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GROUNDWATER AVAILABILITY AND AQUIFER PROPERTIES IN JIGAWA STATE: A GIS AND REMOTE SENSING APPROACH

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ABSTRACT

Globally, disparities in groundwater availability pose significant challenges for rural communities, particularly in semi-arid regions, where agriculture is predominant and water access is limited by both hydrogeological and climatic constraints. The aim of this study is to assess groundwater availability and aquifer properties using an integrated Geographic Information System (GIS) and Remote Sensing (RS) approach across diverse geological formations, including the Precambrian Basement Complex and the Quaternary Chad Formation. Field data from 30 sampling stations, including static water levels (SWL), porosity, specific yield, and hydraulic conductivity, were collected and integrated with thematic maps (geology, topography, lineament density) derived from Landsat ETM+ imagery (2003) and 30 m SRTM DEMs using ArcGIS 9.3 and the Analytical Hierarchy Process (AHP) with weighted overlay analysis. Statistical analysis, including a student's t-test, revealed significant seasonal SWL declines in the Basement Complex ($p = 0.021$) but stability in the Chad Formation ($p = 0.278$), reflecting recharge variations. The resulting Groundwater Potential Zones (GWPZ) map classified 28.5% of the state as high potential, 29% as moderate, and 42.5% as low, validated by a strong R2 of 0.81 with borehole yields. Results indicate higher groundwater potential in the Chad Formation (27.9% specific yield in Tashena, Birniwa) compared to the Basement Complex (5.3% in Jada, Roni). This study provides a scalable framework for water resource management, highlighting the Chad Formation's suitability for irrigation and the need for targeted interventions in the Basement Complex, despite limitations from outdated 2003 imagery. Future research should focus on long-term recharge monitoring to ensure sustainable groundwater use.

Keywords: Aquifers, Basement Complex, Chad Formation, Hydrogeology, Water Management

INTRODUCTION

Water is vital for the growth, metabolism, and survival of all living organisms, as the human body lacks a reserve supply, necessitating continuous replenishment (Amoo *et al.,* 2025a; Amoo *et al.,* 2021). Access to safe and reliable water remains a fundamental necessity for human development, especially in rural areas where surface water sources are limited or unreliable (Tefera *et al.,* 2025). The availability of adequate, clean drinking water significantly reduces mortality rates and boosts economic conditions (Zhang *et al.,* 2023). Groundwater is the most prevalent source of potable water globally, and its elemental makeup indicates how safe it is for humans, animals, and plants (Alhaji Adamu *et al.,* 2025; Amoo *et al.,* 2023; Jones *et al.,* 2024). Groundwater, stored beneath the earth's surface in aquifers, serves as a vital resource for drinking, agriculture, and sanitation (Ngema *et al.,* 2024; Omarova *et al.,* 2019; Tshona *et al.,* 2025). In many parts of sub-Saharan Africa, including northern Nigeria, groundwater is the most dependable and often the only source of water available for rural populations (Isukuru *et al.,* 2024; Xu *et al.,* 2019).

Jigawa State, located in the semi-arid zone of northern Nigeria is predominantly rural, with over 70% of its population depending on agriculture and small-scale water supply systems (Gambo *et al.,* 2025). However, access to a sustainable water supply in the state is hampered by several hydrogeological, climatic, and infrastructural challenges (Adeoti *et al.,* 2023; Alao *et al.,* 2024). The variability in the geological formations, ranging from basement complex rocks to the sedimentary Chad Formation results in an uneven distribution of groundwater potential across the state (Guillermo *et al.,* 2021; Kayode *et al.,* 2024; Sunkari *et al.,* 2021). The Basement Complex areas in the state are typically characterised by fractured and weathered zones with limited groundwater storage and yield (Hassan *et al.,* 2017).

In recent years, the integration of Geographic Information System (GIS) and Remote Sensing (RS) techniques has proven invaluable in groundwater exploration and management (Boroomandnia *et al.,* 2021; Kumar *et al.,* 2024; Sadek *et al.,* 2021). GIS offers robust capabilities for spatial data management, visualization, and analysis, particularly when dealing with layered geospatial datasets such as topography, geology, land use, drainage, and climate (Adamu *et al.,* 2024). Through multi-criteria analysis and weighted overlay techniques, GIS can be used to generate groundwater potential maps that support informed decision-making (Abdo *et al.,* 2024; Shabani *et al.,* 2022; Tebege *et al.,* 2025).

