Research Journal of Applied Sciences, Engineering and Technology 4(19): 3775-3782, 2012
ISSN: 2040-7467

Submitted: March 10, 2012 Accepted: April 30, 2012 Published: October 01, 2012

Prediction of Potential Groundwater Over-abstraction: A Safe-yield Approach-A Case Study of Kasena-Nankana District of UE Region of Ghana

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Abstract: There seem too little or no management plan to safe-guard groundwater extraction and ensure sustainability, even though, over 80% of the rural areas in Ghana, which make up about 70% of Ghana's population, depend on groundwater as a source of portable drinking water by means of mostly boreholes, hand-dug wells fitted with hand pumps. This study provides safe measurement as a framework to manage and ensure the sustainability of groundwater extraction in Upper East Region of Ghana. Mathematical relations to estimate *the times* and the *total number of people* required to exceed the safe yields of selected boreholes had been developed. The study revealed that (7) out of the (28) selected boreholes are being over-pumped; (2) of the boreholes currently have less than (25) years to be susceptible to over-pumping and (19) boreholes have more than (25) years to be susceptible to over-pumping. The study has also estimated the maximum number of people each of the selected boreholes could serve. Recommendations has been made for the estimation of safe on all boreholes in the Districts of Ghana to help all stakeholders to be able plan and monitor yields of boreholes to ensure sustainability of rural water supply in Ghana; Spatial Distribution Map of all boreholes and their safe yields must be developed to facilitate monitoring activities. Further studies are on-going to ascertain the current states of those boreholes which are currently being over-pumped.

Keywords: Ghana, groundwater over-use, kasena-nankana, safe yields, target time

INTRODUCTION

Groundwater management is often focused on the long term sustainability of the resource in terms of quality and yield. At the present, many rural communities rely on groundwater as their sole source of supply. In addition, groundwater often provides a basis for economic activity in some areas as irrigation water. Water demands of the population in these areas may have to be satisfied by groundwater resources which may eventually lead to over exploitation of the already limited water resources. It is a well-established phenomenon that once a community has access to a water supply to meet their basic needs demands, the demand steadily increases because of higher living standards, increasing irrigation requirements, more and improved sanitation requirements. All of these increases the risk of increasing the demand above the levels of sustainability and natural recharge.

Safe yield is the amount of water that can be pumped sustainably without lowering the level of water in a borehole to such a point where there will be over-abstraction. The rationale behind safe yield is to prevent pumping rates above the recharge, as this has consequential hydrologic and environmental effects, thus resulting in the depletion of aquifers, drying up of streams, springs and marshes etc. (Theis, 1940).

The concept of Safe Yield (SY) and its relation to sustainability of groundwater resources had been discussed extensively in literature Lee (1915), Theis (1940), Todd (1959), Alley *et al*. (1999), Sophocleous (2000a) and Alley and Leake (2004). Theis definition of safe yield as the amount of rejected recharge plus the fraction of natural discharge that is feasible to be utilised can easily form the basis of sustainable groundwater management. According to Theis, under pristine conditions, aquifers are in a state of approximate dynamic equilibrium where natural recharge equals natural discharge. Discharge by pumping is a stress superimposed on the existing stable system. The state of dynamic equilibrium requires an increase in the natural recharge

- A decrease in natural discharge
- A loss in storage in the aquifer

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Recently, emphasis has shifted to sustainable yield (Alley and Leake, 2004; Maimone, 2004). There is currently a lack of consensus as to what percentage of safe yield should constitute sustainable yield. The issue is complicated by the fact that knowledge of several related earth sciences is required for the correct assessment of sustainable yield. Additionally, there are socio-economic and legal implications that have a definite bearing on the analysis. The concept of sustainable yield emerged in the late 1980s, forcing a reconsideration of safe yield practices. According to (Sophocleous, 1997, 2000a, b), sustainability refers to renewable natural resources. Thus sustainability implies renewability. Groundwater is however, neither completely renewable nor completely non-renewable. The question therefore is how much of groundwater-pumping is sustainable? To ensure a sustainable utilisation of groundwater resource, abstraction of groundwater must not exceed the safe yield of the aquifer. The reason being that, once abstraction rates exceed the safe yield, wells will experience permanent drawdown and the only remedy is artificial recharge.

