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Hydrogeological Study of Groundwater for Dry Season Farming in Northern Region of Ghana

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Abstract: The nature of geological and hydrological conditions in Northern Region is complex resulting in low drilling success rate and high variability of borehole yields. The voltaian formation in the Northern Region is known to have high-low potential of groundwater resources as the flows mainly occur in fracture zones with some areas characterised by low porosity and along bedding planes for some areas. This kind of formation occurs in the Northern belt of the region and a smaller portion in the South. The groundwater resource potential within Northern Region was studied using typical hydrogeological factors such as transmissivity, overburden thickness, borehole success rate and groundwater potentiometric level. The research targeted areas of high groundwater success rate so as to minimise the gap in the computation that would be affected as a result of dry boreholes. The study considered 38 boreholes out of functional boreholes numbering 890 within Northern Region. The permanent groundwater reserve and the recoverable groundwater reserve were estimated to be approximately 533,108,995.2×10^6 m^3 and 213,243,598.1×10^6 m^3, respectively for the aquifer basement complex of 38 boreholes.

INTRODUCTION

The spatial and temporal variability of water resources in Sub-Saharan Africa (SSA) is influencing agricultural development that can ultimately affect food insecurity and poverty in the region. Although, groundwater development has relatively low cost and does not require expensive infrastructure, groundwater is still underused in the SSA[1]. Irrigation is the backbone of high agricultural productivity in some Sub-Sahara African (SSA) countries and mostly West Africa. The scarcity of water supply for dry season farming (irrigation) is on the ascending since most of the SSA countries depend on rain fed agriculture which threatens agriculture and food security[2]. Mygatt[3] estimated that about 2 billion people in urban and rural communities worldwide depend on groundwater for daily consumption. Groundwater is often the sole water resource in arid and semi-arid regions; therefore the assessment of quantity and quality of groundwater is vital[4]. Such an assessment will provide better understanding of the dynamics of groundwater for sustainable use and help planning and management of resources.

Unreliability of rainfall and change in patterns might result from the spatial and variability in temperatures within the voltaian Basin in West Africa[5]. Most of the SSA countries have been noted to have severe drought as compared to Central Africa. Taylor and Howars[6] mentioned that adoption of groundwater-irrigation can yield sufficient agricultural production alongside protecting food security in SSA countries. Uncharacteristically, groundwater is not endangered by extreme droughts and climatic variability[7, 8].

The colossal unseen nature of groundwater has made it underdeveloped when it comes to agriculture despite its enormous advantages. SSA countries are behinds regions in the world like India and China in terms of the usage of groundwater for irrigation[9]. Estimations from Food and Agricultural Organizations (FAOs) suggest that the renewable underground water resources within the SSA countries are around 1700 km^2/y, similarly, to China and India[10]. These countries agricultural economics has been hugely transformed by the usage of groundwater[9].

In spite of this, the utilization of groundwater for agricultural purpose is minimal[11], although, isolated cases of high usage of groundwater for irrigation exist[12]. In a study conducted in Ghana, Van de Berg[13], discovered that only 5% of groundwater is been used for irrigation compared to the 29% used for domestic purposes, 28% for construction and 39% for livestock in the Atankwidi catchment in the White Volta Basin which is a little absurd.

The underdevelopment of groundwater for irrigation purpose in the SSA countries can be attributed to numerous factors. These include; disparities between climate and geology[14]; high cost of groundwater exploration and well failures and more importantly complexity and lack of understanding of the hydrological and hydrogeological environment of the area[15]. Over the years, little information has been acquired on groundwater potential within the SSA countries in order to develop the idea of groundwater been a better alternative for irrigation leading to failures on irrigated-agricultural farms.

Study area: The description of the study area is to highlight unique characteristics and to complement the hydrogeological synthesis in the area.

The research area used to occupy an area of about 70,383 km^2 or 31% of Ghana's land area until December 2018 when the Savannah and the North East regions were created from the Northern Region. It is one of the now sixteen regions of Ghana and considered to be the largest region in terms of land area. The research targeted the typical Northern Region and parts of the North East Region. It shares boundaries with Upper West and Upper East Region to the North, Brong-Ahafo Region to the South and two neighbouring countries, Togo to the East and La Cote d' Ivoire to the West. The land is mostly low lying except in the north eastern corner with Gambaga escarpment and along the Western corridor (Fig. 1).

Geology: They consist of the voltaian sedimentary basin which is bounded to the East by the Pan-African Dahomeyide Belt. The Voltaian Sedimentary Basin (VSB) consists of a large sedimentary basin that was developed in a gentle synform depression of the West African Craton. About 90% of the study area constitute the voltaian while 10% is made up of the Birimain (Fig. 2).