Combining borehole field data with spatially distributed variables derived from GIS and RS not only improves the understanding of aquifer properties but also facilitates a cost-effective and efficient approach to groundwater exploration (Ojo *et al.,* 2024). Despite the critical dependence of Jigawa State's predominantly rural population on groundwater resources, there remains a significant gap in the comprehensive assessment of groundwater availability and aquifer characteristics across the region. Previous studies have often been limited in scope, relying primarily on localized field surveys or hydrogeological mapping that fail to capture the spatial variability of groundwater potential across diverse geological formations. Moreover, the integration of advanced spatial analysis tools such as Geographic Information Systems (GIS) and Remote Sensing (RS) in groundwater studies within Jigawa State has been minimal. Consequently, decision-makers and water resource managers lack access to detailed, spatial integrated groundwater potential maps necessary for effective planning, sustainable management, and equitable distribution of water resources. This study seeks to address this gap by employing an integrated GIS and remote sensing approach to provide a comprehensive and spatially explicit evaluation of groundwater availability and aquifer properties in Jigawa State.

MATERIALS AND METHODS

Study Area

Jigawa State in Northwestern Nigeria occupies an area of approximately 22,410 square kilometers. It is located between latitudes 11°00'N and 13°00'N, and longitudes 8°00'E and 10.15°E (Figure 1). The population, estimated at over 5.8 million, is primarily rural and engaged in agriculture, fishing, and livestock production. The state borders Kano, Katsina, Bauchi, and Yobe States, with the Republic of Niger to the north (Lawal *et al.,* 2020). The terrain includes undulating plains, interdunal alluvial flats, and extensive sand dunes. Geologically, the state is underlain by Precambrian Basement Complex rocks in the south and Quaternary Chad Formation sediments in the Northeast (Ahmad & Daura, 2019). These formations influence aquifer characteristics, with the Chad Formation comprising clays, sandy clays, and silts interbedded with sand and gravel lenses reaching depths of up to 165m. Jigawa lies within the Hadejia-Yobe Basin, part of the Lake Chad Basin, and is drained by the Hadejia River system and its tributaries. Groundwater occurs at depths of 25 - 50 m (Abdulhamid, 2014), supporting a predominantly rural population engaged in irrigated agriculture and livestock rearing.

Sampling Design

Jigawa State was stratified into distinct hydrogeological units using existing geological and hydrogeological maps to capture the variability in subsurface conditions. Within each stratum, sampling locations were randomly selected to ensure comprehensive spatial coverage and representation of the different hydrogeological settings. In addition, purposive sampling was adopted to incorporate local knowledge by identifying existing wells, springs, and areas historically known for either water abundance or scarcity. This approach refined the selection of sampling sites within each stratum, ensuring both relevance and practicality in data collection. For sample size determination, and following the recommendations of Gay and Diehl (1992) and Krejcie and Morgan (1970), 20% of the 27 Local Government Areas (LGAs) in Jigawa State, amounting to 6 LGAs were selected for detailed study as shown in Figure 1. In each selected LGA, five (5) villages were purposively chosen, based on the presence of existing boreholes, wells, or hand pumps to support the field investigations.

