


# Estimating the groundwater storage for future irrigation schemes

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## ABSTRACT

Presented in this paper is a feasibility study of groundwater for agricultural use (irrigation) in Northern Ghana. The study was conducted using geo-electrical data, boreholes drill logs, results of water quality, and results of the pumping test. The geo-electrical results were to unearth the lithology of the study area; it was found to be underlain with varying geology of both Precambrian and Paleozoic sedimentary formation. These formations consist of phyllite, schist, granite, meta-sediments, and meta-volcanics making up the Precambrian and sandstone, shale, siltstone, mudstones, granitoids also, of the Paleozoic sedimentary. Areas of low resistivity were targeted for drilling per the geophysical results of the profile, values between 24 and 100 ohm.m were zones of probable groundwater occurrence in the study. The groundwater storage capacity and the extractable storage capacity were estimated to be approximately 710,000 km<sup>3</sup> and 290,000 km<sup>3</sup>. The pumping test results acquired from 81 boreholes from the study were used to analyze the sustainability. However, groundwater depth was studied using the Static water level (SWL), areas of SWL around 22 m and 25 m are likely to have a shallow depth whereas areas of 17 m would have deeper groundwater depth.

**Key words** | geo-electrical, groundwater, Paleozoic, Precambrian, pumping, sedimentary

## HIGHLIGHTS

- Groundwater resistivity was determined from the VES values.
- The groundwater storage and extractable storage were computed from borehole data.
- Overburden thickness suggest thick weathering.
- Pumping test reveals the quantity of groundwater discharged.
- Groundwater irrigation might be possible per this study.

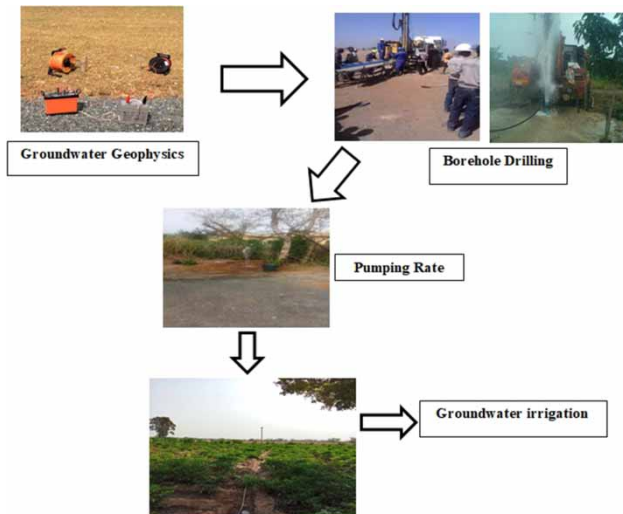
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## GRAPHICAL ABSTRACT



## INTRODUCTION

In recent times, the search for water to address the needs of agriculture across Sub-Saharan Africa and many parts of the world have been retarded directly and indirectly by climate change. It has been established that over 150 million of the rural population in Africa rely on groundwater services for domestic and agricultural use (Adelana & MacDonald 2008). It necessary to value the quality of groundwater in this study as irrigation is the subject. An appropriate evaluation of the water quality before its use in irrigation will help to arrest any harmful effect on plant productivity and the hydraulic properties of irrigation soils. The suitability of water for irrigation is determined in several ways including the degree of acidity or alkalinity (pH), electrical conductivity (EC), residual sodium carbonate (RSC), sodium adsorption ratio (SAR), exchangeable sodium ratio (ESR), as well as the effects of specific ions (Sadat-Noori *et al.* 2014). The study area is known to solely rely on groundwater as a source of drinking water and also for agriculture during the dry season when there are no rains. The importance of agriculture in the socio-economic conditions of these communities in the study area cannot be overemphasized. To safeguard these interests, there is an urgent need to carry out a comprehensive assessment of the groundwater resources for sustainable

development and management for irrigation. This is because the sustainable development and management of a resource begin with an assessment of its quantity and quality. The adoption of groundwater for irrigation tends to elevate agricultural productivity to a greater height (Moench 2003). There has been supply water for about 200 million hectares of irrigational activities in SSA over the decades (Giordano 2006). The use of groundwater has been robust, supporting most of the SSA countries despite the 1,000 mm/y annual precipitation recorded (Foster *et al.* 2006). Siebert *et al.* (2010), discovered Thailand and Myanmar to be the largest cultivators using groundwater-irrigation.

The area receives an annual rainfall averaging 1,000 mm, which is considered to be enough for a single farming season. Temperatures are generally high, averaging 34 °C. The maximum temperature could rise as high as 42 °C and the minimum as low as 16 °C (West Mamprusi District Assembly 2014). The low temperatures are experienced from December to late February, during which the North-East Trade winds (harmattan) greatly influence several activities in the district. Generally, high temperatures as well as the low humidity brought about by the dry harmattan winds favor high rates of evaporation and transpiration, leading to water deficiencies in the ground. Undoubtedly, these high

temperatures force certain plants to give up water through evapotranspiration. The major controllers of groundwater occurrence may be geology, hydrogeology, climate change, and lack of systematic data on groundwater. The issues of climate change and variability supersede all other controllers of groundwater production. Vaccaro (1992), Bouraoui *et al.* (1999), Scibek & Allen (2006), Zhou *et al.* (2010), in separate studies identified that the impact of climatic variability could be the fluctuation in water levels; however, irrigation is another way of replenishing and restoring the groundwater abstracted.