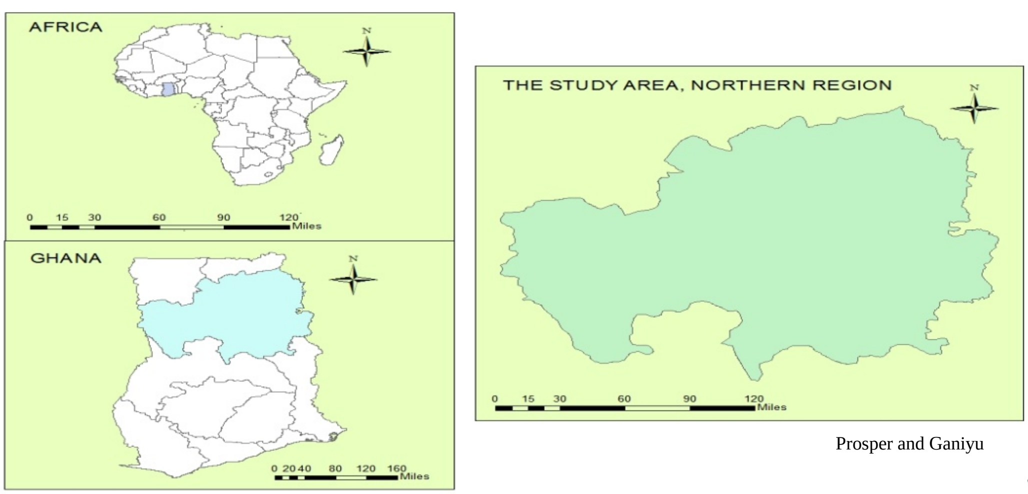

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Fig. 1: Map of the study area (Northern Region)

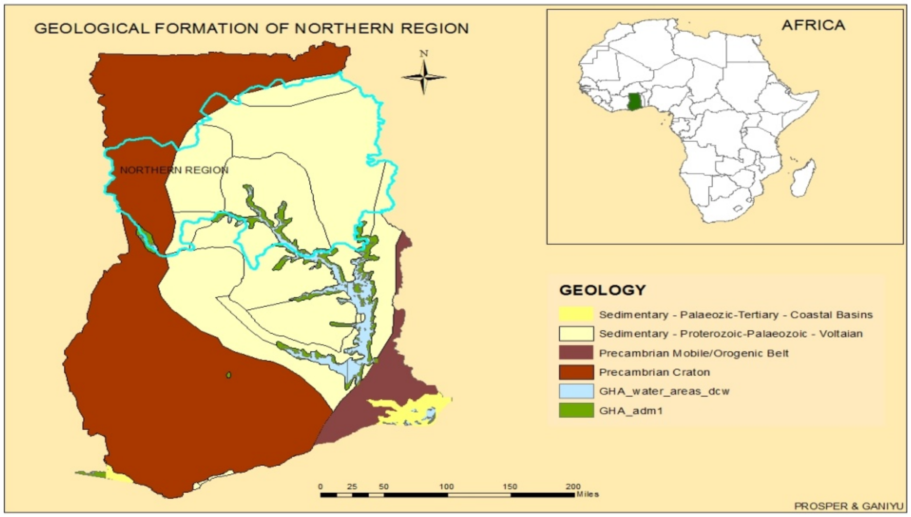

Fig. 2: Geology of Northern Region

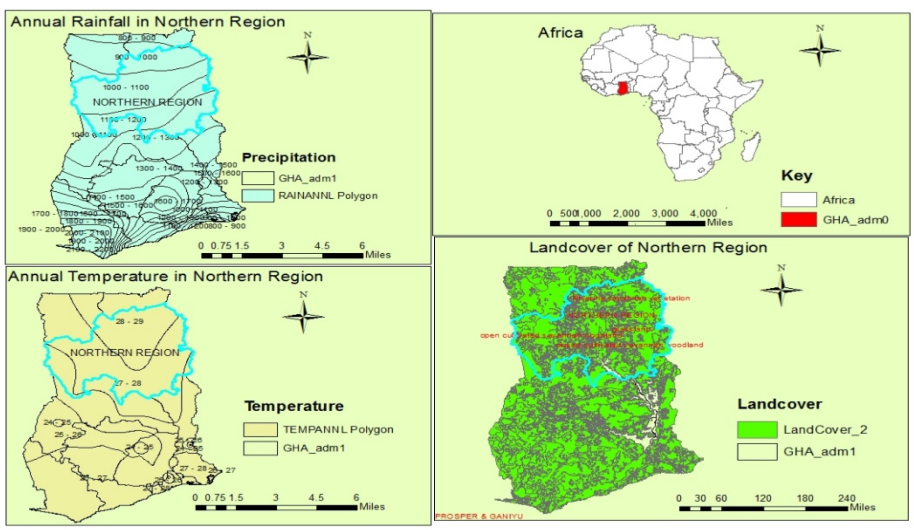

Fig. 3: Climatic and vegetation map of the study area (Northern Region)

Climate and vegetation: Rainfall in the Northern Region generally decreases with increasing latitude and its distribution throughout the year is irregular. Typically, the Northern Region is characterised by a single rainy season from late May to October. The intensity and duration of the rainy season varies with latitude and the extreme North usually experiences a shorter and more intense rainy season than the South. Annual rainfall values ranges from 900-1200 mm and are characterised by standard deviations ranging from 15-20% of rainfall. Temperatures in Northern Region are relatively high with annual averages ranging from 27-29°C and annual extremes ranging from about 17-40°C. Due to the rather low relief, the major influence on temperature is the distance to the sea. Temperatures are thus, hotter in the North than in the South (Fig. 3).