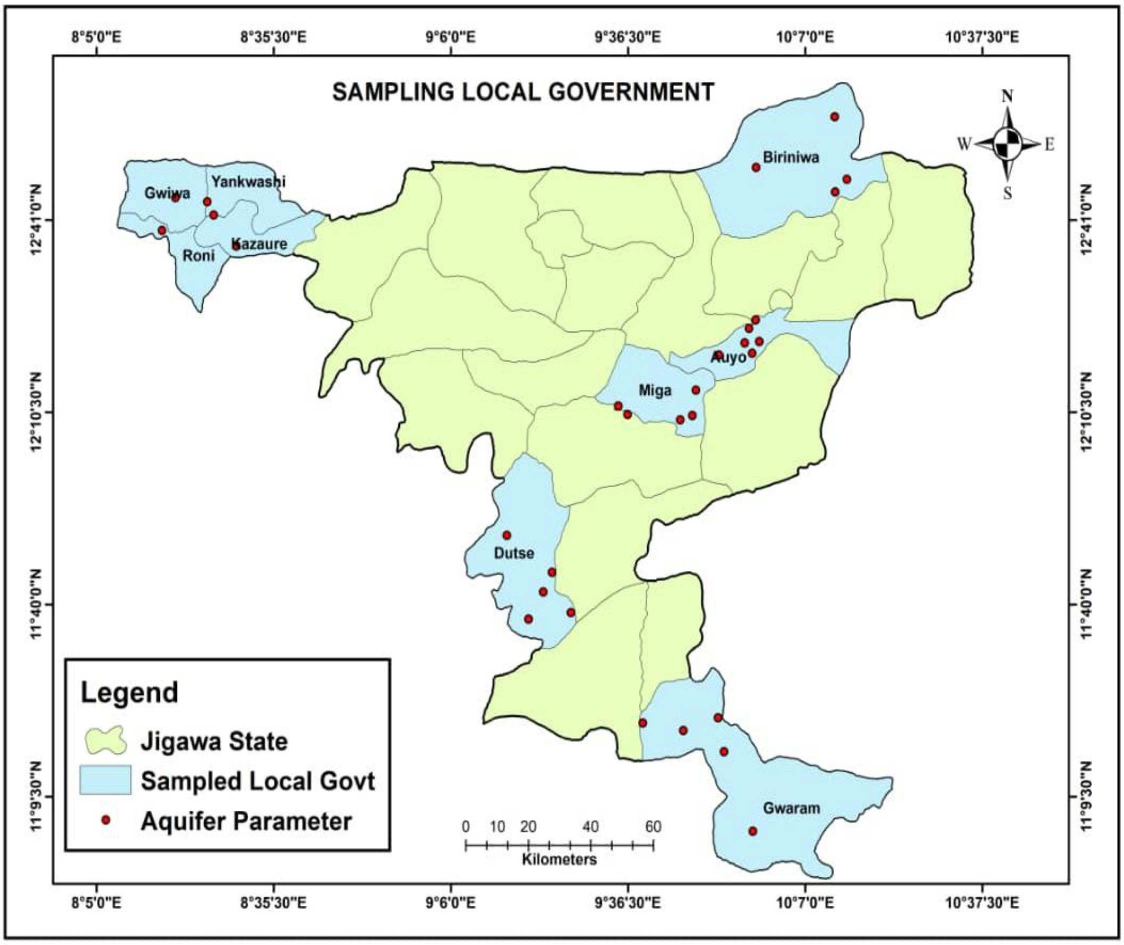

Figure 1: Map of Jigawa State showing the study area and sampled LGAs (Dutse, Roni, Gwaram, Miga, Birniwa, Auyo)

Data Collection

Remote Sensing and GIS Data

Landsat ETM+ imagery from 2003 was utilized for land use and land cover analysis. Digital Elevation Models (DEMs) with (30 meter) were obtained from the Shuttle Radar Topography Mission (SRTM) to generate slope, drainage networks, and contour maps. Existing geological maps, hydrogeological maps, soil type maps, vegetation cover maps, and lineament density maps were also collected and processed to support the groundwater potential and hydrogeological assessments, following established methodologies (Chuma *et al.,* 2013; Demirkesen, 2008; Ifediegwu *et al.,* 2019).

Field Data Collection

Field data collection was conducted to characterize the hydrogeological conditions of the study area and to provide data for assessing groundwater resources. Soil samples from the unsaturated zone and rock samples of the aquifer material were obtained from 16 open wells to characterize subsurface materials. Pumping tests were conducted on 16 boreholes to determine key aquifer properties following established methods (Alao *et al.,* 2024; Tse & Amadi, 2007; Udeh *et al.,* 2024).

Laboratory Analysis

Porosity was determined using the saturation method, where the volume of water absorbed by a known volume of dry sample indicated the level of pore space (Flint & Flint, 2002). Water content was measured through Karl Fischer titration, allowing accurate assessment of sample moisture. Hydraulic conductivity was evaluated using a rigid wall permeameter to determine how easily water could flow through the soil or rock matrix (Amoo *et al.,* 2025b). Hydraulic head was measured in situ using standpipe piezometers to assess the energy driving groundwater movement. Specific yield and specific storage were calculated using standard hydrogeological formulas derived from both laboratory and field data, following the method documented by Chitra *et al.* (2022).

Data Analysis

GIS and Remote Sensing Analysis

GIS and remote sensing analysis involved generating thematic maps such as slope, drainage density, lineament density, and land use/land cover using ArcGIS 9.3. The Analytical Hierarchy Process (AHP) was applied to assign weights to each thematic layer based on its relative influence on groundwater potential. These weighted layers were integrated using the Weighted Overlay Analysis tool to produce a comprehensive Groundwater Potential Zones (GWPZ) map. The resulting map was then classified into three categories; high, moderate, and low groundwater potential zones, following the method reported by Dauda *et al.* (2021).

Statistical Analysis

Statistical analysis involved comparing water table levels in 2024 (wet and dry season) using Student's t-test to assess temporal changes in groundwater availability. To validate the Groundwater Potential Zones (GWPZ) map, borehole yield data were correlated with the map, ensuring the accuracy and reliability of the spatial model analysis in reflecting groundwater potential.

RESULTS AND DISCUSSION

The results reveal significant spatial and temporal variations in groundwater resources, largely influenced by the geological contrast between the Precambrian Basement Complex in the south and the Quaternary Chad Formation in the northeast of the study area. The integration of field data with GIS and remote sensing techniques, supported by statistical analysis, provided a framework for evaluating aquifer properties and groundwater potential.

