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CHALLENGES ASSOCIATED WITH GROUNDWATER RESOURCES DEVELOPMENT IN NORTHERN GHANA

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Abstract

It is estimated that groundwater contributes about 62 per cent of the total water requirement of Ghana. It contributes an average of 67 per cent to Northern Ghana's domestic water needs. The groundwater resources of Northern Ghana are obtained from a variety of hard rock units, comprising basement complex (crystalline) systems and varying Neoproterozoic sedimentary rock types and, therefore, have varying hydrogeological characteristics. Some of the hard crystalline and Neoproterozoic rocks are overlain by thick argillaceous overburden of high porosity and low permeability characteristics. Groundwater development in these hard rocks is structurally-controlled and successful boreholes are characterised by variable yields, which range from less than 0.2 $m^3 h^{-1}$ to 500 $m^3 h^{-1}$ at depths ranging from 40 - 160 m. The hard rock aquifers of Northern Ghana are generally discrete, giving rise to localised flows, thus, making regional aquifer evaluations rather challenging. Even though groundwater constitutes the main water supply sources, its development is fraught with challenges that range from exploration through drilling to water quality issues. These challenges have been noted to be highly related to the nature and characteristics of the underlying geological formations. This paper discuses some of the challenges that have been experienced during long period of hydrogeological field practices in the northern part of the country.

Introduction

As it pertains to many countries worldwide, groundwater is an invaluable resource that supports several socio-cultural and economic activities such as domestic, agriculture and industry. Even though Ghana abounds in many surface water resources, the emerging effects of population pressure through anthropogenic activities, continuously-growing industrialisation, improper land-use, and waste disposal and management practices, as well as illegal mining activities have led to high reliance on groundwater resources as the only alternative and reliable source of water supply.

It is reported that groundwater contributes about 0.6 per cent of the total water resources worldwide (Meenkshi & Mehshwari, 2006), and provides the world with 25 per cent to 40 per cent of its drinking water needs. Many rural communities depend on groundwater due to unreliable surface water sources, and inadequate treatment system capacities to meet pipe-borne water supply requirements. Undoubtedly, groundwater provides a relatively clean, reliable and cost-effective resource (Bovolo, Parking & Sophocleus, 2009) with good natural quality for potable supplies with minimal treatment (Yidana, 2010). However, several factors, including anthropogenic and natural factors degrade most prolific aquifers and render them unsuitable for human consumption (Epule et al, 2011). Whilst the quantity of freshwater keeps dwindling, its quality is also threatened from liquid waste disposal and fertiliser applications (von der Heyden and New, 2004). It is estimated that nearly 44 per cent of the population in sub-Saharan Africa faces problems with reliable access and good quality water supply (Dungumaro, 2007).

The occurrence and characteristics of groundwater in Ghana is largely controlled by geology and its structural characteristics (Dapaah-Siakwan & Gyau-Boakye, 2000). The geology of northern Ghana consists of a complex mix of different hard rock types comprising a variety of crystalline igneous/ metamorphic and consolidated Neoproterozoic sedimentary rocks. This wide range of different hard rock types in northern Ghana gives rise to variations in groundwater resources potential with regards to their occurrence and distribution, yield, recharge and other hydro-geological characteristics (Agyekum, Dapaah-Siakwan, 2008). Consequently, groundwater in most parts of northern Ghana occurs under confined or semi-confined conditions, and they are controlled mainly by the development of secondary porosity such as weathering, jointing and fracturing. Aquifer systems developed in these hard rocks are generally discontinuous, discrete and localised in nature (Darko & Krasny, 2003). The varying geological formations of northern Ghana have their peculiar groundwater development challenges, and the paper discusses some of these.

Geological framework of northern Ghana

The total land size of Northern Ghana is about 97,700 km^2, and 60 per cent of it is underlain by Neoproterozoic sedimentary rocks, which are locally referred to as 'Voltaian' rock formation. The remaining 40 per cent comprises Precambrian crystalline basement complex rocks belonging to the Granitic and Birimian rock types, with some isolated patches of Tarkwaian, Togo and

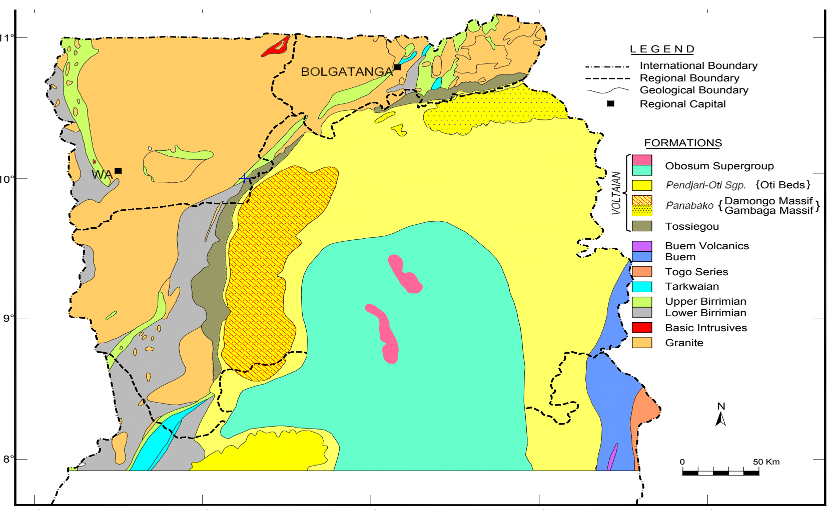

Fig. 1. Geological Map of the study area (simplified after Affaton *et al*., 1980)

Buem rock formations (Fig.1).