Studies have shown that the safe yield which creates a long term balance between the annual amount of groundwater abstracted and the annual amount of recharge (Lee, 1915; Pounce, 2007) is not estimated in Ghana for boreholes fitted with hand pumps, but estimated for mechanised boreholes. This is with the notion that abstractions from rural boreholes fitted with hand pumps do not have any negative impact on the aquifer. This may become a problem in areas with low average annual recharge and restricted aquifer extents, as boreholes can be over-pumped or overexploited. These conditions are synonymous to the northern part of Ghana, where aquifers are usually not extensive, restricted and occur in patches (Dapaah-Siakwan and Gyau-Boakye, 2000). Therefore, without appropriate management policies, the future of groundwater abstraction is at risk. In Ghana, this trend may place some communities on a sure path towards groundwater mining. Managing groundwater abstraction means ensuring a safe and adequate supply to meet a community’s demand while preventing deleterious impacts (Pounce, 2007). Thus, safe yield is an important component of water supply, which is a means of placing a limit on groundwater abstraction to attain a long term balance between withdrawal and recharge.

As part of Government of Ghana’s policy objectives to achieve the Millennium Development Goal (MDG) based on economic growth and poverty reduction strategy, the government has embarked on water supply in rural communities by providing mostly, boreholes fitted with hand pumps. The overall coverage of safe drinking water in Ghana is about 30% and fifty percent (50%) of Ghanaians use “unprotected” source of water (M.O.H., 1999). Rural communities in Ghana, which constitute about 70% of the total population, rely heavily on groundwater as the main source of drinking water. About 70% of the population in rural communities depend on groundwater a main source of potable drinking water (Kortatsi and Tay, 2008). Abstractions in these communities are done without due attention to the safe yield (optimum yield) for sustainable management of the aquifer.

This study is aimed at providing the framework to manage and ensure the sustainable use of groundwater in Upper East Region of Ghana.

MATERIALS AND METHODS

Location, climate and vegetation: The study area (Kasena-Nankana District) is one of the six (6) Districts of the Upper East Region of Ghana. It is lies within latitudes 10º30′ N and 11º10′ N and longitudes 1º 01 W and 1º 30′ W. It is bounded to the north by Burkina Faso, to the east by Bolgatanga and Bongo districts and to the west by the Builsa district and Upper West Region. It covers a total area of 1674 km^2 (K.N.D.A, 1998) (Fig. 1). The Kasena-Nankana District falls within semi-arid climatic region otherwise referred to as the Tropical Continental or Interior Savannah climatic region of Ghana, which is characterised by a single rainy season from May to October followed by prolonged dry season. It is influenced by two air masses which are the Southwest Monsoon and the Northeast Trade Winds (Harmattan). The study area is influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ) and it is among the areas with lowest rainfall values in Ghana. The mean annual rainfall is about 100-115 cm. The study area is characterised by generally high temperature and is among the driest places in the Ghana. The highest mean monthly and daily temperatures of 33 and 42ºC, respectively are recorded in March-April; whilst the lowest mean monthly value of 26.5ºC is registered during the peak Harmattan season in December and January each year. Relative humidifies of 70-90% are recorded during the rainy season and in the dry season, the lowest value of 20% is observed (Dickson and Benneh, 1980).The vegetation of the study area is the Interior Wooded Savannah type. This is characterised by major trees such as baobab, dawadawa, acacias and Shea butter trees that are adaptive to the long dry conditions

Relief, drainage, geology and groundwater occurrence: The topography of the Kasena-Nankana District is fairly flat with an average height of 100m above sea level, with few isolated areas (e.g., Zambao) rising to about 300 m above the mean sea level, where topography appears undulating. Small rounded inselbergs