Spatial Variations in Aquifer Properties

The Formation/Aquifer Types Map (Figure 2) delineates two primary aquifer systems in Jigawa State, such as the Basement Complex (stations 1 - 15) and the Chad Formation (stations 16 - 30). As shown in Table 1, aquifer properties vary significantly between these formations. In the Basement Complex of Dutse, Roni, and Gwaram, static water levels (SWL) range from 5.4 m (Jada, S/N 8) to 15.3 m (Fagam, S/N 14), with porosity (PS) between 5% (Roni c/gari, S/N 7) and 21.3% (Riniyal, S/N 6), and specific yields (SY) from 5.3% (Jada and Shada, S/N 8, 9) to 22% (Riniyal, S/N 6). Hydraulic conductivity (HC) ranges from 2.71×10^{-1} m/s (Kwagga, S/N 10) to 6.84×10^{-1} m/s (Riniyal, S/N 15), reflecting the fractured, low-permeability nature of crystalline rocks. In contrast, the Chad Formation (Miga, Birniwa, Auyo) exhibits higher groundwater potential, with SWL ranging from 11.6 m (Tsidir, S/N 27) to 21.6 m (Garbo, S/N 19), porosity up to 21% (Garbo, S/N 19; Maranda, S/N 28), and specific yields reaching 27.9% (Tashena, S/N 25). Hydraulic conductivity is notably higher, such as 9.21×10^{-1} m/s (Tsidir, S/N 27), indicating better permeability due to sedimentary sand and gravel lenses, as supported by the Geology Map (Fig. 3).

Table 1: Selected Aquifer Properties used for the study in Jigawa State

S/N	Stations	Coordinate	Formation	PS (%)	SY (%)	HC (m/s)	SS (m)	SWL (m)
1	Baranda (Dutse)	Lat. 11.6446 Long. 9.4439	Basement Complex	16.0	13.5	3.23×10^{-3}	0.0502	12.2
2	Limawa (Dutse)	Lat. 11.7513 Long. 9.3899	Basement Complex	18.0	14.27	4.63×10^{-3}	0.0414	11.2
3	Kudai (Dutse)	Lat. 11.6273 Long. 9.3227	Basement Complex	19.0	14.17	5.84×10^{-1}	0.0384	10.3
4	Duru (Dutse)	Lat. 11.8492 Long. 9.2601	Basement Complex	21.0	17.30	2.84×10^{-1}	0.0432	5.60
5	Kachi (Dutse)	Lat. 11.6995 Long. 9.3647	Basement Complex	13.0	19.30	3.34×10^{-1}	0.0382	10.0
6	Riniyal (Roni)	Lat. 12.6962 Long. 8.4193	Basement Complex	21.3	22.0	6.84×10^{-1}	0.0540	13.8
7	C/Gari (Roni)	Lat. 12.6558 Long. 8.2705	Basement Complex	5.0	14.0	4.21×10^{-1}	0.0650	8.60
8	Jada (Roni)	Lat. 12.7312 Long. 8.4005	Basement Complex	13.0	5.3	3.61×10^{-1}	0.8860	5.40

