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Hydro-geophysical assessment of aquifer zones in Niger semi-arid regions

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Abstract

Recognizing the critical role of groundwater as the primary drinking water source for millions worldwide, particularly in semi-arid regions like Niger, the UN Sustainable Development Goal (UN-SDG) aims to prioritize its sustainable management. Addressing water scarcity challenges through accessible, pure, and naturally filtered groundwater supports UN-SDG objectives for clean water and sanitation (Goal 6), ensuring its availability for domestic, agricultural, and industrial needs. This research contributes to the understanding groundwater potential zones and aquifer protective capacity in Niger's semi-arid region, supporting sustainable water resource management in Niger's semi-arid regions, Tillabery, Niamey, Dosso, Thoua, and Maradi. Using Vertical Electrical Sounding (VES) techniques, 166 data points were collected employing the Schlumberger electrode configuration. Geoelectric properties (resistivity and layer thickness) were derived, and Dar-Zarrouk parameters were calculated. Contoured maps visualizing longitudinal conductance (S), transverse resistance (T), and electrical anisotropy (λ), helped classify groundwater potential zones. The northeastern part showed low resistance, indicating a good groundwater potential zone. The aquifer is encountered at a depth of 11 m to 15 m in a sandy clay environment. Assessment of longitudinal conductance revealed a moderate to very good aquifer protective capacity, particularly in the southwestern and central-western sectors. To validate, eighteen borehole sites were analyzed, correlating findings with borehole drilling data to create a 3D aquifer thickness model. We found that the aquifer thickness is from 1.5 to 3.5 meters in certain regions exhibiting robust protective capacity, enhancing aquifer resilience against surface contamination. Analysis of the electrical anisotropy coefficient provided insights into geological structures like fractures and bedding planes, influencing fluid flow dynamics and contaminant movement.

Keywords: Vertical Electrical Sounding (VES), Dar-Zarrouk parameters, Arc Scene, 3D Aquifer model, Semi-arid region, Niger

INTRODUCTION

Niger is a country located in the African continent within the semi-arid Saharan region, and its main challenge is aridity. The study area is mostly desert and the bulk of the population relies on the Niger River for agriculture and irrigation. (Arora et al., 2023). The population relies on groundwater for essential drinking and domestic water needs, which requires a comprehensive understanding of the aquifer in the challenging hard rock terrain. Reliable information on groundwater recharge mechanisms and rates are scarce in this region, so reliance on seasonal rainfall and flooding is evident to replenish shallow aquifers. Unfortunately, diminishing rainfall by 25-40% since 1930-1960, has made this vital water source precarious (Nicholson et al., 2000). Although recharge rates are generally low across the country, some areas witness adequate water yields from the dug wells, albeit in scarce numbers. Compelling groundwater exploration in the Niger, demands a systematic scientific approach due to inherent uncertainties. With the climate patterns shifting and rainfall increasingly erratic, a nuanced understanding of aquifer composition becomes pivotal for sustainable water management. Addressing these challenges will ensure water security and resilience in evolving climatic conditions.

Leduc et al. (1997) used hydrodynamics and geochemical methods during the early 1990s to evaluate natural groundwater recharge on a regional scale in unconfined aquifers. To determine delineation of aquifer zones, they relied on direct current (DC) resistivity soundings, which is a widely used geophysical technique (Van Nostrand and Cook, 1960; Zohdy, 1974; Koefoed, 1979; Patra and Mallick, 1980; Dutta et al., 2006; Dar et al., 2017; Arora et al., 2023). The electrical resistivity of the subsurface is closely linked to pore spaces, with layers featuring larger pores filled with fluid exhibiting lower resistivity than those with more compact pore structures. Groundwater exploration can be challenging due to the geological heterogeneity of the subsurface. It introduces complexities, highlighting the need for a nuanced understanding of subsurface geological variations. Thus, a scientific approach integrating hydrodynamics, geochemistry, and geophysical techniques can contribute to a more comprehensive understanding of natural groundwater recharge dynamics on a regional scale.

Groundwater exploration was conducted in the present study area, utilizing 166 electrical-sounding surveys by employing the Schlumberger electrode configuration. The gradual variation in DC sounding provides a reliable representation of subsurface changes with depth, similar to other geophysical methods. This data was then inverted to create a representative subsurface model. To enhance the reliability of the information, data from 18 specific sites were cross-referenced with borehole drilling data. These records provided a comprehensive understanding of subsurface characteristics, enabling the identification and delineation of potential aquifer zones. The obtained information was validated at 18 specific sites through correlation with borehole drilling data. This integration of data from borehole drilling served as a critical source, offering a comprehensive understanding of subsurface characteristics. This approach facilitated the delineation of potential aquifer zones tailored specifically for prospecting drinking water resources. The combination of electrical sounding surveys and borehole drilling data analysis, enhances the scientific rigor and accuracy of the groundwater exploration process, particularly in urban settings like Niger.

STUDY AREA AND HYDROGEOLOGY

Situated in the heart of West Africa, Niger is a landlocked country officially known as the Republic of Niger. It shares borders with several neighboring countries, including Algeria, Libya, Chad, Nigeria, Benin, Burkina Faso, and Mali (Figure 1). The study area boasts a diverse topography encompassing deserts, semi-arid plains, mountains, and fertile valleys. The region's topographic elevation varies from 174 to 302 meters above mean sea level (msl). The Sahara desert dominates the north, while the Sahel, a transitional zone between desert and savanna landscapes, characterizes the southern region. The study area includes, Tillaberi, Niamey, Dosso, Tahoua, and Maradi of Niger regions, together with Tillaberi, show casing a hard rock terrain having an Archean basement. Figure 2 shows the geology and soil maps of the study area . Granite is the primary rock type, with gneisses serving as a basement for intrusive rocks. The gneisses are a massive, rich in quartz, feldspar, and mica minerals, and the area is highly dissected with lineaments such as dolerite dykes and quartz veins (Arora et al., 2023). The Niger river, one of Africa's longest rivers, is a significant geographical feature traversing the Niamey region in the Niger. Originating in the Guinea Highlands, it converges with its primary tributaries, the Bani and Milo rivers, before flowing through Mali and entering into Niger. The Niger river, coursing eastward, culminates its journey in the Atlantic ocean via Nigeria. Along the Niamey region, geological formations reflect a history of erosion and deposition, intricately shaping the landscape over time. These processes have sculpted the region's geological characteristics (Chappell and Oliver, 1997). The Dosso region, located in a sedimentary terrain, is characterized by abundant lacustrine and marine deposits, particularly fine to medium-grained sand. Notably, the Niger river has Gondwana sandstone deposits in the Dosso. Niamey, Tahoua, and Maradi regions which are characterized by sedimentary terrains composed mainly of laterites and sandstone. In Maradi's composite soil cover, dry laterites and sand is prevalent. These geological features give each region its unique sedimentary composition and topography. Meanwhile, the Dosso region, located along the Niger river, boasts an abundance of Gondwana sandstones and fine to medium-grained sand. The Niger river is renowned for its vast alluvial deposits, which consist primarily of sedimentary materials like sand, silt, and clay. These deposits are formed as the river continually erodes adjacent rocks and deposits sediment along its path. The fertile floodplains make the Niger river, a critical water resource for agriculture in the area.