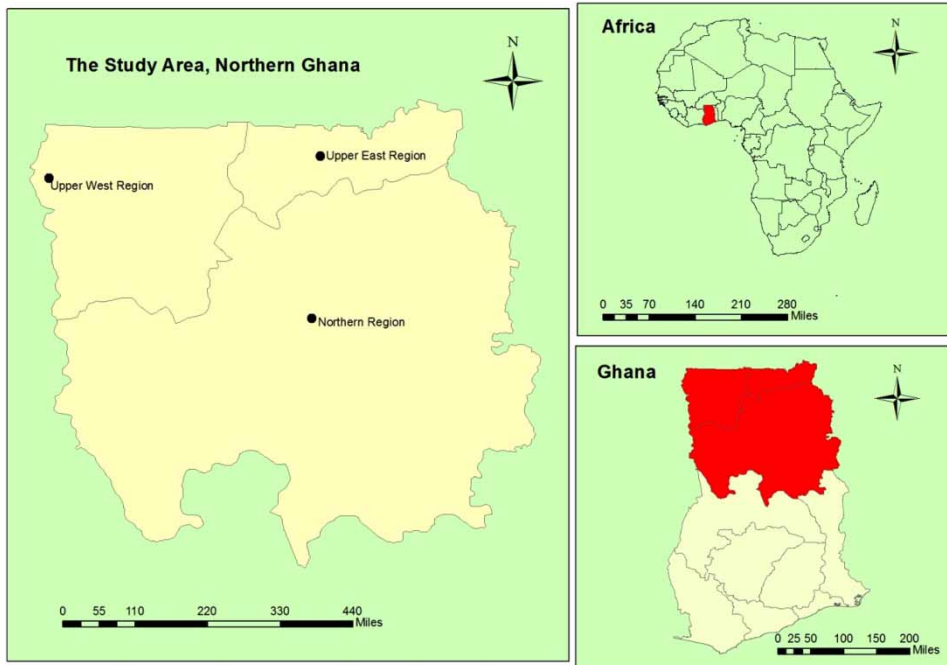
The occurrence of groundwater depends on the existing geology. It occurs within fractures and spaces (pores) where these fractures have high interconnectivity in the rock. Sandstone and limestone formations (Paleozoic sedimentary) are recommended for groundwater development because of their potential gradient having an average borehole success rate of about 77% in the world. However, the Upper and lower Birimain (Wa Granite) has an average borehole success rate of 80% with a yield of  $\geq 0.55$  L/s. In the context of classification, the SSA falls under the Precambrian hydrogeological province. This kind of formation determines the nature and occurrence of groundwater. The study area is characterized by the Precambrian basement and the sedimentary fractured aquifers, which are both locally high in terms of groundwater production. For sustainable and successful extraction of groundwater for irrigation it is imperative to understand the hydrogeological and geological condition of the study area. The desired drilling method is determined by the geology and hydrogeology of the study area; for instance, mud drilling would be suitable for coastal aquifers compared to air drilling, which will be the option for crystalline formations. The dominant geologic units in the study area comprise shales, fresh granite, and meta-rocks mainly of a crystalline form. Air drilling would be absolute per the underlying geologic units in the area. This kind of formation is recognized for its high yielding of groundwater in fractured conditions (Abdul-ganiyu *et al.* 2020; Prosper *et al.* 2020).

The essence of this research is to study and understand the groundwater in the study area using hydro-geophysical techniques. This gives insight into the groundwater and hydrogeological behavior of the area. Furthermore, the quantity of groundwater stored and the extractable quantity

was estimated to conclude on the feasibility of groundwater irrigation in the study area. The unanswered question is, can groundwater be resilient and also a better alternative to supplement irrigation? Similar studies have been done around the globe using different approaches to achieve a single goal, which is investigations into whether groundwater can supplement existing water resources for irrigation and also finding suitable alternatives in the absence of existing water resources. Findings from these previous works show that groundwater can indeed supplement the existing irrigational water with proper management practices. China, Thailand, Algeria, Libya, Europe, and some parts of the world have the largest irrigation systems and have put measures in place to minimize the complete mining of these resources (Abdul-ganiyu & Prosper 2020). Regionally, the groundwater storage capacity has been studied in some parts of Ghana, findings from these papers confirm that the presence of these high yielding aquifers is capable of boosting agriculture in the dry season.

### The study area

Figure 1 depicts the boundaries of the study area, which roughly comprises the upper-half of the country and is located between latitudes  $7^{\circ}58'N$  and  $11^{\circ}11'N$  and longitudes  $2^{\circ}57'W$  and  $0^{\circ}34'E$ . It consists of the three Northern regions of Ghana, namely the Upper East Region, Upper West Region, Northern Region, and the recent two regions created (Savannah and North-Eastern Region), which respectively account for 9, 19, and 72% of the total study area (108,671 km<sup>2</sup>). The study area is bordered by Côte d'Ivoire to the West, Burkina Faso to the North, Togo to the East, and the Volta and Brong-Ahafo Region to the South. The study area is predominately flat and gently undulating with slopes of about 5% to 1% in many areas (Quansah 2000). It is characterized by three main ecological zones, which are: Guinea Savannah, Transition zone and the Sudan Savannah, defined in the context of climate and the natural vegetation influenced by the regolith and rainfall in the study area. Rainfall often decreases with increasing latitude and its distribution throughout the year is uneven; it is known for a single rainfall pattern, which is from late April to October. The annual precipitation within the study area is 900 to 1,200 mm. Temperatures within these



**Figure 1** | Study area map of Northern Ghana.

regions are extensively high, ranging from 27 °C to 29 °C, and annual extremes of temperature between 17 °C to 40 °C.

## Groundwater resources

### Geological and hydrogeological description

The geological units present in the study area are the basement crystalline rocks and the Paleozoic consolidated sedimentary formations. The overlying regolith is defined by a weathered layer of varying lithology found meters away from the unsaturated zone (Martin 2006). The regolith thickness within the study area ranges between 2.7 m and 44 m but can be up to 125 m in certain areas around the North West (Apambire *et al.* 1997), factors that influence the thickness of the regolith include structural characteristics, nature of the lithology, climate, vegetation, and erosion. The basement crystalline geology is sub-grouped into the Birimian, Tarkwan, Dahomeyan, Granite, Buem, and Togo formations. However, this geology of Precambrian age comprises quartzite, schist, granite-gneiss-greenstone rocks, anorogenic intrusion, and deformed metamorphosed rocks. The Voltaian formation also refers to the Paleozoic consolidated sedimentary, which consists mainly of sandstone, shale, mudstone,

arkose, pebble beds, and limestone. The Voltaian formation is sub-grouped into the upper, middle, and lower Voltaian (Obuobie & Barry, 2010). The upper Voltaian is noted for its massive and thin-bedded quartzite sandstone, which is intercalated with shale and mudstone. The middle Voltaian (Obusum and oti beds) has a the dominance of sandstone, shale, mudstone, siltstone, and arkose. The lower Voltaian comprises massive quartzite sandstone and grit (Obuobie and Barry, 2010). The regolith is less thick compared to the Precambrian basement formation; the thickness varies from 4 m to 30 m.

