

Research Paper

Evaluation of aquifer hydraulic properties from resistivity and pumping test data in parts of Gwagwalada, Northcentral Nigeria

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Abstract: Population upsurge in Gwagwalada increased water demand in the area, thereby stressing water resources in the area. Aquifer properties in parts of Gwagwalada in North-Central Nigeria were therefore investigated using resistivity and hydrogeological approaches. Static water level measurements of hand dug wells were used to determine the groundwater flow direction for the area which coincides with the North East-South West joint direction. Constant rate pumping test was adopted for the research and 10 boreholes were pumped. The weathered/fractured basement range from 7.5 m to 56.7 m. The transmissivity values in the area ranged from 0.35 m²/d to 3.63 m²/d while the hydraulic conductivity range from 0.045 m/d to 0.18 m/d. The Vertical Electrical Soundings (VES) were carried out on the area. The geoelectric sections revealed four to five layers and the longitudinal conductance varied from 0.11 Ω⁻¹ to 0.37 Ω⁻¹. The results of the investigation characterized the groundwater potential in the study area into low and moderate while the aquifer protective capacity into weak and moderate zones. The efficacy of resistivity and pumping test data in quantifying aquifer properties has been established in this study. The findings of this study shed light on the properties of ground water and aquifer protective capacity in the area, hence assist in the effective future groundwater resources exploitation.

Keywords: Transmissivity; VES; Dar Zarrouk Parameters; Groundwater Potential; Aquifer Protective Capacity

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Introduction

Freshwater, made up of surface water (rivers, streams and lakes) and groundwater (Mishra,

2023), is the main source of water for various human activities such as agriculture, domestic use, fisheries among others (Gleick, 1996). Indeed, surface water resources are the most efficient way to meet water demand on planet (Van der Meulen et al. 2020). However, freshwater resource is unevenly distributed around the world (Khilchevskyi and Karamushka, 2021), hence not readily available to all (Nazario et al. 2023; Kasidi, 2017).

Federal Capital Territory (FCT) Abuja is underlain by the basement complex (Sunkari et al. 2021; Dinneya and Adigun, 2022) where surface sources of water supply are either inadequate, intermittent

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or polluted (Kasidi, 2017; Ighalo and Adeniyi, 2020). Consequently, domestic and industrial supplies depend heavily on groundwaters (Okogbue and Omonona, 2013; Rojanasakul et al. 2023). Evidently, groundwater is the main source of potable water supply in Abuja (Omada et al. 2024), supplementing the surface water which had become inadequate in both quality and quantity (Okogbue and Omonona, 2013; Umar et al. 2019). Nevertheless, this water source does not find everywhere in FCT (Sunkari et al. 2021), neither the yields of boreholes within the geological zones is efficient (Olasehinde et al. 2016). Notably, many folks are in dire need of this scarce resources (Asije and Igwe, 2014; Sunkari et al. 2021). Moreover, water resources' need increase as the population density and economy of metropolitan cities especially in developing countries (e.g. FCT) increase (Nugraha et al. 2022; Nazari and Keshavarz, 2023). Unfortunately, such drastic increase in population goes hand in hand with the continuous contamination of surface waters (Lapworth et al. 2022) and shallow aquifers. Gwagwalada area of Abuja is at the centre of the upsurge in population (Achichi et al. 2023) owing to (1) its location in the Federal Capital of Nigeria, (2) presence of the university and teaching hospital, (3) as well as mining, (4) agricultural and (5) industrial activities (Etu-Efeotor, 1998). Consequently, this has led to increase in the demand for groundwater to meet the water need of the people in the area (Dan-hassan et al. 2012).

There are several techniques and methods to assess groundwater, such as geophysical (Olasehinde, 1999; Hazell et al. 1992; Wiederhold et al. 2021), geological (Rizwan, 2018; Chilton and Forester, 1993; Haque et al. 2020), geospatial (Adewumi and Anifowose, 2017; Pal et al. 2020), and pumping test methods (Olorunfemi and Fasuyi, 1993; Amadi et al. 2020; Hasan et al. 2021). However, there is scanty information on the use of resistivity methods in Gwagwalada area, FCT. Thus, the current research aimed at evaluating the aquifer hydraulic properties in parts of Gwagwalada through resistivity method by computing Dar-Zarrouk parameters and pumping tests. Vertical Electrical Sounding (VES) techniques are widely used to obtain Aquifer parameters (Olayinka, 1990; Dan-Hassan and Yaya, 2007; Nugraha et al. 2022). Dar-Zarrouk parameters consists of longitudinal conductance, S (Ω^{-1}) and Transverse resistance, T (Ωm^2) (Henriet, 1976; Egbai and Iserhien-Emekeme, 2015; Naidu et al. 2021; Mahmud et al. 2022) and are derived from resistivity values (Egbai and Iserhien-Emekeme,

2015; Yusuf et al. 2021). Aquifer test is the most suitable means for estimating hydraulic characteristics (Fetter, 2001; Dan-hassan, 2013), since digests field data that reflects not only the point behavior of well location but also a certain volume of aquifer material around the well within the cone of depression (Sen, 2015).

In the current research, the groundwater potential map was drawn up based on hydraulic properties, namely transmissivity and hydraulic conductivity. The findings are expected to shed light on understanding of the aquifer systems and their properties to ensure sustainability of dependent life in Gwagwalada, especially the community in dire need of this water source. This would undoubtedly be achieved through the use of established groundwater potential and aquifer protective capacity maps of parts of Gwagwalada, the useful tools for effective future groundwater exploitation in this area.