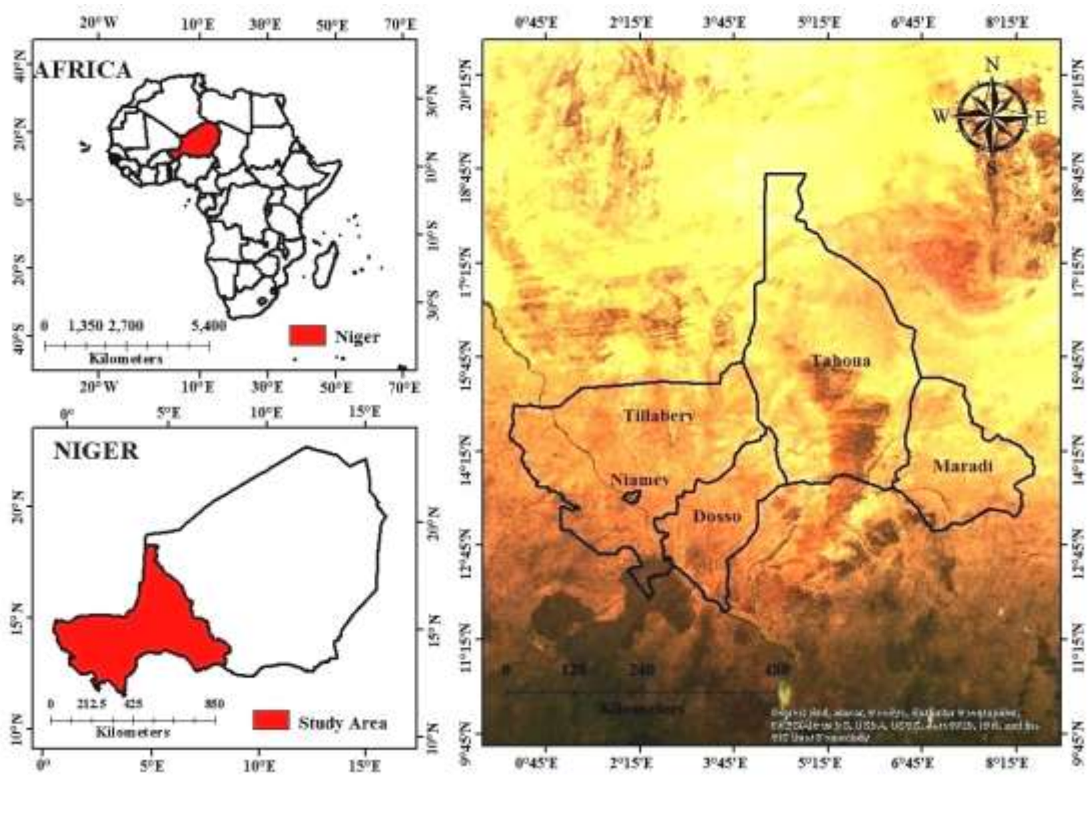

Figure 1. Location map of the study area including cities of Niamey, Tillabery, Tahoua, Maradi and Dosso in Niger.

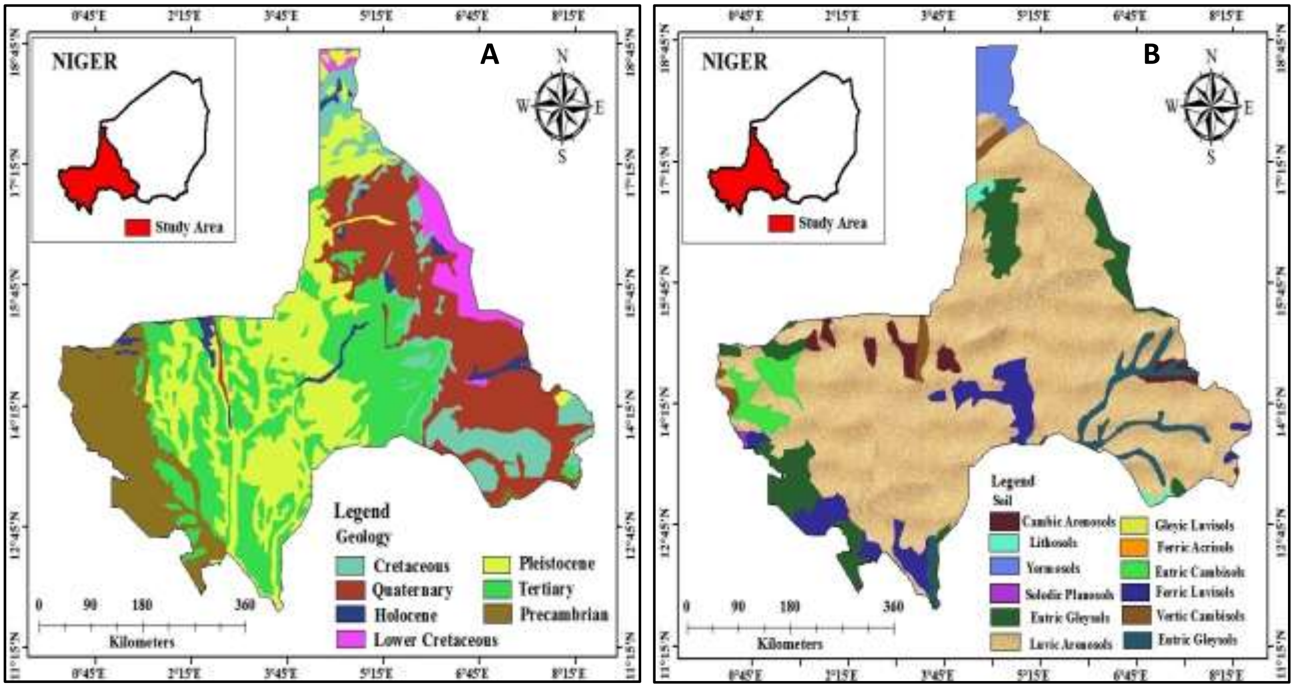

Figure 2. (**A**) Geology map, and (**B**) Soil map of the study area in Niger.

A previous study done by Arora et al. (2023) has recorded water table depths ranging from 3 to 50 m below ground level in southwest Niger; the potential aquifer zones identified are located in sandy clay or sandstone formations, exhibiting unconfined and confined aquifers (Vouillamoz et al., 2007), attributed to the accumulation of unconsolidated formations above the basement. This complex interaction between geological formations and water movement dynamics, highlight the importance of impermeable layers in determining groundwater conditions. Along the Niger river and its tributaries, diverse alluvial deposits with varying compositions, serve as potential aquifers (Thevoz et al., 1994). Accurate determination of layer thickness is thus essential. The Niger river plays a significant role in the hydrogeology of the Niamey region, recharging local aquifers through direct infiltration. Therefore, sustaining ecosystems and supporting human activities rely heavily on replenishing groundwater systems along the river.

The main objective of the study is to identify potential groundwater resources within the five regions (Niamey, Tillabery, Tahoua, Maradi, and Dosso) of Niger, using the integration of the vertical electrical sounding and lithological information. This involves mapping the extent and thickness of the aquifer utilizing GIS. By integrating various datasets and analytical techniques, the spatial distribution of groundwater resources and their availability for sustainable utilization is to be assessed.

