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ESTIMATING THE STORAGE AND MAXIMUM ANNUAL YIELD OF THE AQUIFER SYSTEM IN NORTHERN GHANA AND THE POTENTIAL FOR IRRIGATION

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Despite the water scarcity for sustainable agricultural production for improved livelihood for a majority of the Africa population, not much effort has been put in the exploitation of groundwater for irrigation. This may be partially attributed to lack of information on the storage capacities of the aquifer systems. An attempt has been made to estimate the maximum storage and average annual yield of the aquifer system in northern Ghana as a guide for groundwater irrigation in the area. This area is one of the poorest regions of the country and suffers from perennial seven months of severe drought. Though there have been some recharge studies, it is not clear if the aquifer system has enough storage capacity to accommodate the 1.26×10^{10} *m*^{3}*/year as the volume of water reported in literature. Data from population, long-term time series data of precipitation and discharge from rivers were analyzed in this study. The results show that the maximum groundwater storage is* 6.44×10^9 *m*^{3} *with average maximum yield of* 4.57×10^9 *m*^{3}*/year. Current groundwater abstraction trends show that there is enough groundwater to support irrigation provided careful management principles of the aquifer system are adhered to.*

INTRODUCTION

Poverty reduction is one of the important United Nation's Millennium Development Goals (MDG) which envisages that by 2015 world poverty will have been halved. The fight against poverty, however, may not be achieved if the rural poor are not elevated to at least the middle level income status. It is estimated that about one billion people live on less than US$1 a day. The poverty rate for Sub-Saharan Africa for example rose from 42% in 1981 to 47% in 2001 whereas the world's poverty rate reduced from 40% to 21% respectively (BBC News July 20, 2004). The fast and accelerated developments in formerly comparable poor countries in Asia, for example, have been attributed to high food security through irrigation. The impact of irrigation on poverty has been well reviewed by Lipton et al. (2003).

The role of groundwater in combating poverty and diseases cannot be over-emphasized. About 76% of irrigated land in India and 55% in South Asia are generally irrigated from groundwater sources (Shah et al., 2006). About 51% of groundwater in Australia was used for irrigation in 1996 (CSIRO, 2001). The use of groundwater is important for irrigation since it can be accessed during periods of drought. Groundwater systems seem to have a significant stock component, and are less influenced by short-term climatic variability than surface water systems. In view of this, it tends to form a buffer against reduced surface water availability, with extractions increasing during droughts (Goesch et al., 2007).

According to Giordano (2006), a comparison of groundwater use for agriculture (especially irrigation) between Asia and Africa shows that Asian countries' economies have improved tremendously as a result of sufficient food obtained mainly from irrigation. The low exploitation of groundwater for irrigation in Africa, though it has abundant groundwater reserves, is due to lack of technology and funds to exploit it. The high cost of drilling in Africa and lack of technology to maintain the drilled wells might have contributed to the low usage of groundwater for agricultural purposes. Other reasons could be political instability, geology, low precipitation, and aquifers.

Viable groundwater for irrigation purposes could be located in hard rock areas in shallow as well as deeper zones which might involve higher costs of exploitation. The limiting factor for groundwater for irrigation in Africa is an uneven spatial distribution of renewable groundwater supplies. Over half the annual renewable groundwater supplies in Sub-Saharan Africa are located within only four countries: The Democratic Republic of Congo, The Republic of Congo, Cameroon and Nigeria.

Groundwater storage and maximum annual yield evaluations of aquifers are necessary for understanding the local availability of groundwater for domestic and other uses. Aquifer storage capacity is the maximum amount of water that can be stored in a given aquifer. It can be estimated using transient water balance methods. The maximum annual yield of an aquifer is determined using graphical mass-curves which were previously used in sizing surface reservoirs, but have been modified to estimate aquifer yield (Loáiciga, 2008). In order to have a fair idea of aquifer storage system, detailed drilling and pumping test data are required. The volume of water stored in the aquifer is estimated by multiplying the storativity of the aquifer by its thickness and areal extent. However, the reliability of the estimated value of storativity from pumping tests still remains uncertain. Besides, the cost of conducting pumping tests to obtain suitable and reliable data remains a big challenge (Loáiciga, 2008; Devlin and Sophocleous, 2005). Long-term time series data of recharge, pumping, discharge and evapotranspiration are useful in evaluating the storage capacity and average maximum yield. The storage capacity of the Edwards' aquifer system in Texas, USA was estimated using long-term series data of recharge, discharge and pumping (Loáiciga, 2008).

Ghana, one of the stable Sub-Saharan African countries with support from its donors, is working assiduously to achieve the MDGs by halving the proportion of the poor population by 2015. It is estimated that about 27% of the country's population (IMF, 2006) are poor, most of who are in the rural areas. The per capita income of Ghana was estimated to be US$1,400 in 2007 (CIA, 2007). The value implies that the average Ghanaian lives on US$ 3.89 a day. This means that poverty is still high and the country might not meet the expectation of achieving a middle level income by 2015.

