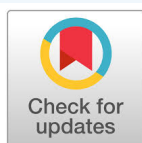


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Groundwater potential assessment using integrated multidisciplinary techniques in Shadadi, central Nigeria

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ABSTRACT

Rising demand for potable water, rapid urban expansion, industrialization, and the essential role of water in human existence have increased pressure on groundwater resources. In Shadadi, central Nigeria, this pressure is compounded by numerous unproductive boreholes. This study integrated geographic information systems (GIS), remote sensing (RS), geological mapping, and geophysical techniques to account for geomorphological features and subsurface architecture. Seven thematic parameters were superimposed in GIS to develop a groundwater potential map (GWPM), and each criterion and subclass was evaluated, weighted, and normalized using the analytic hierarchy process (AHP). Interpreted vertical electrical sounding (VES) and geoelectric-section results, constrained by lithologic logs, delineated topsoil, sandy clay, weathered basement, fractured basement, and fresh basement layers. Aquifers occur within the weathered and fractured basement zones. Aquifer depth varies regionally, from less than 15 m in northern and western areas to more than 60 m in southern and northeastern sectors. The AHP-derived GWPM was classified into very high, high, moderate, low, and very low zones, representing 0.7%, 23.8%, 60.5%, 14.9%, and 0.1% of the study area, respectively. Validation using 49 drilled boreholes supported the reliability of the GWPM; Cohen's kappa was 0.78, indicating substantial agreement between observed and projected yield classes.

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1. INTRODUCTION

Increasing global demand for freshwater, driven by socioeconomic and environmental factors including urbanization, agriculture, population growth, and the climate crisis, has encouraged a shift from reliance on hand-dug surface wells for domestic and industrial uses toward cleaner and safer groundwater [1, 2]. This shift is also driven by the susceptibility of surface water sources,

such as hand-dug wells, to multiple contaminant sources, including anthropogenic, biotic, and geogenic contamination [3]. In contrast, groundwater offers greater accessibility, sustainability, and lower-cost maintenance and extraction technologies, further reinforcing this preference. Groundwater occurs beneath the Earth's surface within the zone of saturation. The migration, distribution, and recharge of an aquifer are commonly understood to be controlled by geological structures and their interconnectivity. These structural elements manifest as secondary porosity when hard rock units are subjected to brittle deformation post-formation. Furthermore, pore spaces in weathered rock units, to-

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gether with joints, faults, and fractures in crystalline basement, coupled with the extensive residuum of coarse non-clayey material overlying the basement, have been reported to be zones in which groundwater can be stored for abstraction [4, 5]. Satellite imagery that has been spatially enhanced enables the identification of these mappable structural units, which can be easily highlighted and extracted through visual inspection in a geographic information system (GIS) domain [6]. Strong correspondence between the field-mapped structures and those identified via the satellite system provides an effective basis for defining lineaments as reliable indicators of regional structures [7–9]. The geology, topography, drainage, and climate of an area are the primary factors controlling groundwater movement, storage, and extraction [10–12]. Notably, the GIS setting provides three-dimensional management capabilities for data and incorporates an analytical tool that facilitates the aggregation, storage, manipulation, analysis, and visualization of geospatial and geological data, encompassing both positional and attribute-based information [13].

Conventional hydrogeological and geophysical survey techniques have long been used to identify and distinguish high- and low-groundwater-potential (GWP) zones for exploitation [14–16]. However, fractures and aquiferous units are known to be restricted both vertically and laterally in the basement complex [17, 18], making it costly, laborious, and time-consuming to rely solely on a single technique when prospecting for groundwater on a broad scale. Recently, the integration of multicriteria decision analysis (MCDA), geophysical survey (GS) techniques, and remote sensing (RS) in a GIS setting has been widely favoured by researchers as a valuable tool for GWP mapping worldwide [12, 16, 19–22]. Building on this multidisciplinary approach, some researchers have developed a range of models to advance sustainable groundwater development globally [23, 24]. However, existing models lack universality and regional prospectivity evaluation, limiting their applicability in diverse geographic settings with complex environmental and geological relationships. They also struggle to capture varied geomorphological features and overlook variations in spatial distribution, geohydraulic factors, and mobility pathways for groundwater.