1 Materials, methods and data processing

1.1 Study area

The study area is situated in the South-West of Gwagwalada, which is a part of FCT Abuja in Nigeria, lying between latitude $8^{\circ}54'00''$ to $9^{\circ}00'00''$ N and longitude $7^{\circ}00'00''$ to $07^{\circ}06'00''$ E (Fig. 1). The communities within the study area include Dukpa, Deshi Paiko, Paiko, Passu, Korokola, Kaida, Checheyi, Bako and Gwagwalada. The area is easily accessible due to a good road network.

Abuja is characterized by a well-defined dry and rainy season; the rainy season falls between April and October while the dry season is between Novembers to March. The rainy season is characterized by rise in water table and most streams have water while during the dry season, most of these streams are dried up. Federal Capital Territory, Abuja consists of 85% igneous and high-grade metamorphic rocks of the Nigerian basement complex and Cretaceous sedimentary rocks of the Bida Basin, which cover the remaining 15%. These rocks consist of gneiss, granite-gneiss and granites (Fig. 2) and are generally oriented from North-Northeast-South-Southwest (NNE-SSW). In most cases the rocks have weathered into reddish sandy clay to clay materials capped by laterite with lots of mica flakes (Offodile, 1992). In the study area, granite-gneiss are well represented among the three aforementioned major rock categories. The structural pattern in the area is characterized by

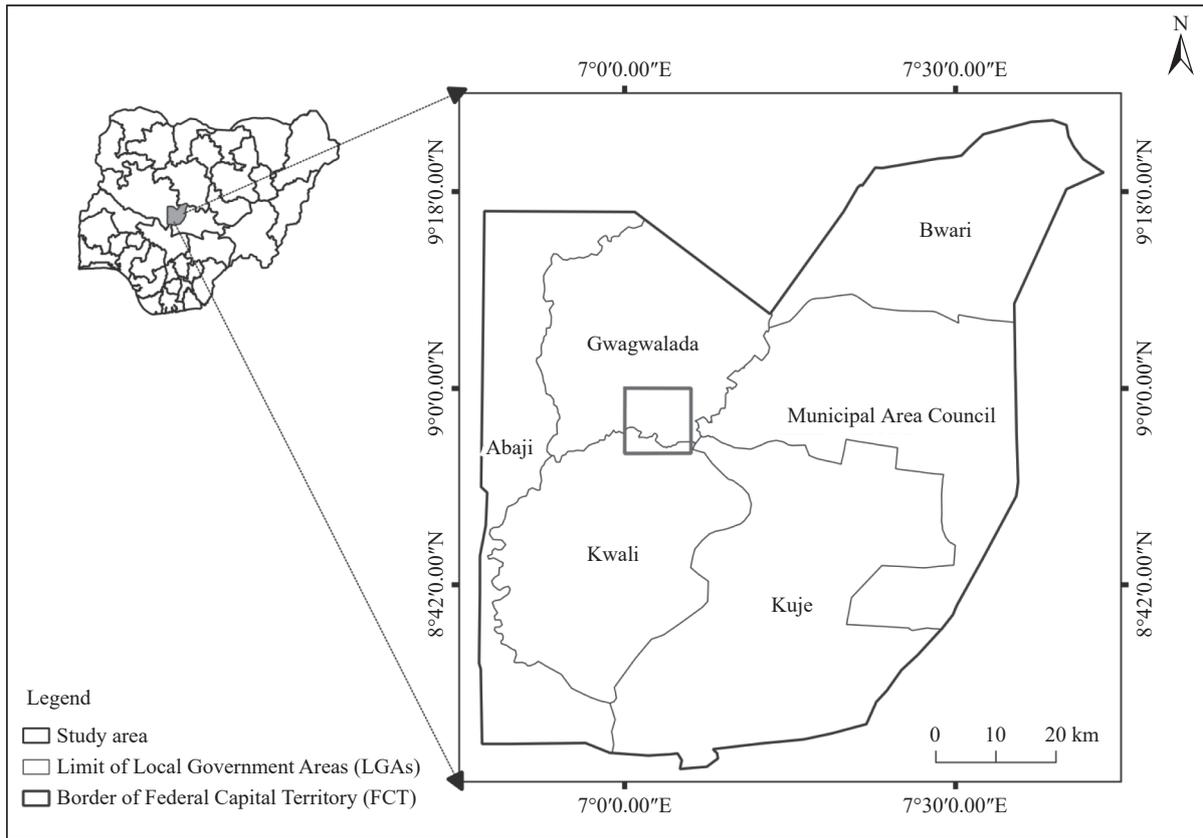


Fig. 1 Location map of the study area (modified from Elimian et al. 2020)