The woodland savannah is characterised by drought-resistant trees such as acacias, mango trees, shea nut trees, neems, dawadawa, mahogany and many more. Land classified as cultivated is usually used for small-scale rain-fed agriculture in the form of compound or bush farming. Compound farms are located near the farmer’s homes and crops grown usually include maize, vegetables and tobacco. In bush farms which are generally located within 10 km of the community, a mixture of cereals/vegetables crops notably maize, sorghum, millet,

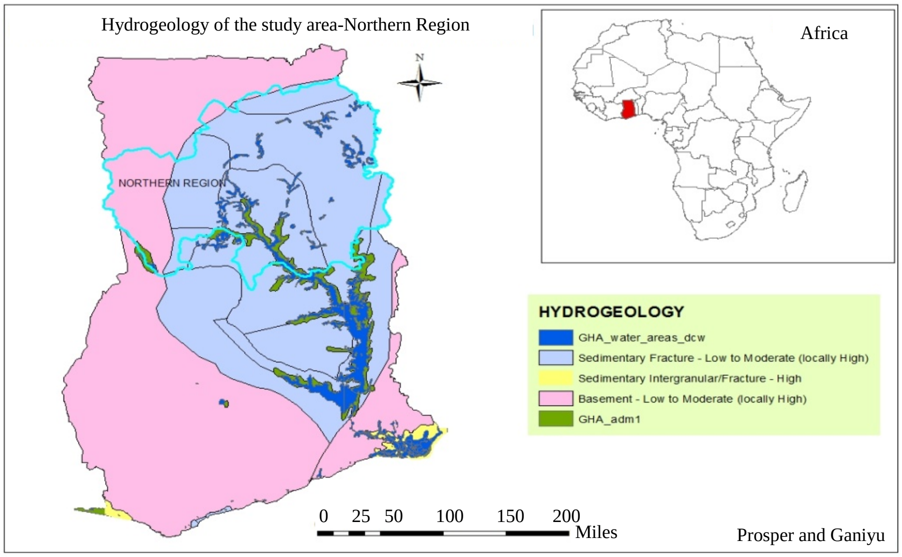

Fig. 4: Hydrogeology of Northern Region

rice, yam, cassava and groundnuts are generally cultivated. Irrigated agriculture is also practiced in Northern Region (Botanga, Golinga, etc.) though the irrigated land area only occupied about 30 km^2 as of 2000.

Hydrogeological setting: Groundwater mainly occurs and flows in fractured zones and along bedding planes for some areas, since, the primary pores of these rocks has been destroyed through cementation and consolidation. The overburden is reported to be unsaturated in many areas and would thus only provide minor amounts of groundwater locally[16]. The mean thickness of the overburden over the voltaian sedimentary rocks is approximately 8 m[17].

However, studies in the Nanumba and West Gonja districts revealed average overburden thickness of 5 m and 11.2 m, respectively[18].

The relatively thin overburden in the VSB can be partly explained by the stable clay (in shale) or quartz (in sandstone) composition or by the fine texture or ductile nature of sedimentary rocks found in the voltaian (e.g., soft unmetamorphosed mudstone).

Deeper weathering may, however, occur in some areas such as those underlain by the arkosic sandstone (e.g., in Pendjari-Oti Group) as K-feldspar weathers more easily than quartz and clay minerals. Underlying fracture zones are commonly developed in the base-rock at depths >22 m below ground surface[19] but on average, required yields for rural supplies are obtained at depths shallower than 100 m (Fig. 4).

MATERIALS AND METHODS

Four major groundwater factors were considered in the study of groundwater as a better alternative water supply for agricultural activities. These factors include; groundwater geophysics, borehole loggings, pumping rate of boreholes and potentiometric level of boreholes. The methodology used for this paper includes; Vertical Electrical Sounding (VES) and Schlumberger profiling array for the groundwater geophysics, rotary drilled boreholes and Constant Rate Test (CRT-6 h) for pumping rate. Figure 5 is a diagrammatic representation of the methods employed.