Shadadi is a growing community, partly because of an influx of settlers from Abuja city centre associated with the frequent demolition of unplanned settlements and the high cost of living; additional boreholes are therefore needed to meet the immediate water needs of relocating residents. The study area has also received relatively little groundwater investigation, leaving a gap in knowledge of its subsurface hydrology. To delineate the GWP within the study area, a robust approach involving the integration of geophysics, RS, MCDA and GIS was applied. This integrated approach takes advantage of both surface geomorphological phenomena and subsurface architecture to improve understanding of the hydrological and geological processes that partition the GWP zones into different yield classes in Shadadi. The seven criteria: elevation, slope, drainage density, lineament density, overburden thickness, lithology, and aquifer resistivity, were selected based on their direct control on groundwater occurrence in Precambrian basement terrain and the availability of reliable, spatially explicit data for Shadadi.

In hard-rock environments, aquifer storage is governed mainly

by the degree of weathering, fracture networks, and structural controls rather than by surficial properties. Overburden thickness, lithology, lineament density, and aquifer resistivity therefore represent the subsurface architecture most critical for borehole productivity. Elevation, slope, and drainage density were included to represent surface runoff-infiltration dynamics and topographic controls on recharge. The objectives were to: (1) investigate and characterize the subsurface geological features of the study area by integrating geoelectrical survey methods and borehole-log data; (2) develop hydrogeologically relevant thematic maps from geological mapping, remotely sensed data, and geoelectrical survey output; (3) produce a GWP map for the study area by synthesizing the selected hydrogeological parameters within a GIS environment; and (4) validate the accuracy of the GWP map using the kappa statistic and available borehole data.

1.1. STUDY AREA

The study area is located in Kuje Area Council, in the Federal Capital Territory, central Nigeria, between latitudes 8°51'28"N and 8°54'6" N and longitudes 007°10'45" E and 007°14'0" E (Figure 1). Accessibility to the study area is via the Gwagwalada-Chibiri-Kuje and Lugbe-Kuje routes. The Northern Guinea Savannah, with an annual average rainfall of 1650 mm [25], and an annual temperature that ranges between 22.1°C and 36.5°C are the principal climatic characteristics of the region. The streams and numerous rivulets that dot the landscape of the study area drain in a dendritic style, depicting a flat to low-lying topography of the region; the peak elevation is of 310 m above sea level. Geologically, Shadadi lies within the Precambrian crystalline basement complex of Central Nigeria. The Nigerian basement complex has been described by earlier researchers [26–28].

2. MATERIALS AND METHODS

The methodology involved geological mapping, remote sensing, geophysical surveys, MCDA, and GIS as outlined in Figure 2. The GIS environment supported three-dimensional data management and tools for the aggregation, storage, manipulation, analysis, and visualization of geospatial and geological data, encompassing both positional and attribute-based information [13]. Fieldwork included detailed geological mapping using stream traverse and exposure mapping techniques. Strike and dip measurements of the different rock exposures mapped during fieldwork, as well as the orientation of fractures, faults, joints, and quartz veins were recorded using a Silva compass-clinometer. These measurements were plotted on rose diagrams and a geological map to visualize their spatial distribution.

2.1. GEOPHYSICAL SURVEY

Geoelectrical sounding was carried out using a Petrozenith 03 resistivity meter [29–31]. A total of 109 vertical electrical sounding (VES) points were acquired with a maximum current-electrode spacing (AB/2) of 150 m during the course of the field geoelectrical investigation (Figure 3). The Schlumberger array was used to measure the resistivity variability in a vertical plane, as well as determine layer parameters (quantity and thickness) of the subsurface. Data processing involved the use of partial curve matching, and repetitive software-based iteration using