METHODOLOGY

The Vertical Electrical Sounding (VES) method, a geophysical electrical survey technique, efficiently probes the earth's shallow subsurface resistivity structure. Renowned for its convenience and minimal environmental impact, it utilizes direct current as its energy source. Resistivity is the inherent property of a material that quantifies its resistance to electrical current flow. Ohm’s Law describes the relationship between voltage (V), current (I), and resistance (R) in a circuit, is given by

$$V = I \times R \qquad (1)$$

The SYSCAL resistivity equipment was used as the main instrument for this investigation. It worked as a signal averaging system, calculating voltage by multiplying current and a constant field configuration. The apparent resistivity values were plotted on a bi-logarithmic sheet, with the X-axis denoting the distance AB/2 and the Y-axis indicating the resistivity values. We created resistivity models and used the IX1D (Interpex, 2006) computer software to interpret the data.

The lithological model is constructed from stacked raster surfaces, representing the vertical arrangement of sedimentary layers, with the highest surface being the Digital Elevation Model (DEM) and the lowest being the upper boundary of ancient Precambrian basement rocks. By visualizing lithostratigraphic logs, this method accommodates various stratigraphic data sources, including boreholes, outcrops, and water wells.

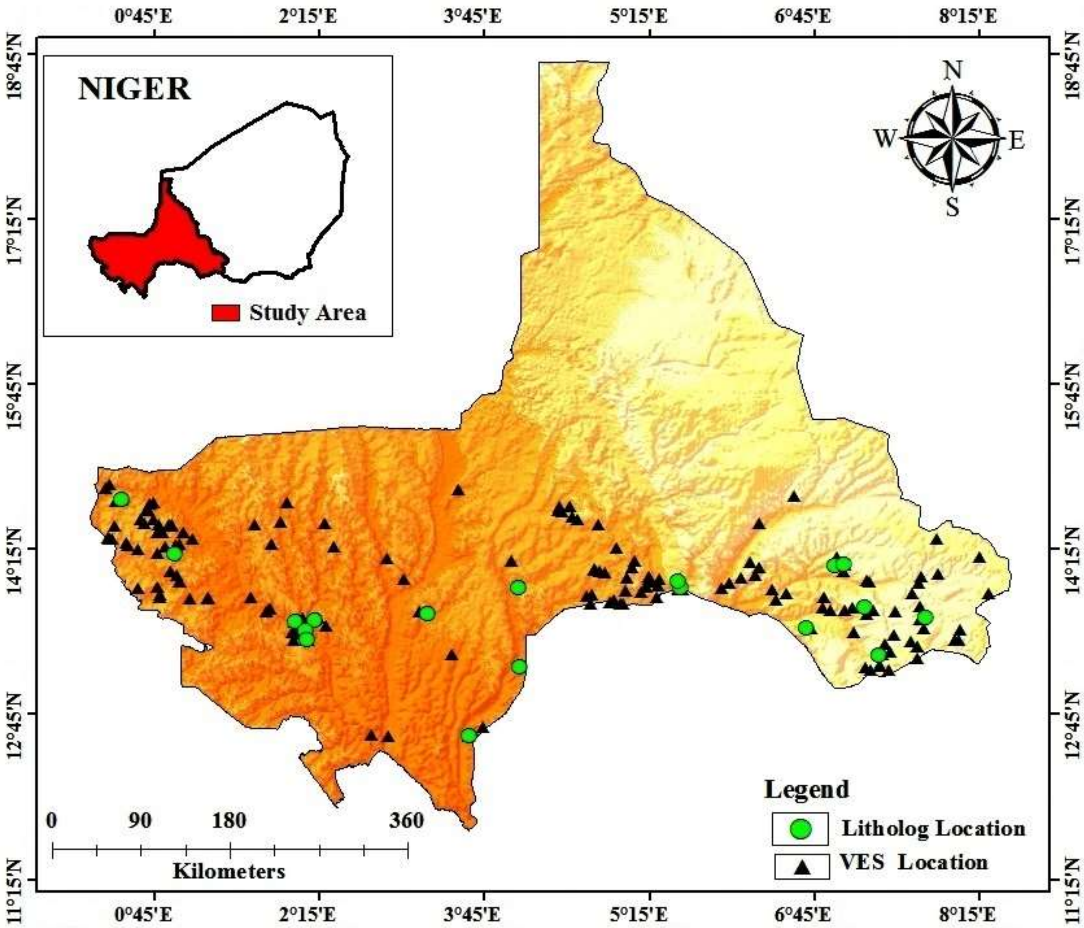

Figure 3. Map of the study area showing the location of Vertical Electrical Sounding (VES) and drilled litholog locations within the various regions of the study area. DEM: digital Elevation Model.

The study incorporates 18 locations with lithological data (Figure 3), encompassing three geological layer boundaries, each with distinct XYZ coordinates.

Dar-Zarrouk parameters

The Dar-Zarrouk (D-Z) parameters, which include transverse resistance (T) and longitudinal conductance (S), were first introduced by Maillet (1947). These parameters, especially longitudinal conductance (S) and transverse resistance (T), are crucial for interpreting subsurface characteristics and identifying water-bearing zones (Sri Niwas and Olivar, 2003). Transverse resistance measures the resistance perpendicular to groundwater flow for a unit cross-sectional area. In contrast, longitudinal conductance measures the conductance parallel to groundwater flow for a unit cross-sectional area. These parameters are essential in resistivity soundings, as they help determine the hydrological properties of aquifers. In this study, we analyze the data using the D-Z parameters, specifically longitudinal unit conductance (S), transverse unit resistance (T), and electrical anisotropy (λ), as outlined by Batte et al. (2010) and Singh et al. (2004).

Let us consider a prism of unit cross-section, which is characterized by its thickness 'h' and resistivity ρ. Then, the resistance (T) perpendicular to the face of the prism (Mondal et al., 2013) can be written as:

$$T = h \times \rho \tag{2}$$

and

$$S = \frac{h}{\rho} \tag{3}$$

It is considered that the prism consists of n-geoelectric layers and is entirely characterized by its thickness h_1, h_2…… h_n and resistivity's ρ_1, ρ_2…..ρ_n, respectively. Then, the total resistance of the current flowing perpendicular to the layers will be the sum of resistance offered by each layer and that can be expressed as follows

$$T = h_1\rho_1 + h_2\rho_2 + \cdots + h_n\rho_n \tag{4}$$

or

$$T = \sum_{i=1}^{n} h_i \rho_i \quad (5)$$

Where T is transverse resistance.

The transverse resistivity to the current flowing perpendicular to the layers is given by

$$\rho_t = \frac{T}{H} \quad (6)$$

where H is the sum of n layers in the prism.

Similarly, the total conductance of the current flowing parallel to the layers is given

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n} \quad (7)$$

or

$$S = \sum_{i=1}^{n} \left(\frac{h_i}{\rho_i}\right) \quad (8)$$

which is longitudinal conductance.

The longitudinal resistivity of the current flowing parallel to layers is given by

$$\rho_l = \frac{H}{S} \quad (9)$$

and the coefficient of anisotropy (λ) is given by

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}} \quad (10)$$

The above parameters were used to delineate the subsurface freshwater zones in the study region and determine aquifer protective capacity.

