundary because the hydraulic conductivity had decreased significantly relative to the value in the top model layers. The entry and exit boundaries of the river were modeled as constant head boundaries, using the river and the Lake Volta water level as the constant head for the top layer. This is because the water level in both the river and the lake must be maintained at a constant level of 90-300m to achieve ecological stability.

Recharge in the study area is principally by precipitation. Annual recharge was computed as between 3.8-5% of the annual precipitation of 1,000 to 1,200mm.Maximum recharge values were assigned to cells in the top layer located in the low lying areas of the model. Other cells in the top layer located around highland areas were assigned reduced recharge values.

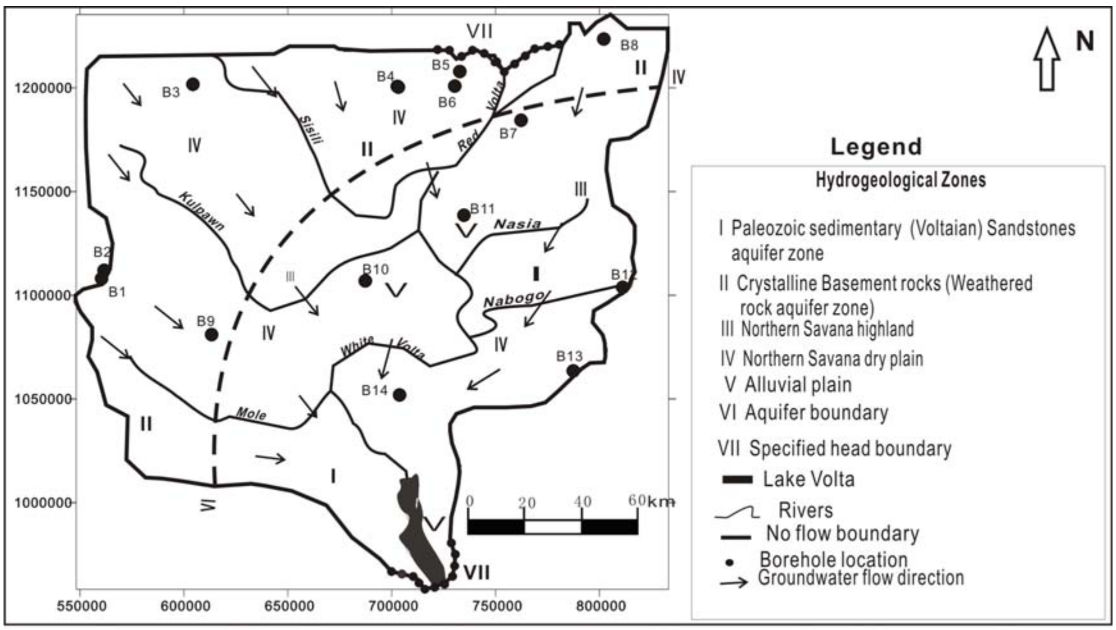


Fig.4 : Conceptual Model Map of the White Volta Basin

6. Numerical Model

The aquifers in the study are of varying depths and are widely apart. They are thick and complex in nature with very vibrant horizontal flow and less active flow in the vertical direction. The hydrogeologic parameters of the aquifers are complex, they vary with time and in space, allowing the model medium to be described as heterogeneous, anisotropic, with a transient groundwater movement. The equation that describes this condition of flow of the groundwater system can be mathematically

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-w=S_s\frac{\partial}{\partial t} \quad (1).$$