Groundwater geophysics:

$$\rho = R \times a/l \quad (1)$$

Where:

ρ = Resistivity
R = Resistance
a = Cross-area
l = Lenght of profile

But the Schlumberger configuration is given as:

$$\rho = \left\{ \frac{\frac{(AB)^2}{2} - \frac{(MN)^2}{2}}{MN} \right\} \Delta \frac{V}{I} \quad (2)$$

Where:

MN = Distance between potential electrodes (m)
AB = Distance between current electrodes (m)
Δ = Potential difference (v)
I = Applied current

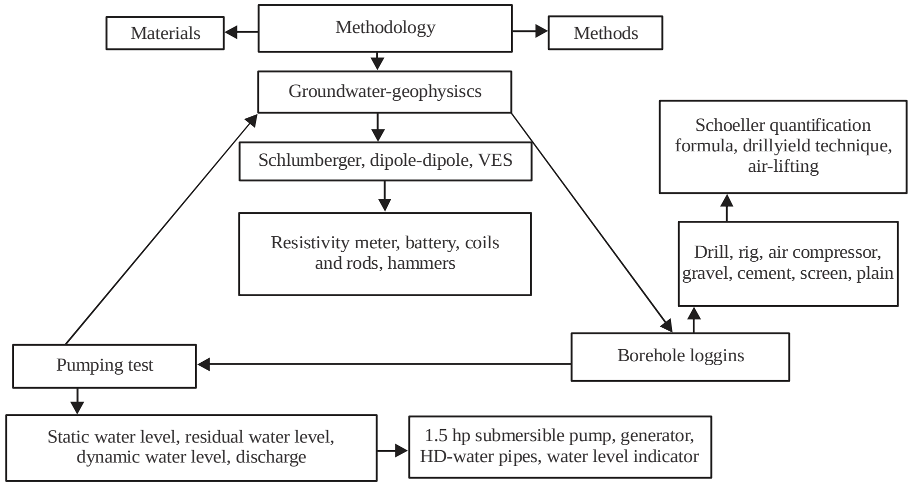

Fig. 5: Methodological flowchart

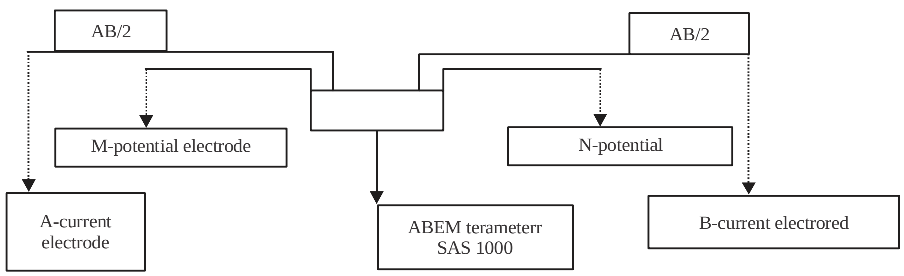

Fig. 6: Schlumberger configuration array

The geophysical devices used to measure these resistivity was the resistivity meter, this consists of coils and rods for the transmission of electrical current into the groundwater. The idea behind studying electrical resistivity was to detect the occurrence of groundwater as well as investigate the lithology. The data generated was analyse with the help of the IPI2win and 1X1D software package (Fig. 6).

Borehole loggings: Over 38 borehole loggings were collected in the study area, however, data suggest that there were about 890 boreholes that existed functionally. Information on the loggings include drilling penetration rate, depth of water-strike, lithological units, yield and airlift-yield and materials used for the development. Rotary drilling was the prefer drilling method because it is widely used within the Northern Section of Ghana (crystalline formations).

Pumping rate:

$$\text{Borehole discharge} = dq/dt \text{ (LPM)} \quad (3)$$

Where:
dt = The drawdown
dt = Time

Information collected from the pumping test data sheet included; Static Water Level (SWL), Dynamic Water Level (DWL), Residual Water Level (RWL) Discharge rate, average recovery and height of datum. The data gathered was then analysed using a Microsoft excel pumping test sheet plotting drawdown with runtime and residual drawdown with time.

RESULTS AND DISCUSSION

Geophysics and geology: The essence of conducting geophysics in this research is study the geological units in the study area and its impact on irrigation. The vertical electrical sounding results were collected using the resistivity meter with AB/2 distance of 5 m interval and MN distance increasing progressively. Table 1 gives the resistivity ranges with the corresponding geological units.

Table 1 shows the range of resistivity values from the VES data in the 10 districts of the research area describing the geology of Northern Region. Northern region falls within the votaian Basin which consists of the sandstones, mudstones, shale, siltstones and highly metamorphosed materials[20]. Areas of resistivity between 240.80-14.1 Ωm suggest clay dominant zones (Karaga, Nanumaba North and Kpandai).

Table 1: Summary of VES results and lithological description in Northern Region

Locations	Water-points	Range (Ωm)	Mean (Ωm)	Description
Kpandai	6	1643.11-137.26	890.185	Lateritic-clay and Shale base-rock
Namumba North	2	202.26-152.70	177.480	Laterite and high metamorphism
Nanumba South	3	240.80-43.17	123.985	Clay and shales
Saboba	3	2931.45-70.71	1501.080	Gravel, dry-clay and sandstone
Yendi	4	270.49-24.34	147.415	Laterite and shales
East Gonja	7	9185.27-28.17	4606.720	Gravel, sand-shales
Gushiegu	3	165.27-41.98	103.625	Laterite, pebbles and sandstone
Karaga	2	217.34-14.1	115.720	Clay, felsic-material and mudstones
Tatale	3	354.18-24.70	189.440	Clay and shale as base-rock
Bunkurugu	5	212.40-92.66	152.530	Lateritic-clay, gravel and shales