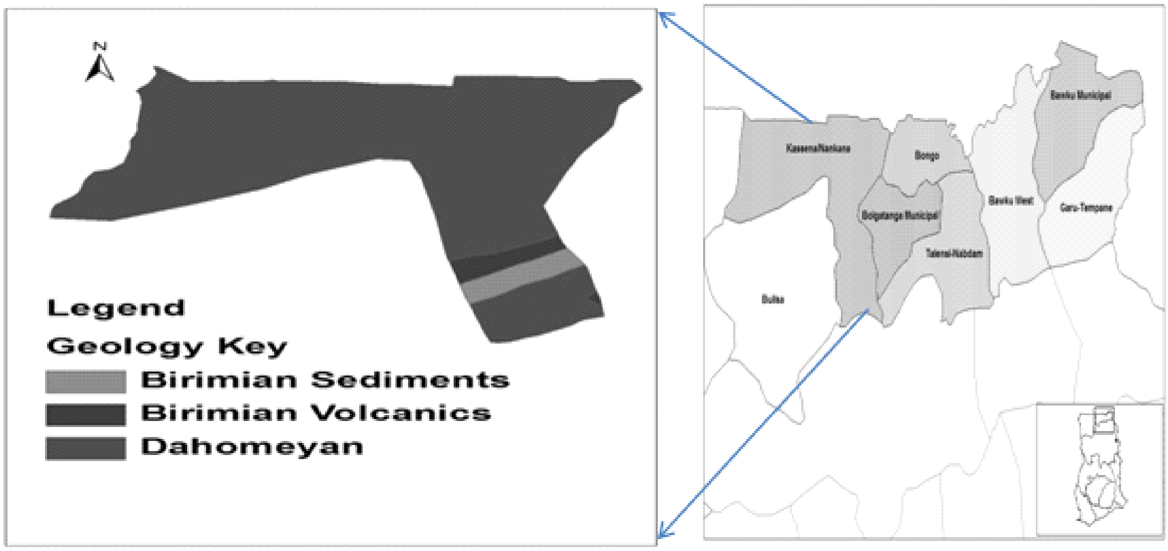

Fig. 1: Location of Kasena-Nankana district in upper east region, Ghana

of granitic outcrops are found on high plains. The main rivers draining the area are Asibelika and Afumbeli, which are tributaries of the Sissili River, (K.N.D.A, 1998). The overburden is usually shallow and the texture of the soils is coarse-grained sandy-loam (Kesse, 1985). The major rock is the belt granitoids (described as *Bongo granites*), which is composed of Precambriancrystalline igneous rocks and covers about 95% of the district. The remaining 5% of the district is composed of Precambrian Birimian Meta-Volcanic and Meta-Sedimentary rocks (Wright *et al*., 1985). The belt granitoids are basically biotite-rich granites, granodiorites, hornblende granites and hornblende-diorites. They consist of highly altered feldspars, typically unfoliated and are rich in hornblende and are found in association with the meta-volcanics. Basin granitoids composing of gneisses, migmatites that are rich in Potassium are also found in the study area in association with Meta-sedimentary rock formation (Kesse, 1985).The meta-volcanic sedimentary rocks occur in a general NE-SW direction that are dominantly volcaniclasticsinterbedded with subordinate argillites and occasional minor mafic flows, which were deposited fairly proximal to the volcanic ridges. They are characterised by relatively short widths varying between 20 to 70 km and in some places wider and long strikes that can be measured up to about 1000 km. Common lithologies include metamorphosed lavas, pyroclastics rocks, hypabyssal intrusive, phyllites and greywackes. Common fractures found within the meta-volcanics are joints, fault and shear zones (Griffis *et al*., 2002).