Basically, there are ten political administrative regions in Ghana, which vary significantly with respect to spatial distribution of population, natural resources, poverty and disease (Gyau-Boakye et al., 2008). According to the Ghana Statistical Survey (2002), about 20% of the people live in northern Ghana (Figure 1) which comprises the Northern, Upper East and Upper West Regions. On the average, 80% of the people in these regions are poor (Ghana Statistical Survey, 2000).

Rain-fed agriculture by peasant farmers constitutes the main economic activity of the people in the three regions, though there is an appreciable amount of groundwater especially in the Upper Regions. Groundwater could be a potential solution to fight poverty through irrigation since it is relatively cheaper and more reliable.

Out of the potential irrigable area of 346,000 hectares, only about 22,000 hectares have been developed (World Bank, 2006; Water resources Aquasat, 2004). It is estimated that about 16,000 hectares of land is being irrigated using groundwater in the country (Giordano, 2006). Generally, the trend shows that irrigation is not well promoted in the country. Some individuals who have attempted to carry out irrigation have relied on low quality water such as waste water and water from shallow hand-dug wells which dry very fast during the dry seasons. The use of groundwater for irrigation is therefore not widespread probably due to lack of education and cost benefit analysis and knowledge of the storage capacity of the aquifer. Considering the advantages of groundwater over surface water in high evaporation areas, especially in Northern Ghana, it is important to assess the potential of available groundwater for irrigation. Though groundwater recharge studies have been conducted in the study area (Lutz et al., 2007; Martin and van de Giesen, 2005; Acheampong et al., 2000; Cobbing and Davies, 2004) and an average value of 1.26E+10 m^3/year is reported, the aquifer system of northern Ghana has not been studied to determine if the reported recharge exceeds its storage capacity. There is also no information on the maximum annual yield of the aquifer system.

The objectives of this paper include: (1) using long-term series of rainfall data and major river discharges to assess storage and maximum average annual yield of the aquifer system in northern Ghana, and (2) to inform policy and decision makers, academia and development practitioners on the need to manage groundwater usage according to the maximum yearly yield for safe abstraction.

THE STUDY AREA

The study area (Figure 1) with a total area of 97,702 km^2. comprises Northern, Upper East and West regions. The regions are considered the poorest in the country with poverty rates being 70%, 80% and 90% for Northern Region, (NR) Upper West Region (UWR) and Upper East Region (UER) respectively (Ghana Statistical Survey, 2000). This has not only affected the quality of life of the people but is also one of the causes of mass seasonal migration of the youth to the southern