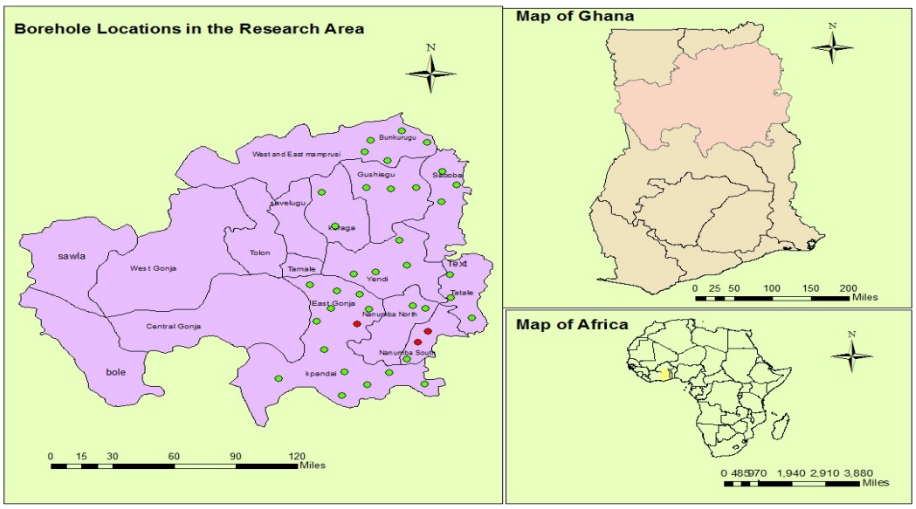

Fig. 7: Map of Borehole location

Bunkurugu showed a 100% success rate in the drilling of borehole; this is as a result of the promising VES data ranging from 212.40-92.66 Ωm in the area. The data suggest dominant shale materials as the parent rock overlain with clay and laterite. A community within East Gonja (Kafaba) showed a different resistivity values uniquely from the other communities (ranges from 211.72-66.53 Ωm) which is usually know to be a motted-zone area (muddy). In regolith geology, quartz has a unique chemical compound of Silicon Oxide or Silica (SiO_2) having a specific hexagonal crystalline form which weather to form sand or quartzitic sand in the process. Also, the end product of weathering of feldspar-mineral rocks (felsic materials) is clay; the presence of quartz and feldspatic minerals as the base-rocks explains the dominance of clay and lateritic-clay in the Northern Region of Ghana[21]. Thus, the high presence of clay in northern region suggest dominate felsic mineral rock and also, the topmost part of the overburden consist of laterites; there are two reason for the presence of laterite it can be present as result of residual formation process: it is been exposed from beneath the earth surface from road cuttings and other means. The other method can be as a result of transportation from one geologic environment to the other. They are often been carried by running water or airlifting processes over long distances. The continue rubbing (sorting) against each other accounts for the smooth surface of the laterite. Kpandi, Nanumba North, Bunkurugu, Tatale, Karaga and Yendi showed promising results of the availability groundwater resources even before data analysis. Information from the drilling data would be the only proof to validate the presence of groundwater in Northern Region.

Boreholes successes (Rate): A total of 38 boreholes were drilled within the Northern region. The voltaian Basin was categorise into three formation namely; sandstone, shale and mudstone formation. The sandstone formation had a success rate of 99% of 5 success boreholes out of the five drilled, the shale formation had a success rate of 91% of 29 boreholes out of the 32 drilled and finally, the mudstone formation recorded a success rate of 99% of one borehole drilled. The study area had a combine success rate of 96.3% which is >93% of the Sub-Sahara Africa regional average[7] (Fig. 7).

The 96.3% success was authenticated by computing for the total groundwater storage and the extractable groundwater, this was done using Eq. 4 and 5[22].

Table 2: Summary of borehole results from Northern Region

Parameters	Sandstone	Shale	Mudstone	Mean values
Height of weathered zone (H)m	27.5	35.5	41.5	34.83
Average depth to water surface (h)m	19.74	20.84	17.31	19.30
Saturation Depth D (D = H-h)m	7.76	14.66	24.91	15.78
Number of boreholes drilled (T)	5	32	1	38
Successful boreholes (S)	5	29	1	35
Unsuccessful boreholes (U)	0	3	0	3
Groundwater Coverage C = S/T	0.99	0.91	0.99	0.96

Table 3: Summary of pumping test results for Northern Region

	Range			
Regions	Boreholes analyzed	Borehole depth (m)	Borehole discharge (LPM)	SWL
Sandstone	5	105-60	225-9	17.65 -8.81
Shale	32	90-45	310-11	24.95-4.21
Mudstone	1	90	245	12.90

Total Groundwater Storage (G_s) = Groundwater Coverage (C)×Effective Porosity (Ø)×Depth of saturation (H)×Land Area (A).