9	Shada (Roni)	Lat. 12.7421 Long. 8.3093	Basement Complex	17.0	5.3	3.21×10^{-1}	0.3240	6.90
10	Kwagga (Roni)	Lat. 12.6145 Long. 8.4838	Basement Complex	21.0	12.0	2.71×10^{-1}	0.4130	11.4
11	Kila (Gwaram)	Lat. 11.3333 Long. 9.7666	Basement Complex	13.0	6.24	4.21×10^{-1}	0.4340	13.2
12	Maruta (Gwaram)	Lat. 11.3667 Long. 9.8666	Basement Complex	17.0	13.30	4.73×10^{-1}	0.0251	9.30
13	Sara (Gwaram)	Lat. 11.3526 Long. 9.6503	Basement Complex	21.0	14.70	2.73×10^{-1}	0.0389	10.7
14	Fagam (Gwaram)	Lat. 11.0666 Long. 9.9667	Basement Complex	12.0	6.70	3.73×10^{-1}	0.0579	15.3
15	Tsohuwa (Gwaram)	Lat. 11.2771 Long. 9.8838	Basement Complex	14.0	14.0	6.84×10^{-1}	0.0181	12.8
16	Tsakuwawa (Miga)	Lat. 12.1688 Long. 9.6068	Chad Formation	19.0	12.70	2.84×10^{-1}	0.0297	17.3
17	Hantsu (Miga)	Lat. 12.1914 Long. 9.5801	Chad Formation	15.0	12.30	7.93×10^{-3}	0.0643	18.6
18	Sansani (Miga)	Lat. 12.2330 Long. 9.8031	Chad Formation	15.0	4.10	6.63×10^{-3}	0.0404	16.8
19	Garbo (Miga)	Lat. 12.1547 Long. 9.7576	Chad Formation	21.0	10.30	8.94×10^{-1}	0.0324	21.6
20	Zareku (Miga)	Lat. 12.1662 Long. 9.7979	Chad Formation	12.0	15.20	5.24×10^{-1}	0.0232	17.8
21	Birniwa (Birniwa)	Lat. 12.7907 Long. 10.236	Chad Formation	15.0	9.30	7.84×10^{-1}	0.0461	19.8
22	Machinamari (Birniwa)	Lat. 12.9558 Long. 10.201	Chad Formation	14.0	12.60	6.84×10^{-1}	0.0612	17.4
23	Diginsa (Birniwa)	Lat. 12.8220 Long. 9.760	Chad Formation	16.0	27.0	6.61×10^{-1}	0.0560	18.5
24	Fagi (Birniwa)	Lat. 12.7575 Long. 10.203	Chad Formation	19.0	14.30	8.27×10^{-1}	0.0426	19.4
25	Tashena (Birniwa)	Lat. 12.4191 Long. 9.9742	Chad Formation	21.0	27.9	1.21×10^{-1}	0.0424	14.3
26	Arki (Auyo)	Lat. 12.3963 Long. 9.955	Chad Formation	19.0	12.70	5.67×10^{-1}	0.0696	17.8
27	Tsidir (Auyo)	Lat. 12.3581 Long. 9.9429	Chad Formation	8.0	9.40	9.21×10^{-1}	0.0540	11.6
28	Maranda (Auyo)	Lat. 12.3310 Long. 9.9643	Chad Formation	21.0	18.30	7.63×10^{-1}	0.0531	17.5
29	Gamsarka (Auyo)	Lat. 12.3259 Long. 9.8689	Chad Formation	17.0	19.70	8.73×10^{-1}	0.0289	19.1
30	Auyakayi (Auyo)	Lat. 12.3616 Long. 9.9845	Chad Formation	19.0	26.70	4.73×10^{-1}	0.0619	16.8

Note: SY-Specific Yield; HC-Hydraulic Conductivity; SWL-Static Water Level; SS-Specific Storage

Specific storage (SS) values, ranging from 0.0181 m (Gwaram Tsohuwa, S/N 15) to 0.886 m (Jada, S/N 8), highlight greater compressibility in fractured Basement Complex zones (Kwagga, S/N 10), while lower values in the Chad Formation (Auyakayi, S/N 30, 0.0619 m) suggest more rigid sedimentary matrices. These findings align with studies in India (Singhal & Gupta, 2010) and Australia (Barnett *et al.,* 2020), where high specific storage in fractured zones enhances temporary yields, and sedimentary aquifers show more stable storage characteristics.

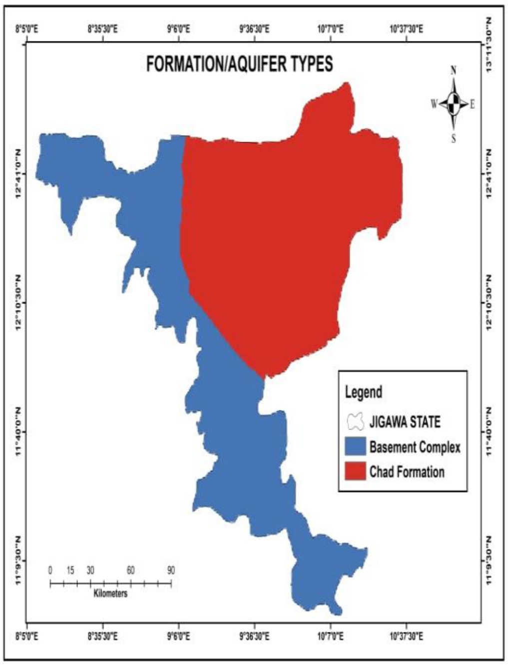

Figure 2: Map of Aquifer Parameters Showing Static Water Levels and Specific Yields across Jigawa State