The Voltaian rocks are made up of well-consolidated and gently-folded rocks, consisting predominantly of sandstone, shale, mudstone, sandy and pebbly-beds and limestone. Based on lithological differences, Carney *et al.* (2008) and Affaton, Sougy & Trompette, (2008) subdivided the Voltaian formation into three main lithostratigraphic units comprising Bombouaka, Pendjeri Oti and Obosum Supergroups.

Previously referred to as the Upper Voltaian formation, the Panabako sub-unit of the Bombouaka group formation forms the uppermost unit of the larger Bombouaka lithostratigraphic unit from the Lower Voltaian. Consisting predominantly of quartzitic sandstone and siltstone, this sub-unit forms the higher terrain bordering the southern, western and northern fringes of the Voltaian basin.

Located within the Damongo and Gambaga areas of northern Ghana, the Panabako formation is generally inherently impermeable, but is characterised by well developed and extensive open joints, permeable open planes and faults. Based upon lithological composition and mineralogical content of these rocks, Affaton (2008) and Carney *et al.* (2008) sub-divided the Panabako formation into Damongo and Gambaga massifs. The Damongo massif comprises fine to coarse-grained feldspathic, massive and thin-bedded quartzitic and well consolidated sandstone, with relatively thin quartz-arenite and thickly overlain by flaggy, micaceous beds and siliceous sediments. The Gambaga massif on the other hand comprises mainly mudstones and siltstones.

Previously referred to as Middle Voltaian Obosum and Lower Voltaian Oti beds, Carney *et al*. (2008) re-named this rock as Pendjari-Oti and Obosum supergroup. Located within the mid portion and underlying large portions of the Northern Region of Ghana, the Obosum and Pendjari-Oti groups generally comprise well consolidated and closely compacted and impermeable rocks, which include grey, laminated, siliceous and tillite-dolomite limestone rocks, variegated mudstone, clays and siltstone inter bedded with micaceous sandstone and conglomerates. These rocks are characterised by cross-bedding, with the presence of nodular structures and intense weathering (Bates, 1995).

Granitic rocks underlie almost 93 per cent of the Upper West and Upper East regions of northern Ghana, and they are typically foliated, undifferentiated granites that are gneissic, migmatic and potassium-rich (Kesse, 1985). The main rock types are biotite and muscovite-rich granites, granodiorites, pegmatite and biotite-schist. Birimian rocks, which are often intruded into the granitic rocks, are found mainly in the eastern and western portions of northern Ghana. Due to structural differences and lithological composition, Bates (1995), subdivided the Birimian rocks into the Lower and Upper Birimian series. The Lower Birimian rocks consist of strongly foliated and jointed rocks, comprising predominantly great thicknesses of alternating, arenaceous and argillaceous meta-sediments of shale, phyllite, siltstone, schist and greywacke. The Upper Birimian on the other hand, comprises conglomerates, pyroclastic and hypa-bassal basic intrusive rocks with gneiss, phyllite, schist, migmatite, granitic-gneiss and quartzite as the major rock types.

Groundwater occurrence and potential

Hydrogeologically, the Voltaian terrain is the most complex, the least explored and the least understood of all the geological formations in Ghana. The Bombouaka, and Pandjeri Oti sedimentary sub-units consist of shallow superficial sandy deposits, which overlie siltstone and sandstone rocks; whilst the Obosum supergroup is characterised by thick overburden of clay and shale, overlying inter-bedded mudstone, sandstone, arkose and conglomerate rocks. Kesse (1985) reported that, the overburden thickness of the Obosum shale and mudstone formation can reach as high as 50 m. However, groundwater occurrence in the overburden is very low due to the high argillaceous content of the supergroup. The regolith layer in the Bombouaka and Pandjeri Oti beds is thin (less than 20 m) and unsaturated and, therefore, provides only limited amounts of groundwater.

The underlying bedrock of the Voltaian formation has lost much of its primary porosity as a result of consolidation and cementation. Groundwater in the bedrock occurs mainly in fracture zones and also along bedding planes. According to Acheampong (1996), the fracture zones are mainly subvertical and are generally developed in bedrocks at depths greater than 30 m below ground surface. The bedrock is characterised by high permeability and low primary porosity. The thickness of the fracture zone largely depends on depth, weathering intensity, lithology and structural history.