But porosity (Ø) = V_v/V_t where, V_v is the void volume and V_t is the total volume of unconsolidated material[23] (Table 2):

$$G_s = C\times\varnothing\times D\times A \quad 4()$$

Extractable Groundwater (E_G) = Groundwater Coverage (C)×Specific Yield (Y)×Depth of saturation (H)×Land Area (A).

Bear[23] expressed specific yield as $Y = V_{wd}/V_t$. Where, V_{wd} = volume of water drained and V_t is the total rock or material volume:

$$E_G = P\times Y\times H\times A \quad (5)$$

Using Eq. 4 and 5; taking specific yield and effective porosity to be 2 and 5%, respectively[24, 25] for an area of 70, 383 km^2. The groundwater coverage was determined by rationing the number of successful boreholes to the total number of boreholes consider for this study (C = S/T). After computation the mean values for the storage of Groundwater (G_s) and Extractable Groundwater storage (E_G) were estimated to be approximately 533,108,995.2× 10^6 m^3 and 213,243,598.1×10^6 m^3, respectively. The groundwater potential within Northern Region from this computation is sufficiently enough to support the idea of this study. The extractable storage represents the quantity of groundwater that can be drawn without posing a threat to the aquifer.

The pumping test (Rate): The pumping test results show the quantity of water that was discharged from the wells, the quantity attest to the idea of groundwater been a better alternative water supply for irrigation. The pumping test combined with the geophysical test will predict sites favourable for irrigational programs for the future if this research is to be manifested. Table 3 presents the summary of pumping test results for Northern Region of Ghana.

From Table 3, the values for the discharge range within Northern Region shows there is enough groundwater to support the idea of using groundwater for irrigated agriculture; discharge of 310 LPM and 245 LPM are correspondingly high. Communities around Tatale-Zabzugu (Nakpale) had an airlift yield of 340 LPM. The Static water level (SWL) shows areas of shallow and deep groundwater resources[2].

Figure 8a, b both shows a negative correlation between borehole depth and yield in the shale and sandstone formation. This can be attributed to the fact that the shale and sandstone falls under the Voltaian geological formation which are massive and have the same in its weathering process under suitable condition and groundwater behaviour (Fig. 9).

Predicting areas of high groundwater potential: The map shows areas of high groundwater potential. In the future where the idea is to be manifested this map can serve as a guiding block. In the Northern Region areas around Kpandi, Wulensi (Nanumba South), Bimbilla (Namnuba North), Tatale and Bunkurugu are promising sites that may be suitable and favourable for irrigated agricultural activities.

Implication on agriculture: Recent studies have shown the economic benefits farmers derive as a result of the usage of groundwater for dry-season cultivation[26]. Thus, the development of groundwater for agriculture, especially in the dry season, is very crucial. However, the awareness of where to site or develop has often hindered this at various levels. Efforts by NGOs to drill boreholes using manual methods in Northern Region failed to materialise. This can partly be attributed to lack of information on potential areas for groundwater development in the region (Appendix 1 see in Fig. 10).

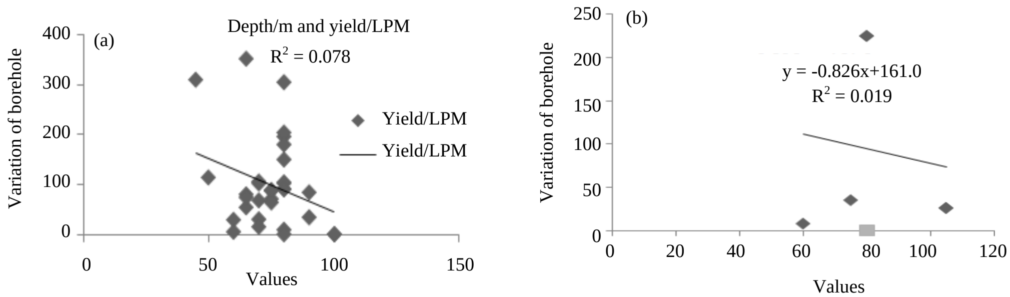

Fig. 8(a, b): (a) Variation of borehole yield with depth in the shale formation and (b) Variation of borehole yield with depth in the sandstone formation