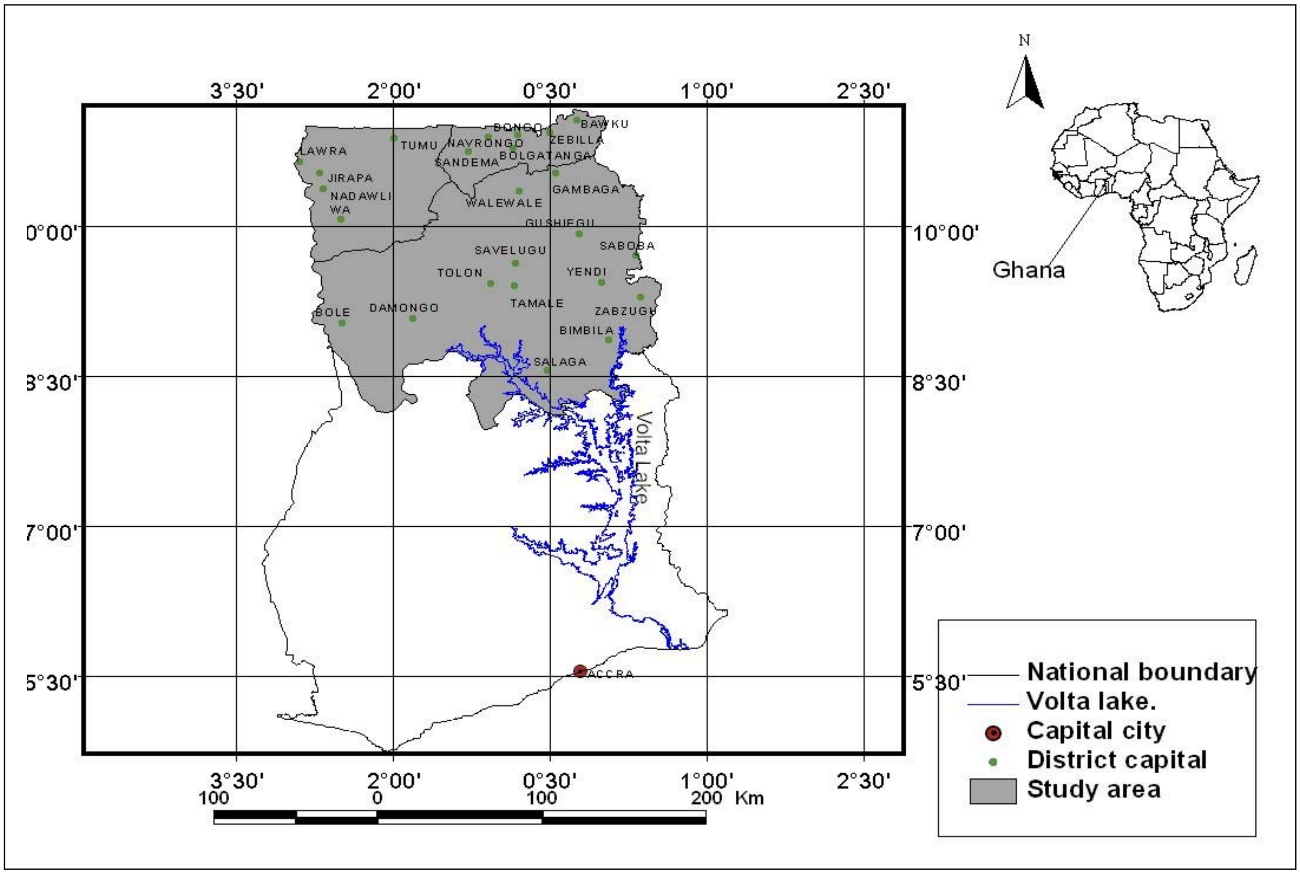

Figure 1. Map of study area.

part of the country in search of nonexistent jobs.

About 70% of the people in northern Ghana depend basically on agriculture as a source of employment. The main agricultural system is subsistence rain-fed farming. In a few cases, irrigation dams have been provided for dry season farming for some communities including Via (Bongo) and Tono (Navrongo) in the Upper East Region and Botanga (Tolon) in Northern Region. Apart from these big dams, satellite small dams and dug-outs exist in many communities for irrigation. However, these surface waters dry up quickly after the rainy season or are inadequate for irrigation purposes. Besides their insufficiency, the surface dams also present a conducive environment for regular flooding and breeding mosquitoes, the main cause of malaria. Dams are expensive to construct and require specific suitable sites in the communities. Another challenge is the over reliance on erratic rainfall pattern to supply water to the dams for irrigation.

Among the three regions, the Upper East has the highest population density which is between 500-1000 people per square kilometer, hence limiting the availability of land for farming and even construction of surface dams. Boreholes are therefore very useful since they do not occupy much space on the surface and groundwater is stored far below the ground surface. Most NGOs and the Government of Ghana have therefore provided many boreholes to exploit groundwater in the area. For example, the Canadian International Development Agency (CIDA) in conjunction with the Ghana Government provided over 3000 boreholes fitted with pumps in the area especially in the upper regions in the 1970s (Nampusuor, 2000).

The study area is generally characterized by flat to fairly undulating ground (less than 200 m above mean sea level) with shorter trees and savanna grass land (Akudago et al., 2007). The Gambaga Scarp which trends east-west and is about 350-400 m high, is the highest elevation in the area (Dickson and Benneh, 1980).

Rainfall in the study area lasts for about 5 months or shorter and usually begins from May each year. The rainfall ranges from 110 mm/year to 800 mm/ year with average evapotranspiration estimated to be about 890 mm/year, but may reach 1000-1300 mm/year in wet years and 650 mm/ year in dry years (Kwei, 1997). Since 1989 the rainfall pattern has decreased from 1673.2 mm to 769.5 mm/year in 2005. Drainage of run-off is done by parallel streams and small rivers into the Black, White and the Oti rivers. The study area basically lies within the catchment areas of the White and Black rivers which are the main tributaries to the Volta Lake, Ghana's source of hydroelectric-power. Temperature ranges from 43ºC in April to about 12ºC in January with the average daily temperature ranging from 25ºC in July to 32ºC in April (Kwei, 1997).