The yield potential of the Voltaian formation is highly variable, and they are closely related to the local climatic conditions ,hence, borehole yields in the sedimentary formation have been known to decrease in the order of sandstones, limestone, siltstone, mudstone and shale. Until the beginning of the Canadian International Development Agency (CIDA) funded Hydrogeological Assessment Project (HAP) in 2005, borehole depths were limited to 60 m in the Voltaian formation. Drilling success rate was about 34 per cent, and yields were lower than 3 $m^3 h^{-1}$. However, recent studies conducted under the HAP indicated higher yielding potential and also higher drilling success rate at depths greater than 100 m. Available hydrogeological information indicate that, majority of productive boreholes that were drilled into the Voltaian basin and which produced high yields tapped water from the fractured aquifer system at depths ranging between 80 and 150 m below ground level (Agyekum *et al*., 2006). Table 1 shows data on boreholes drilled between 2005 and 2011, into some rock formations, especially into the Voltaian formation that yielded higher at deeper depths under HAP groundwater monitoring project of the three Northern regions.

Groundwater experts such as Dapaah-Siakwan & Gyau-Boakye (2000), Agyekum (2002) and Darko & Krasny (2003) have commented on the low and the variable borehole yielding capacity of the various rock formations of Ghana, especially the sedimentary Neoproterozoic rock formations as shown by the borehole yield map of Ghana (Fig. 2).

The crystalline basement rocks underlying the study area are largely impervious, but contain openings that are developed through secondary and tertiary porosity such as weathering, fracturing, jointing and faulting. Where these openings are exten-

Table 1

Hydrogeological characteristics of some HAP deep monitoring boreholes

Location	*District*	*GPS location*	*Geological formation*	*Depth (m)*	*Yield (lpm)*	*Transmissivity (m^2 d^{-1})*	*Specific capacity (m^3 d^{-1} m^{-1})*
Murugu HAP1	West Gonja	9.348°N 0.7021°W	Panabako Sandstone	110	320	20.1	22.6
Kanshegu HAP4	Savelugu-Nanton	9.5742°N 0.8369°W	Obosum shale	130	180	19.8	20.4
Yagbum WVB10	West Gonja	10.014°N 1.317°W	Panabako Sandstone	100	450	35.1	20.1
Zabaraya HAP7	Nanumba	8.9505°N 0.06976°W	Oti Siltstone	115	260	19.5	20.6
Tuuni HAP14	East Mamprusi	10.2980°N 0.3653°W	Oti Siltstone	120	25	0.24	0.87
Tamaligu HAP17	Karaga	9.8499°N 0.7275°W	Oti Siltstone	153	300	9.35	30.57
Sakpeigu HAP18	Yendi Municipality	9.5465°N 0.0246°W	Oti Siltstone	100	360	48.3	39.3
Palari HAP20	Yendi Municipality	9.1851°N 0.3031°W	Obosum Mudstone	153	400	6.85	20.7
Kabilpe HAP25	Central Gonja	8.8876°N 1.4240°W	Siltstone	153	600	3294	426.6
Tinguri WVB12	West-Mamprusi	9.948°N 0.1787°W	Pandjari Oti Siltstone	51	120	0.32	0.43
Wa-Danko (WVB1)	Wa Municipality	10.030°N 2.4630°W	Granite	104	20	0.38	0.66
Tumu (WVB3)	Sissala-West	10.872°N 1.980°W	Granite	104	500	2.7	9.1
Bonia (WVB4)	Navrongo	10.872°N 1.1390°W	Granite	72	170	23.1	10.52
Gowrie- (WVB5)	Bongo	10.859°N 0.8530°W	Granite	90	200	30.85	20.7
Bawku (WVB8)	Bawku Municipality	11.059°N 0.2580°W	Granite	100	300	0.86	4.20

WVB – White Volta basin, HAP - Hydrogeological Assessment Project

sive, they produce appreciable quantities of groundwater to boreholes

In their study of the regional transmissivity characteristics of the various rock types in Ghana (Table 2), Darko & Krasny (2003) concluded that the Neoproterozoic sedimentary rocks underlying Northern Ghana has intermediate to low transmissivity with large variations in heterogeneous environment.