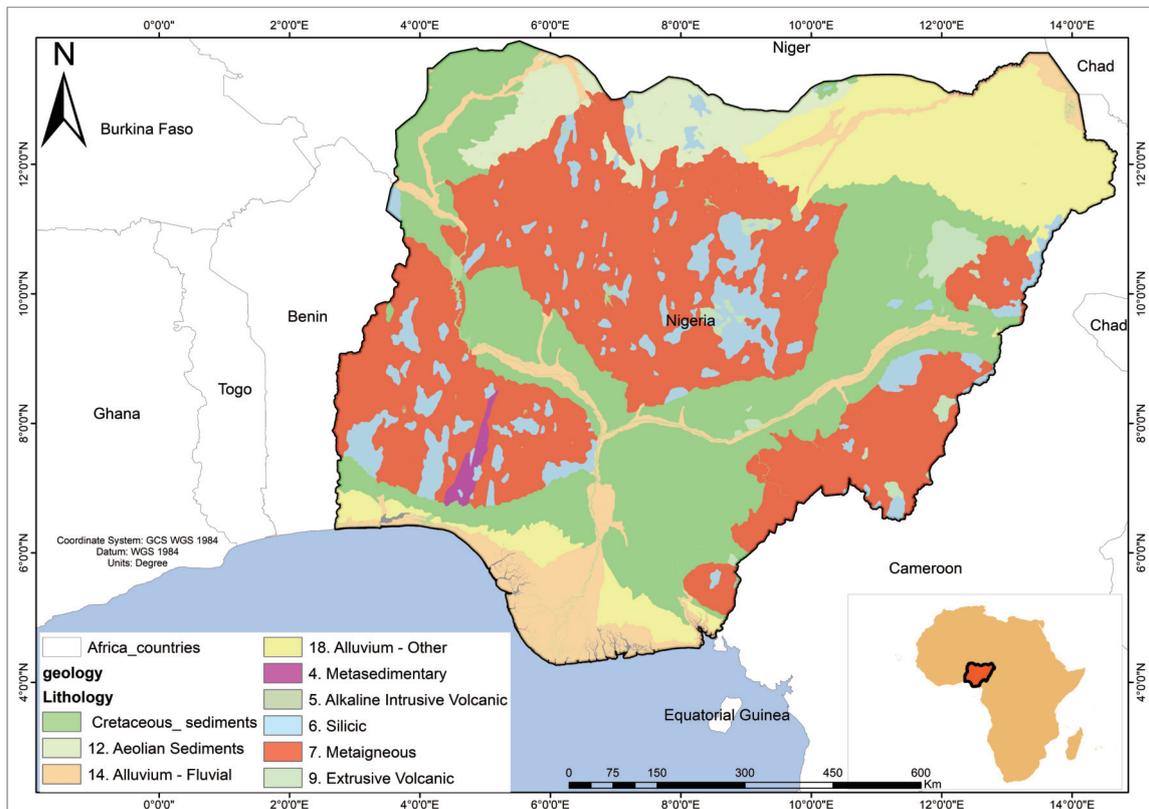


Fig. 2 Geological map of Nigeria (modified from the Nigeria Geological Survey Agency, NGSA, 2004)

two joint directions, NE-SW as the major, then the SE-NW direction; implying that the area has witnessed two orogenic events that are different in time and direction.

1.2 Methods

Electrical resistivity surveying involving Vertical Electrical Soundings (VES) was carried out in this research. As such, ten VES measurements were employed within the study area using the Schlumberger array configuration, chosen preferably by the side of the boreholes subjected to pumping test. The electrical resistivity measurements were performed using the ABEM SAS Terrameter 1000 powered by 12V D.C power source. For the current injection and voltage record, four cable wheels and four electrodes were used, while, four hammers and a measuring tape were used for fixing the electrodes and their separation measurements respectively. Current electrode separation, AB/2, and potential electrode, MN/2, were ranged respectively from 1 meter to a maximum of 160 meters and from 0.5 meter to 20 meters. The resistivity data was obtained by injecting the current electrodes (A and B) into the ground, thus the voltage difference between potential electrodes (M and N) was determined. Based on voltage (V) and current (I) values obtained, the apparent resistivity (ρ_a) was calculated as follows:

$$\rho_a = k \frac{V}{I} \tag{1}$$

The resistivity survey helped to determine the subsurface conditions of the area. VES data were interpreted using the curve matching technique. The curves were obtained by plotting the apparent resistivity data (ρ_a) as ordinates against the electrode AB spacing as abscissa in the log-log plot through the computer iteration using WINRESIST software. The subsurface conditions were deduced from a measured sounding curve in terms of the number of layers, their resistivities and thicknesses. Resistivities and thicknesses of each geoelectric layers are combined together to obtain the Dar Zarrouk parameters (Yusuf et al. 2021; Egbai and Iserhien-Emekeme, 2015), consists of Longitudinal conductance, S (Ω^{-1}) and Transverse resistance, T_r (Ωm^2) (Egbai and Iserhien-Emekeme, 2015). For a sequence of n layers of resistivity ρ_i and thickness h_i , the longitudinal unit conductance, S and the transverse unit resistance, T are defined by:

$$S = \sum_{i=1}^n h_i/\rho_i \tag{2}$$

$$T_r = \sum_{i=1}^n h_i\rho_i \tag{3}$$

Where: S is the longitudinal conductance (Ω^{-1}); T_r is the transverse resistance (Ωm^2)

The protective capacity and longitudinal unit conductance are considered to have a proportional relationship. Longitudinal unit conductance, S can be used directly in the protective capacity evaluation of aquifers to signify the regulation of percolation of contaminants into the aquifer (Henriet, 1976; Yusuf and Abiye, 2019).

The determination of the groundwater flow direction involved the measurement of Static Water Level (SWL) from 30 existing hand dug wells, their topographic elevations and coordinates in nearby communities within the study area. The weighted tape was lowered into the wells and as it touches the water, the SWL was read out on the ground surface and recorded. The elevations and topographic coordinates were determined with a Geographic Positioning System (GPS). By subtracting the SWL measured of each well from its topographic elevation above mean sea level, the hydraulic head of each well was obtained (Equation 4), which was used to produce the groundwater flow direction map of the area.

$$h = Z - d \tag{4}$$

Where: h is the Hydraulic Head (meter); d is SWL or Depth to water (meter); Z is the Topographic Elevation above mean sea level (meter).