Groundwater occurrence in Kasena-Nankana District is commonly found in decomposed or weathered metasedimentary rocks, quartz and aplite veins occurring in poorly decomposed or fresh igneous rocks. The probability of encountering aquifer zones is found to be higher in the decomposed rocks than the fresh rocks. Good yielding aquifer has been encountered in decomposed quartz-rich rocks and fractured quartz veins in moderately decomposed rocks (Wardrop and Associates, 1999). Aquifer are therefore structurally controlled, limited in extent and highly irregular in configurations in the study area. Their thickness varies from a few centimetres in fractured quartz veins toover 30 m in moderately decomposed granites of over 30 m thick. Aquifers encountered in the study area were semi confined in nature and wells had their Static Water Level (SWLs) higher thanthedepth of waterstrike.

Methodology: The methodology included collection ofhydrogeological data (e.g., static water level, dynamic water level, yield, screen depth, drilled depth) on all twenty-eight (28) boreholes, data on current population that each borehole is serving in the study area and Community water and Sanitation Design Guidelines. These information were then analysed to determine the safe yield of the boreholes

Safe yield estimation: The advantage of the safe yield estimation is to determine the maximum rate at which a borehole can be pumped without lowering the water level to the screen. Safe yield is estimated using the total abstraction from the aquifer and the groundwater level data in the area. The safe yield of a borehole is estimated, based on Fig. 2 and Eq. (1) (US EPA, 1994):

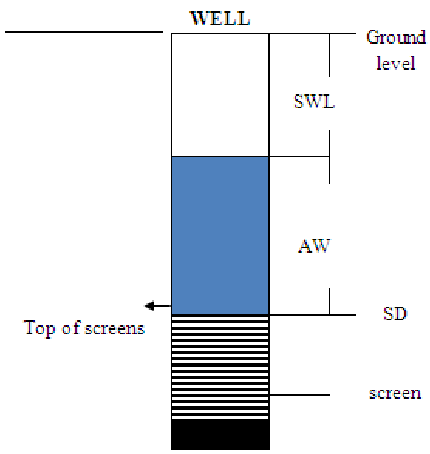

Fig. 2: Diagram showing the determination of safe yield of an aquifer (semi-confined)

$$SY = AW \times SC \tag{1}$$

where, AW: available water; SC: Specific capacity

In determining the safe yield of the wells within the study area, the confined aquifer approach in measuring the available water was assumed since the identified aquifers are semi-confined. Referring to Fig. 2, the available water can be determined as:

$$AW = (SD - SWL) \times f \tag{2}$$

where, SD: depth to top of screen and SWL: static water level in metres (the lowest value of the year)
f-Factor of safety = 0.6-0.9 (US EPA, 1994)

- The determination of factor of safety must be based on the experience of the local hydrogeology

The specific capacity is one of the key hydrogeological quantities used to characterise aquifers. Hence in the determination of the safe yield, this parameter must not be over looked. The specific capacity of a well is normally determined using the relation:

$$SC = Q/\Delta S \tag{3}$$

where, Q-the pump rate, *m^3/day; Δs*-the drawdown, m.

The drawdown which is a needed parameter to establish the specific capacity was determined using Fig. 2 and Eq. (4):

$$\Delta s = DWL - SWL \tag{4}$$

where, DWL-dynamic water level, m; and SWL-static water level, m

Hence safe yield can finally be determined as:

$$SY = 0.9(SD - SWL)[Q/DWL - SWL] \tag{5}$$

Predicting groundwater over-abstraction: Groundwater over-abstraction in the context of this research is the time when the safe yield has been exceeded. To predict the groundwater over-abstraction, the demand of the population (hereafter referred to as Target population) will meet and exceed the safe yield and the time limit (hereafter referred to as target time) required to reach this population must be estimated.

Estimation of Target population (Tp): The Target Population, required to meet the safe yield of a well with that minimum yield is determined as:

$$T_p = \text{Safe yield/Per capita minimum annual yield} \tag{6}$$

Where, T_p is the Target Population
Simplifying Eq. (5) in (6) will give:

$$T_p = 0.03805\ (SD - SWL) \times SC \tag{7}$$

Estimation of Target time (T_t): Generally, the projected population can be estimated using either linear relation:

$$P_t = p_{o(1+r_g)} \text{ Or} \tag{8}$$

The geometric growth rate equation:

$$p_{t = p_{o(1+r_g)^t}} \tag{9}$$

where,
P_t : Target population (Pt), Po-Current Population utilising the borehole,
r_g : Annual average growth rate and
Tt : Target time in years.