The Voltaian and Precambrian formations, which dominate the study area, both have low porosity, rendering the rocks impermeable, but groundwater occurrence in this study area is attributed to secondary porosity. However, groundwater potential in the Voltaian formation is of low gradient compared to the Precambrian formation (Dapaah Siakwan & Gyau-Boakye 2000). In the Mesozoic and Cenozoic (minor geologic formations), three aquifers can be found (Obuobie and Barry, 2010). First is the unconfined aquifer, with a depth ranging from 2 m to 6 m, which occurs in recent sand very close to the coast. The second is the leaky aquifer, made up of continental deposits of clay and gravel with aquifer depth from 8 m to 120 m. The third type is the

limestone formation aquifer, which has a depth between 130 m to 300 m. Groundwater under this formation is artesian (freshwater) with a yield varying from 5.5 m<sup>3</sup>/h to 58 m<sup>3</sup>/h (Dapaah Siakwan & Gyau-Boakye 2000). The geological cross-section of an unconfined aquifer is evident from the Atankwidi catchment of the Volta Basin in Ghana; this is indicative that groundwater in this formation is high (Martin 2006). Boreholes within the Northern Sector have depths of around 80 m and are believed to be sourcing from the productive zone (Martin 2006). The productive zone is referred to as the areas below the regolith and above the fractured bedrock. The fractured zone is mainly sub-vertical and generally develops at a depth greater than 20 m below the ground surface (HAPS 2006). The fractured zone varies with thickness, the factors that account for these are the degree of weathering, structural history, lithology, and depth. Hydrogeologically, the Voltaian formation is the least understood formation because of its complexity.

## Groundwater irrigation in Ghana

In the Upper Regions, dug-out and hand-dug well were means of extracting groundwater from alluvial channels along streams for vegetable production during the dry season. Water was lifted from this well manually to irrigate 0.07 to 0.3 hectares of vegetable farms (Kortatsi, 1994). Research has shown that about 100 to 200 hectares were irrigated using groundwater in the Atankwidi catchment in the Upper East Region. Elsewhere in the study area, leafy vegetables are cultivated in urban and peri-urban areas of Tamale using shallow groundwater resources; these farmers irrigate land areas of about 1.2 hectares. Most of the crops are cultivated on small plots and made readily available after harvest on markets, these crops include okro, pepper, cabbage, onions, shallots, and carrots. Less than 5% of the groundwater usage is attributed to irrigation and livestock watering.

## MATERIALS AND METHODS

### Geophysical technique

Groundwater is considered to be a hidden natural resource, taking into consideration its location and extraction process.

Given this, a thorough geophysical study needs to be done to delineate suitable groundwater zones. The common geophysical methods used around the world for groundwater investigation are the Electrical Resistivity (ER) and Electromagnetic (EM) techniques. These techniques operate on different phenomena and principles surrounding rock physics. In northern Ghana, the ER method is the common method used because groundwater surveys and their success rate have proven to be undeniable. Vertical Electrical Sounding (VES) is the profiling technique used in the ER survey for measuring variations and discontinuities in resistivity with depth as identifiable signatures of groundwater beneath the earth (profiles). The VES simultaneously investigates both vertical and lateral distribution of resistivity beneath the profiles. Moreover, this method can further be used for mineral exploration surveys, geological and geotechnical surveys, environmental and agricultural geophysics. The ER method detects water-bearing formation between two points of the survey; the nature, topography, and vegetation of the study area were an added advantage in the survey. The everyday device for measuring groundwater and lithological resistivity in this part of the world is the ABEM terrameter. This device consists of coils and metal rods and also comes in different resolutions (specs), which are: SAS 800, 1,000, and 4,000 (ie related to the depth of penetration). Depending on the depth of groundwater in the study area, the preferred resolution of Terrameter is chosen. The coils and rods are oriented differently depending on the goal of the investigation, which gives information on the kind of configuration to be used (Wenner, Schlumberger, Dipole-Dipole, and Pole-Pole). However, each configuration has a maximum depth of study. The geophysical goal was to study the lithology and delineate zones of high productivity aquifers. Apparently, the Schlumberger configuration has a deeper depth of study and also can be used to study lateral variation between profiles concerning resistivity. This configuration was chosen in this research to accomplish the geophysical goal (groundwater and lithological survey). The average profile length was about 1.5 km with a current electrode spacing of 400 m. Communities around the Northern Region had a stretch of profile length of about 1.2 km as a result of complex and varying geology. The resistivity can be calculated by first estimating the geometric factor (K) using Equation



(1b). The geometric factor is a constant that varies from one setting to another and also depends on the configuration used for the survey. The geometric factor ( $K$ ) is then substituted into Equation (1a) to calculate the resistivity at each station interval.

$$\rho = K \times \frac{\Delta V}{I} \quad (1a)$$

$$K = \frac{AM \times AN}{MN} \times \pi, \quad \text{where } \pi = 3.142 \quad (1b)$$

$MN$  = distance between potential electrodes (m),  $AN$  and  $AM$  = distance between current electrodes (m),  $\Delta V$  = potential difference measured (volts) and  $I$  = applied current strength.

### Borehole loggings

Primarily, cuttings from each drilling process were sampled after every 5 m of penetration through the formation. The process aids in studying and correlating the lithological units to results from the geophysical survey. The lithological sampling helps in determining the nature of the aquifer and possible related characteristics of the aquifer, which can only be revealed after the pumping test. The machinery and techniques involved in borehole drilling vary depending on the intended use, geological condition of the study area, and the manufacturer. The Indian Drill (Ashok) and German Rigs are purposely used for air drilling, which is the preferred drilling method in Northern Ghana. The main differences between these rigs are the length of drill rods and the nature of the compressors. Data was collected from mounting to dismounting of the drill rig. The data collected during the drilling phase assisted in computing some parameters for defining the groundwater in the area. However, the Schoeller (1967) equation was used in estimating the groundwater storage of the basin.