3D Modeling in Arc Scene

The available borewell data was used to create a lithology unit in Arc Scene. Arc Scene was used to improve mathematical precision while interpolating surfaces for analysis and building sedimentary packages for layers. Depending on the dispersion and trends in the data points, point clouds for each interpreted surface were imported into Arc Scene and interpolated with either inverse distance weighting (IDW) or Kriging. For surfaces having a clear trend to the data points, such as a steady inclination in one direction, a Universal Kriging (UK) interpolation method using a Semi-variogram model of "linear with ordinary" was applied. The UK interpolation approach extends ordinary kriging by integrating the local trend inside the chosen neighborhood search radius as a smoothly evolving function of the coordinates (Li and Heap, 2008). For surfaces with higher imperfections, such as the top surface of a sedimentary package containing huge boulders, ordinary kriging with a spherical semi-variogram model, or IDW, was utilized for interpolation. IDW determines the values in the voids between the points using a linear combination of values from sampled points.

In this case, the values of the nearest data points are weighted more heavily in the distance function for interpolation, presuming that they are more comparable to the unsampled region than the values of the data points further away (Kristine and Karlsen–, 2019). The outcomes of these interpolations consist of raster data, wherein each cell holds a single height value with a spatial resolution of 0.16. These interpolated raster datasets were then transformed into a Triangular Irregular Network (TIN) model, creating a three-dimensional representation. It is observed that the points extracted from the CSV file alongside the corresponding TIN-generated surface derived from Grid 2. The final stage in constructing a three-dimensional model for underground sedimentary layers involved utilizing the "Extract Package" tool in Arc Scene. This tool facilitated the generation of radar packages between specific radar surfaces, culminating in representing subsurface sedimentary sequences in a 3D format. Generating TIN (Triangulated Irregular Network) models, through interpolation, was explicitly undertaken to obtain 3D outcomes for Grid 2. The data at 50 MHz was initially acquired in 2D profiles, which inherently constrains the 3D representation of subsurface structures. The points corresponding to the borehole data beneath the ground, were transformed into polylines to address this limitation. This transformation was accomplished utilizing Arc Scene's Data Management tools' "Points to Line" function. Subsequently, the "Extrusion" technique was applied to the layer properties of each point dataset, allowing for the elevation-based extension of the point data into 3D space.

RESULTS

Aquifer characteristics using the Dar-Zarrouk parameters

The Dar-Zarrouk (DZ) parameters were systematically computed for the subsurface layers encompassing local aquifers composed of sand, clay-mixed sand, weathered formations, and fractured rocks extending down to the bedrock within the investigated region. Potential groundwater zones were delineated by the geoelectric characteristics derived from resistivity interpretation and the calculated DZ parameters. The assessment of groundwater potential in the study area hinged upon using maps generated from VES interpretation results, explicitly focusing on the anisotropic coefficient, transverse resistance, and longitudinal conductance. These maps serve as valuable tools for identifying optimal yield areas within the aquifer, particularly in the challenging terrain of shallow aquifers within hard rock formations. The presentation and discussion of these maps offer valuable insights into realistic groundwater modeling within the specified geological context.

Longitudinal conductance (S)

The S map of the study area is divided into three potential zones: good, moderate, and low. The area's longitudinal conductance (S) ranges from 0.02 Siemens at VES-136 to 9.6 Siemens at VES-59, with a contour interval of 1. Areas with an S value of less than 2 Siemens is considered good groundwater potential zones, those with S values between 2-4 Siemens are moderate, and those above 4 Siemens are of low potential zones (Ndatuwong and Yadav, 2015). **Figure 4** shows low S values in 83% of the study area, while 8% have moderate S values, and 9% have high S values.

Aquifer protective capacity can be classified into poor, weak, moderate, good, very good, and excellent using longitudinal conductance (S) values (Oladapo et al., 2004). Clayey overburden is known to have high longitudinal conductance, protecting against contaminants permeating the underlying aquifer (Oladapo and Akintorinwa, 2007).

Table 1 shows that the modified classification system quickly categorizes an area's protective capacity. The longitudinal conductance map (Figure 4) shows that 38.54% of the area falls within the good protective capacity, 5.42% within the very good protective capacity, and 1.20% within the excellent protective capacity. About 35.54% fall within the moderate protective capacity, and 7.85% within the poor protective capacity. These results indicate that the study area is dominated by moderate to excellent protective capacity.

Transverse Resistance (T)

Aquifer transmissivity indicates the ability of the layer of known hydraulic conductivity to transmit fluids through its entire thickness. On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to transverse resistance (Henriet, 1976; Ward, 1990). The transverse resistance ranges from 126.79 Ωm^2 at VES 154 to 80101.66 Ωm^2 at VES 34 as shown with contour interval 10,000 Ωm^2 in Figure 5. It is classified into good, moderate, and low potential zones. Values of T that range between 20,000-40,000 Ωm^2 and those above 40,000 Ωm^2 are considered moderate and good potential zones respectively and while values less than 20,000 Ωm^2, are considered low potential zones (Ndatuwong and Yadav, 2015). Figure 5 shows low T values in 73% of the study area while 17% have moderate T values, and 10% have high T values. This suggests that about 27% of the study area is characterized by moderate to high transverse resistance, considering the groundwater potential zone. This increasing T value also indicates the high transmissivity of the aquife

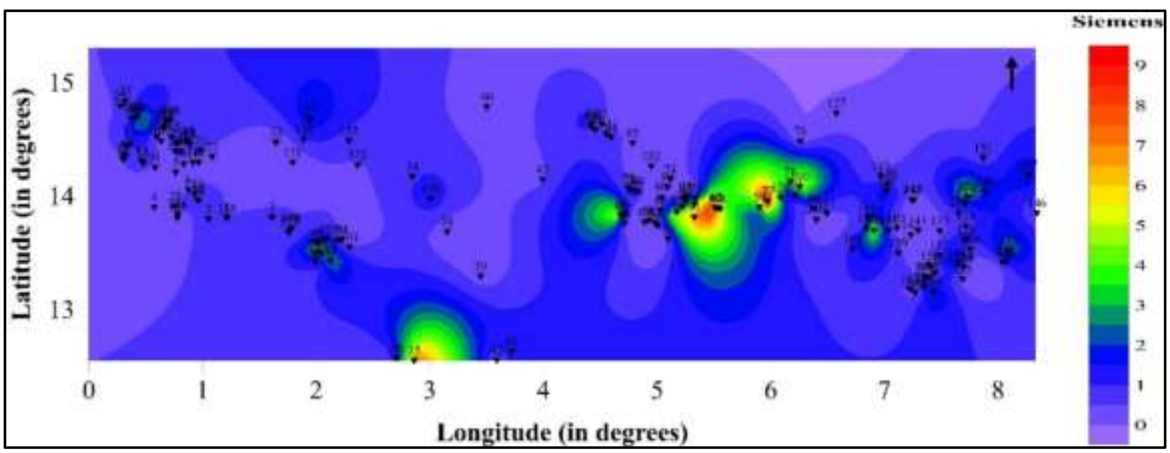

Figure 4. Spatial distribution of longitudinal conductance (S) in Siemens in the study area.

