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CHARACTERISTICS OF A CRYSTALLINE GRANITIC AQUIFER IN NORTH-WESTERN GHANA

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Abstract

The groundwater potential of north-western Ghana has been assessed in terms of transmissivity and specific capacities of the basement aquifers. Data from short-term and constant-discharge pumping tests on 14 boreholes were analysed. The Cooper-Jacob straight line analytical method was used to determine the aquifer characteristics. The computed transmissivity values of the aquifers varied significantly from 0.37 to 44.5m^2 d^{-1}; with their specific capacity values ranging from 1.04 to 56.7 m^3 d^{-1}m^{-1}. The storage coefficient from four observation boreholes indicated that the aquifers were under confined conditions with values in the order of 10^{-5}. Total head losses of the boreholes attributed to laminar and turbulent flows ranged from 28 per cent to 84 per cent. The aquifer characteristics confirm that groundwater occurrence is localised, confined and controlled by the development of secondary porosity. Therefore, to obtain adequate water for sustainable use, groundwater abstraction in the study area should be preceded by extensive geophysical investigations using integrated methods.

Introduction

The Upper West Region of Ghana has a total land size of 12,478 km^2, and forms about 12.7 per cent of the total area of the country (Ghana Statistical Service , 2000). It is considered one of the smallest regions in the country. In 2000, the population of the region was estimated to be 576,583, representing 3 per cent of the national population (Ghana Statistical Service, 2000). The Region is located within the semi-arid region where the mean annual evapo-transpiration exceeds the mean annual rainfall by about 49 per cent (Gyau-Boakye &Timbulto, 1996). Due to this high evapo-transpiration rate, nearly all the surface water sources dry up completely during the dry season. Consequently, nearly all communities in the Region rely on groundwater as their main source of water supply. In the last few years, most communities within the Region relied on shallow hand-dug wells that were constructed using simple technology and local tools.

The hand-dug wells were constructed into the overburden, and were limited to low-lying areas and valley bottoms. However, owing to the extreme seasonal variations in the area, many of the hand-dug wells experienced decline in their water levels, and some of them dried up completely during the peak of the dry season. To ensure reliable supplies of water to the communities in the Region, several boreholes have been drilled by the government and many private and donor agencies. One of these water projects is the Community Water and Sanitations Agency's (CWSA) small towns water supply project; which seeks to drill a network of boreholes that are connected to a central overhead storage tank for redistribution through public standpipes in small towns and peri-urban communities.

The paper is intended to assess the potential and characteristics of the underlying aquifers of the study area. The study is based upon the analyses and interpretation of pumping test data on 14 boreholes drilled in 10 beneficiary peri-urban communities in the Upper-West Region. These boreholes were drilled purposely to supply uninterrupted and safe drinking water through mechanised public stand-pipe distribution system. Under the project, a successful borehole is considered to have a yielding potential of not less than 5 $m^3 h^{-1}$. However, in extremely low groundwater potential areas, boreholes that yield as low as 1.0 m^3hr^{-1} are acceptable.

Experimental

The study area

The 10 beneficiary communities of the study area are scattered within the entire Upper West Region of Ghana.

Climate

The study area falls within the semi-arid climatic region, where the rainfall values (less than 950 mm/year) are amongst the lowest in the country, with marked seasonal distribution. Their intensity and duration, however, vary considerably from month to month. The area is characterised by generally high temperatures with low yearly variations. The highest mean monthly temperature of about 42 °C occurs at the peak of the dry season in April, while the lowest mean monthly value of 26.5 °C is registered during the months of December and January each year. The area is characterised by one rainfall regime that occurs in only four months between July and October each year (Dickson & Benneh, 2004).

Hydrogeology

Geologically, the study area is underlain largely by crystalline basement complex rocks, comprising mainly granites, which are foliated, undifferentiated and comprises outcrops of boulders of varying sizes (Kesseh, 2004). On the average, there is about 89 per cent chance of obtaining successful boreholes in the fractured portion of the underlying Pre-Cambrian crystalline igneous geological formations in the area (Agyekum, 2008).