### Pumping test

The process by which a borehole is pumped at a controlled rate and the drawdown is measured against time in one or more surrounding wells. The importance of carrying out a pumping test cannot be overlooked in a borehole

development stage. In the pumping test, the common techniques are the Constant Rate Test (CRT) and the Step Drawdown Test (SDT). The distinction between the CRT and SDT is that SDT involves a sequence of constant-rate steps at the control well to estimate borehole performance such as borehole loss and efficiency (Abdul-ganiyu *et al.* 2020). The CRT was the pumping method used here; the groundwater in the aquifer was pumped at a controlled rate constantly, to show the storage capacity of the basin can supplement the irrigation water in the area. The aim of conducting a pumping test is to determine transmissivity, hydraulic conductivity, and storativity which helps predict the aquifer characteristics. The pumping test was done with the help of a 1.5 horsepower (Hp) Superdub submersible pump, a diesel generator, 80 m HD pipes, a water level indicator, and some pumping test kits. Prominent data generated from the pumping test include discharge rate, drawdown, and static water level. The data gathered was plotted on an Excel pumping test software package; the constant discharge was plotted with the recovery test.

### Water quality analysis

All major ions ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ), as well as minor elements, such as  $\text{NO}_3^-$ , and  $\text{F}^-$ , were analyzed using a Dionex DX-120 ion chromatograph at the water quality laboratory of the Water Research Institute, Tamale. The bicarbonate ion concentration in the water was determined by titration. Following the international standards, results with an ionic balance of more than 5% were rejected. The TDS was estimated by summing up all the major cations and anions in the sample using Microsoft Excel software. The sodium adsorption ratios (SAR) indicate the effect of relative cation concentration on sodium accumulation in the ground, this is calculated from the relationship in Equation (2):

$$\text{SAR} = \frac{\text{Na}^+}{\frac{\sqrt{\text{Ca}^{2+} + \text{Mg}^{2+}}}{2}} \quad (2)$$

where  $\text{Na}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  are in Mg/L.

## RESULTS AND DISCUSSION

### Geo-electrical (VES) results

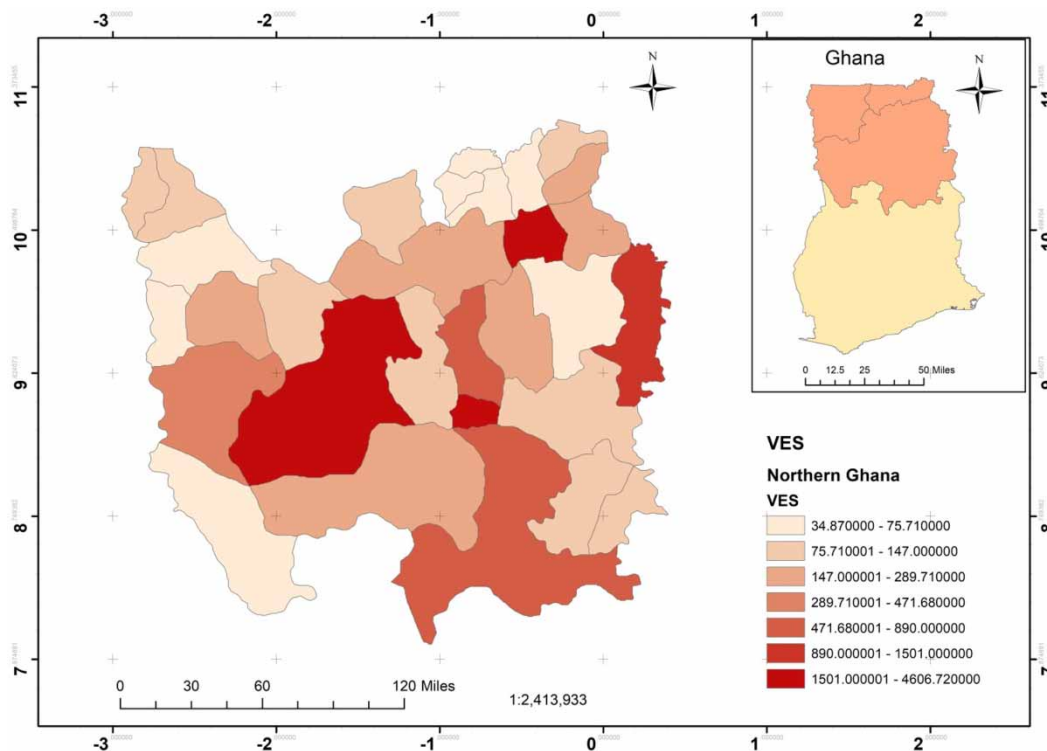
The results collected from the geophysical profiling aided in studying the geology of the study area (geo-electricity) and also giving insight into the petrography of the rocks. In irrigation, the quantity and quality of water define the life span of the scheme and hence investigating the geology, which

controls the water source is an important step of sustaining an irrigational scheme. Moreover, the existing geology gives an overview of how rich the regolith (soil) will be and determines suitable crops to be cultivated if detailed soil research is carried out.

Table 1 and Figure 2 show the range of resistivity values from the VES results within the districts of the research area describing the geology of some parts in the Northern Region. It falls within the Voltaian basin, which consists of

**Table 1** | Summary of VES results and lithological description in northern region

Locations	Res - points	Resistivity range Ohm.m	Mean Ohm.m	Formation
Kpandai	5	140–1,600	890	Lateritic-clay and shale base-rock
Namumba district	4	47–200	125	Laterite, sandy-shales
Saboba	3	71–2,900	1,500	Gravel, dry-clay and sandstone
Yendi	3	24–270	147	Laterite and shales
Salaga	6	28–9,200	4,600	Gravel, sand-shales, mudstones
Karaga Areas	4	25–320	173	Clay, felsic-material, shales and mudstones
Zabzugu	3	25–350	190	Clay and shale as base-rock



**Figure 2** | Pictorial representation of VES in the study area.

the sandstones, mudstones, shale, siltstones, and highly metamorphosed materials (Martin 2006). Areas of resistivity between 47 ohm.m and 200 ohm.m are mainly clay dominant zones (Karaga, Nanumba North, Kpandai). A community within Salaga (Kafaba) showed different resistivity values uniquely from the other communities (ranges from 67 to 210 ohm.m), which accounted for the mottled nature (completely weathered) during the drilling. In regolith geology, continuous weathering of felsic mineralized rocks turns to clay, thus the high presence of clay in the Northern Region suggests dominant felsic mineral rock and also laterites as the surface materials thus occur as a result of frequent transportation and sorting. Kpandi, Nanumba North, Tatale, Karaga and Yendi showed promising results of the available groundwater resources even before data analysis (Prosper *et al.* 2020). Information from the drilling results would be the only proof to validate the presence of groundwater in the Northern Region.