$$h\,(x, y, z, 0) = h_0\,(x, y, z)$$

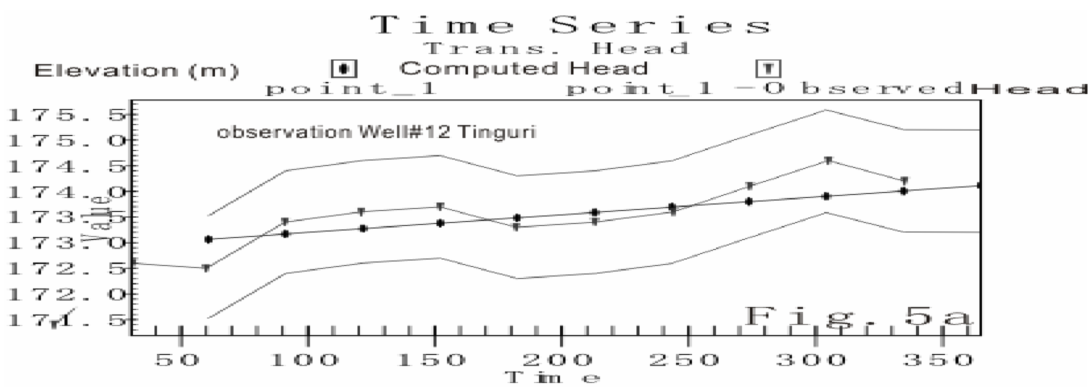
$$h\big|_{B1} = f(x, y, z, t)\big|_{B1}\,; \quad K\frac{\partial h(x,y,z,t)}{\partial h}\Big|_{B2} = q(x, y, z, t)\big|_{B2}$$

Where $K_{xx,}$ K_{YY} and K_{ZZ} are values of hydraulic conductivity along x, y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (LT^{-1}); h is the hydraulic head (L),

w is the volumetric flux per unit volume and represents sources or sinks of water (T^{-1}), S_S is the specific storage of the porous material (L^{-1}), and t is time. h is the initial hydraulic head (L), $f(x, y, z, t)\big|_{B1}$, is the first boundary; $q\ (x, y, z, t)\big|_{B2}$ is the second boundary. In general, S_S , K_{xx} , K_{YY} , K_{zz} may be functions of space ($S_S = S_S\ (x, y, z)$, $K_{xx} = K_{xx}\ (x, y, z)$, etc,) and W may be a function of space and time $W = (W(x, y, z, t)$. Equation (1) describes groundwater flow under nonequilibrium conditions in a heterogeneous anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate's directions (McDonald and Harbaugh, 1988).The finite difference code, MODFLOW (McDonald and Harbaugh; 1988) in the GMS package was chosen to solve Equation (1) for hydraulic heads in the area. Transient conditions were assumed in other to make limited predictions, and to further evaluate the combined long-term effects of increased pumping, the suitability and the dynamic response of the system for average groundwater flow conditions. The simulation period was defined for January 1st 2007 to December 31st 2007. Each month was considered a stress period so the total stress period was twelve months with a time step of ten days.

7. Model Calibration

The model developed under transient conditions was calibrated using water levels in 14 observation wells monitored between the periods of 2005 and 2006. Calibration was achieved varying the hydraulic conductivities of each of the layers defined in the model. The sources and sinks (recharge) was also adjusted within the ranges of (3.8- 5%) of the annual precipitation for the purpose of the calibration. There were no significant changes in groundwater extraction in the study area between 2005 and 2008, therefore the same transient conditions were assumed during the calibration. Recharge and hydraulic conductivity values were adjusted until a reasonable match was obtained between the heads of the 14 wells and model calculated heads.



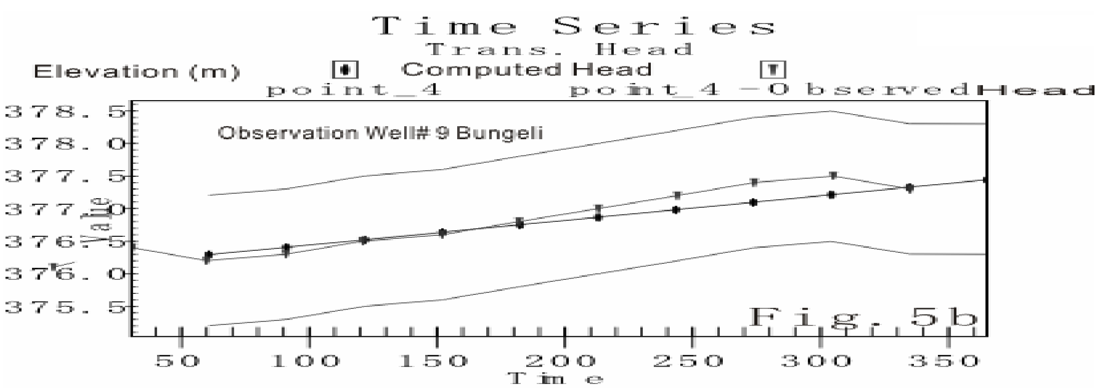


Fig. 5a&5b Fitting graph of time series of groundwater levels from January 2004 to December 2004.