The pumping test involved applying a stress to the aquifers by extracting groundwater from a pumping well and measuring the aquifer response to that stress by monitoring drawdown in function of time. Pumping tests were carried out on 10 boreholes within the study area to determine the aquifer hydraulic properties such as transmissivity and hydraulic conductivity, and incorporated them into appropriate well-flow equations (Equations 5 and 6). A constant rate and recovery test was used in this study through single-well aquifer test: the pumping test and the drawdown measurements were made in the same borehole. The details of the well such as the depth, the radius, the static water level, and the pump setting depth were recorded before starting the pumping. The pumping duration was ranged between 180 minutes to 360 minutes, according to when the steady state was reached. The measuring interval used was 1 minute for the first ten minutes, 5 minutes for the period from 10 minutes to 60 minutes of pumping, 10 minutes from 60 minutes to 120 minutes and finally 30 minutes from 120 minutes until pumping was exhausted. During the aquifer test, the

discharge rate of the well and the changes in water levels (drawdown and recovery) in the well were adequately measured.

Transmissivity (T)

In this study, where the abstraction wells were used as observation wells, Cooper-Jacob method was found suitable (Abimiku *et al.* 2019). The method gives a simpler algebraic solution to the Theis equation and permitted to determine the drawdown without the use of well functions (Okogbue and Omonona, 2013).

$$T = 2.303Q/4\pi\Delta s \tag{5}$$

Where: *T* is the transmissivity (m²/d); *Q* is the steady pumping rate (volume per unit time) measured during pumping test; Δs is the drawdown difference per log cycle (meter), obtained by plotting the time against the drawdown in the semilogarithmic plot.

Hydraulic conductivity (K)

It follows that hydraulic conductivity is the ratio of transmissivity to the Aquifer thickness (Equation 6).

$$K = T/b \tag{6}$$

Where: *K* is the hydraulic conductivity (m/d); *T* is transmissivity (m²/d); *b* is the aquifer thickness (m).

The transmissivity values were obtained from pumping test data while the aquifer thicknesses were deducted from the borehole lithologic logs.

2 Results and discussion

2.1 Geo-electrical characterization

The subsurface conditions in terms of the number of layers in the substrate, the thickness of each

layer and the ratio of the resistivity varied according to the layers (Table 1). The results of the quantitative interpretation revealed that typical 4- and 5-geoelectrical subsurface layers characterize the area, generating eight types of resistivity curves. The type curves include 2-KH, 2-HK, 1-HKH, 1-AA, 1-HA, 1-KQH, 1-HAK and 1-KHK (Fig. 3).

The surface layer, averaging 0.98 m thick and ranging from 0.5 m to 1.8 m, is observed in all VES locations. It exhibits a wide variation in resistivity ranging from 45.0 Ωm to 1,194.4 Ωm with an average of 281.23 Ωm and is identified as laterite by correlation with the general lithological log of the area. Meanwhile, the underlying laterite is a layer correlated to reddish brown, sandy clay and clayey sands, with thickness range from 1.4 m to 8.4 m, averaged 4.68 m, and resistivity range of 13.1 Ωm to 531.1 Ωm with an average of 168.94 Ωm (Table 1). The weathered and/or fractured bedrock found in the third and fourth geoelectric layers. In fact, the third layer, showed a range of resistivity between 33.7 Ωm and 1414.1 Ωm with an average value of 499.78 Ωm, with an average thickness of 29.93 m. On the other hand, in the fourth layer, the weathered/fractured zones revealed a resistivity range of (72.7–5378) Ωm and an average thickness of 42.68 m (Table 1).

2.2 Groundwater flow determination

The measured Static Water Level (SWL), the topographic elevation and the computed hydraulic heads varied among the six selected locations in the study area (Table 2). Indeed, the average hydraulic head values were 212.53 m, 190.1 m, 175 m, 171.8 m and 158.9 m for Dukpa, Passo, Paikon-Kore, Kaida and Koroko locations respectively. However, the Gwagwalada location where

Table 1 Results of resistivity, layer thickness surveys and classification of curve types

S/N	1 st layer		2 nd layer		3 rd layer		4 th layer		5 th layer		Curve type
	h ₁ /m	ρ ₁ /Ωm	h ₂ /m	ρ ₂ /Ωm	h ₃ /m	ρ ₃ /Ωm	h ₄ /m	ρ ₄ /Ωm	h ₅ /m	ρ ₅ /Ωm	
VES 1	0.5	1,194.4	8.4	96.5	69.9	446.9	∞	341.0	-	-	HK
VES 2	0.5	367.5	2.7	118.6	13.4	166.4	29.7	771.3	∞	83.7	HAK
VES 3	0.8	404.3	4.7	48.4	15.4	1414.1	∞	5,044.1	-	-	HA
VES 4	1.8	131.0	5.2	13.1	59.2	818.9	∞	265.1	-	-	HK
VES 5	1.4	59.0	2.0	80.5	10.7	33.7	∞	5,378.0	-	-	KH
VES 6	1.0	252.2	6.7	469.6	25.6	157.1	92.2	632.7	∞	365.1	KHK
VES 7	1.3	77.0	3.8	531.1	2.7	159.4	12.7	72.7	∞	8846.5	KQH
VES 8	0.9	128.8	6.8	151.5	31.1	139.5	∞	1,734.7	-	-	KH
VES 9	0.6	153.8	1.4	21.5	12.9	513.4	36.1	163.6	∞	1204.7	HKH
VES 10	1.0	45.0	5.1	138.6	32.5	630.2	∞	5,290.4	-	-	AA