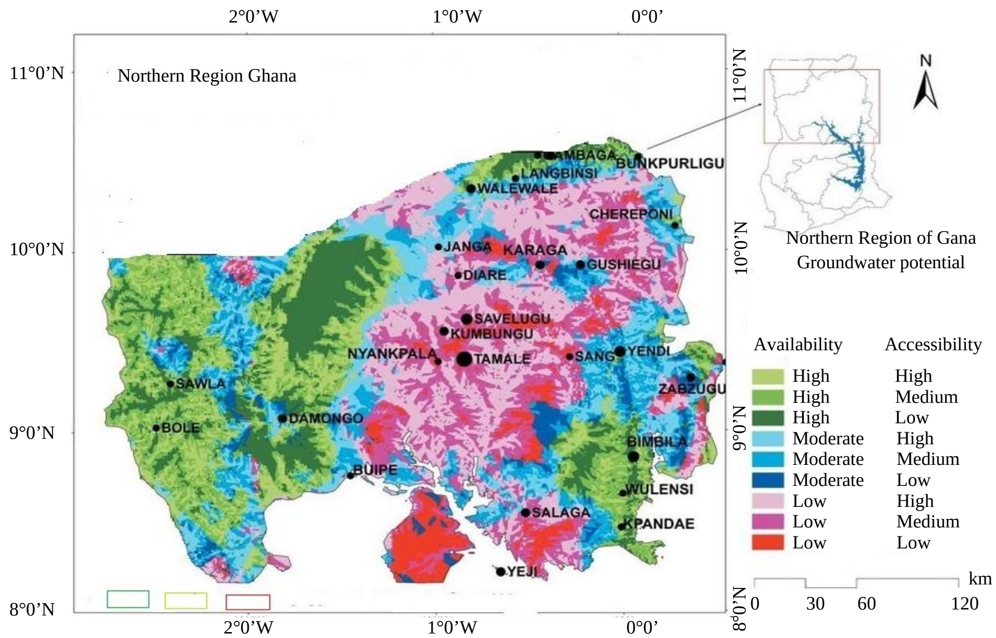

Fig. 9: A Map showing areas of high groundwater potential[2]

CONCLUSION

The data was collected from recent sited and drilled boreholes within January-May, 2019, it was analysed using both qualitative and quantitative methods to estimate and predict sites of high groundwater potential. The geophysical data showed that the Northern Region is underlain with the voltaian rocks which comprises of sandstone, shales and mudstone while the overburden has an average thickness of 34.83 m which is made up of laterite and clay. The total permanent groundwater storage and the total recoverable groundwater storage in Northern region were estimated to be approximately 533,108,995.2×10 m^3 and 213,243,598.1×10^6 m^3, respectively. The research targeted areas of high groundwater success rate so as to minimize the gap in the computation that may be affected as a result of the dry boreholes. The pumping rate showed that large quantity of groundwater discharged from the boreholes, hence, the exploration of groundwater as an alternative water supply for irrigation and agricultural production within Northern Region completely feasible.

RECOMMENDATIONS

The recommendations from this research are of great essence for possible future exploration[27, 28] in separate studies in some SSA countries, noted that groundwater potential is an essential maker of water security during the periods of drought in SSA. Thus, the prediction of viable sites of high groundwater potential is important and will assist developers in selecting areas that need urgent attention with regards to groundwater exploration (i.e., areas of high groundwater reserves). Facts exists that, for the voltaian basin, for instance, deeper wells (especially in sandstones) normally yield high quantity of groundwater for urban supply, industrial uses and agricultural irrigation[14].