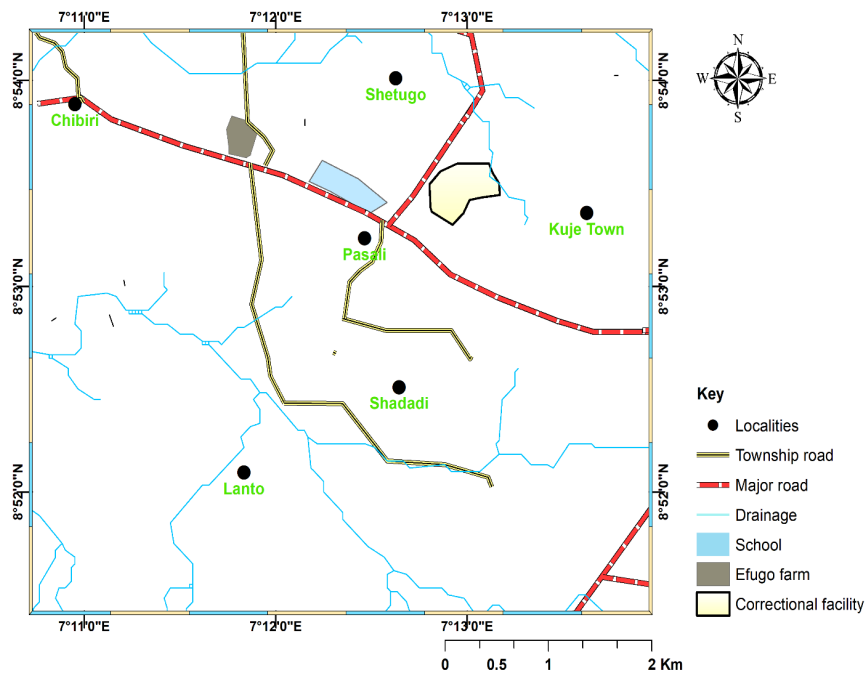


Figure 1: Map of Shadadi showing topography, localities, and the drainage network.

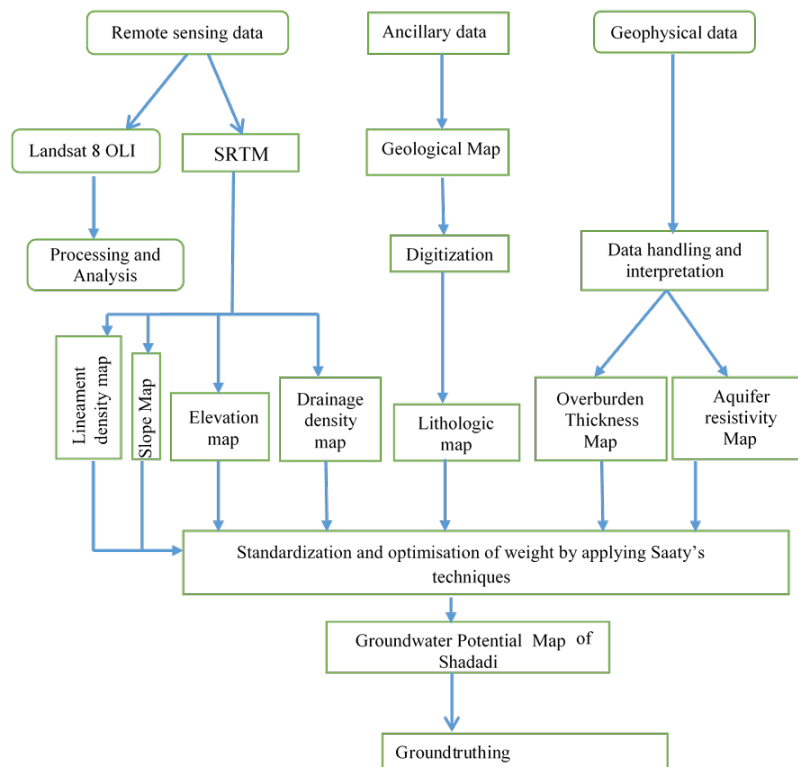


Figure 2: Flow chart of the research workflow.

WinResist, following the approach of Akinlalu *et al.* [4]. Borehole lithology data from adjacent wells were used to validate and constrain the interpretation of geoelectrical survey data, ensuring

accurate subsurface boundary layer identification at each sounding station. The subsurface profile stretching across the NW to SE axis was drawn across the strike of the lithology using subsur-

face layer indices extracted from the WinResist-processed VES model. Consequently, the processed VES data were employed to produce the different curve types, geoelectric sections, and thematic maps showing the thickness of the overburden, and the resistivity of the aquiferous layers in a GIS setting, and finally delineating the estimated drilling depth for boreholes within the study location.

2.2. REMOTE SENSING

A subset of the Landsat 8 Operational Land Imager (OLI) scene (path 189, row 54) was prepared using a shapefile of the study area. Additionally, bands 5 and 8 of the Landsat imagery were used for lineament extraction. To ensure minimal interference from vegetation and better visualization of lineaments, the Landsat-8 OLI image was acquired during the dry season (February 2020) with zero percent cloud cover [32]. Both the Environment for Visualizing Images (ENVI) and IDRISI (Sobel edge detector algorithm tool) image processing tools were employed and applied separately on the Landsat-8 OLI digital images for correction of radiometric distortions associated with the recorded data and also for spatial filtering (edge enhancement) so that identifying characteristics and features of interest can be clearly emphasised for better interpretability of the digital imagery. Afterwards, lineaments were extracted manually from the Landsat imagery.