Table 1. Modified longitudinal conductance/ protective capacity ratings (Oladapo et al., 2004)

Longitudinal conductance (S)	Protective capacity rating
<0.1	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–4.9	Good
5–10	Very good
>10	Excellent

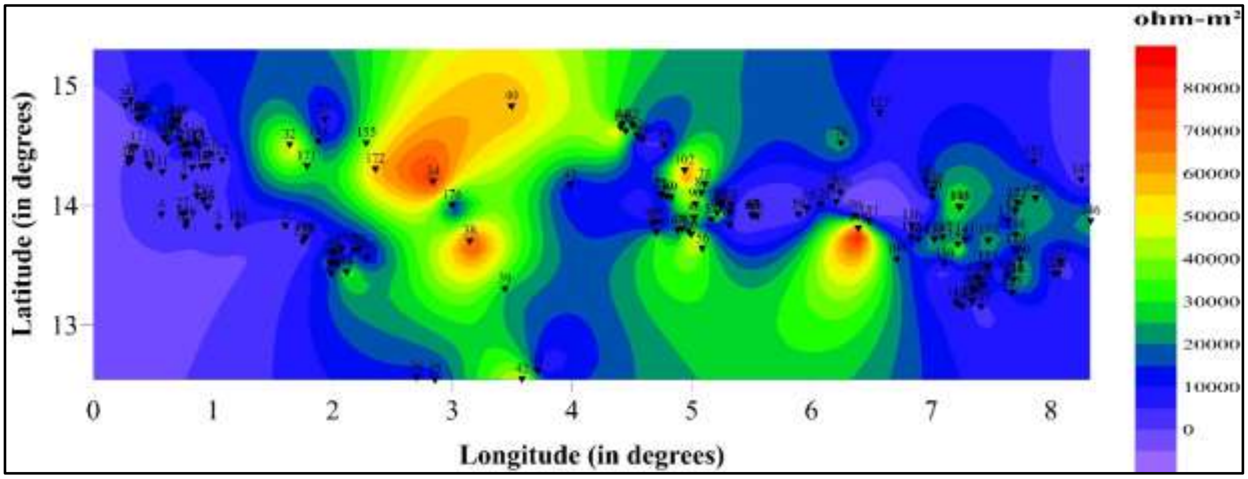

Figure 5. Spatial distribution of transverse resistance (T) in Ohm-m^2 in the study area.

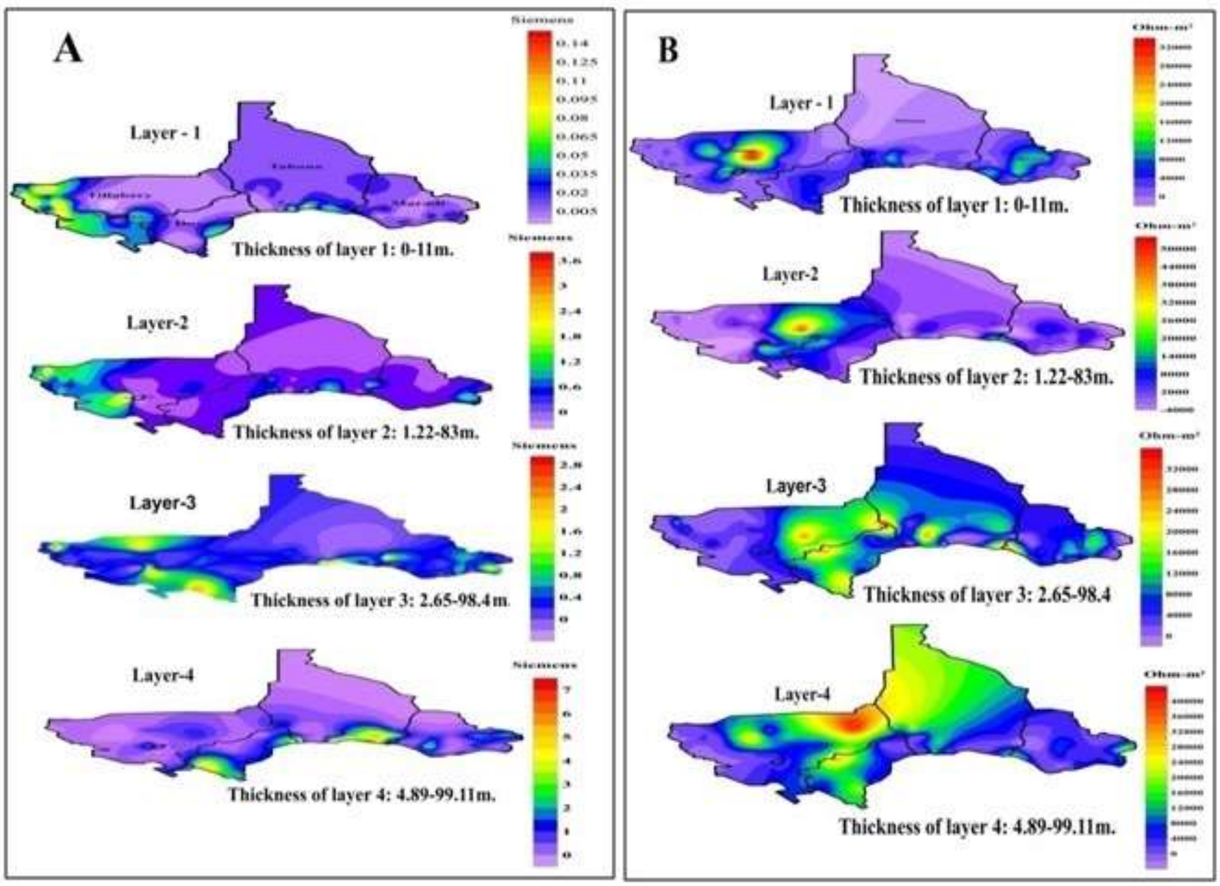

Figure 6. **(A)** Layer-wise spatial variation of longitudinal conductance in Siemens, and **(B)** transverse resistance (T) in Ohm-m^2 in the study area.

Depth-wise layered variation of longitudinal conductance (S) and transverse resistance (T)

Based on the observations illustrated in Figure 6, it is evident that there is a discernible pattern in the longitudinal conductance (S) and transverse resistance (T). Notably, there is a horizontally elongated zone in both conductance and resistance. Further analysis of the borehole data corroborates these observations. Figure 6 clearly represents the variation in S and T values as we delve deeper into the earth, from the first layer to the last. The S value increases from the top to the bottom, with the second and third layers displaying moderate S values that suggest promising potential zones. Similarly, the second and third layers in the transverse resistance map show moderate values, indicating good aquifer transmissivity. Thus, based on the findings in Figure 6, we can conclude that the second and third layers, from a depth of 11 m to the third layer, may harbor a good groundwater potential zone.

Electrical anisotropy

Incorporating transverse and longitudinal resistivity introduces the anisotropy coefficient, which measures basement terrain heterogeneity resulting from near-surface effects, weathering, and structural elements (Adelusi et al., 2014).The values of longitudinal resistivity and transverse resistivity are used to compute anisotropic coefficient. The longitudinal resistivity value ranges from 9.64 Ωm at VES-20 to 1885.54 Ωm at VES-95. The value of longitudinal resistivity indicates the geoelectric inhomogeneity in the subsurface (Murali and Patangay, 1998). The transverse resistivity value ranges from 3.55 Ωm at VES-8 to 74001 Ωm at VES-95. According to Salem (1999)'s observation, transverse resistivity (ρ_t) tends to be greater than longitudinal resistivity (ρ_l). This suggests that current flow and hydraulic conduction along lithological boundaries (longitudinal) are more robust than perpendicular to the boundary plane.