Groundwater occurrence in the study area is confined to thick regolith, the contact zones between the fresh and the weathered rock and the fractured portions of the rock (Agyekum, 2008). Shallow aquifer depths, ranging generally between 25 and 52 m were recorded in the area with yields ranging from 0.5 to 9m^3 hr^{-1}. Groundwater occurrence in the study area is largely influenced by rainfall, topography, overburden thickness and geology, whilst aquifers are localised, discrete and discontinuous and are controlled by secondary porosity including weathering, fracturing, jointing and faulting, as well as the degree of fracture intensity and their extent of interconnections. Borehole depths lie at a mean depth of 42 m (range 33 – 108 m). Aquifers were intercepted at a mean depth of 30 m (range 13–42 m), while static water levels (swl) stood at a mean depth of 5 m below ground level. Borehole yields averagely 3 m^3 hr^{-1} and varied from 0.6 to 9.0m^3 hr^{-1}, with higher yields occurring in highly-fractured rocks.

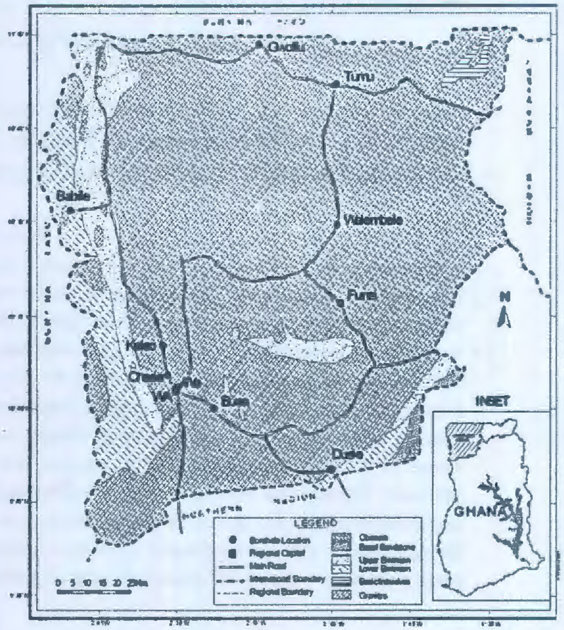

Fig. 1. Location map of the study area

Pumping test data generated from 14 boreholes were used for the study. The static water level (swl) of each borehole was recorded before