GEOLOGY AND HYDROGEOLOGY

The geology of northern Ghana is characterized by rocks of the Precambrian complex and the sedimentary formation, locally referred to as the Voltaian system (Figure 2). These rocks form the two major hydrogeological provinces in the study area, namely the Precambrian (Basement Complex) and Palaeozoic sedimentary (Voltaian) provinces (Dapaah-Siakwan and Gyau-Boakye, 2000). The Precambrian Province comprises granitic complexes, mafic volcanic and sedimentary rocks metamorphosed to greenschist facies (Kesse, 1985). The granite and gneisses associated with the Precambrian complex, locally referred to as the Birimian Formation, are less permeable, but due to fracturing and weathering, have developed secondary permeability and porosity. The weathered and fractured zones are target areas for groundwater development during water supply schemes (Akudago et al., 2007). The Birimian phyllites, schist, slate, greywacke, tuff and lava are very foliated and fractured. These fracture zones act as groundwater flow paths and are also favourable locations for groundwater exploitation. According to Apambire et al. (1997), about

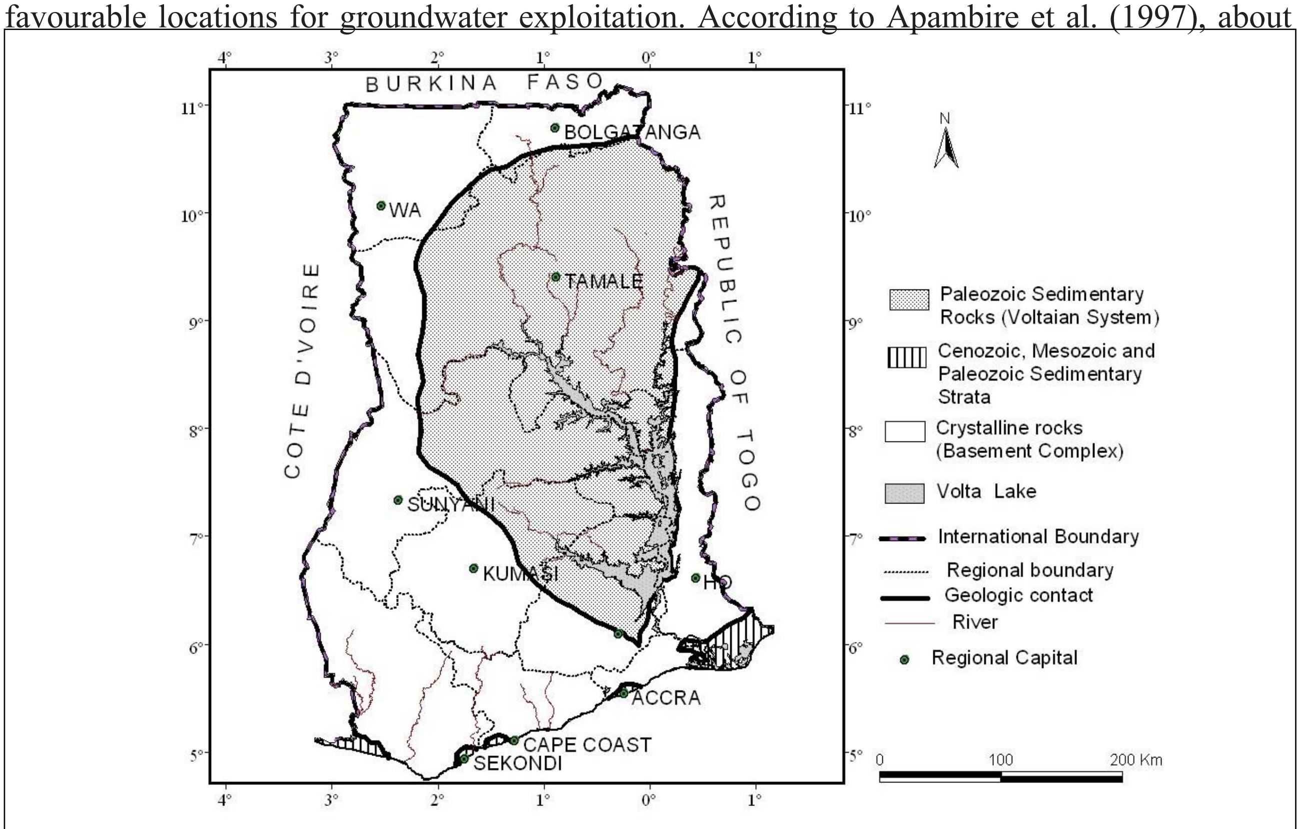

Figure 2. Geological map of study area.

95% of boreholes in the Upper East and Upper West regions are completed within the overburden. The overburden thickness extends to 30m in some places and borehole yields in many areas are generally low, between 9 and 22.5 l/min, but sufficient for hand pumps (Wardrop and Associates, 1980).

The Voltaian hydrogeologic province is of the late Proterozoic to early Palaeozoic Era (Anani, 1999) and is underlain by consolidated sedimentary rocks, which include mudstone, sandstone, conglomerate, shale and some limestone. Aquifers are mostly located in fractures and are confined or semi-confined

In both geological provinces of the study areas (Figure 2), groundwater is exploited through boreholes fitted with hand or electric pumps. Groundwater quality generally conforms to the World Health Organization (WHO) standards. However, higher concentrations of fluoride, arsenic and salinity have been reported in some parts of the Upper East and Northern Regions (Apambire, 1996; Lutz et al. 2007; Kwei, 1997).