The anisotropic coefficient typically range from 1 to 2, as noted by Zohdy et al. (1974) and Dutta et al. (2006), which is influenced by rock hardness and compaction. Areas with higher rock hardness and compaction are associated with higher coefficients, indicating lower porosity and permeability. According to Keller and Frischknecht (1966), this parameter measures the competency of subsurface materials. In addition, it is vital in identifying areas with high porosity and permeability and, thus, used in mapping groundwater potential zones. In the studied region, this coefficient was utilized to identify subsurface freshwater zones and evaluate the aquifer's protective capacity. Understanding such zones helps delineate the distribution of porous and permeable layers within the aquifer system.

The study area's anisotropy coefficient varies from 1 at VES-154 to 4.17 at VES-44 (Figure 7). This parameter is handy in identifying groundwater potential zones, with values of 1.5 or lower indicating high porosity and permeability. The anisotropy coefficient map categorizes areas with values <1 as low potential, between 1 and 1.5 as good potential, and values >2 as areas with lower porosity and permeability (Keller and Frischknecht, 1966). This comprehensive analysis provides valuable insights into subsurface characteristics and identifies areas with favorable groundwater potential for further exploration and resource management.

Aquifer Thickness Map

The creation of the 3D Lithological model serves the purpose of facilitating hydrogeological modeling of the Niger sands groundwater. The geological surfaces, obtained by interpolating borehole data, define the sedimentary formations' spatial and vertical extents. The raster surfaces constituting the geological model act as practical barriers, enabling the precise delineation of aquifers for hydrogeological modeling (Dar et.al., 2017). When viewed from a northeast perspective, the depiction reveals the presence of alluvial sediment deposits along the Niger river and its tributaries, which are markedly different from the eastern region, where the stratigraphic sequence is more comprehensive. In the latter area, sedimentary layers span from the Quaternary period to the entire Proterozoic series, ultimately reaching the Precambrian bedrock.

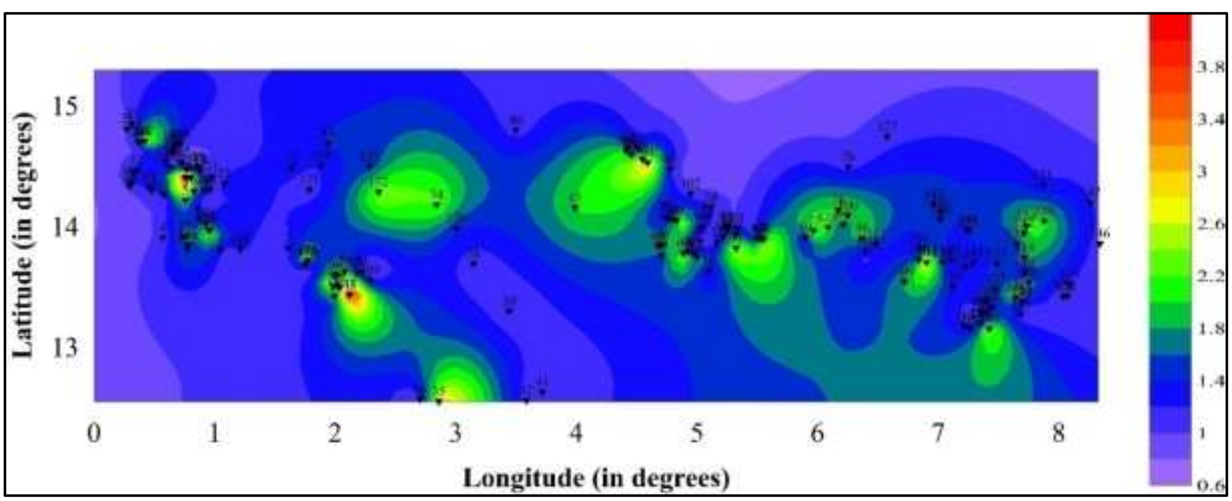

Figure 7. Spatial distribution of electrical anisotropy coefficient (λ) in the study area.