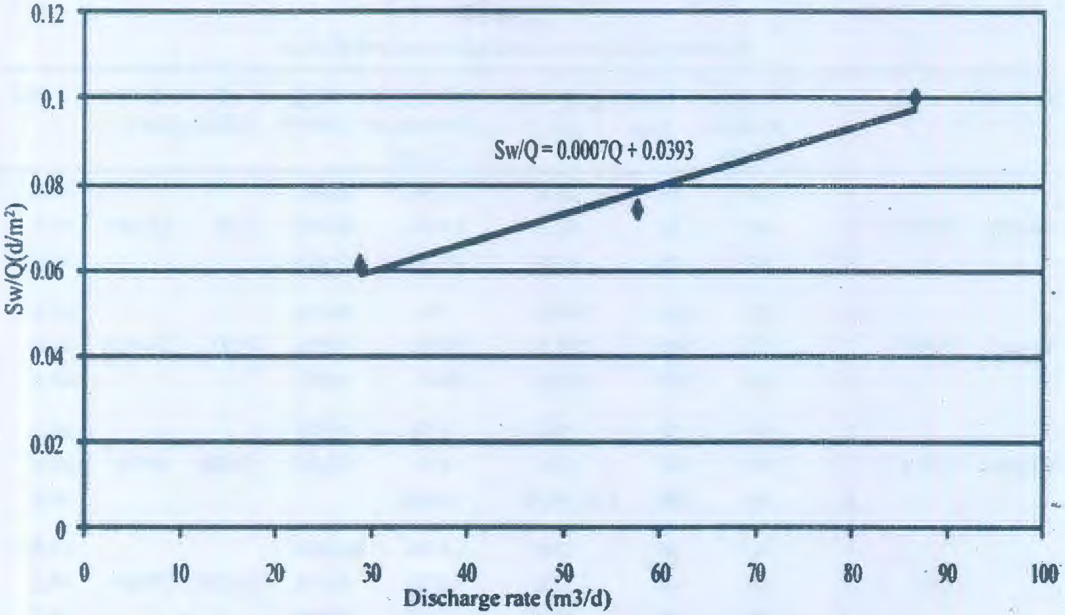

Fig. 2. Estimation of B and C values to determine borehole efficiencies

beginning the pumping test. Based upon the static water levels and their total drilled depths, the pump placement depth was determined for each borehole. Short-duration pumping test was conducted on nine of them, which were relatively higher-yielding to provide an initial estimate of their yields, and further to determine the optimum discharge rates to be used for the constant-discharge test. The short-duration test result was further used to determine the efficiency of each borehole at selected discharge rates. This test was conducted using three different discharge rates lower than their estimated discharge rates for 60 min each. After the short-duration test, constant-discharge test was carried out on each of the 14 boreholes after water levels of each borehole had recovered fully.

Each borehole was pumped at a certain optimum discharge rate that ranged from 43.2 to 288.0 m^{3}d^{-1}, and at pumping duration that ranged between 3 and 30 h. Water level drop were recorded at regular time intervals during the course of pumping. During the constant-discharge pumping test, interference studies were conducted concurrently on two observation wells in two communities. The boreholes were separated 73 and 85 m away from the pumping boreholes. This was done by measuring water level drops in the observation wells at regular time intervals as the constant-discharge pumping test in the pumping boreholes was in progress.

Results

For each borehole, a linear graph of drawdown against time was plotted from the step-test results. Using Rorabaugh's (1953) simplified version of Jacob's equation, the relationship between the drawdown S_w, and the pumping rate is given as

$$S_w = BQ + CQ^2, \quad (1)$$

TABLE 1
Step-drawdown results and efficiency calculation

Location	*No.*	*Step*	*Pumping duration (min)*	*Pumping rate, Q lpm*	*(m^3/d)*	*Maximum drawdown S_w (m)*	*S_w/Q (d/m^2)*	*B (d/m^2)*	*C (d/m^5)*	*E (%)*
Wa-N/E	WVB 2	1	60	15	21.6	8.94	0.414	0.26	$6*.10^{-3}$	69.4
		2	60	30	43.2	19.34	0.448			50.7
		3	60	45	64.8	43.12	0.665			40.7
Tumu	WVB3	1	60	100	144.0	7.4	0.052	0.03	$10\text{-}40^{-4}$	67.4
		2	60	200	288.0	18.92	0.066			43.0
		3	60	300	432.0	39.6	0.092			40.8
Charia	CH 1	1	60	20	28.8	1.24	0.043	0.026	$4*10^{-4}$	69.2
		2	60	60	86.4	4.0	0.046			43.0
		3	60	80	115.29.56	0.083				36.0
	CH2	1	60	20	28.8	1.76	03.061	0.039	$7*10^{-4}$	65.9
		2	60	40	57.6	4.26	0.074			49.2
		3	60	60	86.4	8.64	0.100			39.2
Busa	BS1	1	60	50	72.0	4.5	0.063	0.047	$2*10^{-4}$	76.5
		2	60	100	144.0	10.5	0.073			61.7
		3	60	120	172.8	14.9	0.086			57.6
	BS2	1	60	30	43.2	4.3	0.100	0.057	$9*10^{-4}$	59.4
		2	60	60	86.4	10.54	0.122			42.2
		3	60	100	144.0	26.8	0.186			30.5
Babile	BAB1	1	60	30	43.2	2.46	0.057	0.046	$2*10^{-4}$	84.2
		2	60	60	86.4	5.70	0.066			72.7
		3	60	100	144.0	11.8	0.082			61.5
Kaleo	BRD	1	60	80	115.2	5.2	0.045	0.039	$2*10^{-4}$	62.9
		2	60	100	144.0	10.9	0.076			57.5
		3	60	150	216.0	14.4	0.067			47.4
Funsi	FUN1	1	60	30	46.2	16.3	0.377	0.04	$7*10^{-4}$	57.0
		2	60	60	86.4	29.4	0.34			40.0
		3	60	100	144.0	44.5	0.31			28.4