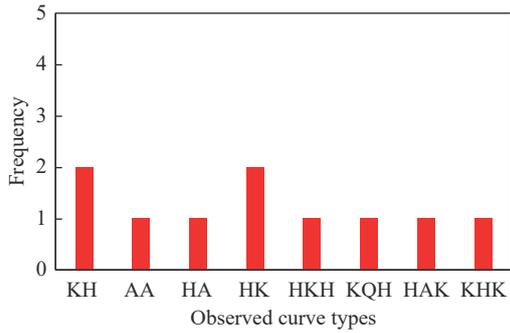


Fig. 3 Frequency distribution of the observed curve types in the study area

only one existing dug well was tested, the hydraulic head value of 211.8 m was correspondingly measured (Table 2). The groundwater flow direction map designed from the hydraulic head values and corresponding coordinates through Surfer 21 software, revealed that the high hydraulic head value is located in the Northwest, through which groundwater in the area flows towards southwest, south and west directions (Fig. 4). Indeed, groundwater flows from regions of high hydraulic head to regions of low hydraulic head.

The NE-SW groundwater flow direction is shown to be the main one, coinciding with the

Table 2 Data obtained from measured hand dug wells within the Study Area

Location	No. of wells tested	Elevation/m	Static water level/m	Depth of well/m	Hydraulic Head/m
Dukpa	9	139–224	0.8–3.1	4–7	135.9–282.5
Gwagwalada	1	214	2.2	5.5	211.8
Passo	6	180–202	0.2–3.5	4.1–5.7	177.5–201.8
Paikon Kore	4	174–184	0.0–5.5	3.2–6	169.5–183.9
Kaida	5	158–192	1.9–2.7	4.4–5.7	155.7–189.3
Koroko	5	154–170	1.8–2.8	3.0–4.9	152.2–167.5

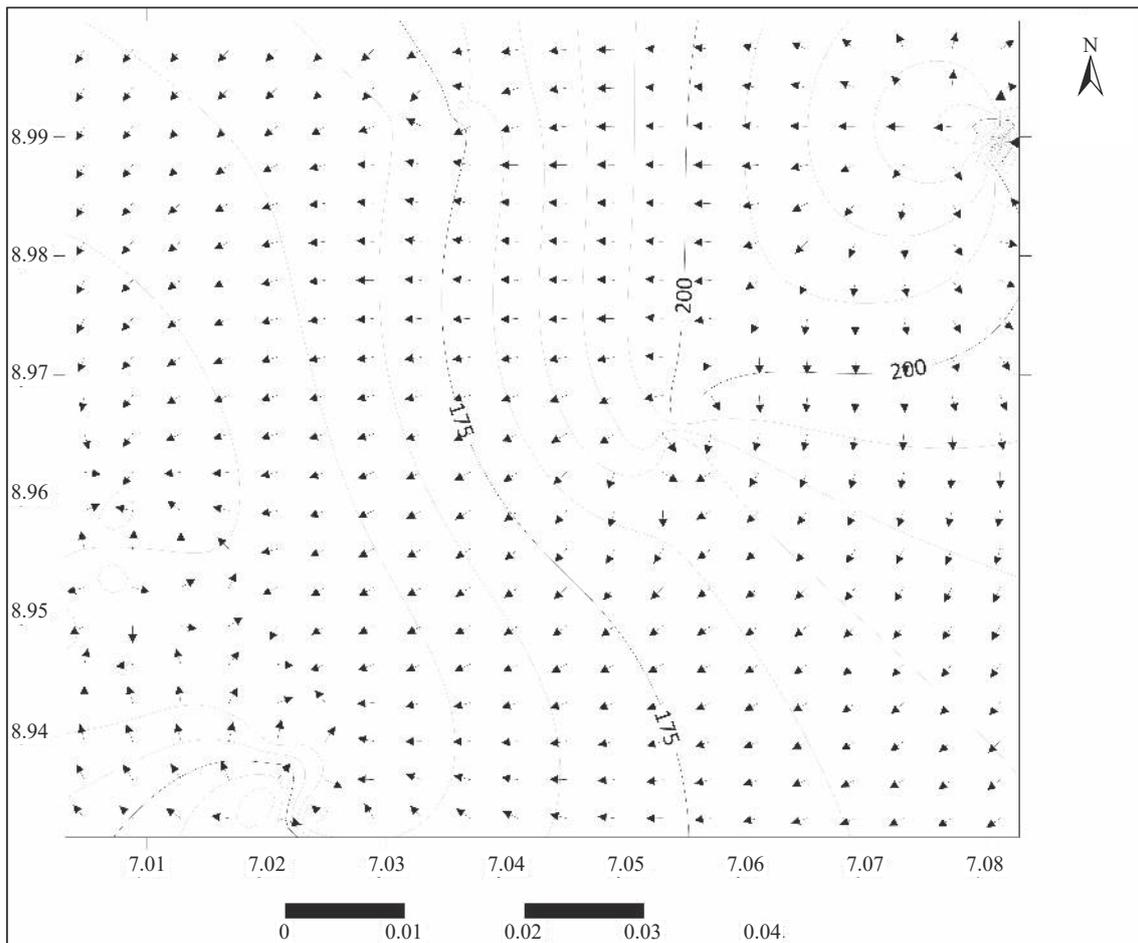


Fig. 4 Groundwater flow direction map of the area

major principal joint direction, portending that the groundwater flow direction in the area is structurally controlled. This further explains the overlapping and interwoven nature of geology, structural geology and hydrogeology in relation to groundwater studies.