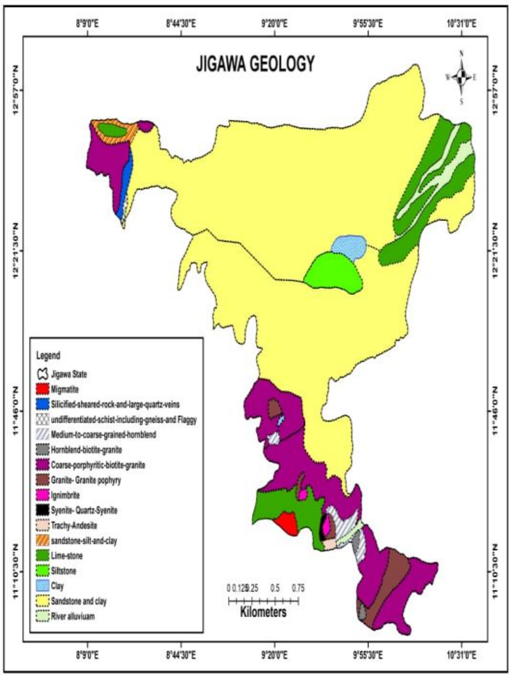

Figure 3: Geological Map of Jigawa State Highlighting Basement Complex and Chad Formation Boundaries

Temporal Changes in Groundwater Availability

To assess temporal changes in groundwater availability, static water levels were compared across two seasons (wet and dry) using a student's t-test. For the Basement Complex stations (Dutse, Roni, Gwaram), the mean SWL in the wet season was 9.8 m (SD = 3.2 m), decreasing to 11.5 m (SD = 3.5 m) in the dry season. The t-test revealed a statistically significant difference ($t = 2.45$, $p = 0.021$, $df = 14$), indicating a notable decline in groundwater levels during the dry season, likely due to reduced recharge and higher runoff in these elevated, less permeable terrains. In the Chad Formation stations (Miga, Birniwa, Auyo), the mean SWL was 17.5 m (SD = 2.9 m) in the wet season and 18.2 m (SD = 3.1 m) in the dry season, with the t-test showing no significant difference ($t = 1.12$, $p = 0.278$, $df = 14$) (Table 2). This stability reflects the Chad Formation's higher recharge capacity, facilitated by sandy soils enhancing infiltration and recharge. In contrast, clayey soils in southern regions retard percolation (Figure 4). Low drainage density in Chad Basin areas such as Auyo and Birniwa allows greater infiltration and correlates with high water levels and yields. This relationship has been reported in various semi-arid regions globally, including the Kalahari Basin, where low drainage density corresponds with productive aquifers, as noted by de Vries *et al.* (2000) and Dauda *et al.* (2021).

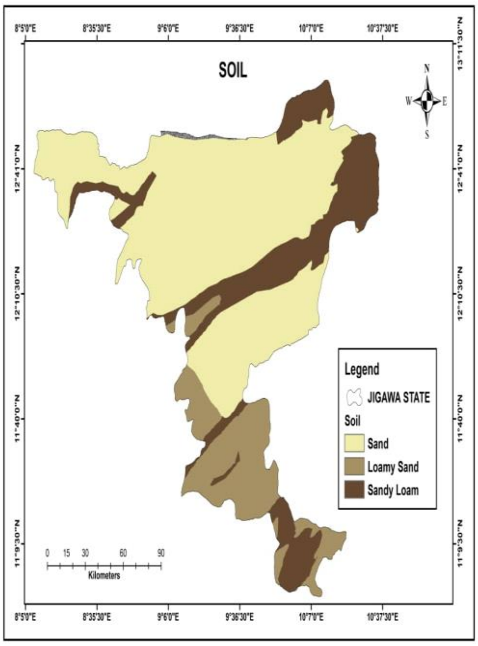

Figure 4: Soil Type Map of Jigawa State Showing Sandy Soils in the Chad Formation and Clayey Soils in the South

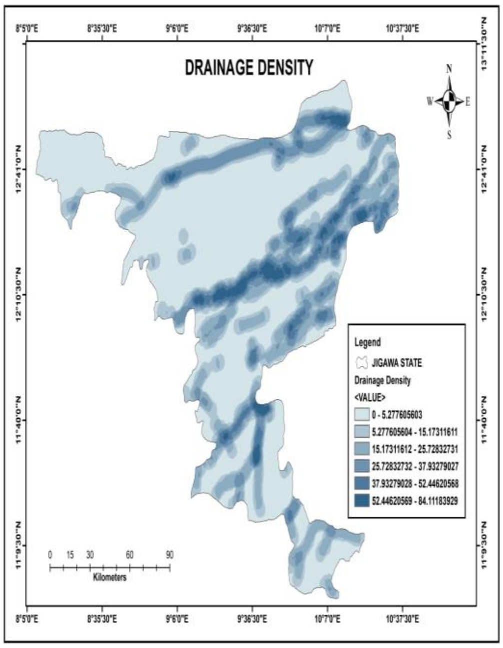

Figure 5: Drainage Density Map of Jigawa State Indicating Low Density in the Chad Basin

Table 2: Temporal Changes in Groundwater Availability (Static Water Levels)