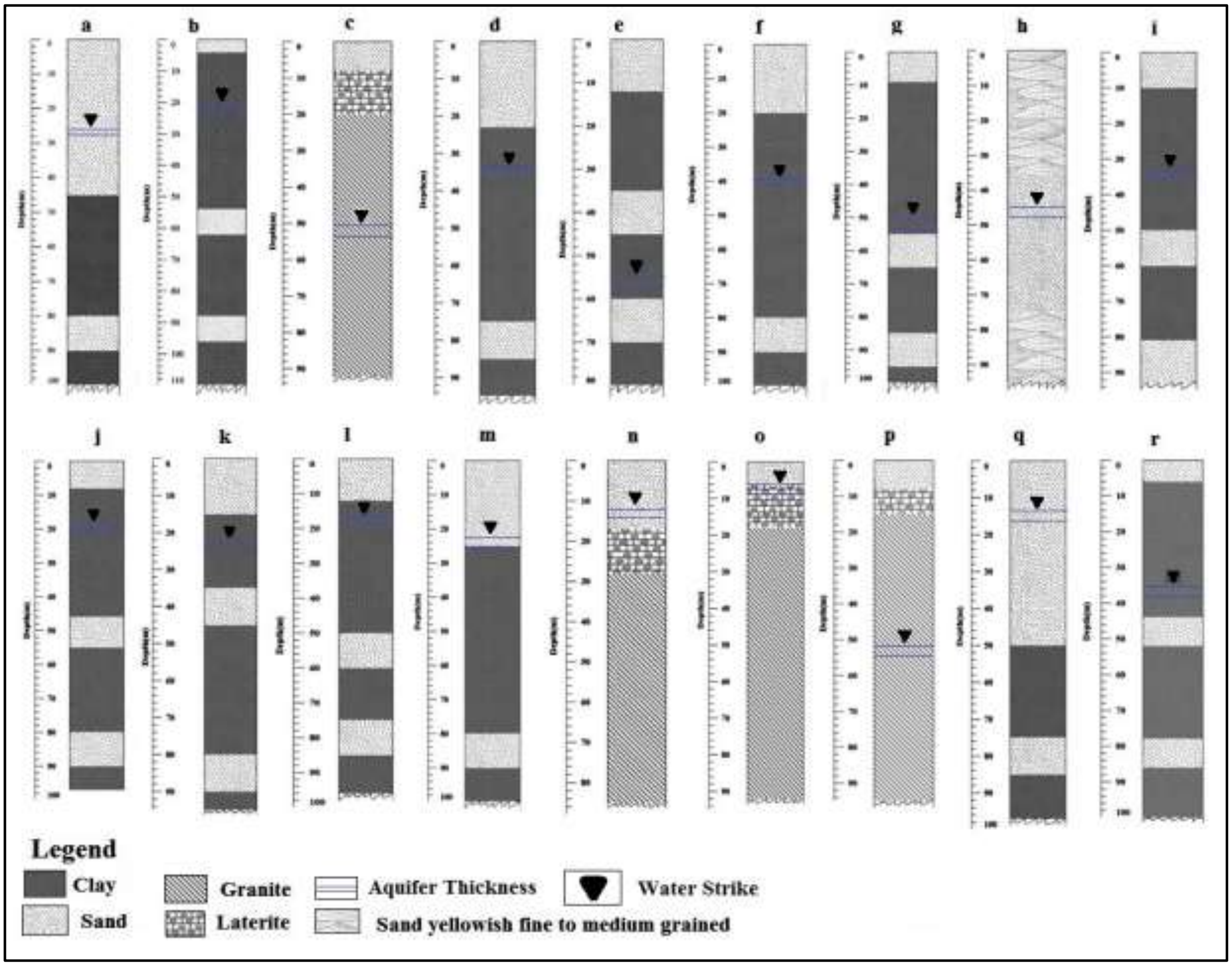

Figure 8. Details of the 18 litholog sites down to a depth of 110 m, revealing various geological litho-units. **(a)** BalideySoujedey, **(b)** Karki, **(c)** Wadata, **(d)** AngoulMayaki, **(e)** GuidanDamou, **(f)** Guidan Karo, **(g)** Guidan Kata, **(h)** GuidanTokkou, **(i)** Toudawa, **(j)** GorouKongou, **(k)** SoudourePeulh, **(l)** TchroudiElhSadoua, **(m)** Timire, **(n)** Dabagawa I, **(o)** GuidanBararou, **(p)** KozoroHahi, **(q)** Malbaza and **(r)** Boulokogo.

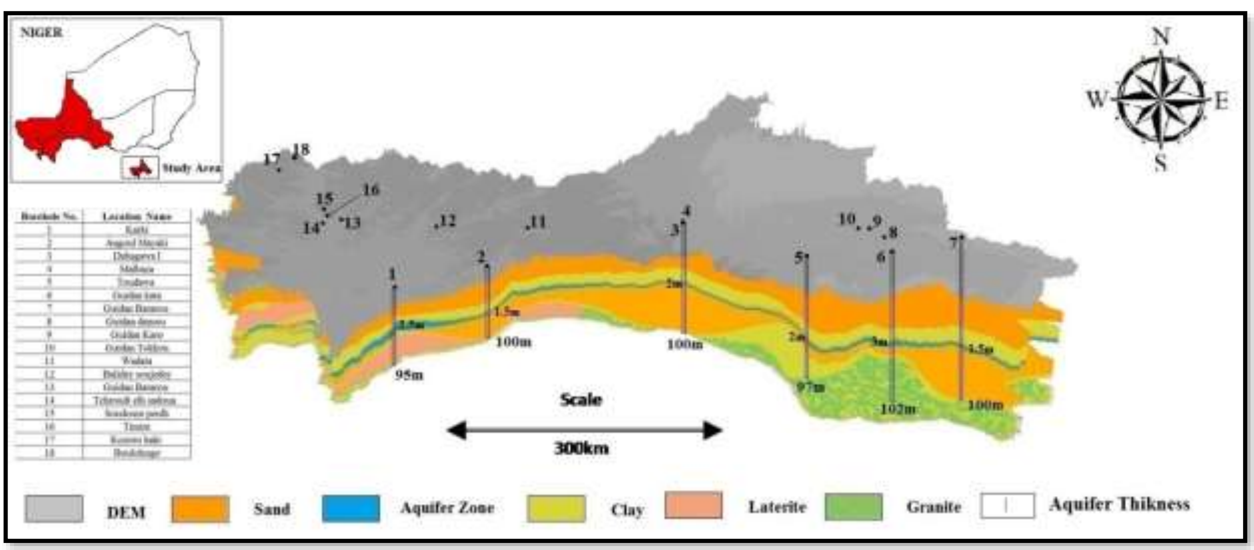

Figure 9. Aquifer thickness distribution spatial patterns and variability in the studied area

The interpolation of drilling data results in raster top surfaces for each geological layer, allowing the visualization of boreholes, outcrops, and other geological data sources as lithological columns. These modeled geological layers can be displayed collectively or individually using Arc Scene, offering clear visualization. 18 locations with lithological data have been charted within sedimentary deposits, with eight of them identified as aquifers in which Karki, Angoul Mayaki, Dabagawa, Toudawa, Guidan kata, and Guidan Bararou, consist of sand/granite (SG), and the sub-sand/granite laterite (SSGL). In the study areas of northern, southern-central, and southeastern regions, the presence of sub-sand/granite (SSG) is prevalent.

As per Table 2, the litholog of Balidey Soujedey and Malbaza, correlates very well with the VES locations 34, 37, 38, 166, 58, 70, 69, and 90. Balidey Soujedey aquifer thickness lies in a range of 1.5 to 4.5 m, and Malbaza aquifer thickness in a range of 1.5 to 5 m. The litholog of Wadata, Guidan Karo, Guidan Kata, GuidanTokkou, and Gorou Kongou, correlates very well with the VES locations 42, 79, 120,121, 134, 137, 138, 100, 101, 125, 126, 127, 141, 120,121, 134, 135, 136, and 50. The thickness range in these locations varies from 2 to 5 m. The litholog data of Angoul Mayaki and Timire, correlates moderately with the VES locations 38, 44, 45 and 48, where the aquifer thickness lies within a range of 3 to 8 m, because the aquifer present here is, clay saturated and due to the presence of clay, the resistivity value show high aquifer thickness. The litholog data of Karki and Kozoro Hahi correlates at the limit with the VES location 35, 36, 40, 41, 5, 6, 16, 17, 18, 151. Karki aquifer thickness lies in a range of 4 to 8 m, while KozoroHahi aquifer lies in a range of 2 to 5 m.

Table 2. Comparison between aquifer thicknesses from the litholog and VES data.

Sr. No.	Litholog name	Latitude	Longitude	Aquifer thickness (m)	VES Locations in the vicinity	Aquifer thickness (m) from VES Data	Remarks
1	Balidey Soujedey	13.666	3.233	1.5	34, 37, 38, 166	1.5-4.5	Correlate very well
2	Karki	12.55	3.6	2.5	35, 36, 40, 41	4-8	Correlative at the limit
3	Wadata	13.893	4.051	2	42, 79	2-5	Correlate very well
4	Angoul Mayaki	13.176	4.070	1.5	38	3-8	The aquifer present here is clay-saturated and due to the presence of clay, the resistivity value shows high aquifer thickness.
5	Guidan Damou	13.718	7.2027	2.8	98, 106, 132, 133,	2.5-6	Correlate very well
6	Guidan Karo	14.0988	6.933	2	120,121, 134, 137, 138	2-5	Correlate very well
7	Guidan Kata	13.2833	7.333	3	100, 101, 125, 126, 127, 141	2-5	Correlate very well
8	GuidanTokkou	14.112	7.018	2.5	120,121, 134, 135, 136	2-5	Correlate very well
9	Toudawa	13.527	6.676	2	92, 102	1-5	Correlate very well
10	Gorou Kongou	13.606	2.202	2.2	50	2-5	Correlate very well
11	Soudoure Peulh	13.590	2.024	2.5	43, 52	2-6	Correlate very well
12	Tchroudi ElhSadoua	13.511	2.125	2.5	46, 47, 49	3-6	Correlate very well
13	Timire	13.430	2.136	2.5	44, 45, 48	3-8	The aquifer present here is clay-saturated and due to the presence of clay, the resistivity value shows high aquifer thickness.
14	Dabagawa I	13.902	5.529	2.5	55, 57, 59, 60	1-6	Correlate very well
15	Guidan Bararou	13.622	7.754	1.5	109, 111, 110,	1-4	Correlate very well
16	Kozoro Hahi	14.206	0.929	1.7	5, 6, 16, 17, 18, 151	2-5	Correlative at the limit
17	Malbaza	13.960	5.507	2	58, 70, 69, 90	1.5-5	Correlate very well
18	Boulokogo	14.697	0.441	3.5	24, 26, 152, 153	3-5	Correlate very well