Two shaded relief maps with varying sun azimuth and sun elevation were created from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) imagery. The hill-shaded images were merged to produce a single relief map of Shadadi. Subsequently, with the aid of the ArcGIS 10.3 program, manual extraction of lineaments was performed on the combined relief map of Shadadi. These lineaments, together with those extracted from the Landsat-8 OLI imagery, were then combined to obtain the final composite lineament map of Shadadi. The SRTM DEM was further used to generate the drainage density, slope, and elevation thematic maps

2.3. MCDA AND VALIDATION OF THE GWPM

The analytic hierarchy process (AHP), a form of MCDA developed by Saaty [33], was used to identify the relative influence of criteria controlling the occurrence of a particular phenomenon [4, 33, 34]. AHP was used to assign weights and ranks to the selected criteria on a scale of 1-9, based on Saaty's approach [33, 35]. Detailed mathematical operations and their applicability have been simplified in previous works [4, 19]. Notably, the utilization of this AHP started with a pairwise comparison, which employs a qualitative approach to ascertain the relative significance of each criterion relative to the others, to determine the degree of priority of one over the other, within a pair in a matrix format as stated in Eq. (1).

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}. \quad (1)$$

The matrix judgement is represented by A , with a_{mn} denoting the criterion-comparison entries. The next stage comprises computational steps for normalizing the output weights, computing

the eigenvalue and consistency index, and evaluating the consistency ratio using Eqs. (2) and (3).

$$CR = \frac{CI}{RI}, \quad (2)$$

where CR is the consistency ratio, RI is the random index, which depends on matrix size, and CI is the consistency index given by Eq. (3).

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (3)$$

where $\lambda_{\max}$ is the maximum eigenvalue of matrix A (the weighted-sum to normalized-weight ratio) and n is the number of site-specific parameters in the square matrix. AHP consistency is accepted when the consistency ratio is below 0.1. The online Business Performance Management Singapore (BPMSG) AHP tool [36] was used for the pairwise comparison. Seven thematic factors—elevation, slope, drainage density, lineament density, overburden thickness, geology, and aquifer resistivity—were superimposed to generate the Shadadi GWPM using weighted overlay analysis in ArcGIS 10.3. Borehole-yield information was obtained from active drilling contractors in the region. Based on established yield-classification criteria [37], the GWPM was divided into five potential zones: very low (abortive borehole), low ($< 75 \text{ m}^3 \text{ day}^{-1}$), moderate ($75\text{--}100 \text{ m}^3 \text{ day}^{-1}$), high ($100\text{--}150 \text{ m}^3 \text{ day}^{-1}$), and very high ($> 150 \text{ m}^3 \text{ day}^{-1}$).

Borehole-yield data were used to validate the GWPM through Cohen's kappa coefficient (κ), which evaluates agreement between predicted and observed classes while accounting for chance. Following Landis and Koch [38], κ values of 0.01–0.20, 0.21–0.40, 0.41–0.60, 0.61–0.80, and > 0.80 indicate slight, fair, moderate, substantial, and almost perfect agreement, respectively:

$$K = \frac{P_o - P_e}{1 - P_e}, \quad (4)$$

where P_o is the observed proportion of agreement and P_e is the proportion of agreement expected by chance.

3. RESULTS

3.1. GEOLOGY OF SHADADI

In Shadadi, migmatite gneiss, migmatite augen gneiss, muscovite schist, biotite-hornblende gneiss, and coarse- to medium-grained biotite granite were mapped as the principal rock types, with migmatite gneiss identified as the dominant unit (Figure 4). The multi-phase deformational and orogenic events that impacted the regional basement complex of central Nigeria were reflected locally in various geologic structures, manifesting as joints, fractures, faults, shear zones, folds, and small-scale folds of various types and sizes. These structures range from millimetre to centimetre scale. Characterizing these structures was crucial to understanding the hydrogeologic importance of these structural elements. Examination of the azimuth-frequency rose diagram derived from Landsat 8 OLI- and SRTM-extracted lineaments (Figure 5(a)) showed that scattered trends are observable. These trends encompass orientations in the NNE–SSW, NW–SE, N–S, and E–W directions. The dominant trends were in the NW–SE and NNE–SSW directions. These variable trends are consistent with those generated from field data (Figure 5(b)) and are in-