E% = Efficiency values of the boreholes

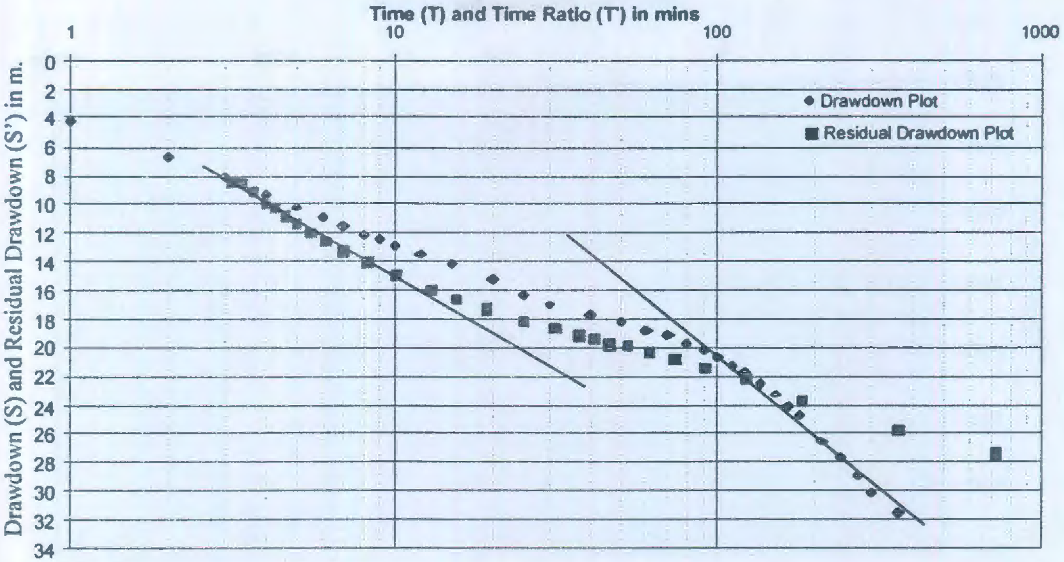

Fig. 3. Drawdown and residual drawdown plot for the computation of aquifer characteristic

TABLE 2
Transmissivity and specific capacity results

Location (ID No.)	*Depth (m)*	*Pumping rate, Q*		*Pumping duration (min)*	*Draw-down (m)*	*Trans-missivity (m^2/d)*	*Specific capacity ($m^3/d/m$)*
		lpm	*m^3/d*				
Wa-N/E	56	30	43.2	360	9.6	2.1	4.5
Tumu	100	200	288.0	360	31.6	2.7	9.10
Dusie Camp	72	10	14.4	300	16.0	0.97	0.90
Charia 1	36	80	115.2	360	27.2	2.6	3.18
Charia 2	35	30	43.2	180	22.3	1.9	0.79
Busa 1	39	80	115.2	1200	18.4	6.3	5.63
Busa 2	33	80	115.2	1440	19.0	6.0	7.02
Babile 1	41	50	72.0	180	31.5	2.3	2.75
Babile 2	37	50	72.0	360	30.9	4.07	2.33
Kaleo 1	31	150	216.0	1800	3.81	56.7	44.5
Kaleo 2	55	90	129.6	1440	16.2	8.0	20.7
Funsi	108	30	43.2	180	37.6	1.2	0.5
Gwollu	61	20	28.8	360	35.2	1.1	2.1
Wallembelle	54	20	28.8	420	40.1	1.0	1.5