Table 2 and Figure 2 shows values of VES in the Upper Region, which falls under the Pre-cambrian formation popularly known as the Birimain, this geological formation is made up of meta-volcanics rocks, meta-sedimentary formation, metamorphic rocks, and basaltic flows. The Wa municipality generally has thick granitoids as base-rock of mostly mica-homblende-boitite mineralization, these kind of rocks under high pressure undergo shearing which results in fractures and joints within it. These fractures serve as pathways and high reserves for underground resources, the VES values for Wa municipality and central depict meta-sedimentary rocks, these can be evident from the drill log of boreholes around kpaguri, Dondoli, limanyiri and Bamahu. The drill logs show a formation of phyllitic sediments which accounts for the VES values of 38 ohm.m –

540 ohm.m and 34 ohm.m – 250 ohm.m. Tegbera, Wadhi, and Loho (Jirapa road) show defined geology of the Birimain, these areas are predominantly meta-volcanics and metamorphosed granitoids. The VES values ranges from 63 to 190 ohm.m, depicting crystalline formation with isolated areas of high clay deposit. The Birimain formation has a borehole success rate of 96% with an average depth of 65 m (Okrah *et al.* 2012). The average profiling length for the Upper East area was 200 m, the Zebilla catchment falls under the Birimain formation which is known to have high groundwater potential. The VES values for these areas were uniform, but there was an anomaly in one area; which is the Tempane JHS where the resistivity values range from 120 ohm.m to 710 ohm.m. The geology between the Upper East and Upper West is not widely different this accounts for the uniqueness in geology and the high groundwater potential within these Regions.

### Groundwater storage capacity

The accessibility of water, especially for drinking and agriculture, has been of great concern to underprivileged communities around the world. The demand for water around African countries is not just a major challenge for the beneficiaries but also on the duty bearers and researchers to investigate the potential of groundwater resources for consumption. This study brings to light the groundwater available in the study area and its feasibility in supporting current irrigation water. However, groundwater is 15% of African renewable water resources, accounting for the total water in the aquifer (ACPC 2013). Several attempts have been made to estimate the quantity of groundwater available in storage around the world for different activities.

**Table 2** | Summary of VES results and lithological description in the upper regions (west and east)

Locations	Res -points	Resistivity range Ohm.m	Mean Ohm.m	Formation
Wa municipal	6	38–540	290	Clay, meta-sedimentary formation
Wa central	5	34–250	140	Lateritic-clay, meta-sediments
Jirapa Road	11	63–190	130	Laterite, clay, schist, gneiss
Zebilla	21	47–140	95	Sand-clay, meta-sedimentary formation
Garu	8	42–100	73	Lateritic-clay, meta-sediments
Tempane	3	93–700	400	Laterite, clay, granitoids



Some of these studies have been conducted around China and some parts of Europe to determine the potential of groundwater irrigation (MacDonald & Davies 2000). However, investigation has been done into quantifying the storage of groundwater in some parts of Ghana and the study area. Research has proven that groundwater is one of the abundant water sources in this part of the world which has the tenacity of meeting agriculture, especially in irrigation. The quantity of groundwater within the area was computed as well as the extractable storage capacity; the essence of these computations was to quantify the amount of groundwater in storage as well the amount that can be extracted economically and legally for irrigation (Prosper *et al.* 2020). Also, this research assessed high performing boreholes to minimize the gap that may result in the computation to reflect the true potential of groundwater in the study area.

Table 3 shown computations of the average weathered depth and the depth of saturation from the boreholes drill logs study area. The area under study has a combined success of 95% which is more than the Sub-Sahara Africa success rate of 93% (Carter & Bevan 2008). The success rate of boreholes drilled is either in percentage or in a ratio. This is computed by dividing the number of successful boreholes by the total number of boreholes drilled or finding the percentage of successful boreholes drilled. The saturated depth involves two quantities; first is the depth of weathered formation from ground level and second is the depth to water strike. The difference between these two quantities of depth is the saturation depth. This study estimated the total groundwater storage and the extractable storage in the basin complex. The essence of storage and extractable storage is to ensure that the groundwater available is

drawn economically and legally to supplement future irrigation without harming the aquifer (Zango *et al.* 2014; Prosper *et al.* 2020). Aside from the availability of groundwater, the quality likewise is of immense importance and should be analyzed in a recognized laboratory before using it for any agricultural-related activities. Equation (3a) and (3b) were used to compute the storage capacity (Schoeller 1967).

$$Q_s = P\emptyset HA \quad (3a)$$

where Total Groundwater Storage ( $Q_s$ ) = Percentage of Groundwater Coverage ( $P$ )  $\times$  Effective Porosity ( $\emptyset$ )  $\times$  Saturation Depth ( $H$ )  $\times$  Extent of Study Area ( $A$ )

But Porosity ( $\emptyset$ ) =  $V_t/V_v$ ;  $V_v$  is the void volume and  $V_t$  is the total volume of unconsolidated material.

$$Q_e = PS_y HA \quad (3b)$$

Extractable Groundwater ( $Q_e$ ) = percentage groundwater coverage ( $P$ )  $\times$  Specific Yield ( $S_y$ )  $\times$  Saturation Depth ( $H$ )  $\times$  Extent of Study Area ( $A$ ).

But  $S_y = V_{wd}/V_t$ , Where  $V_{wd}$  is the volume of water drained and  $V_t$  is the total rock or material volume (Bear, 1979).

The capacity of groundwater was computed based on the data generated from the boreholes using Equation (3a) and (3b), taking specific yield and effective porosity to be 2 and 5% respectively (Asomaning 1993) for an area of 108,671 km<sup>2</sup>. After computation of the total groundwater storage capacity and extractable storage was approximately 710, 000 Km<sup>3</sup> and 290, 000 Km<sup>3</sup> respectively.