The geometric growth rate relation was used in determining the Target time (T_t).

By substituting Pt in the geometric growth rate relation, target time is given by the relation:

$$T_t = \log_{10}\left(\frac{\lfloor 0.03805 \times (SD - SWL) \times SC \rfloor}{P_0}\right) \times \frac{1}{1 + r_g} \tag{10}$$

RESULTS AND DISCUSSION

The CWSA, in fulfilling part of its objectives of ensuring sustainable water and sanitation facilities through Community Ownership and Management (COM)

Table 1: Estimates of safe yield, annual abstraction, target population and target time

BH no.	Community	Yield (m^3/d)	Specific cap (m^2/d)	Safe yield (m^3/year)	Current pop. (P_o)	Annual abstr. (m^3/year)	Target pop (T_p)	Target time (T_t)
451 F02	Chiana JHS	1728	194	10658	383	9059	451	14.9
451 F03	ChianaAsunia	12442	1270	71139	257	6079	3008	224.9
451 F13	Chiana Market	5184	1127	33142	650	15374	1401	70.2
451 F18	Chianawurania	21600	2541	208780	350	8278	8827	295.0
451 E02	Yogbania	3309	719	35150	328	7758	1486	138.1
451 E04	Namolo	2333	265	11169	532	12583	472	-10.9
451 E05	Namolo	1987	382	14856	1045	24716	628	-46.5
451 E12	Nawognia	1987	584	38763	372	8799	1639	135.5
451 E15	Wuru	1944	778	44968	407	9626	1901	140.9
451 E20	Nogsenia	12830	4139	71212	346	8184	3011	197.8
451 E21	Yogbania	2333	402	19856	142	3359	840	162.4
451 E23	Boania	950	156	5548	325	7687	235	-29.8
451 E24	Korania	4666	1414	41610	783	18520	1759	74.0
451 E25	Gongnia	1987	406	13067	636	15043	552	-12.9
451 E28	Korania	2333	864	33580	803	18993	1420	52.1
451 E29	Korania	1944	1620	51246	825	19513	2167	88.3
452 F02	Doba	6221	1830	41647	869	20554	1761	64.6
452 F03	Nayagnia	3888	720	31974	598	14144	1352	74.6
452 F36	Nayagnia	1210	269	15805	924	21854	668	-29.6
452 I07	Vunania	2592	1234	19199	516	12204	812	41.4
455 A22	Natugnia	2419	417	19929	487	11519	843	50.1
455 A26	Natugnia	2074	309	11498	487	11519	486	-0.2
455 A36	Manyoro	3456	326	17374	779	18425	735	-5.4
455 D02	Kandiga	5616	1478	42085	275	6504	1779	170.7
455 D05	Mirigu	15552	2287	200604	498	11779	8481	259.1
455 D10	Mirigu	2938	402	17630	370	8751	745	64.0
455 D11	Kandiga	1175	111	6826	219	5180	289	25.2

Table 2: Boreholes being overexploited (annual abstraction>safe yields)

BH no.	Community	Yield (m^3/d)	Safe yield (m^3/year)	Current pop. (P_o)	Annual abstr. (m^3/year)	Target pop (T_p)	Target time (T_t)
451 E04	Namolo	2333	11169	532	12583	472	-10.9
451 E05	Namolo	1987	14856	1045	24716	628	-46.5
451 E23	Boania	950	5548	325	7687	235	-29.8
451 E25	Gongnia	1987	13067	636	15043	552	-12.9
452 F36	Nayagnia	1210	15805	924	21854	668	-29.6
455 A26	Natugnia	2074	11498	487	11519	486	-0.2
455 A36	Manyoro	3456	17374	779	18425	735	-5.4

and other strategies, has adopted standards for the delivery of water. One of such standard was declaring as successful, borehole fitted with hand-pump with a minimum yield at 13.5l/min.