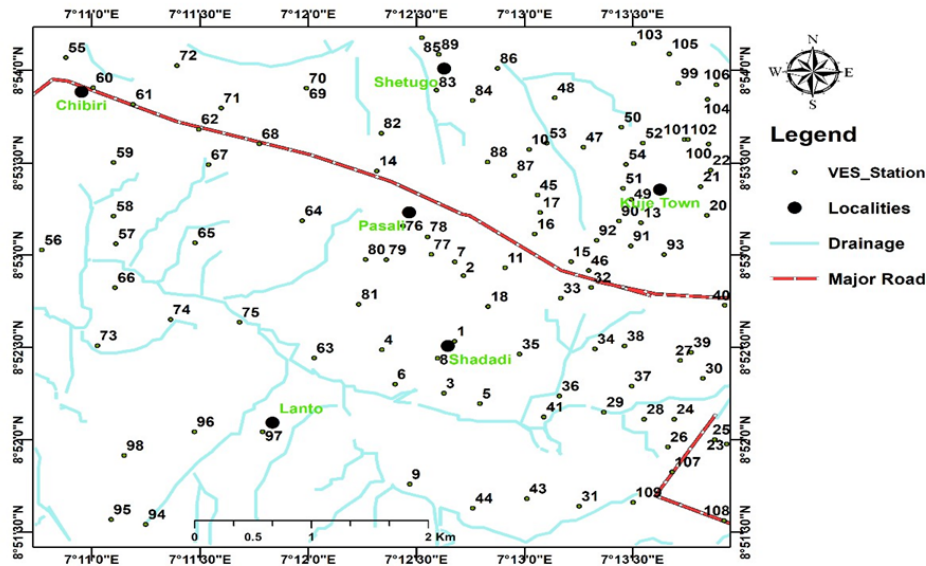


Figure 3: Location map showing the distribution of VES points.

dicative of the various effects of polycyclic ductile and brittle deformations that have significantly impacted this study area [39]. A right-lateral fault observed on the schist outcrop with a lateral displacement of 3.5 cm was also observed, studied, and captured in Figure 6(a). A porphyroblast is set in a migmatite-gneiss located 4 m north of Chibiri-Gwagwalada road (Figure 6(b)). Figure 6(c) depicts a NNE-SSW trending joint set formed in a gently dipping biotite-granite.

3.2. GEOPHYSICAL DATA

The WinResist-processed VES data revealed several types of field curves. The corresponding frequency of occurrence of the various field curves, alongside the number of layers, is shown in Figure 7. The H-type field curve had the highest frequency of occurrence, at 34.9%, while others occur in varying proportions. In the 14 model curve types, three- to six-layer subsurface sequences are represented, namely: H, A, Q, QH, KH, AK, HAA, HA, QHA, QHAK, AA, HKH, HKHA, and KHA. The H-type being the prominent curve type has a

percentage coverage area of 34.9% of the study area, the HA-field curve takes up 16.5%, A-type controls 14.7%, KH-curve covers 11.9%, QH-field curve occupies 9.2 % of Shadadi, while HAA and AA each accounted for 2.8%. KHA accounted for 1.8%, while QHA, AK, Q, QHAK, HKHA, and HKH each accounted for approximately 0.9% (Figure 7).

3.2.1. Geoelectric profile of Shadadi

The construction of the geoelectrical profile involved a qualitative interpretation approach of the characteristic model curves [4, 40, 41]. Five traverses, A–A', B–B', C–C', D–D', and E–E', were represented as geoelectric sections in Shadadi. In traverse A–A' (Figure 8(a)), the geoelectric profile is characterized by four subsurface layers in VES 103 and VES 99 and three layers in VES 104. The resistivity values of the uppermost soil layer fluctuate between 106 Ω m and 784 Ω m. The thickness values

vary from 0.5 m to 1.6 m. The next layer below, which thickens towards the southeast, is the weathered layer. The resistivity undulates between 148 Ω m to 884 Ω m and the thickness increases from 3.1 m to 16.4 m