2.3 Groundwater potentials evaluation

The groundwater potential was established through comparison of transmissivity and hydraulic conductivity values deduced from pumping test data (Fig. 8). Indeed, the details of aquifer parameters are summarized in the table 3, whereas the transmissivity values ranged from a minimum of 0.35 m²/d to a maximum of 3.63 m²/d at Borehole 5 and Borehole 2 respectively, with an average value of 1.36 m²/d. A contour map of transmissivity in the study area is shown in Fig. 5. Based on the Krasny's transmissivity classification standards by Krasny (1993) (Table 4) the tested aquifers are of two categories namely very low and low. Therefore, they are qualified for small sustainable withdrawal for local water supply.

The transmissivity map shows that the area of very low productivity found in the Northern and Eastern regions of the study area, covering almost 50% while the area of low productivity includes the Central, western and South-western regions. The general borehole lithologic log of the area and the weathered/fractured layer thicknesses obtained from the borehole driller, proved that the subsurface in the study area is made up of lateritic soil, sandy clay or clayey sand, weathered basement, fractured and fresh bedrock (Fig. 6). As such, the aquifers in the area are located within the weathered and/or fractured layer of the bedrock. The weathered/fractured layer thicknesses are ranged

from 7.5 meters (borehole 5) to 56.7 meters (borehole 10) with an average value of 18.81 meters (Table 3).

Hydraulic conductivity values are ranged from 0.045 m/d to 0.18 m/d, implying that the targeted area is semi-pervious (Table 5). The hydraulic conductivity contour map (Fig. 7) indicates an emphasis of K values in the south-western part of the study area, indicating that the permeability is somewhat more pronounced in this part of the study area. In fact, the high variability in the hydraulic properties, such as transmissivity and hydraulic conductivity from place to another in the targeted area can be subjected to the degree of weathering/fracturing of the geological materials. While assessing the homogeneity of an area, the pair-wise transmissivity revealed that only two cases (BH1 versus BH8 and BH4 versus BH9) found to be less than 5% over 45 (Table 6). Thus, the explored area does not have transmissivity homogeneity.

The spatial distribution of groundwater potential (Fig. 8) is established on the basis of comparing transmissivity and hydraulic conductivity values. The groundwater potential map shows that the areas where elevated transmissivity values intercept elevated hydraulic conductivity values are located particularly in the south-western portion of the area, thus marking the moderate groundwater potential area of approximately 30 percent. The remaining 70% with low groundwater potential are located in the north and the south-Eastern part of the targeted area (Fig. 8).

2.4 Aquifer protective capacity

The longitudinal conductance values vary from 0.11 Ω⁻¹ to 0.37 Ω⁻¹, with an average value of