In Ghana, borehole fitted with hand-pump is to serve a population of up to 300 (Community Water and Sanitation Agency, 1997). Hence per capita annual demand of water from a constructed borehole with the minimum yield of the 13.5l/min will be 23.652 m^3/year- This results in a minimum annual abstraction of 7095.6 m^3/year for a population of 300.

Two basic assumptions have been made during this study;

- Drawdown is measured at the worst season (i.e. peak of dry season)
- Population growth rate is constant and equal to the average national value

Data on 28 boreholes fitted with handpumps in communities within the study area were collected and analysed. Information on the population being served by each of these boreholes was also obtained. Using Ghana's average national population growth rate of 1.1% (Ghana Statistical Service, 2000) and Eq. (5), (7) and (8), the following results had been generated in Table 1.

Safe yield and annual abstraction: Safe yield is a long term balance between the annual amount of groundwater abstracted and the annual amount of recharge (Lee, 1915). By the CWSA standard (Community Water and Sanitation Agency, 1997), the minimum requirement of water by a successful borehole depends on two factors; the minimum yield and the population to be served. As has been discussed earlier, 7095.6m^3 of water from a successful borehole must serve three hundred (300) beneficiaries in a year. From (Lee, 1915) and Theis (1940), this quantity of water must equal the safe yield of the borehole or aquifer if depletion or overexploitation is to be avoided. Thus, by CWSA standard of 13.5l pm yield of a successful borehole for a population of 300 (7096.6 m^3/year), the sustainable exploitation of such a borehole (or aquifer) requires a yield greater than the safe yield. In this study, the safe yields of the boreholes varied between 5548-208780 m^3/year whilst the annual abstraction rates varied between 3359-24716 m^3/year (Table 1). Seven (7)

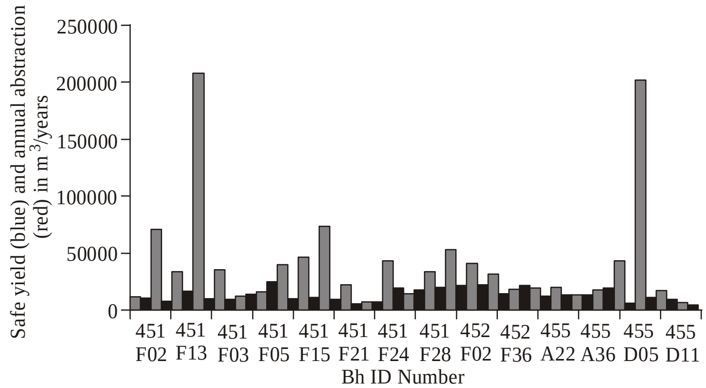

Fig. 3: Comparison between safe yield and annual abstraction of each borehole

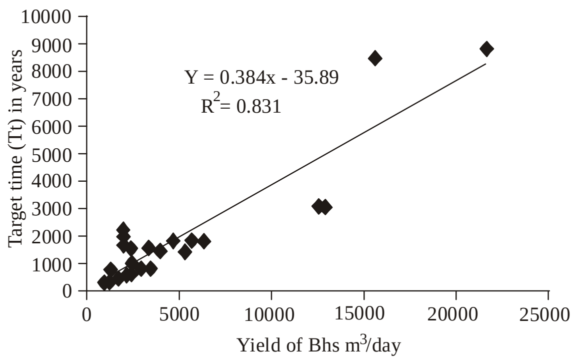

Fig. 4: Relationship between estimated yields and Target time (Tt)