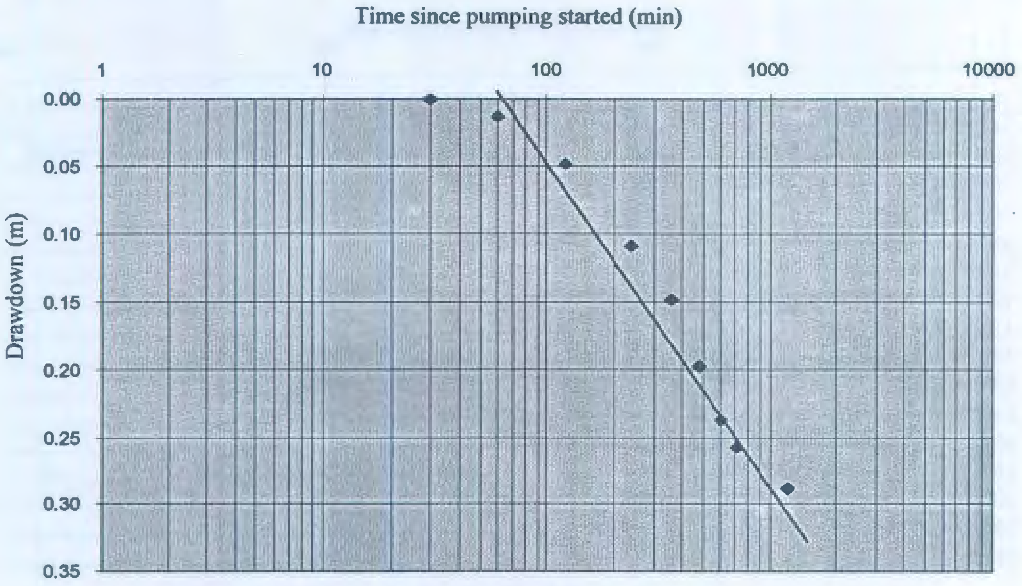

Fig. 4. Time-drawdown curve from an observation well

TABLE 3

Results of interference studies

Community	*Dist. (r) between BH1 and BH2 (m)*	*Pumped B/H*	*Observed B/H*	*Discharge rate, $Q(m^3/hr)$*	*Pumping duration (hrs)*	*Recorded and computed from observation boreholes*		
						SWL (m) before pumping	*DWL(m) after pumping*	*Storage coeff. S*
BUSA	**73 m**	**BUSA 1**	**BUSA 2**	**4.8**	**20**	**5.45**	**5.74**	**$4.12*10^{-4}$**
		BUSA 2	BUSA 1	4.8	24	6.34	6.43	$1.16*10^{-4}$
BABILE	85 m	BAB 1	BAB 2	3.0	12	2.97	3.20	$7.1*10^{-5}$
		BAB 2	BAB 1	3.0	6	3.69	3.79	$8.9*10^{-6}$

where BQ is the aquifer loss term due to laminar flow, and CQ^2 is the well loss term owing to turbulence flow (attributed to inefficiency of the well).

Jacob (1947) showed that well losses in boreholes may include partial penetration, non-Darcian flows in the zone of gravel-pack, losses through screen slots, frictional losses in casings, as well as losses inside well screens due to momentum and friction. Re-arranging equation (1), we obtain

$$S_w/Q = CQ + B \tag{2}$$

Values of S_w/Q were plotted against Q from the results of the step-drawdown test to yield a straight line graph with slope equal to C and y-intercept equal to B. The computed B and C values for each borehole were used to estimate the efficiency value (E%) of each discharge rate of the step-drawdown test for the high-yielding boreholes, using the relation

$$E(\%) = \frac{BQ * 100\%}{(BQ + CQ^2)} \qquad (3)$$

Fig. 2. shows sample plot of S_w/Q against Q values from which the parameters B and C were computed for estimating the efficiencies of one of the wells whilst the results of the step-test showing the computed efficiency values from nine relatively high-yielding boreholes are presented in Table 1.