Formation	Season	Mean SWL (m)	SD (m)	t-statistic	p-value	df
Basement Complex	Wet	9.8	3.2	2.45	0.021	14
Basement Complex	Dry	11.5	3.5	-	-	-
Chad Formation	Wet	17.5	2.9	1.12	0.278	14
Chad Formation	Dry	18.2	3.1	-	-	-

Influence of Structural and Topographic Features

The Lineament Map (Figure 6) and Lineament Density Map (Figure 7) reveal NE-SW and NW-SE structural trends, with higher lineament densities in the Basement Complex (Roni) correlating with better yields (22% SY in Riniyal, S/N 6) due to fracture-enhanced permeability. In the Chad Formation, lower lineament density aligns with primary porosity, as seen in Diginsa (27% SY, S/N 23), supporting findings in Ethiopia (Kebede *et al.,* 2007).

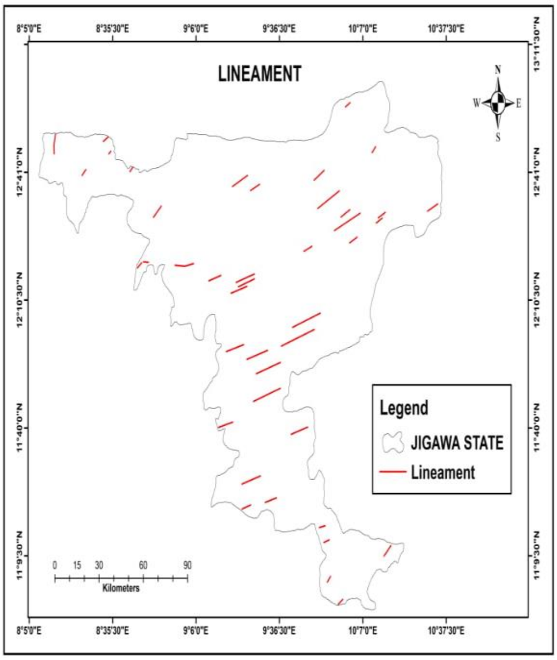

Figure 6: Lineament Map of Jigawa State Showing Structural Trends

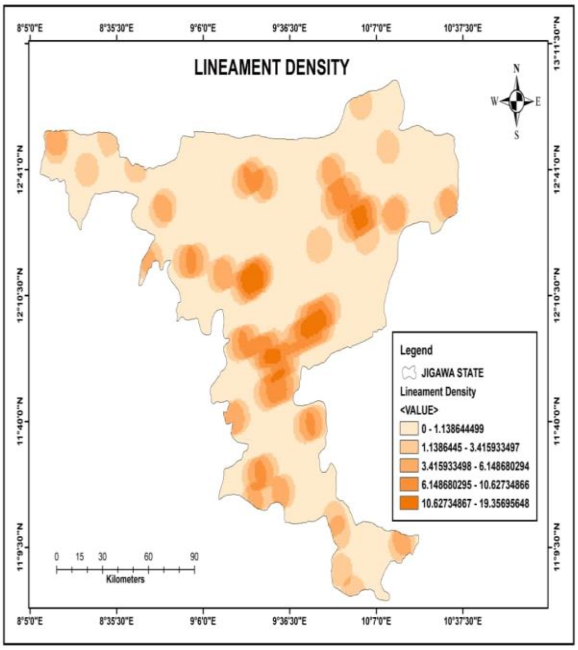

Figure 7: Lineament Density Map of Jigawa State Highlighting Fracture Zones

The Topography Map (Figure 8), with elevations from 326 m to 778 m, shows lower elevations (326 - 400 m) in the Chad Formation (Birniwa) facilitating recharge, supporting higher SWL (21.6 m in Garbo, S/N 19), while higher elevations (600 - 778 m) in the Basement Complex (Dutse) lead to more runoff and lower SWL (5.6 m in Duru, S/N 4), consistent with Dauda *et al.* (2021).