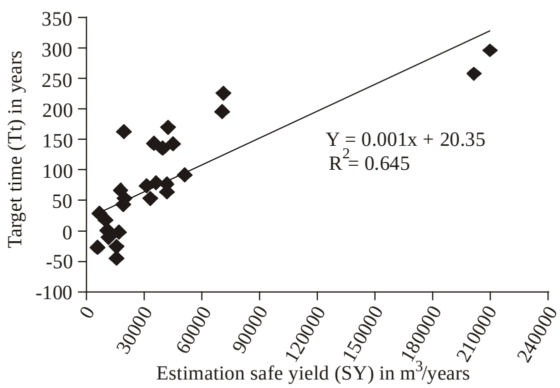

Fig. 5: Relationship between estimated safe yield and Target time (Tt)

boreholes (Table 1 and 2; Fig. 3 and 7), were found to have safe yields less than their respective annual abstraction rates-estimated based on the Ghana's CWSA Standard (Community Water and Sanitation Agency, 1997) (i.e. 300 people to 13.5l pm (7095.6 m^3/year)).

Safe yield, target population and target time: There is generally, a direct correlation between the yield of a

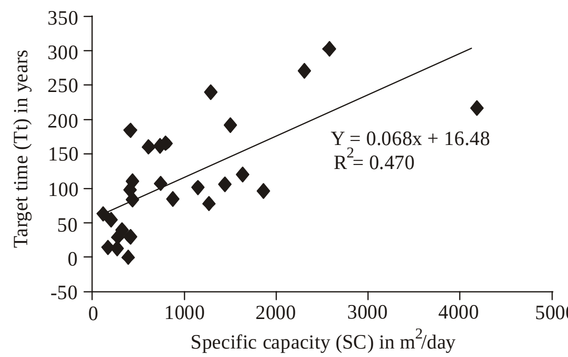

Fig. 6: Relationship between Specific Capacity (SC) of boreholes withTarget time (Tt)

borehole, the specific capacity the safe yield and Target time (Tt), which is dependent on the Target population (Tp) (Table 1; Fig. 4, 5, 6 and 7). By establishing the current population and the growth rate of a community and estimating the safe yield of a borehole, the target population and the time (target time) required to exceed the safe yield could be predicted. Figure 4 shows the various boreholes that are currently being overexploited (i.e. those with negative target time). From the various estimations and analyses carried out, it is clear that population is a key factor in establishing the limit of borehole (and for that matter groundwater) overexploitation, though, other factors such as inadequate yield, well inefficiency resulting from improper well design and construction and large drawdown resulting in pumping water level getting below the first screen, especially in a multi-screen well as is the case in fractured and semi-confined aquifers (Freeze and Cherry, 1979). The contribution of population to groundwater over-use is clearly depicted in Table 1 and 2. All the seven (7) communities whose wells are being over-used have populations exceeding their respective Target populations (i.e., the population required to consume water up to the safe yield). Thus, it follows that once the Target

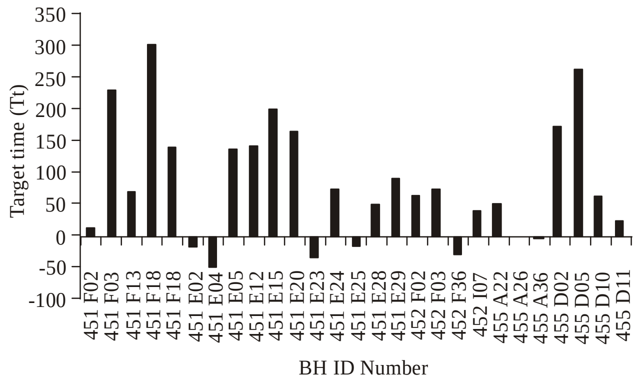

Fig. 7: Boreholes currently being overexploited (with negative target time in years)

population (Tp) for a borehole is exceeded, the Target time (Tt) will be in the negative-meaning the well will be over-abstracted (i.e., abstraction rate > safe yield).