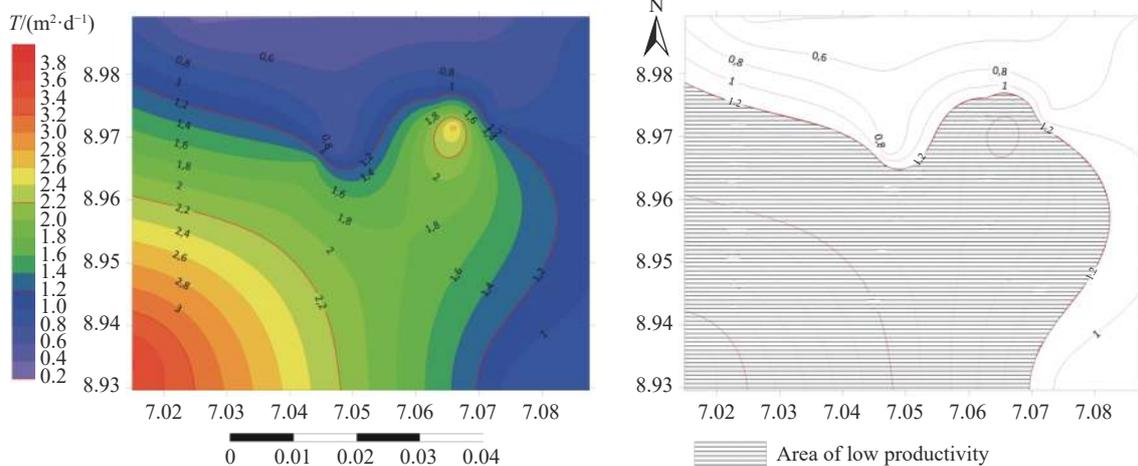


Fig. 5 Transmissivity-*T* (m²/d) contour map for the study area

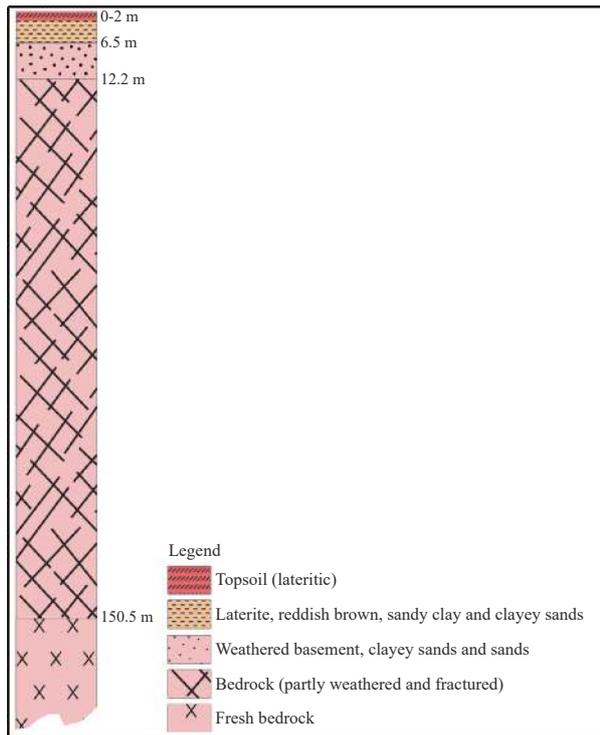


Fig. 6 General borehole lithologic log of the area

0.243 Ω^{-1} (Table 7). Therefore, based on criteria highlighted in the Table 8, the protective capacity for aquifer in the study area can be categorized into two weak and moderate. When comparing various longitudinal conductance, VES 2, VES 3 and VES 10 showed the lowest longitudinal conductance values containing in the interval between 0.1 and 0.19 Ω^{-1} , indicating that they have weak aquifer protective capacity (Table 7). Meanwhile, the longitudinal conductance values computed from VES 1, VES 4, VES 5, VES 6, VES 7, VES 8 and VES 9 are included in the bracket ranging from 0.2 Ω^{-1} to 0.69 Ω^{-1} , portending moderate aquifer protective capacity (Table 7).

The longitudinal conductance values were computed through Surfer 21 software to model the aquifer protective capacity pattern in the study area (Fig. 9). The Aquifer protective capacity map shows that approximately 50% of the study area are characterized as area of low protective capacity and tended to be oriented in a NE-SW direction, including the north-eastern, central and south-western as illustrated by purple, blue, green and yellow colors respectively. The remaining 50% are char-

Table 3 Results of aquifer test parameters

Parameters	Minimum	Maximum	Mean
Borehole depth (m)	124	200	155
SWL (m)	1.2	19.4	6.8
Yield (m ³ /d)	82.1	319.7	158.5
Drawdown (m)	6.6	84.6	38.7
Drawdown per log cycle (m)	4.8	56	28.6
Weathered/fractured layer thickness (m)	7.5	56.7	18.8
Transmissivity (m ² /d)	0.35	3.6	1.36
Hydraulic conductivity (m/d)	0.045	0.18	0.07

Table 4 Magnitude and variation transmissivity of Krasny classification (Asfahani, 2021)

Coefficient of T/ m ² /d	Class	Magnitude	Groundwater supply potential
> 1,000	I	Very high	Withdrawals of great regional importance
1,000–100	II	High	Withdrawals of lesser regional importance
100–10	III	Intermediate	withdrawal for local water supply
10–1	IV	Low	Smaller withdrawal for local water supply
1–0.1	V	Very low	withdrawal for local water supply with limited consumption
< 0.1	VI	Imperceptible	Source for local water supply is difficult

Table 5 Hydraulic Conductivity Classifications (Sen, 2015)

Km/s	10 ²	10 ¹	10 ⁰	10 ⁻¹	10 ⁻²	10 ⁻³	10 ⁻⁴	10 ⁻⁵	10 ⁻⁶	10 ⁻⁷	10 ⁻⁸	10 ⁻⁹	10 ⁻¹⁰
Relative permeability	Pervious			Semi-pervious			Impervious						
Aquifer	Good			Poor			None						
Consolidated rock	Highly fractured			Oil reservoir rock			Fresh sandstone		Fresh limestone, dolomite			Fresh granite	

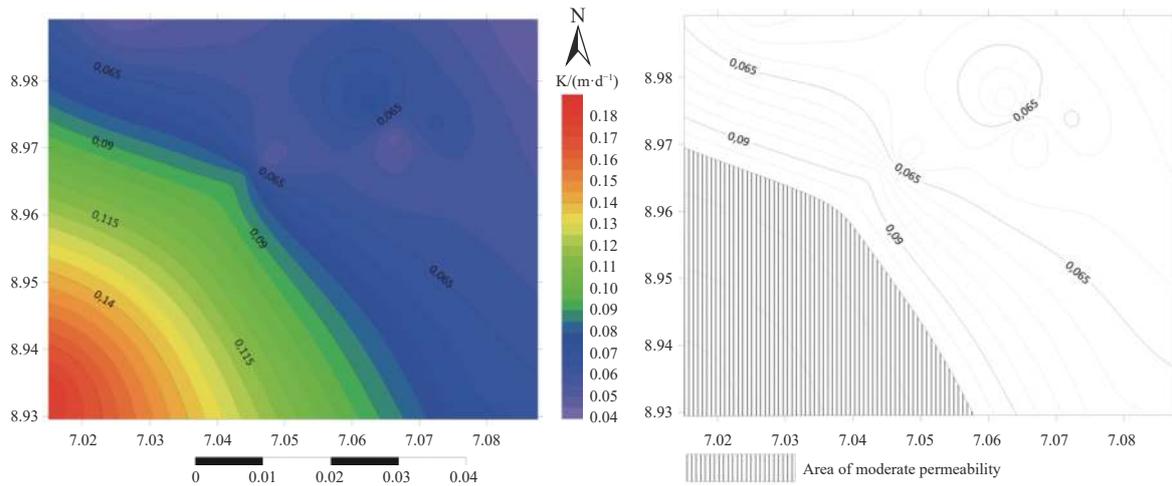


Fig. 7 Hydraulic conductivity-K (m/d) contour map for the study area

Table 6 Relative Errors from pair-wise of transmissivity values

Transmissivity	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10
BH1	74.9	45	8.1	61.4	33.4	23.2	1.3	7	66.5
BH2		54.3	77	90.3	83.3	67.3	75.2	76.6	24.9
BH3			49.5	78.8	63.3	28.3	45.7	48.8	39.2
BH4				58	27.5	29.5	6.9	1.3	69.3
BH5					42.1	70.4	60.9	58.5	87.1
BH6						48.9	32.5	28.4	77.7
BH7							24.2	28.6	56.4
BH8								5.7	67
BH9									68.9