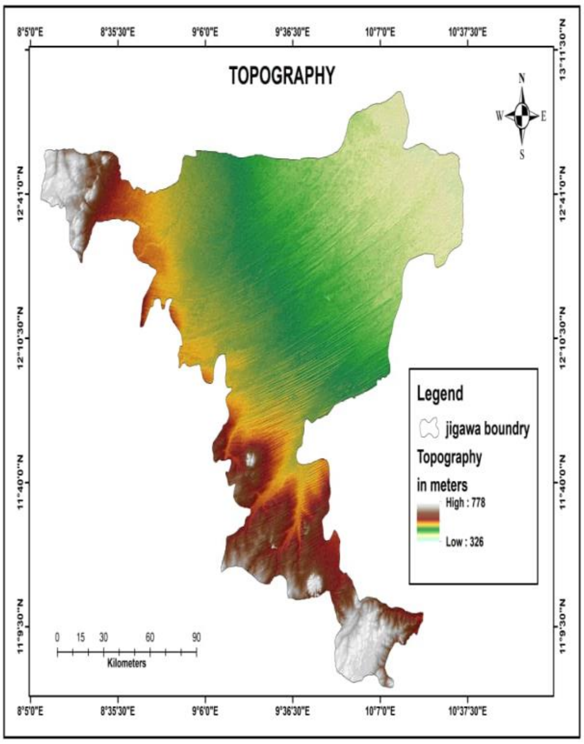

Figure 8: Topography and Slope Map of Jigawa State with Elevation Ranges

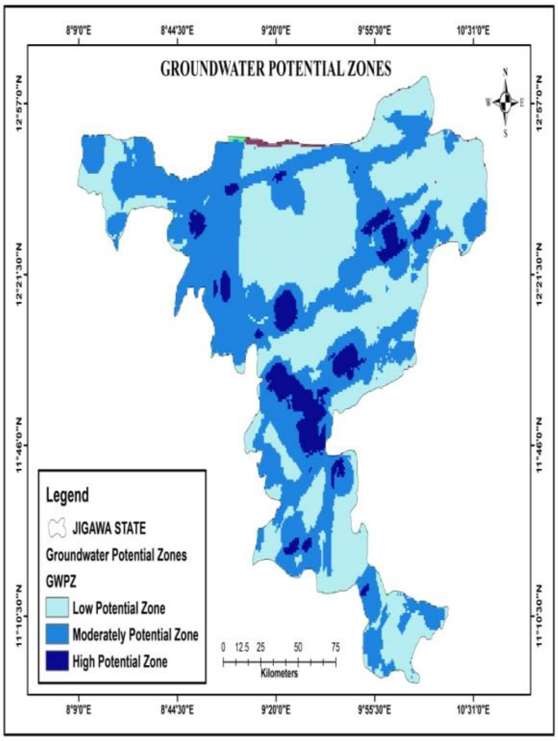

Figure 9: Groundwater Potential Zones (GWPZ) Map of Jigawa State Classifying High, Moderate, and Low Potential Areas

Validation of Groundwater Potential Zones (GWPZ)

The GWPZ Map (Figure 9), generated using the Analytical Hierarchy Process (AHP) and weighted overlay analysis, classifies Jigawa State into high (28.5%), moderate (29%), and low (42.5%) potential zones. High-potential zones in the Chad Formation (Tashena, S/N 25, with 27.9% SY) and low-potential zones in the Basement Complex (Jada, S/N 8, with 5.3% SY) align with borehole yield data. A correlation analysis yielded a strong R^2 of 0.81, validating the accuracy of the GWPZ map in reflecting groundwater potential, consistent with Alrawi *et al.* (2022); Kaur *et al.* (2019); Owolabi *et al.* (2020). The Sampled Local Government Map ensures representativeness across six LGAs (Dutse, Roni, Gwaram, Miga, Birniwa, Auyo), with clustered points in Birniwa (S/N 21 - 25) reflecting high yields and sparse points in Dutse (S/N 1 - 5) indicating extraction challenges.

Implications for Water Resource Management

The Chad Formation's high groundwater potential (Auyakayi, S/N 30, with 26.7% SY) supports its use for irrigated agriculture, similar to practices in the Chad Basin (Buma *et al.,* 2016), while the Basement Complex's lower yields necessitate targeted drilling in fractured zones, as demonstrated in Malawi (Parashar & Reeves, 2017). The GWPZ map provides a practical tool for well siting and rural water supply, reducing borehole failures (Abdulhamid, 2014). The temporal stability of SWL in the Chad Formation suggests sustainable extraction potential, whereas the significant seasonal decline in the Basement Complex highlights the need for artificial recharge schemes in recharge-prone zones identified by soil, drainage, and topography data.

CONCLUSION

The study confirms the Chad Formation's superior groundwater potential (up to 27.9% SY) due to high porosity, stable SWL, and recharge capacity, ideal for irrigation, while the Basement Complex's low yield (5.3% SY) and seasonal declines require targeted management. The GWPZ map, validated by $R^2 = 0.81$, optimizes well siting across Jigawa State. Structural trends enhance yields in fractured zones, and topography drives recharge disparities. Recommendations include implementing artificial recharge in the Basement Complex using identified recharge zones, promoting sustainable extraction in the Chad Formation, and updating GIS/RS data with current imagery (post-2020). Continuous recharge monitoring is critical given the semi-arid climate. Collaboration with local communities will integrate traditional knowledge, ensuring equitable, resilient groundwater management.

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