Constant discharge results

The Cooper-Jacob semi-log straight line method was used to estimate the transmissivity coefficients (T) and specific capacities (Sp. Cap) of the boreholes. These parameters were computed from the results of the drawdown-time graph plotted for each well (Fig. 3). Similarly, plots of residual drawdown values (S') obtained during recovery periods *versus* the time-ratios (t/t) on linear scale also yielded straight line graphs, which were also used to estimate the residual transmissivity values (T). The average values of T (Tav) obtained from pumping and recovery periods gave the representative transmissivity estimate of the individual aquifers. The basic formulae underlying these computations are given by:

$$\text{Transmissivity } (T) = 0.183Q/\Delta S \qquad (4)$$

$$\text{Specific Capacity (Sp. Cap.)} = Q/S_w \qquad (5)$$

where Q is the discharge rate in $m^3\ d^{-1}$, ΔS is the drawdown of water level of the pumped borehole within one log cycle of time, and S_w is the maximum drawdown. The computed transmissivity and specific capacity values are presented in Table 2.

Interference studies

Interference studies were carried out on each of the two boreholes at Busa and Babile communities, which were separated 73 and 85 m apart, respectively. Thus, while BH1 in each community was being pumped, water level drops in BH2 was being monitored and *vice versa*. The resulting drawdown data collected on the observation wells during these studies were plotted against time on a semi-log graph sheets (Fig. 4.). The storage coefficient (S) value for each aquifer was subsequently computed from the relation:

$$S = 2.25*T*t_o/r^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where T is the transmissivity of the aquifer in m^2d^{-1}, t_o is the intercept of the straight line at zero drawdown in days and r is the distance (m) from the pumped borehole to the observation well. The results of the computed storage coefficient values are presented in Table 3.

Discussion

The results of efficiency calculations showed that between 28 and 84 per cent of the total head loss of the production boreholes was due to a combination of laminar and turbulent flow, respectively (Driscoll, 1995), and provides evidence of poor borehole design and or insufficient development. However, Mackie (1982) and Kelly *et al.* (1980) have noted that significant well losses may as well occur in properly designed and constructed boreholes when the primary source of the hydraulic conductivity is from fractures rather than inter-granular porosity. The efficiency values were further noted to decrease with increasing discharge rate, a situation which indicates higher frictional losses at higher pumping rates. The computed aquifer characteristics (transmissivity and specific capacity) are highly variable. Whereas the transmissivity values range from 0.97 to 56.7 $m^2\ d^{-1}$, the specific capacity values are in the range of 0.5-44.5 $m^3\ d^{-1}m^{-1}$.

In accordance with Krasny's (1986) transmissivity classification, the transmissivity magnitudes in the study area may be classified as low to intermediate, with the groundwater supply potential from the aquifers being only adequate to supply water to small communities for local consumption. Relating the combined transmissivity and specific capacity values to the hydraulic heterogeneity classification developed by Krasny (1990), the underlying aquifers of the study area is considered as fairly to very heterogeneous.

The computed storage coefficient values from four observation boreholes in two communities of the study area averaged 10^{-5}, and clearly indicate that aquifers in the study area occur under confined conditions. Driscoll (1995) has indicated that the upper limit of storage coefficient in confined aquifers is 10^{-3}. The aquifer characteristics were observed to be independent of the depth at which aquifers were intercepted as well as borehole depths.

Conclusion

Over 90 per cent of the geology of Upper West Region of Ghana is made up of crystalline basement complex rocks, comprising mainly granites. Groundwater occurrence in these rocks is mainly influenced by rainfall intensity, topography and overburden thickness. Aquifers developed in these rocks are discrete, localised and discontinuous, and are controlled by the development of secondary porosity, the degree of fracture intensity and their interconnections. The computed transmissivity and specific capacity values indicated that the transmissive capacity of the underlying aquifers vary widely, and may be classified as having intermediate to low magnitudes, with medium to low groundwater withdrawal potential for local water supply. Consequently, for sustainable groundwater development in the area, intensive geophysical studies involving integrated methods should guide the selection of suitable drilling points.

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