Groundwater development challenges

The topography of a greater part of north-

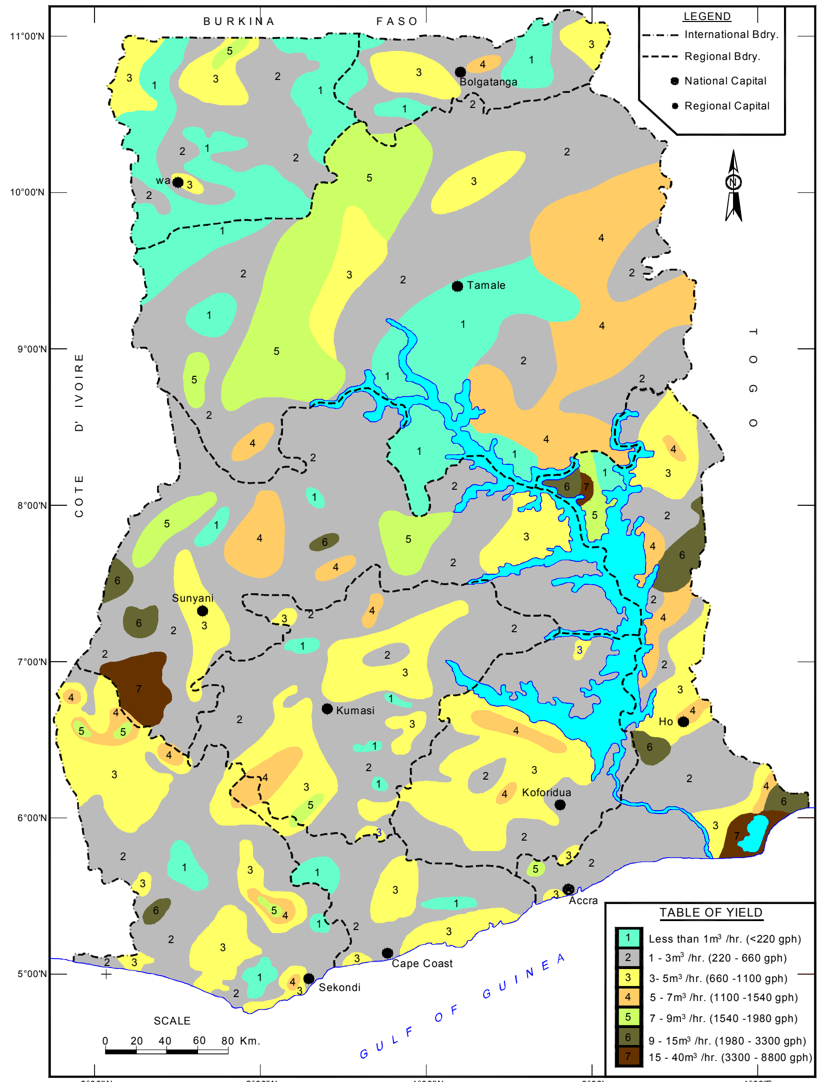

Fig. 2. Bolehole yields map of Ghana (WRI, Accra)

ern Ghana is flat with elevations not higher than140 m above mean sea level, and hydrostratigraphic cross sections through the Neoproterozoic formation show that the overburden, which is made up of shale and mudstone remnants, is about 50 m thick (HAP, 2011). It has been argued that shale, clay and mudstone overburden has very high porosity and low permeability with poor hydraulic conductivity characteristics. For this reason, the central part of northern Ghana, which is mainly underlain by the Obosum shale and mudstone rocks, is prone to regular flooding during the rainy season. Despite

TABLE 2

Regional hydraulic characteristics of the various rock types in Ghana

Hydrogeologic Unit	*Drilling success (%)*	*Drilling yield ($m^3 h^{-1}$)*	*Transmissivity ($m^2 d^{-1}$)*	*Regional hydraulic Characteristics*
Granites	45-77	0.9-48	0.3-114	Low to intermediate transmissivity of moderate variation in fairly heterogeneous environment
Voltaian	29-43	0.4-9	0.3-267	Intermediate to low transmissivity with large variation in a heterogeneous environment
Dahomeyan	24-54	0.6-9	0.3-42	Moderate variation to fairly heterogeneous medium with low transmissivity
Birimian and Tarkwaian	67-92	3.6-90	0.2-119	Low to intermediate transmissivity with moderate variations in a fairly heterogeneous hydrogeological environment
Togo and Buem	40-86	1.2-12	0.9-43	Low to intermediate transmissivity with small to moderate variation in fairly heterogeneous environment
Tertiary to Recent	79-93	7-20	7-1,624	Medium to high transmissivity with moderate variation in a fairly homogeneous environment.

After Darko and Krasny (2003)

the poor hydraulic nature of the overburden soils, the flood waters disappear within some few days due to the high evapo-transpiration rate of 1800 mm yr^{-1}, which exceeds the annual rainfall by 560 mm yr^{-1} (WARM, 1998).

As mentioned earlier, groundwater may occur in the deep fractured portions in the hard rocks, and geophysical resistivity technique is the commonest investigation method used in Ghana to effectively detect these fractures. However, MacDonald *et al*. (2008) reported that, due to the high conductive nature of clay-rich rock such as mudstone, there is lack of resistivity contrast between the host rock and water-bearing formations, and this makes the application of resistivity exploratory method to site boreholes in areas underlain by Obosum shale and mudstone formation rather challenging, and this often leads to wrong decision in selecting promising drilling points. To solve this problem in such geological formations, two-dimesional resistivity survey technique, which is able to investigate much deeper (>200 m deep), and can perform both profiling and depth probing concurrently, helps to produce resistivity pseudo-section of the sub-surface geology, can help to increase the chances of obtaining successful boreholes.