**Table 3** | Summary of borehole results from northern Ghana

Parameters	Northern Region	Upper West Region	Upper East Region	Mean values
Depth of weathering (D) m	42	27	29	31
Depth of water-strike (h) m	23	15	18	19
Saturation depth (H = D-h)m	19	12	11	14
Total number of boreholes drilled (T)	27	22	32	81
Total number of successful boreholes (S)	24	21	31	76
Total number of unsuccessful boreholes (U)	3	1	1	5
Probability of having groundwater $P = S/T$	0.88	0.99	0.99	0.95

## Pumping test results

The discharge rate is referred to as the discharge that shows the quantity of groundwater that has been pumped out over a specific period of time (dt). It is computed by dividing the time taken for pumping by drawdown (da) as it is in Equation (4a), the drawdown in context is the level of water drop in a borehole during pumping at successive time intervals.

$$\text{Discharge rate } (dq) = \text{Drawdown } (da) / \text{Runtime } (dt) \quad (4a)$$

Tables 4 and 5 show information that was gathered during the pumping test (CRT); specifically, Table 3 depicts ranges of borehole depth and static water level (SWL) while Table 5 depicts borehole transmissivity and yield (per day). This section is key to the study because it reveals the traits the aquifer possesses to supply groundwater for possible future irrigation schemes. The SWL of a borehole is the level of water in the well when all conditions are in equilibrium. The equilibrium stage is when the point of recharge (inflows) equals the point of discharge (pumping). In ideal cases, it is recommended to take the SWL of a well a few days after drilling, this is because the well takes a period of time to attain the point of equilibrium. In my view, SWL varies depending on the kind of aquifer; for instance, a confined aquifer may have an SWL as low as 2–4 m, especially in artesian cases.

**Table 4** | Summary of pumping test results for northern Ghana

Regions	Boreholes analyzed	Borehole depth (m)	Static water level (SWL)
		Range	Range
Northern	24	40–90	4.2–25
Upper West	22	45–120	8.9–17
Upper East	31	55–95	5.5–22

**Table 5** | Aquifer characteristics from pumping test result

Regions	Boreholes analyzed	Borehole discharge (m <sup>3</sup> /day)	Transmissivity (m <sup>2</sup> /day)
		Range	Range
Northern	24	19–320	0.85–1.4
Upper West	22	8.6–400	0.81–1.7
Upper East	31	79–120	0.72–1.5

Here, the confining impervious layer in a confined aquifer creates a high pressure (pressure increases with depth), which forces the water to rise to the surface after the penetration (drilling) of the confining bed and this is contrariwise for unconfined aquifers. On this note, it is obvious that boreholes having low SWL (8.9–17 and 5.5–22) are likely to have a deeper groundwater depth (confined) while boreholes of high SWL (4.2–25) are also likely to have shallow groundwater depth (unconfined). The study area (Upper West and East Region) is underlain with the Precambrian rock, which includes granities and meta-rock that usually make up the confined aquifer system as shown in the drill logs. The Upper Regions certainly have low SWL, which accounts for the bore depth (Table 4), while the Northern Region has high SWL, accounting for the borehole depth (Table 4). Moreover, the relation between volume (V) and depth (D) indicates that at a depth of 100 m, the volume occupied by the same mass of fluid (groundwater) is 10 times smaller at the top surface. This shows a direct relation between borehole depth and yield in terms of aquifer type. The transmissivity measures borehole capacity to transmit groundwater throughout the saturated formation. Mathematically, it is directly proportional to the product of hydraulic conductivity and aquifer thickness (hydraulic conductivity,  $K \equiv$  aquifer thickness,  $AT$ ) as shown in Equation (3b).

$$\text{Transmissivity } (T) = \text{Hydraulic Conductivity } (K) \times \text{Aquifer Thickness } (AT) \quad (4b)$$

Therefore transmissivity (T) increases with an increase in hydraulic conductivity (K) of an aquifer. If an aquifer has high transmissivity then it may possess a characteristic of high yielding. In Table 5, it is shown that the Upper Regions have high transmissivity (0.81–1.7 m<sup>2</sup>/day and 0.72–1.5 m<sup>2</sup>/day) compared to the Northern Region (0.85–1.4 m<sup>2</sup>/day) which correlates to the yields of boreholes. These attributes of the aquifers in the study area confirm that the groundwater available is of appreciable characteristics to support the idea of groundwater irrigation in years to come.

## Water quality standards

Table 6 shows the results of water samples confirming acceptable standards of parameters as to whether it may be suitable

for irrigation or not. The limits indicate that the aquifer is of maximum quality and has no adverse effects on plants. Results from pH, EC, TDS, and SAR are of recommendable quality for irrigational activities in the future. From Table 6, it can be seen that pH ranges from 5.6 to 9.8, indicating that a few of the samples might either be acidic or basic but not too excessive to render the water unsuitable, while SAR ranges from 0.47 to 2.3, which is wholesome for irrigation. The evaluation of groundwater quality for irrigation in this research is based on the following factors: salinity (total amount of dissolved salts in water), sodium hazard (the amount of sodium in the water compared to the summation of calcium and magnesium), and Magnesium hazard (MH). The most influential water quality guideline for crop productivity is the water salinity hazard as measured by electrical conductance (Yidana *et al.* 2012). The high concentration of salinity/EC in irrigation water affects crop yield through the inability of the plant to compete with ions in the soil solution for water, which results in an osmotic effect or physiological drought). The severity of an osmotic effect may vary with the plant growth stage and in some cases may go unnoticed because of a uniform yield decline over the plant (Abanyie *et al.* 2020). Sodium hazard is defined separately because of sodium's specific detrimental effects on soil physical properties. Excessive  $\text{Na}^+$  content in irrigation water renders it unsuitable for soils containing exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions, as the soil takes up  $\text{Na}^+$  in exchange for  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  causing deflocculation (dispersion) and impairment of the tilth and permeability of soils. The sodium hazard is typically expressed as the sodium

adsorption ratio (SAR). Sodium adsorption ratio (SAR) is an important parameter for determining the suitability of groundwater for irrigation because it is a measure of alkali/sodium hazard to crops.