The third layer, which is absent in VES 104 is the fractured aquiferous layer with resistivity values beginning from 111 Ω m and terminates at 1070 Ω m. The thickness value of this fractured layer is between 3.1 m and 4.6 m. The fourth layer which is the fresh basement rock possesses a resistivity value that oscillates between 1574 Ω m and 1985 Ω m and is infinite at depth. Three (3) to five (5) layers were defined in traverse B–B' (Figure 8(b)). This traverse contains VES 83, VES 84, VES 47 and VES 21. Only the topsoil, the weathered layer and the fresh basement only exist in VES 84. Five (5) subsurface layers are distributed in VES 21, namely the topsoil layer, the sandy-clay layer, the weathered layer, the fractured layer and the fresh basement layer. VES 83 and VES 47 are left with four (4) subsurface layers namely; the top layer, the weathered layer, and the fractured basement layer and the fresh basement layer. The C–C' transverse line accommodates VES 70, VES 88, VES 87 and VES 13. The geoelectric layers range from three (3) to four (4) layers (Figure 8(c)). The consistent topsoil layer, present across the entire profile, has a vertical extent of 0.4 m to 2.6 m and layer resistivity values ranging from 69 Ω m to 441 Ω m. The sandy soil layer, which is peculiar to only VES 87, displays a resistivity value of 48 Ω m and a thickness of 0.8 m. A weathered layer, consistent across the profile, possesses layer resistivity values ranging from 42 Ω m to 151 Ω m, with thickness values vacillating between 2.8 m and 9.2 m. A slightly fractured basement layer is limited to VES 13, with a resistivity value of 1144 Ω m and a thickness of 16.0 m. The basement layer terminates the profile at each VES station, occurring either as a fractured basement or a fresh basement facies: the fractured basement, encountered at VES 70 and VES 13, records resistivity values of 1972 Ω m and 984 Ω m respectively, while the fresh basement, encountered at VES 88 and VES 87, records

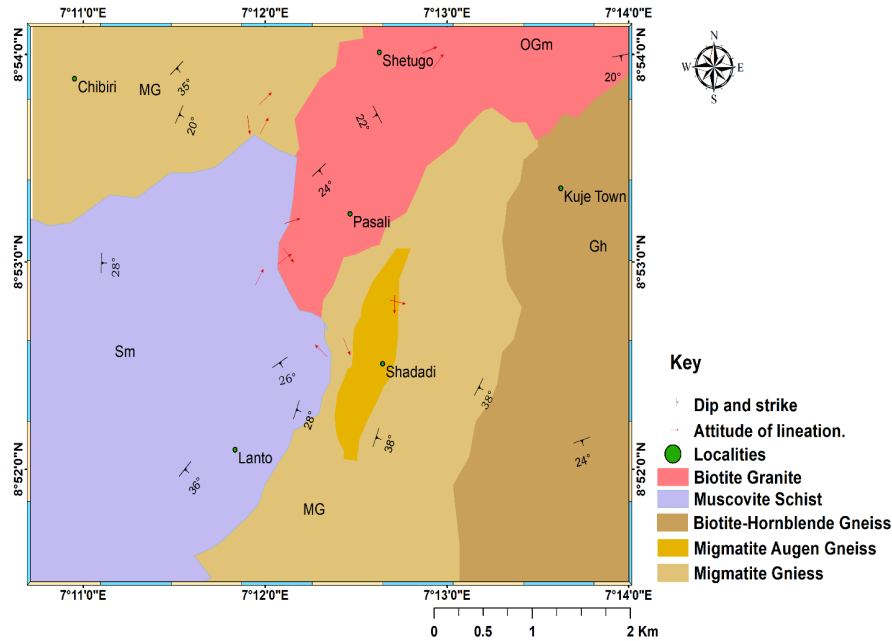


Figure 4: Geological map of Shadadi showing the attitude of lineation.