The thickness of the overburden (clay and shale) in the Obosun shale and mudstone rock formation could be more than 50 m, and this implies that drilling through such soft formations could require long drilling casings to protect drilled holes from caving-in, especially if the rock formation is unstable. In addition, the cost of drilling in this geological formation is relatively high due to the depth of drilling, and its attendant cost of construction, and the long time it takes to wash the borehole clean of all fine particles to acceptable levels.

Groundwater salinity is another major problem associated with groundwater development in Northern Ghana. Geophysical borehole logging conducted by Agyekum (2009) on selected HAP deep groundwater monitoring boreholes (>100 m) in the various geological formations in Northern Ghana indicated relatively higher groundwater conductivity with increasing depth for boreholes drilled into Obosum shale/mudstone and Oti siltstone rocks. Fig. 3 shows the profile of groundwater conductivity with depth in the various rock types of Northern Ghana. The study indicated a sharp increase in groundwater conductivity beyond 1500 μS cm^{-1} in Obosum shale and mudstone rock units at depth beyond 60 m, whilst groundwater conductivity increases sharply beyond 1500 μS cm^{-1} beyond 100 m depth in the Oti siltstone rock. Chapman (2008) showed that there is a strong correlation between total dissolved solids (TDS), salinity and conductivity, and this, therefore, translates to high groundwater salinity of boreholes drilled into Obosum and Oti siltstone rocks at increasing depth.

Agyekum (2009) concluded that, the high groundwater conductivity with increasing depth in the Neoproterozoic rock formations could be because the rocks are old remnants from marine environment with high level of evaporite that have been developed in hot continental climate containing high amount of potassium, and which have not been flushed out for a long time.

Incidence of high fluoride, iron, chloride and manganese concentrations in groundwater has been recorded in several boreholes in all geological formations throughout northern Ghana. Fluoride concentrations higher than 5 mg l^{-1} in boreholes have been reported in the north-eastern and central part of northern Ghana (HAP, 2011). As a result, problem of tooth decay in adults is prevalent, and

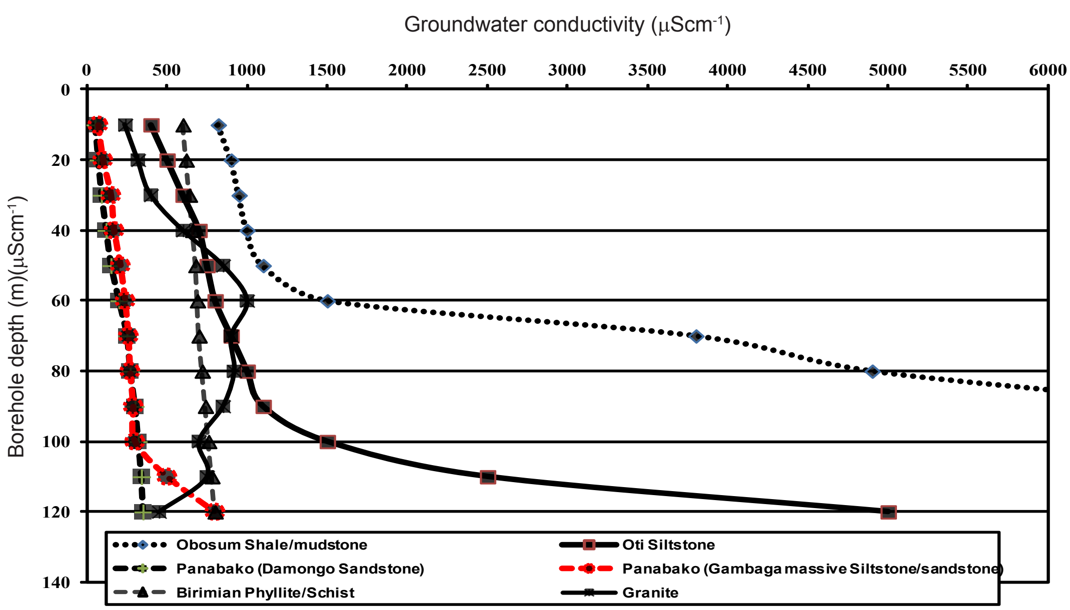

Fig. 3. Groundwater conductivity with depth of the various rock types in Northern Ghana (Agyekum, 2009).

it has been linked to excessive consumption of fluoridated groundwater. Again, negative effects of fluoride on humans, soils and ruminants have variously been reported by several researchers including Pelig-Ba *et al.* (1991), Smedley *et al.* (1995), Apambire *et al.* (1997), Pelig-Ba (1998), Smedley *et al*. (2002) and Abugri & Pelig-Ba (2011). Table 3 shows some of the potential groundwater geo-chemical problems identified with some geological formations of northern Ghana