APPENDIX

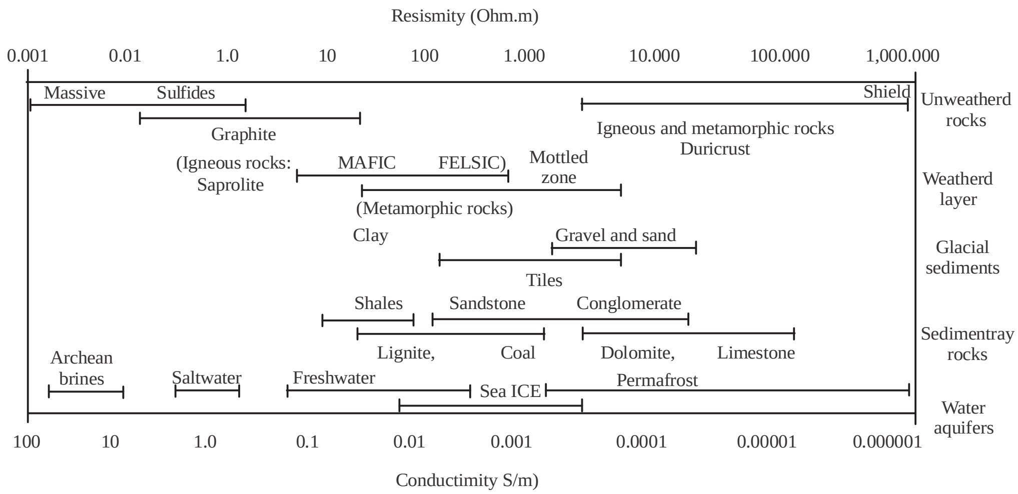

Fig. 10: Resistivity versus geology table

REFERENCES

01. Anayah, F. and J.J. Kaluarachchi, 2009. Groundwater resources of northern Ghana: Initial assessment of data availability. Utah State University, Utah.
02. Forkuor, G., P. Pavelic, E. Asare and E. Obuobie, 2013. Modelling potential areas of groundwater development for agriculture in Northern Ghana using GIS/RS. Hydrol. Sci. J., 58: 437-451.
03. Mygatt, E., 2006. World's water resources face mounting pressure. Earth Policy Institute, Washington, USA.
04. Anayah, F., 2006. Factors affecting water quality in the West Bank and Gaza Strip of Palestine. Utah State University College of Engineering, Logan, Utah.
05. Van De Giesen, N., M. Andreini, A. Van Edig and P. Vlek, 2001. Competition for water resources of the Volta Basin. Proceedings of the 6th IAHS Scientific Assembly Symposium on Regional Management of Water Resources, July 2001, IAHS Publication, The Netherlands, pp: 199-206.
06. Taylor, R. and K. Howard, 2000. A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda. Hydrogeol. J., 8: 279-294.
07. Carter, R.C. and J.E. Bevan, 2008. Groundwater Development for Poverty Alleviation in Sub-Saharan Africa. In: Applied Groundwater Studies of Africa: IAH Selected Papers on Hydrogeology, Segun, M.A.A. and A.M MacDonald (Eds.)., CRC Press/Balkema, Leiden, The Netherlands, pp: 25-42.
08. MacDonald, A.M., R.C. Calow, D.M. MacDonald, W.G. Darling and B.E. Dochartaigh, 2009. What impact will climate change have on rural groundwater supplies in Africa?. Hydrol. Sci. J., 54: 690-703.
09. Shah, T., J. Burke and K. Villholth, 2007. Groundwater: A Global Assessment of Scale and Significance. In: Water for Food, Water for Life, Molden, D., (Ed.). IWMI, London, pp: 395-423.
10. FAO, 2003. Review of world water resources by country. Water Reports 23, FAO, Rome, Italy, pp: 110.
11. Giordano, M., 2006. Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: A first-cut assessment. Hydrogeol. J., 14: 310-318.
12. IUCN., 2004. Institutional arrangements for groundwater man-agement in Dolomitic terrains-water demand assessment. Water Research Commission WRC Project 1324, International Union for Conservation of Nature, South Africa.
13. Van den Berg, J., 2008. Exploring shallow groundwater irrigation: Current status and future application. M.Sc. Thesis, Delft University of Technology, Delft, Netherlands.
14. MacDonald, A.M. and J. Davies, 2000. A brief review of groundwater for rural water supply in sub-Saharan Africa. Technical Report WC/00/33, British Geological Survey, Nottingham, England, UK.
15. Tuinhof, A. and D. Heederik, 2011. Appropriate groundwater management policy for sub-Saharan Africa in face of demographic pressure and climatic variability. Strategic Overview Series No. 5, The World Bank, Washington,

16. Stephen Y. Acheampong, John W. Hess 1998. Hydrogeologic and hydrochemical framework of the shallow groundwater system in the southern Voltaian sedimentary Basin, Ghana. Hydrogeol. J., 6: 527-537.
17. Nathan, R.R. and F.R. Harris, 1970. The occurrence of groundwater. Ministry of Finance and Economic Planning, Nathan Consortium, Accra.
18. Bannerman, R.R., 1990. Appraisal of hydrogeological conditions and analysis of boreholes in the Nanumba and Western Gonja districts-Northern Region. Programme for Rural Action NORRIP/GTZ, Accra, Ghana.
19. Acheampong, S.Y., 1996. Geochemical evolution of the shallow groundwater system in the Southern Voltaian Sedimentary Basin of Ghana. Ph.D. Thesis, University of Nevada, Reno, Nevada.
20. Martin, N., 2005. Development of a water balance for the atankwidi catchment, West Africa: A case study of groundwater recharge in a semi-arid climate. Ph.D. Thesis, University of Gottingen, Germany.
21. Arhin, E., G.R.T. Jenkin, D. Cunningham and P. Nude, 2015. Regolith mapping of deeply weathered terrain in savannah regions of the Birimian Lawra Greenstone Belt, Ghana. J. Geochem. Explor., 159: 194-207.
22. Schoeller, H., 1967. Quantitative evaluation of groundwater resources. Methods Tech. Groundwater Investigation Dev. UN Water Resour. Ser., 33: 21-44.
23. Bear, J., 1979. Hydraulics of Groundwater. McGraw-Hill Inc., New York, pp: 233-235.
24. Asomaning, G., 1992. Groundwater resources of the Birim basin in Ghana. J. Afr. Earth Sci. (Middle East), 15: 375-384.
25. Acworth, R.I., 1987. The development of crystalline basement aquifers in a tropical environment. Q. J. Eng. Geol. Hydrogeol., 20: 265-272.
26. Mdemu, M., W. Laube and B. Barry, 2010. Temporal water productivity of tomato irrigated from a small reservoir and hand-dug-wells in dry season cropping in the Upper East Region, Ghana. Irrigation Manage. Mag., 45: 75-93. USA.
27. Robins, N.S. and D. Banks, 1997. Final report: groundwater management in drought prone areas of Africa. Technical Report WC/97/57, British Geological Survey, Nottingham, England, UK.
28. Calow, R.C., A.M. MacDonald and A.L. Nicol, 2000. Planning for groundwater drought in Africa: Towards a systematic approach for assessing water security in Ethiopia. Technical Report WC/00/13, British Geological Survey, Wallingford, England.