METHODOLOGY

Rainfall data over the last 30 years from the Meteorological Services of Ghana, the discharge of the White and Black Volta Rivers in the UNESCO (1995) report, and the population of northern Ghana were collected for groundwater recharge, maximum storage and abstraction estimation. Due to lack of yearly monitored data on river discharge, statistical indexing was applied on the data and results of the year 1995 were used to estimate the change in soil and groundwater storage for other years. Using the 1995 calendar year as the base year, the groundwater storage capacities were determined over the 30 year period by dividing annual average rainfall value by that of 1995 and multiplied by the storage in 1995. Graphs of cumulative recharge, cumulative net storage and pumping were drawn from which the maximum yield and storage were determined.

Estimation of Recharge

As reported in Lutz et al. (2007), Martin and van de Giesen (2005), Agyekum and Dapaah-Siakwan (2008), average groundwater recharge is estimated to be 5% of annual precipitation. Since there were no quantitative values of recharge, 5% of each year's precipitation (P) was calculated as recharge multiplied by the total area (A) of the aquifer system.

$$R=0.05PA \tag{1}$$

Figure 3 shows the rainfall distribution over the entire period.

Estimation of change in soil moisture and groundwater storage

The water balance method was used to estimate the change in stored volume of soil and groundwater. In this case the total amount of precipitation received is balanced by the sum of total run-off, evapotranspiration and change in soil moisture and groundwater storage as shown in Equations (2) and (3).

$$P = R + E + \Delta S \tag{2}$$

$$\Delta S = P - R - E \tag{3}$$

where ΔS: Change in soil moisture and groundwater storage, P: Precipitation, R: Total run-off and E: Evapo-transpiration.

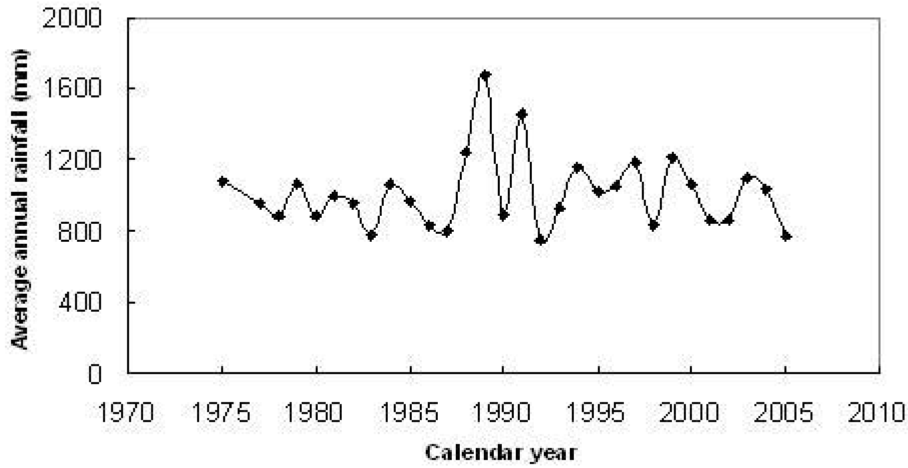

Figure 3. Rainfall distributions over entire period.

Values of R and E for the base year 1995 are stated in Table 1 according to Kwei (1997) and UNESCO (1995).

Estimation of maximum storage in the aquifer system

Supposing an aquifer system has an amount of groundwater in storage at the end of a given base year, say S_0 , and aquifer recharge, discharge and groundwater pumping for the following year are R_t, D_t and P_t, respectively, then the storage for the year t can be expressed by

$$S_t = S_{t-1} + R_t - D_t - P_t \quad t=1,2,3... \tag{4}$$

If backward repeated substitutions of previous storages are made into the water balance Equation (4), a sum of a series can be written as

$$S_t = S_0 + \sum_{k=1}^{t} \left(R_k - D_k - P_k \right) = S_0 + N_T \tag{5}$$

where N_T is the cumulative net gain. However, it is possible for N_T to be negative whenever pumping and discharge exceed recharge.

$$N_T = S_t - S_0 \tag{6}$$

From the estimated change in soil and groundwater storage, the net gain was estimated for every year.

Estimation of Pumping

In order to determine the annual groundwater pumping of Northern Ghana, the population growth since the year 2000 was analyzed. The current population figures were estimated using the population growth rates reported by CIA (http://indexmundi.com/g/g.aspx?c=gh&v=24) and the population figures reported in the census document by the Ghana Statistical Service (2002). The total annual pumped out water in the study area was estimated assuming that the entire population of Northern Ghana depended on groundwater with a water requirement of 50 litres/day/person

Estimation of average maximum yield

From the estimated recharge data over the 30 year span, a graph of cumulative recharge against

Table 1. Summary of the volume of groundwater stored in study areas during 1995 calendar year.