In the assessment of groundwater resource potentials of the Northern Region of Ghana, Ofori Agyemang & Duah (2016) (unpublished), analysed 1,099 geo-chemical data on water samples, and concluded that about 42 per cent of all boreholes drilled into the Obosum shale formation in the Gushiegu-Karaga District of Northern Region contain fluoride concentration higher than 1.5 mg l^{-1} (Table 4). Fig. 4 shows fluoride concentration in boreholes in the Tolon-Kumbungu District of the Northern Region. Eleven out of 82 borehole water samples, representing about 13 per cent, and which were drilled into shale and mudstone rock formation in the Tolon-Kumbungu District, have fluoride concentration higher than the WHO recommended guideline value of 1.5 mg l^{-1}.

Table 4 further indicates boreholes that are likely to have fluoride problems (> 1.5 mg l^{-1}) in the various geological formations in each District of the Northern Region of Ghana. In an attempt to characterise the ground waters of northern Ghana, the HAP study identified that the central part of the Northern Region, which is underlain mainly by shale and mudstone rocks, is made up mainly of Na-Cl waters. The Upper East and Upper West regions, which are underlain by crystalline basement complex rocks of granite and some Birimian units, however, are made up of Ca-Na-HCO_3-Cl and Na-Ca-SO_4-Cl-HCO_3 waters.

Conclusion

Northern Ghana has a huge potential of groundwater resources, which could play an important role in the socio-economic development of the region. However, groundwater occurrence and its spatial distribution is highly controlled by the local geological

Table 3

A summary of some groundwater quality problems of Northern Ghana

Water quality problem	*WHO guideline value (mg l^{-1})*	*Excess concentrations*	*Potential problem areas*	
			Geology	*Specific district*
Total Iron (Fe)	0.3	> 2mg l^{-1}	Obosum shale and Oti siltstone	Bimbila, Yendi, West Gonja
Manganese (Mn)	0.5	> 2 mg l^{-1}	Shale and Oti siltstone	Gushiegu Karaga, Yendi, East Gonja and Nanumba
Fluoride (F)	1.5	> 4 mg l^{-1}	Obosum mudstone and shale, Oti siltstone, granite	Gushiegu Karaga, Yendi, East Gonja, Nanumba and Bongo
Chloride, (Cl) (mg l^{-1})	250	> 1,000 mg l^{-1}	Obosum shale, siltstone and mudstone	Tolon Kumbungu, Bimbila, Saboba Chereponi
Conductivity (µS cm^{-1})	-	>5,000 µS cm^{-1}	Obosun shale,	Gushiegu Karaga, Central Gonja, Yendi, Zabzugu-Tatale etc

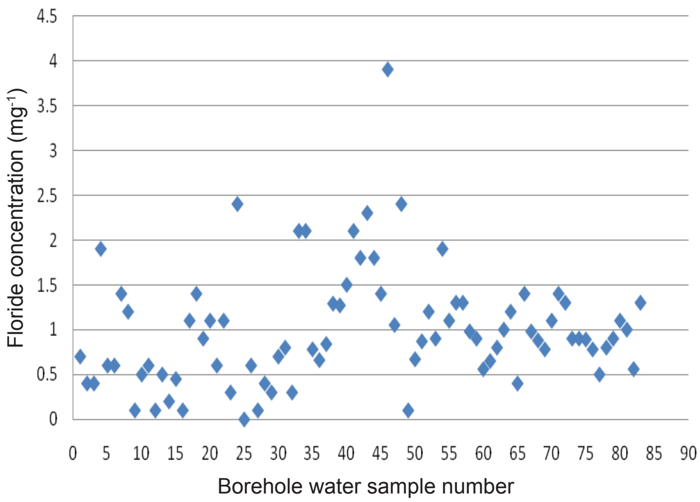

Fig. 4. Fluoride concentration in boreholes in the Tolon-Kumbungu District

limited to rural water supply and low irrigation and cottage industry purposes. Studies of groundwater level fluctuations through observation of boreholes in northern Ghana for six continuous years, from 2005-2011, indicated rising trends in groundwater levels, and this is probably due to the low groundwater abstraction and under-utilisation rates. Groundwater development challenges related to exploration, drilling and water quality issues of chloride, conductivity, salinity, magnesium and fluoride are prevalent in many geological terrains underlying northern Ghana, especially within the central and eastern parts, which is underlain by Obosum shale/mudstone and Oti siltstone rocks. It has been observed that the attempt