8. Discussions and conclusion

In the transient flow simulation, a reasonable match between the model calculated hydraulic heads and water levels observed in the 14 observation wells after several adjustments in hydraulic conductivity of each layer, and recharge (Fig. 5a and 5b) shows a reasonable fit between the computed heads and the observed heads for two of the 14 monitored wells used in the calibration process. The calibrated simulation model indicates that groundwater generally flow from the northern savanna highlands (high topography) of the model to the northern savanna plains (low topography) recharging the Lake Volta in the process (fig.4). Hydraulic heads generally range between 520m in the recharge areas to 60m at the boundary to the Lake Volta. Well yields in the recharge areas, thus towards the fringe of the model are believed to be lower than those in the discharge areas. This is because in the recharge areas, groundwater flows is directed downwards (Freeze and Cherry; 1979) and upwards flow is limited. However, groundwater flow at discharge areas is directed upwards and flows into wells is comparatively easier at these locations in groundwater flow system.

The pattern of flow and distribution of hydraulic heads in the model domain indicates that groundwater in the aquifers of the basin has great potentials to be developed to meet domestic, industrial and other needs of the area. In other to evaluate and predict the groundwater potentials of the basin, a transient simulations was performed using six stress (management periods), (2006-2012) with ten time steps under each stress period. Each represents a management period. Thirty six hypothetical wells were cited on the basis of the hydraulic head distribution.

Total water demand was computed using the per capita water demand and population increase. A 2.5% annual population increase with its corresponding economic activities were taken into consideration. The projected daily water demand requirements were apportioned to the 36 hypothetical wells to simulate the dynamic response of the hydraulic system to these extraction scenarios. These scenarios of increased population and decreased rainfall show extraction rates still remain relatively low to estimated recharge of the basin. Current extractions, however, may be too small to play a significant role in the regional water balance, though concentrated pumping in local areas may result in water level declines.

There are many reasons why groundwater resources in the area offer the best solution to the water delivery situation. First, the aquifers in the basin have been well investigated and their properties are well known. In addition, groundwater for most part is protected from surface activities and thus cleaner than most surface water sources. Above all, groundwater is much protected from the high temperatures and evaporation conditions and if properly developed and managed, can last the entire year. The proper management of groundwater resources in rural communities requires a good understanding of the dynamics of the resource. It is for this reason that communities in the study area have seen the influx of many governmental and non-governmental organizations with focus on developing groundwater resources for various uses. The government of Ghana intends to investigate the possibility of using groundwater resources in the area for irrigation to supplement rainfed agricultural activities. This would offer all year round employment for the youth and raise the standard of living.

Groundwater flow simulation models have not been extensively used in Ghana to advise management decisions on the allocation of groundwater resources. However, globally, groundwater flow simulation models have thus gained global acceptance as good decision support tools. Numerical modeling of groundwater is an attempt to simplify the physical hydrogeological system using physical equations and governing boundary conditions. The effectiveness of a flow simulation model as management support tool depends among other things on the expert knowledge of the local hydrogeological system, and the boundary conditions. Therefore, groundwater flow modeling procedure begins with a proper understanding of the physical system or problem to be investigated. Once the system or problem is well understood, the next step is to translate it into solvable mathematical equations. This has resulted in the familiar groundwater flow and transport equations in common use today.

Simulation models have been used effectively in such countries as India, China and Pakistan among others, to influence groundwater management paradigms. Don et al. (2006) coupled a numerical simulation model with an optimization model to predict groundwater response to settlement and determine the optimal yield for groundwater without violating physical, environmental and socio-economic constraints in Shiroishi area in the Saga Plain in Japan. This model enabled them to determine the effects of climatic and various pumping scenarios on the aquifer system.

This project presents a description of the groundwater flow pattern in the crystalline basement complex, and the weathered sedimentary rock aquifers of the White Volta Basin, using a three-dimensional flow simulation model, for management purposes.

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