The litholog data of Tchroudi ElhSadoua and Boulokogo correlates quite well with the VES locations 46, 47, 49,24, 26, 152, and 153. Tchroudi ElhSadoua aquifer thickness lies within a range of 3 to 6 m and Boulokogo aquifer, in a range of 3 to 5 m. Similarly, the litholog data of Guidan Damou and Soudoure Peulh correlates very well with the VES locations 98, 106, 132, 133,43, and 52. At Guidan Damou, aquifer thickness lies in a range of 2.5 to 6 m, and SoudourePeulh, 2 to 6 m. During the project, government of Niger has drilled eighteen deep exploratory boreholes in five regions (Tillabery, Niamey, Dosso, Thoua, and Maradi) in order to validate the geophysical results. The depth of each borehole is around 90 m to 110 m. All the drilled borehole lithologs were studied in detail for the sand property and for their hydrogeological significance (Figure**.** 8). It was seen that the alternate bands of sand with clay and sand from near surface layer to the bottom 110 m depth is seen at Karki site in Dosso, while sand, clay, sand, fine sand up to 50 m depth, later alternate bands of sand and fine sand, was depicted at the Guidan Tokkou site until 90 m depth. This illustrates the layered structure of the alluvium formation in the study area.

The southwestern region is potentially a significant SG and SSGL recharge area. The lithological model indicates the presence of sand deposits at the land surface, and water well records suggest that these deposits may be relatively thicker to approximately 25 meters. The thickness of the SSGL in this region ranges from 28 to 85 m in the subsurface. While it is improbable that the SSGL aquifer is directly in contacts with the bedrock aquifer, it is underlain by relatively continuous deposits of the Walworth Formation (ranging from 23 to 75 m). An aquifer thickness is 2.5 m in Karki, 1.5 m in Angoul Mayaki, 2 m in Dabagawa and Toudawa, 3 m in Guidan Kata and 1.5 m Guidan Bararou as shown in the Figure 9. Nonetheless, due to the erosion of the fine-grained sand (a regional aquifer confining unit) in the Niger river, this location could serve as an essential recharge area for the regional bedrock aquifer. As demonstrated in this study, the two-dimensional features initially defined in cross sections, can be transformed into a three-dimensional environment. These resulting 3D features can be visualized as fence diagrams within the exact Geographic Information System (GIS) environment using Arc Scene or exported to external software packages to construct 3D lithological models.

DISCUSSION

The geoelectric soundings with Dar-Zarrouk parameters and lithological models, helped to determine the groundwater potential zones and assess the protective capacity and thicknesses of the aquifers. The map of longitudinal conductance indicates that 83% of the study area has low S values, 8% has moderate S values, and 9% has high S values. Using the unit conductance values, the protective capacity of the overburden in the area has been evaluated. The results show that 38.54% of the area falls within the good protective capacity, 5.42% within the very good protective capacity, and 1.20% within the excellent protective capacity. About 35.54% fall within the moderate protective capacity, and 7.85% fall within the poor protective capacity. These findings suggest that the study area has moderate to excellent protective capacity. The map of transverse resistance shows that low T values cover 73% of the study area, while 17% have moderate T values, and 10% have high T values.

The mapping of anisotropy coefficients aided in the delineation of the groundwater potential zones, with areas exhibiting values below 1 classified as having low potential, those between 1 and 1.5 deemed to have good potential, and values exceeding 2 indicatives of lower porosity and permeability. The anisotropy coefficient, ranging from 1 to 4.17 across the study area, served as a valuable indicator of groundwater potential. Lower values (<1.5) correspond to areas with high porosity and permeability, while higher values (>2) indicate lower permeability. Further, the erosion of fine-grained sand along the Niger River, enhances the potential of this region as a critical recharge area for the bedrock aquifer. Utilizing advanced geospatial techniques, two-dimensional cross-sectional features are transformed into three-dimensional representations, facilitating enhanced visualization and understanding of lithological structures. The southwestern region exhibits significant potential as a recharge area for both shallow groundwater (SG) and semi-confined sandstone/granite/limestone (SSGL) aquifers. Geological investigations reveal the presence of surface sand deposits, estimated to be approximately 25 m thick, while subsurface analysis indicates SSGL thickness ranging from 28 to 85 m. Although direct contact between the SSGL aquifer and bedrock aquifer is unlikely, the SSGL is consistently underlain by the Walworth Formation, with thicknesses varying from 23 to 75 m. Notably, localized variations in aquifer thickness are observed across different locations, ranging from 1.5 to 3.5 m. This comprehensive analysis offers crucial insights into subsurface characteristics, guiding further exploration and facilitating effective water resource management strategies.

CONCLUSIONS

Based on the longitudinal conductance, it can be concluded that the study area is dominated by low S values, indicating an excellent potential zone with poor to moderate aquifer protective capacity. Also, based on transverse resistance, it can be concluded that about 27% of the study area is characterized by moderate to high transverse resistance, indicating a good groundwater potential zone. Areas with low longitudinal conductance and high transverse resistance values are promising groundwater zones. Out of 166 studied locations, 44 had these characteristics. This means that 26.5% of the study area has a good potential for groundwater. A depth-wise variation of longitudinal conductance (S) and transverse resistance (T) was also studied. The results showed that in some places, the second layer and in others, the third layer, has favorable characteristics for groundwater potential.

The Dar-Zarrouk parameters also reveal heterogeneous anisotropic lithology in the study area. The concept coefficient of anisotropy measures the degree of in homogeneity in a basement terrain that arises from near-surface effects. The assessment of Dar-Zarrouk parameters for groundwater potential zones and aquifer protection studies, holds significant value in addressing societal concerns related to groundwater exploration and pollution prevention. These findings enhance our understanding of the complex geological characteristics in the study area and establish a foundation for future groundwater resource investigations utilizing the electrical resistivity method. Integration of geophysical data with borehole information, such as lithological logs and groundwater level measurements, enhances the accuracy of aquifer thickness assessments. On the bases of low longitudinal conductance and high transverse resistance values, 44 VES locations have shown good groundwater potential zone, and all these sites correlated very well with the 18 drilled boreholes where aquifer thickness lies with a range of 1.5 to 3.5 m.

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RK: Data curation, data analysis methodology, editing and processing of complete data. This work is a part of his doctorate thesis, TA: conceptualization, data curation, quality checks, methodology, funding acquisition, draft editing and revision and supervision, SP: data analysis, methodology, data structuring, RD: Methodology, data quality check, data curation, RP: preparation of maps

Data availability

DEM Data sourced from https://earthexplorer.usgs.gov; Soil from https://www.fao.org; geology from https://certmapper.cr.usgs.gov and litholog from Unpublished Project Report

Compliance with ethical standards

The authors declare that there is no conflict of interest and adhere to copyright norms.

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