Station (River basin)	Catchment area (km^2)	Total annual runoff ($10^9 m^3$)	Annual runoff/ unit area (mm)	Annual average evapo- transpiration E (mm)	Average annual precipitation P (mm)	Change in storage ? S (m)	Total volume of storage ($10^9 m^3$)
White Volta	41,550	2.27	54.57	890	1022.60	0.078	3.24
Black Volta	134,200	8.24	61.42	890	1022.60	0.071	9.53
Total	175,750	10.51	115.99	890	1022.60	0.15	12.77*
Northern Ghana	97,702	-	-	-	-	-	7.10

a year was plotted. Tangents were drawn through high points on the cumulative recharge curve where there is concave downward curvature. As stated in Loáiciga (2008), the tangent with the gentlest slope was chosen. The tangent so determined must intersect the cumulative recharge curve when projected forward otherwise aquifer storage will not be replenished.

RESULTS AND DISCUSSION

The graphs displayed in Figures 3, 4 and 5 show the results from the analysis of the data. The average annual maximum yield is estimated to be 4.57×10^9 m^3 and the maximum storage capacity of the aquifer system is estimated to be 6.44×10^9 m^3. The volume of groundwater abstraction increases linearly as population grows.

Recharge studies within the region have shown that there is adequate recharge from rainfall (Lutz et al., 2007; Martin and van de Giesen, 2005; Acheampong et al., 2000; Cobbing and Davies, 2004). However, the bone of contention has been the approximate amount of groundwater stored that could be used. It is also not clear if the aquifer has enough storage space for the reported volume of recharge. Using the water balance Equations (2) and (3) to estimate recharge does not give the exact volume of recharge to groundwater because not all the soil water will drain into the aquifer. From the current study, it is observed that the aquifer system has a maximum storage capacity of 6.44×10^9 m^3 (Figure 6). The method of estimating the maximum storage suggests that the yearly net gains (Equations 5 and 6) affect the storage and reflect both drought and wet years. It therefore estimates the actual storage variation over the period that eventually determines the storage capacity. As it can be observed in Figures 5 and 6, the trend of changes in soil and groundwater storage and net gains indicate that there has not been a major and long drought in the aquifer area. The advantage of the method is that it does not assume the storage based on average values as is always reported in water balance budgets.

Martin and van de Giesen (2005) used a quantitative model to estimate the stored groundwater in the aquifer system and reported it to be 1.26×10^{10} m^3, which is an order higher than the estimated storage capacity of the aquifer system. Comparatively, assuming our current estimated capacity is true then groundwater exploitation could be risky since the recharge volume reported in the literature is over estimated. On the other hand if their estimate is correct then the current estimated maximum capacity of the aquifer system could be useful in protecting and managing groundwater usage. This would ensure that there is extra groundwater reserve for ecological growth and long-term sustainable water usage.

For sustainable exploitation of the aquifer system, it is expected that the yearly abstracted groundwater should not exceed the maximum yield estimated. It is worth noting that the maximum average yield is neither sustainable yield nor safe yield but a guide to these two, and readers are

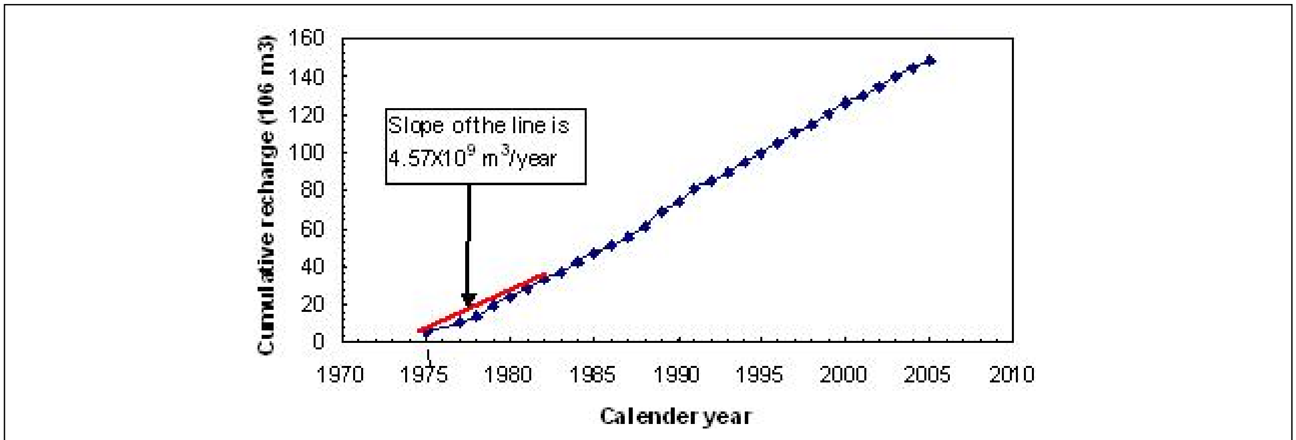

Figure 4. Yearly cumulative recharge.