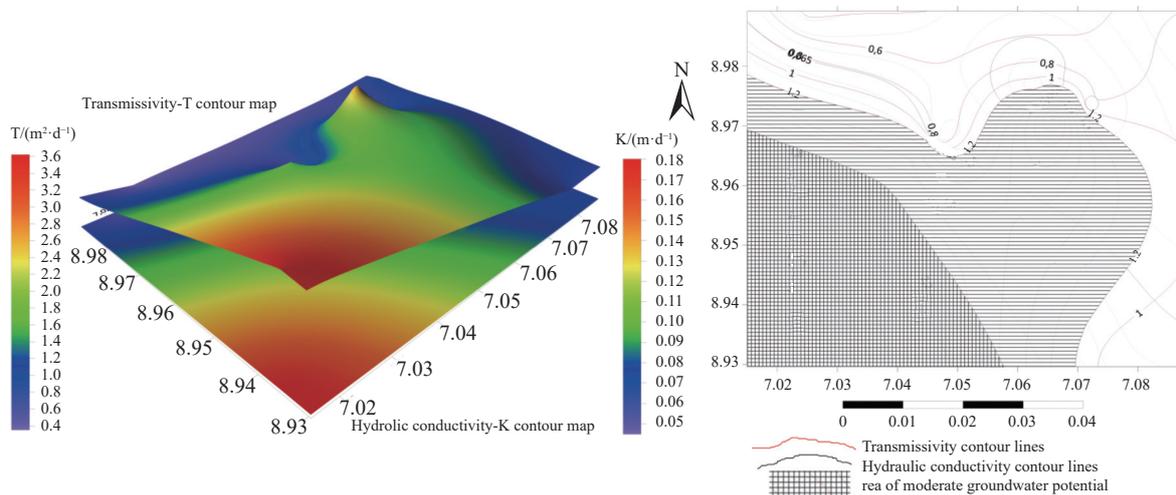


Fig. 8 Groundwater potential map for the study area

acterized as moderate protective capacity and are located in east, south-east and north-west indicated by dark yellow and orange colors.

Infiltration occurs easily in terrains of weak protective capacity than those with moderate protective capacity. Consequently, the transport of contaminants is barely restricted in such areas. Therefore, the areas of weak aquifer protective

capacity are vulnerable to pollution of groundwater resources, mainly of anthropogenic sources which are predominant in the study area.

3 Conclusion

The resistivity and hydrogeological approaches

Table 7 Longitudinal conductance values and aquifer protective capacity

S/N	Longitudinal conductance/ Ω^{-1}	Protective capacity
VES 1	0.242981	Moderate
VES 2	0.143161	Weak
VES 3	0.109976	Weak
VES 4	0.326328	Moderate
VES 6	0.326328	Moderate
VES 7	0.215667	Moderate
VES 8	0.274811	Moderate
VES 9	0.314822	Moderate
VES 10	0.11059	Weak

Table 8 Aquifer protective capacity rating (Nugraha et al. 2022)

Longitudinal conductance/ Ω^{-1}	Protective capacity
> 10	Excellet
5–10	Very good
0.7–4.9	Good
0.2–0.69	Moderate
0.1–0.19	Weak
< 0.1	Poor

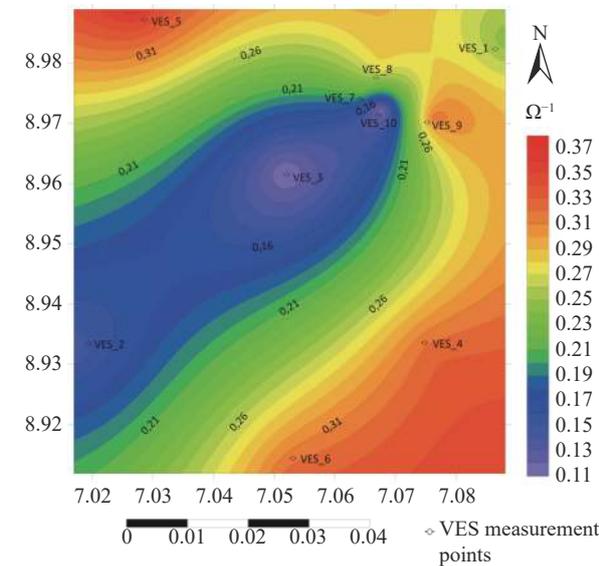


Fig. 9 Aquifer protective capacity map for the study area

applied in current study, have unraveled the aquifer hydraulic properties and details on groundwater in the targeted area. The present findings revealed that the Gwagwalada area is characterized by four to five layers, depicting laterite, reddish brown, sandy clay and clayey sands, underlain by weathered/fractured layer and fresh bedrock. The ground-

water flows from north-east towards southwest, south and west directions with emphasis in south-west direction, coinciding with the principal joint direction. There is enough evidence to conclude that the aquifer transmissivity in the explored area is classified into low and moderate, whereas protective capacity is subdivided into weak and moderate zones according to standard classifications. Since the aquifer with weak protective capacity are prone to groundwater pollution owing to high infiltration rate, the proper waste management by community is highly recommended. Eventually, this study provided a baseline information for efficient estimation of the amount of groundwater available for exploitation in the study area and to ensure its sustainability.

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