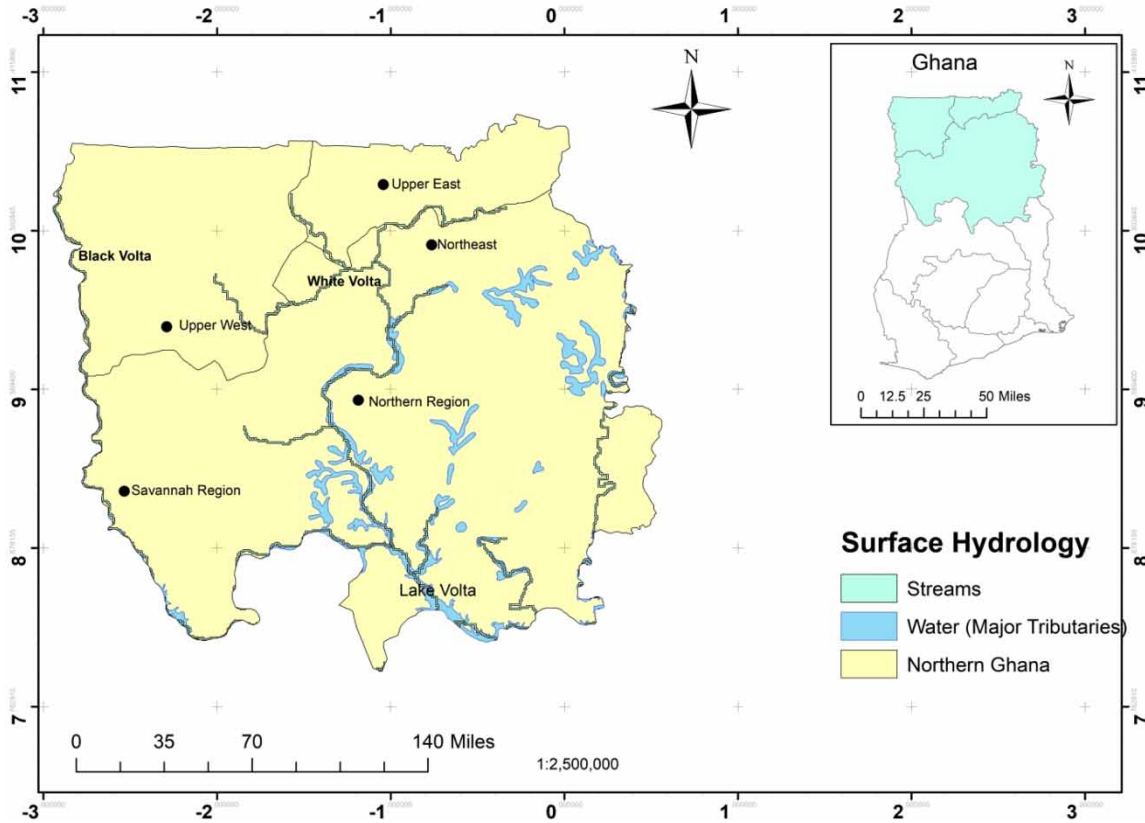
### Surface hydrology versus groundwater

Figure 3 denotes the surface hydrology (streams, tributaries of the white and black Volta) of the study area. The study area is noted for its high seasonal overflow variation in some rivers and this can be attributed to climate, vegetation, and topography. The main rivers in the study area are the black and white Volta which sources from lake Volta. The study area is noted to have several drainage systems comprising dams, canals, streams, and few springs. The number of drainage systems in the area is invalid if these systems are not of high functionality, it is appropriate to investigate the effectiveness of these systems to an extent as it may not be beneficial. The relationship between groundwater and surface hydrology to this research is of great importance (i.e. balancing irrigation water for high productivity). The study area is estimated to have over 570 dams with the ongoing 300 dams funded by the Ghana government under the 'one village one dam' project (Tamale Metropolitan Assembly 2016). Lake Volta has created several tributaries, which have extended towards the Northern sector. The notable tributaries within the area, including Nasia, Mole, Sissli, Mawli, Kulpawn, and many more. Previous study has outlined the functionality of these surface water resources and

**Table 6** | Results of groundwater quality in the study area

S/N	Parameters	Units	Permissible limit	Mean	Max	Min	Remarks
1	pH		6.5–8.5	7.5	9.8	5.6	Accepted
2	EC	mS/m	100	100	320	22	Accepted
3	T	°C	–	24	29	0.01	Accepted
4	TDS*	meq/L	1,000	146	700	20	Accepted
5	$\text{Ca}^{2+}$	meq/L	200	69	210	12	Accepted
6	$\text{Mg}^{2+}$	meq/L	150	51	190	2.4	Accepted
7	$\text{Mn}^{2+}$	meq/L	0.40	0.98	6.7	0	Accepted
8	$\text{Fe}^{2+}$	meq/L	0.30	0.81	6.1	0	Accepted
9	$\text{Na}^+$	meq/L	200	95	500	11	Accepted
10	SAR**		10	0.74	2.3	0.47	Accepted

\*TDS- Total Dissolved Solids \*\*SAR- Sodium Absorption Ratio.



**Figure 3** | Map of surface hydrology within the area of study.

their importance to irrigation for the agricultural sector in northern Ghana. The largest irrigation dam in Ghana is the Tono irrigation scheme, which is found within the study area, also some prominent irrigation systems in the area include; the Golinga scheme, Libiga, Botanga irrigation scheme, Pwalugu irrigation scheme, and some small irrigation schemes scattered around the study area. The limiting factor on the performance of these dams and water resources in the study area is the siltation of reservoirs and high temporal variability. The siltation mostly occurs in the rainy season, making the dams less beneficial for irrigation, whereas high temporal situations tend to dry up dams during the dry season (harmattan) leading to a shortage of water for irrigation. It is in this regard that the study of groundwater resource and its tendency for supplementing the existing irrigation water becomes a target for agricultural productivity not only in Ghana but the whole of Africa and the world at large.