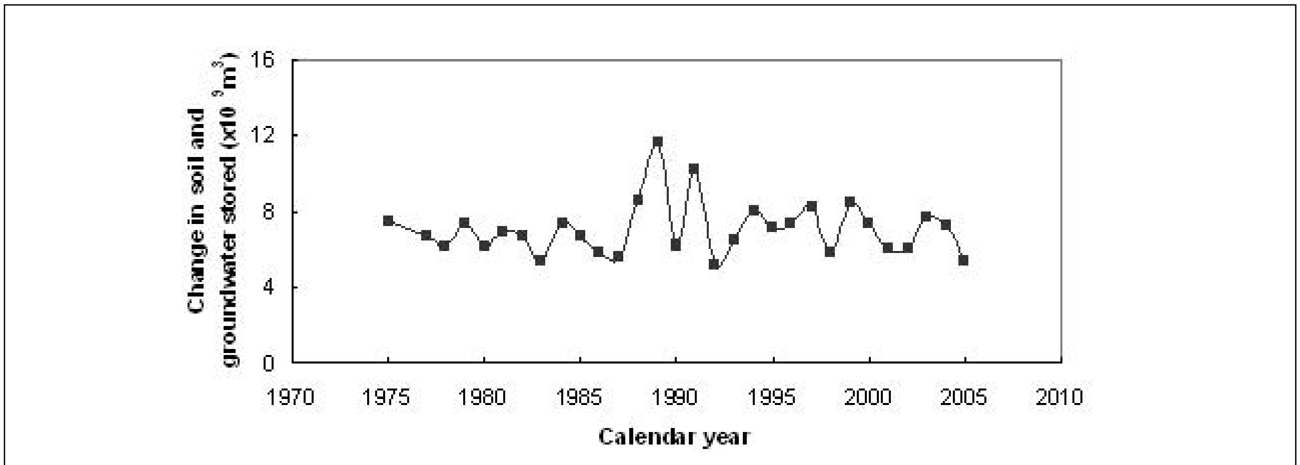

Figure 5. Yearly changes in soil and groundwater storage.

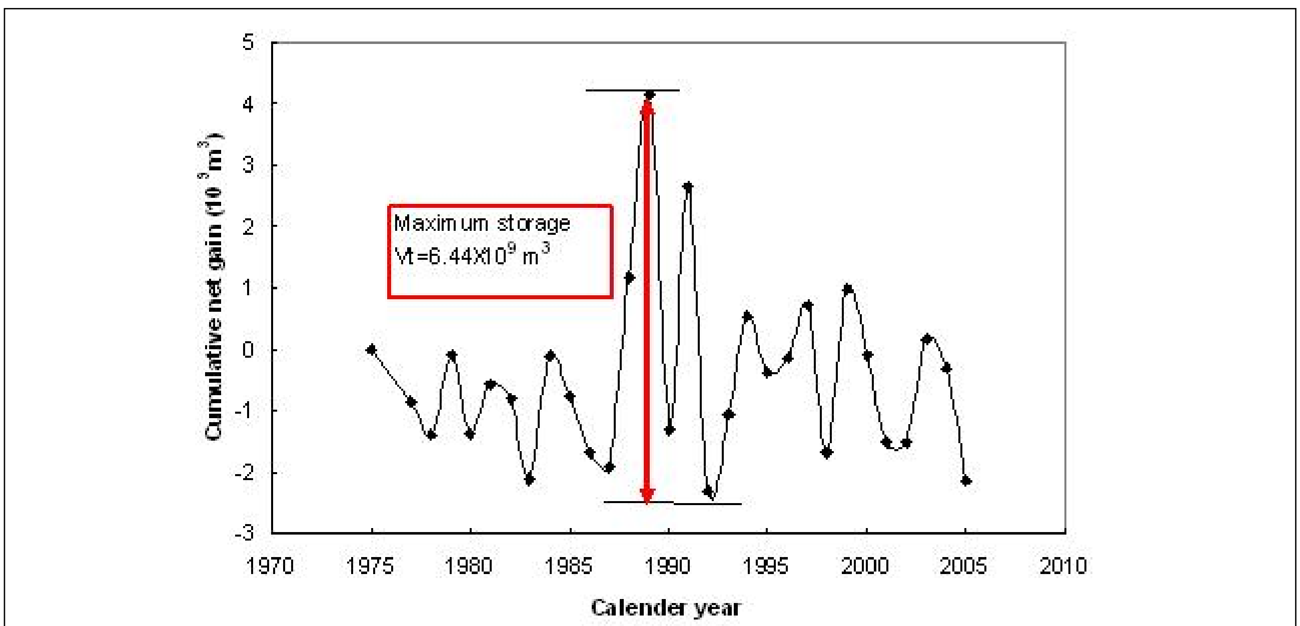

Figure 6. Yearly cumulative net gains in storage.

referred to the following literature for clarification (Devlin and Sophocleous, 2005; Loáiciga, 2003, 2006).