TABLE 4

Fluoride concentrations in boreholes in various districts of Northern Region

District	*Geology*	*No. of boreholes*	*Fluoride (Fl) conc (mg l^{-1})* < 1.5 mg l^{-1}	> 1.5 mg l^{-1}	*% of boreholes with Fl > 1.5 mg l^{-1}*
Bole	Granite	119	110	19	16
Savelugu Nantom	Shale/mudstone	87	78	9	10
Tolon Kumbungu	Shale/mudstone	82	71	11	13
West Gonja	Siltstone	161	150	11	7
East Gonja	Shale/mudstone	141	126	15	11
Central Gonja	Shale/mudstone	28	28	0	0
West Mamprusi	Oti siltstone	108	105	3	3
East Mamprusi	Oti siltstone	23	19	4	17
Gushiegu Karaga	Shale/mudstone	12	7	5	42
Saboba Chereponi	Oti siltstone	17	17	0	0
Zabzugu-Tatali	Oti siltstone	16	11	5	31
Nanumba	Siltstone, mudstone	18	12	6	30
Yendi	Oti siltstone	17	15	2	12
Sawla-Tuna-Kalba	Granite	282	267	15	5
	Total	1,099			

conditions. In spite of the high dependence on groundwater resources and the numerous borehole water supply systems in almost every village and small town in northern Ghana, the groundwater abstraction rate still remains insignificant, as it is mainly to use conventional methods to resolve them has become unsuccessful. However, limited use of isotopic techniques can better be used as an antidote to solving some of the water quality problems.

References

Abugri, D. A. & Pelig-Ba, K. B. (2011) Assessment of fluoride content in tropical surface soils used for crop cultivation. *Journal of Environmental Science and Technology* **5** (a), 653 – 660.

Acheampong, S.Y. & Hess, J. W. (1998) Hydrogeologic and hydrochemical framework of the shallow groundwater system in the southern Voltaian sedimentary basin of Ghana. *Hydrogeology Journal* **6**(4), 527 – 537.

Affaton, P. (2008) Lithostratigraphy of the Volta basin and related structural units. *Abstract volume of the Voltaian basin, Ghana Workshop and Excursion, March 10-17, Accra-Ghana.*

Affaton, P., Sougy, J. & Trompette, R. (1980) The Tectono-stratigraphic relationships between the Upper Precambrian and Lower Paleozoic Volta Basin and the Pan-African Dahomeyide orogenic belt, West Africa. *American Journal of Science* **280**, 224 – 248.

Agyekum, W. A. (2002) Groundwater resources in Ghana with focus on internationally-shared aquifer systems. *ISARM-Africa Workshop on managing shared aquifer resources in Africa, Tripoli-Libya.*

Agyekum, W. A. (2009) Application of geophysical borehole logging for hydrogeological studies of Northern Ghana (PhD thesis). Earth Science Department, University of Ghana, Legon, Accra.

Agyekum, W. A & Dapaah-Siakwan, S. (2008) The occurrence of groundwater in north-eastern Ghana. In *Applied groundwater studies in Africa* (S.M.A. Adelana and A.M. Donald, eds). pp. 199 – 214. IAH Selected papers on Hydrogeology, Volume 13, CRC Press, Balkema, Leiden, The Netherlands.

Agyekum, W. A., Dapaah-Siakwan, S. & Darko, P. K. (2006) *Borehole drilling and installation of divers for groundwater monitoring in the White Volta river basin*. WRI Technical Report to Water Resources Commission, Accra. 72 pp.

Agyekum, W. A. & Kankam-Yeboah, K. (2011) Characteristics of a crystalline granitic aquifer in north-western Ghana. *Ghana Journal of Science* **51**, 3 – 10.

Apambire, W. B., Boyle, D. R. & Michael, F. A. (1997) Geochemistry, genesis and health implications of fluoriferous groundwaters in the upper regions of Ghana. *Environmental Geology* **33**(1), 13 – 19.

Bates, D. A. (1995) *Geological map of Ghana.* Ghana Geological Survey. Reprinted by the Survey Department, Accra, Ghana.

Bovolo, C. I., Parking, G. & Sophocleus, M. (2009) Groundwater resources, climate and vulnerability. *Environmental Research Letters* **4** (3), 035001

Carney, J., Jordan, C., Thomas, C. & McDonnel, P. (2008) A revised lithostratigraphy and geological map for the Voltaian basin, derived from image interpretation and field mapping. *Abstract Volume of The Voltaian basin, Ghana Workshop and Excursion, March 10-17, 2008.*

Chapman, D. (2008) *Water quality assessments - A guide to the use of biota, sediments and water in environmental monitoring.* Chapman and Hall Ltd, 2-6 Boundary Row, London.

CWSA (2010) Community water and sanitation agency (CWSA). *2010 Annual Report*.

Dapaah-Siakwan, S. & Gyau-Boakye, P. (2000) Hydrogeologic framework and borehole yields in Ghana. *Hydrogeology Journal* **8**, 405 – 416.

Darko, P. K. & Krasny, J. (2003) Regional transmissivity distribution and groundwater potential in hard rocks of Ghana. *Proceedings of IAH International Conference on ground-*

water in fractured rocks,(J. Krasny, Z. Hrkal and J. Bruthans, eds). pp. 15 – 19. IHP–VI Series on groundwater, No 7. Praque, Czech Republic.