Boreholes currently being over-used in Kasena-Nankana District in Upper East Region of Ghana have been predicted from the estimation of Safe yields. The safe yields, Annual Abstraction Rates, Target Populations (Tp) and Target Times (Tt) had been estimated as shown in Table 1. Seven (7) boreholes are currently being over-used or overexploited; two (2) boreholes have less than thirty (30) years to be overexploited-One in Kandiga (455D11) has about twenty-five (25) years whilst the other well from Chiana JHS (451F02) has about fifteen (15) to be over exploited. Seven (7) boreholes have between fifty (50)-hundred (100) years to be overexploited whilst nine (9) wells would require more hundred years to be overexploited (Table 1 and 2).

Groundwater occurrence and flow in the study is usually controlled by secondary porosity, developed as a result of chemical weathering, faulting and fracturing. Aquifers are generally not extensive, restricted and occur in patches (Dapaah-Siakwan and Gyau-Boakye, 2000). Recharge is low and mainly rainfall dependent, which is mostly through indirect recharge (through pools of accumulated runoffs, intermittent streams and preferential pathways) as compared to in situ or direct recharge (Lerner *et al*., 1990; Leduc *et al*., 1997) Available data on annual recharge rates (though not comprehensively estimated) from previous researchers reveal low values with high spatial and temporal variations. Conservative values of between 2.5-4% of annual precipitation is normally used (Martin, 2005). The area experiences very high evapotranspiration with potential evapotranspiration exceeding total annual rainfall. Specific data from 1961-1970 (Acheampong, 1988) indicate that Kasena-Nankana District in Upper East Region has potential evapotranspiration of 1781 mm while mean annual rainfall is 988. Estimated actual Evapotranspiration (ETa) in the study area varies between 70-80% of the average total rainfall (Martin, 2005) averaging around 729 mm. With these unfavourable climatic conditions and hydrogeologic features characterising the study area and the fact that groundwater accounts for over 90% of potable drinking water for people in the study area, estimation of safe yield on all boreholes will be important component of managing groundwater abstraction to ensure safe and sustainable rural water delivery in Kasena-Nankana District. This study must be carried out in both similar dissimilar geographical areas in Ghana to develop a compressive safe framework in rural Ghana.

CONCLUSION

The study has developed a mathematical relation which can be utilised in predicting the time require for a particular borehole to be over-pumped, once the pumping test of that drilled well is completed. The relation developed makes use of hydrogeological parameters generated during pumping test which are basic requirement in every borehole completion. The outcome of this study is very important in areas of undefined aquifer boundaries and where groundwater storage capacities cannot be determined. This has been shown from the case study, which was conducted in Ghana where almost all aquifers had not been defined and boundaries unknown. The typical case of Kasena-Nankana district mainly rural and groundwater is the main source of drinking potable drinking water for the inhabitants through basically boreholes fitted with handpumps. It is a water stress semi-arid area where groundwater occurrence and flow is usually controlled by secondary porosity, developed as a result of chemical weathering, faulting and fracturing. Aquifers are generally not extensive, restricted and occur in patches and recharge is relatively low and mainly rainfall dependent with conservative values of recharge rangingbetween 2.5-4% of annual precipitation. The area experiences very high evapotranspiration with potential evapotranspiration exceeding total annual rainfall. The above characteristics, coupled with high almost 100% dependence on groundwater of the study area put high stress on the available groundwater resources. Already, there have been some reported cases of borehole dry-ups and in some cases, significant drop groundwater levels in wells within the study and this thereforerequire the need for the development of a framework for managing groundwater resources by establishing the safe yields of wells, which could help in predicting the time of over-pumping. This will therefore guide Hydrogeologist to set optimum abstraction rates to ensure safe and sustainable rural water delivery in Kasena-Nankana District. This study must be carried out in both similar and dissimilar geographical areas in Ghana to develop a compressive safe framework for managing groundwater resources especially in rural Ghana.

ACKNOWLEDGMENT

Sincere gratitude goes to the District Water and Sanitation Team (DWST) of Kasena-Nankana District of Upper East Region of Ghana for their invaluable contribution through the provision of data, access to boreholes in the district during the field study. Much recognition goes to Felix Aidoo for his contribution to this study at the initial stage and Dr. K. Pelig-Ba for his constructive critique of this study.

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