From the 2000 population and housing census of Ghana, about 54.2% of the population of northern Ghana depends on groundwater (Ghana Statistical Survey, 2002). Although not 100%, assuming everyone in northern Ghana depends on groundwater, the population increases annually resulting in corresponding total estimated pumped out water to be increasing linearly as shown in Figure 7. Despite the linear increasing rate of estimated pumped out water, the value is still far below the maximum yearly yield. This implies the aquifer system is still under exploited. The excess water in storage could be channeled to irrigation.

Groundwater irrigation could be practiced on condition that there is proper groundwater management. Though groundwater reserves might exist in abundance, there is the need for proper management and protection of them from depletion and contamination. For irrigation purposes, the United States Salinity Laboratory Staff (1954) recommends that the electrical conductivity and sodium adsorption ratio (SAR) of groundwater samples should not exceed 1250 µS/cm and 10 respectively. Water quality data from about 500 boreholes in the study area shows that less than 10% of borehole water samples had exceeded the irrigation water quality guideline (Akudago et al., in preparation). However, water quality from more boreholes is being investigated in order to draw a general conclusion. Using water which has high concentration of salt (chloride) and sodium adsorption ratio (SAR) can cause soil salinity as well as groundwater contamination. As water is used for irrigation, the ground surface begins to experience increased salinity especially as evaporation increases and moisture is lost from the ground leaving behind salt deposits. Also, as groundwater usage increases, the depletion of aquifer stored volume may cause salt water intrusion into the aquifer. Farmers may begin to experience reduction in crop yields and during recharge periods, the dissolved salts may end up in the groundwater. The quality of the water becomes unwholesome not only for drinking but also for irrigation purposes. Available literature recommends that the water table should be maintained below 2m from the surface under irrigation conditions (Oosterbaan, 2008; Bennetts et al., 2007; Ibrakhimov et al., 2007; Oosterbaan, 2003; Hillel, 2000; Rhoades et al., 1992; Abrol et al., 1988). In order to reduce these effects, salinity control needs to be taken seriously. This includes:

(1) The initial quality of water for irrigation must be checked to ensure it meets prescribed standards. (2) If possible, a capillary cut material could be put below the root zone of the crops and monitored for replacement over a period of time. (3) Salt absorbing plants could be grown immediately after the irrigation season. (4) Irrigation on lands with groundwater levels less than 2m from the surface should be discouraged. (5) Drip irrigation may be recommended to reduce water usage and level elevations. (6) If an irrigated land experiences high salinity values, flushing the contaminated area with fresh water is recommended. (7) Artificial recharge must be encouraged

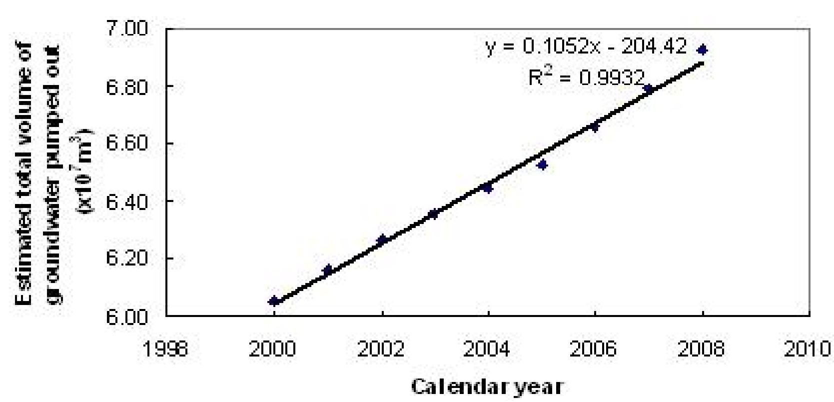

Figure 7. Estimated groundwater abstractions.

to complement natural recharge. (8) Water must be apportioned appropriately to reduce aquifer depletion. (9) Expert advice must also be sought from time to time on good water quantity and quality management.

CONCLUSIONS

(1) The research has shown that the maximum storage capacity of the aquifer system of northern Ghana is $6.44x10^9$ m^3, and is enough to accommodate the current pumping rate.

(2) Groundwater storage has previously been over estimated in the aquifer system of northern Ghana. This could lead to over exploitation of the aquifer.

(3) The maximum storage capacity of the aquifer is an order lower than the value reported in literature (1.26x1010 m3). However, pumping is neither close to maximum yield nor storage capacity; hence, there is more groundwater reserve. The reserve could be used for irrigation if proper groundwater management steps are observed.

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