DeGabriele , J. (2002) *Improving community based management of boreholes: A case study from Malawi.* University of Wisconsin-Madison, USA.

Dungumaro, E. W. (2007) Socio-economic differentials and availability of domestic water in South Africa. *Journal of Physics and chemistry of the Earth* **32**, 1141–1147.

Epule, T. E., Peng, C., Wase, M. M. & Mafany, N. M. (2001) *Well water quality and public health implications: The case of four neighborhoods of the city of Douala, Cameroun* (unpublished).

Gyau-Boakye, P., Kankam-Yeboah, K., Darko, P. K., Dapaah-Siakwan, S. & Duah, A. A. (2008) Groundwater as a vital resource for rural development: An example from Ghana. In *Applied Groundwater Studies in Africa (*S. M. A. Adelana and A. M. MacDonald, eds). pp. 215 – 222. *IAH Selected papers on Hydrogeology, Volume 13, CRC Press/Balkema, Leiden, The Netherlands*.

HAP (2011) *Water Resources Atlas of the Northern regions of Ghana – Hydrogeological Assessment Project (HAP) Report, 2011*. Published for Water Resources Commission of Ghana, Accra

Kankam-Yeboah, K., Gyau-Boakye, P., Makoto, N. & Komatsu, M. (2004) Water Resources and Environmental Management in Ghana. *Journal of the Faculty of Environmental Science and Technology, Okayama University,* **9** (1), 87 – 98.

Kesse, G. O. (1985) *Rock and Mineral Resources in Ghana.* A.A. Balkema, P. O. Box 230, Accord, MA 02018, Rotterdam, the Netherlands.

MacDonald, A. M. (2008) Applied groundwater studies in Africa. *IAH Selected papers on Hydrogeology, Volume 13, CRC Press/Balkema, Leiden*, *The Netherlands*. pp.149 – 169.

Macdonald, A. Jeff D., Roger, C. & Chilton, J. (2008) *Developing groundwater – A guide to rural water supply*. Replika Press Pvt. Ltd, UK.

Meenakshi, S. & Mehesshwari, R. C. (2006) Fluoride in drinking water and its removal. *Journal of Harzardous materials*,**137** (1) 456 – 463.

Milovanovic, M. (2007) Water quality assessment and determination of pollution sources along the AAxios/Vardar River, southern Europe. *Desalination* **213**, 159 – 173.

Ofori-Agyemann, C. & Duah, A. A. (2016) *Groundwater assessment of the northern region of Ghana* (CSIR-WRI Technical Report, unpublished), Accra-Ghana

Olajire, A. A. & Imeeokparia, F. E. (2001) Water quality assessment of Osum river: Studies on inorganic nutrients. *Environmental Monitoring Assessment* **69** (1), 17 – 28.

Pelig-Ba, K. B. (2011) Levels of agricultural pesticides in sediments and irrigation water from Tono and Vea in the Upper-East Region of Ghana. *Journal of Environmental Protection* **2**, (6), 76 – 85.

Pelig-Ba, K. B., Biney, C. A. & Antwi, L. A. (1991) Trace metal concentration in borehole waters from the upper regions and the Accra Plains of Ghana. *Water, Air and Soil Pollution* **59**, 333 – 345.

Pelig-Ba, K. B. (1998) Trace elements in groundwater from some crystalline rocks in the upper regions of Ghana. *Water, Air and Soil Pollution* **103**, 71 – 89.

Pritchard, M., Mkandawire, T. & O'niell, J. G. (2008) Assessment of groundwater quality in shallow wells within the southern districts of Malawi. *Physical and Chemistry of the Earth* **33**, 812 – 823.

Singhal, B. B. S. & Gupta, R. P. (1999) *Applied hydrogeology of fractured rocks*. Kluwer Academic Publishers, Dordrecht/Boston/London.

Smedley, P. L., Nicolli, H. B., MacDonald, D. M. J., Barros, A. J. & Tullio, J. O. (2002) Hydro-geochemistry of arsenic and other inorganic constituents in groundwaters from La Pampa, Argentina. *Applied Geo-chemistry* **17**(3), 259 – 284.

Smedley, P.L., Edmunds, W. M., West, J. M., Garder, S. J. & Pelig-Ba, K. B. (1995) *Health problems related to groundwaters in the Obuasi and Bolgatanga areas, Ghana. British Geological Survey*. Technical Report, WC/95/43. 122 pp.

WARM (1998) *Ghana's water resources management challenges and opportunities*. Prepared for the Ministry of Water Resources, Works and Housing, Water Resources Management Study, Accra, Ghana.

Yidana, S. M. (2010) Groundwater classification using multivariate statistical methods, southern Ghana. *Journal of African Earth Sciences* **57**(5), 455 – 469.

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