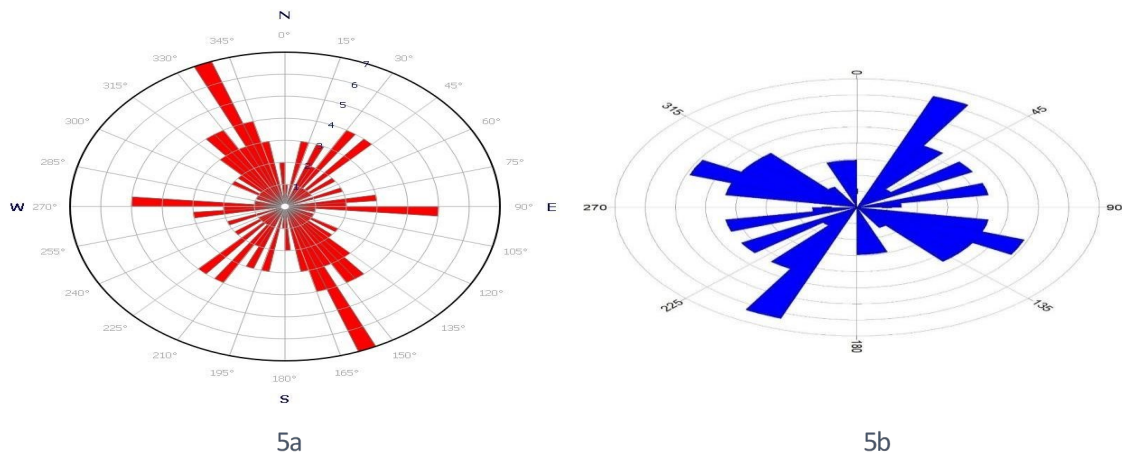


Figure 5: Rose plots showing structural trends: (a) lineaments extracted from digital satellite imagery; and (b) structural elements mapped in the study area. Both show E–W, N–S, NNE–SSW, and NW–SE trends.

resistivity values of 3744 Ω m and 5112 Ω m respectively, and is infinite at depth in all cases.

Three (3) geoelectric layers were mainly found in traverse D–D', with the exception of VES 33, which presents an extra thin layer of sandy clay measuring 1.0 m in thickness and having a resistivity value of 162 Ω m overlying the weathered layer (Figure 8(d)). The topsoil material's resistivity is between 30 Ω m and 226 Ω , with a depth extent spanning from 0.5 m to 2.4 m. The weathered layer resistivity varies from 43 Ω m to 95 Ω m indicating a highly saturated weathered material, presumable of medium to coarse sandy soil. The last layer is the fresh bedrock, manifesting a resistivity range covering values from 1323 Ω m to 11492 Ω m. Traverse E–E' (Figure 8(e)) comprises four VES

stations: VES 44, VES 59, VES 63, and VES 65, with subsurface geoelectric sequences varying between three and four layers. Across all four stations, the uppermost topsoil layer is present, with thickness values spanning 0.8 m to 6.5 m and resistivity readings between 80 Ω m and 711 Ω m. Beneath this, a sandy-clay layer occurs exclusively at VES 59 and VES 65, characterized by resistivity values of 36 Ω m to 274 Ω m and thicknesses of 1.2 m to 8.9 m. A weathered basement layer appears consistently throughout the traverse, with resistivity ranging from 34 Ω m to 165 Ω m and thickness varying between 6.1 m and 17.4 m. Only VES 59 exhibits a fractured basement layer, recording a resistivity of 925 Ω m, whereas the remaining stations: VES 44, VES 63, and VES 65 terminate in fresh basement, with resistivity values