The field water balance gives more insight into why irrigation and groundwater may be practicable. This is an equation used to establish change in water storage in the

soil. The value for the change in storage can either be a positive or negative value, suggesting where it should be added or removed from the soil. At saturated state, the water balance equation is given as:

$$\frac{\Delta \text{Storage}}{\Delta \text{time}} = \sum \text{inflows} - \sum \text{outflows} \quad (5a)$$

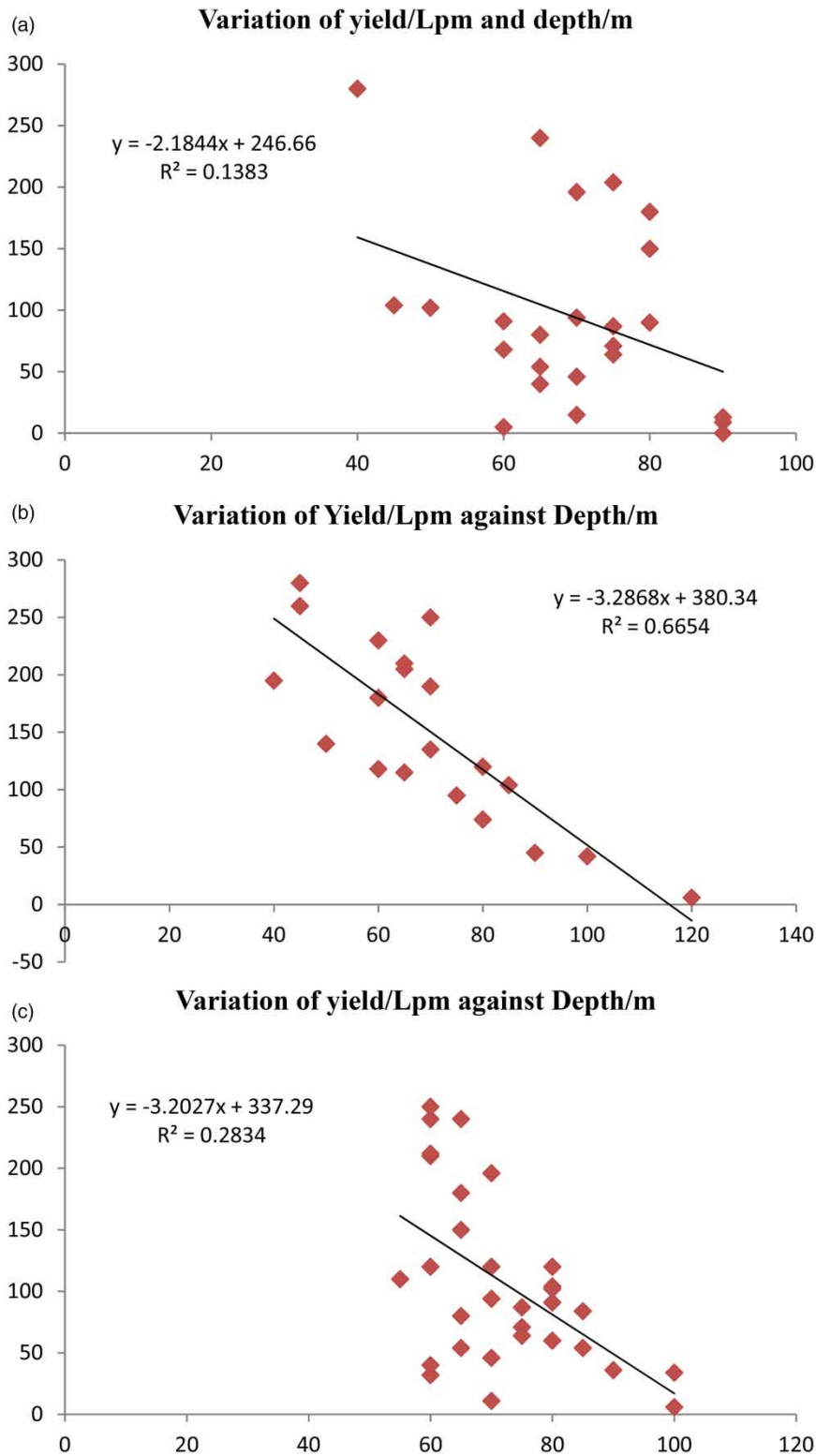
$$\frac{\Delta \text{Storage}}{\Delta \text{time}} = (I_g + P_e + I_{in} + C_a) - (E_{tc} + G_e + L_{out}) \quad (5b)$$

where

$I_g$  = gross irrigation requirement,  $P_e$  = effective rainfall,  $I_{in}$  = lateral Inflow,  $C_a$  = capillary rise,  $E_{tc}$  = evapotranspiration,  $G_e$  = deep percolation,  $L_{out}$  = lateral outflow

$$\sum \text{inflows} = \frac{\Delta \text{Storage}}{\Delta \text{time}} + \sum \text{outflows} \quad (5c)$$

$$\sum \text{inflows} = \frac{\Delta \text{Storage}}{\Delta \text{time}} + (E_{tc} + G_e + L_{out}) \quad (5d)$$



**Figure 4** | (a) Variation of yield and depth in Paleozoic formation. (b) Variation of yield and depth in the Precambrian formation. (c) Variation of yield and depth in the Precambrian formation.



Critically, it can directly be seen that making  $\Sigma$  inflows, the subject will estimate a quantity of water that is been sent into the ground, as shown in Equation (5c) and (5d). This water that is been sent into the ground is a source of replenishment to the existing water-table and also maintains the hydrological cycle. The components for the inflows include effective rainfall and gross irrigation requirement, which is excess water in the soil that is been leached into the aquifer. In summary, the water balance suggests that groundwater that is been used for irrigation goes a long way to replenish the aquifer and hence not to waste.

### Variation of depth and yield

Figure 4(a)–4(c) are results from the pumping test (depth and yield) plotted on a graph to correlate the borehole depth and yield. Graphically, the plotted feature depicted a weak correlation between groundwater depth and yield in the study area. This is a result of the underlying parent rock. Also, this shows that the weathering process and groundwater behavior in the Precambrian and Paleozoic sedimentary formation are the same.

### CONCLUSION

The data generated was from a hydrogeological perspective, analyzing the potential of groundwater within the study and its feasibility to add to the current agricultural work to boost irrigation in the study area. Northern Ghana has varying geology comprising the Precambrian and the Paleozoic sedimentary formation; the Upper Regions and part of the Northern Region of the Precambrian formation are made up of phyllite, schist, granite, meta-sediments, and meta-volcanics, while 90% of the Northern Region is made up of sandstone, shale, mudstones, and granitoids. The total groundwater storage capacity and the extractable storage after computation were approximately 710,000 Km<sup>3</sup> and 290,000 Km<sup>3</sup> respectively. The pumping test results show that the quantity of groundwater pumped out attests to the storage capacity of the study area and hence the tendency of groundwater to be more reliable and also a backup to support irrigation in the dry season.

### DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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