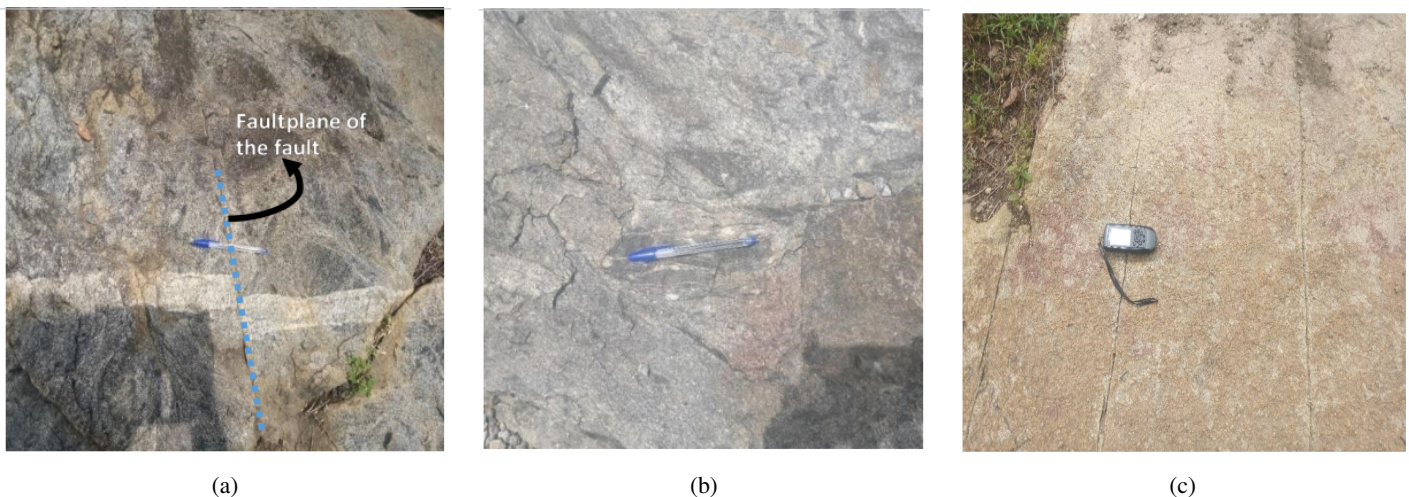


Figure 6: Field photographs: (a) NE–SW-trending right-lateral fault in schist, with 3.5 cm lateral displacement; (b) NW–SE-oriented porphyroblast in gently dipping migmatite gneiss, 4 m north of Chibiri–Gwagwalada Road; and (c) NNE–SSW-trending joint set in gently dipping biotite granite.

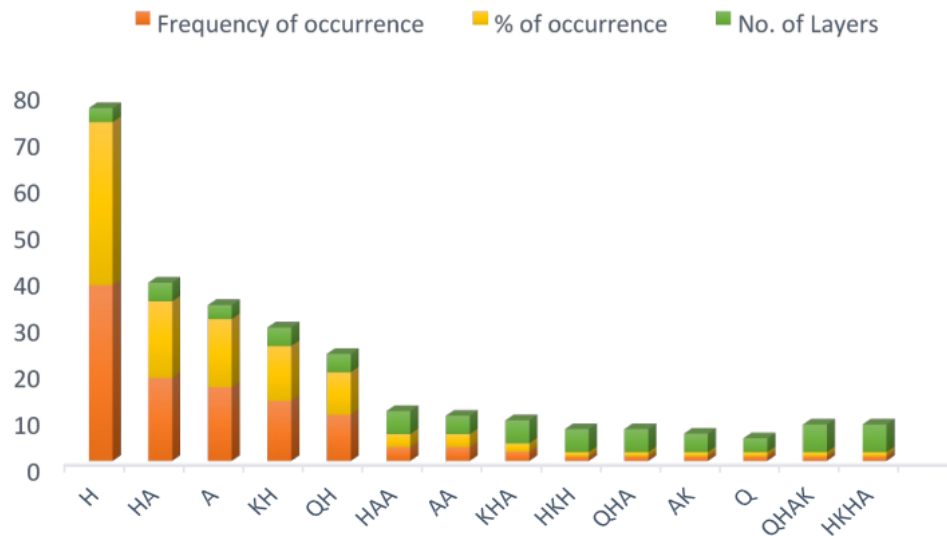


Figure 7: Frequency of occurrence of the model curve types.

ranging from 1238 Ω m to 4476 Ω m.

Tellingly, the significant variability observed in the layer parameters lends credence to the marked heterogeneity characterizing the basement geology of Shadadi. Moreover, the demarcations delineating the basement rocks, including those that exhibit an uneven increase in the thickness of unconsolidated material coupled with the low resistive basement geology, are indicative of storage zones for groundwater [4]. Borehole logs of some of the operational boreholes within Shadadi showed a significant correlation with the neighbouring VES models when compared, with a few exceptions where certain layers highlighted in the lithologs appeared to be commingled in the VES model apparently owing to their similar layer characteristics (Figures 9a-d)

3.3. SPATIAL DATA PRESENTATION

3.3.1. Lineament density factor

Lineaments observed on the land surface commonly occur as linear features and were typically interpreted as surface expressions of fractures or fracture zones that may act as preferential pathways for groundwater flow [7]. Lineaments represent the surface expression of subsurface geological phenomena, and the structural elements that manifest as discernible features on remotely sensed satellite platforms are topographical, geological, and geomorphological in nature. From Figure 10(a), a higher density and greater extent of intersecting lineaments were noticeable in the southeastern and northwestern corners of the study area, portending areas with good potential for groundwater. The configuration of lineaments in parts of the south, southwest, north, and northeastern corridor of the study area also depicts places with moderate groundwater prospects, while a comparatively lower density of lineament arrays is found scattered around the centre,

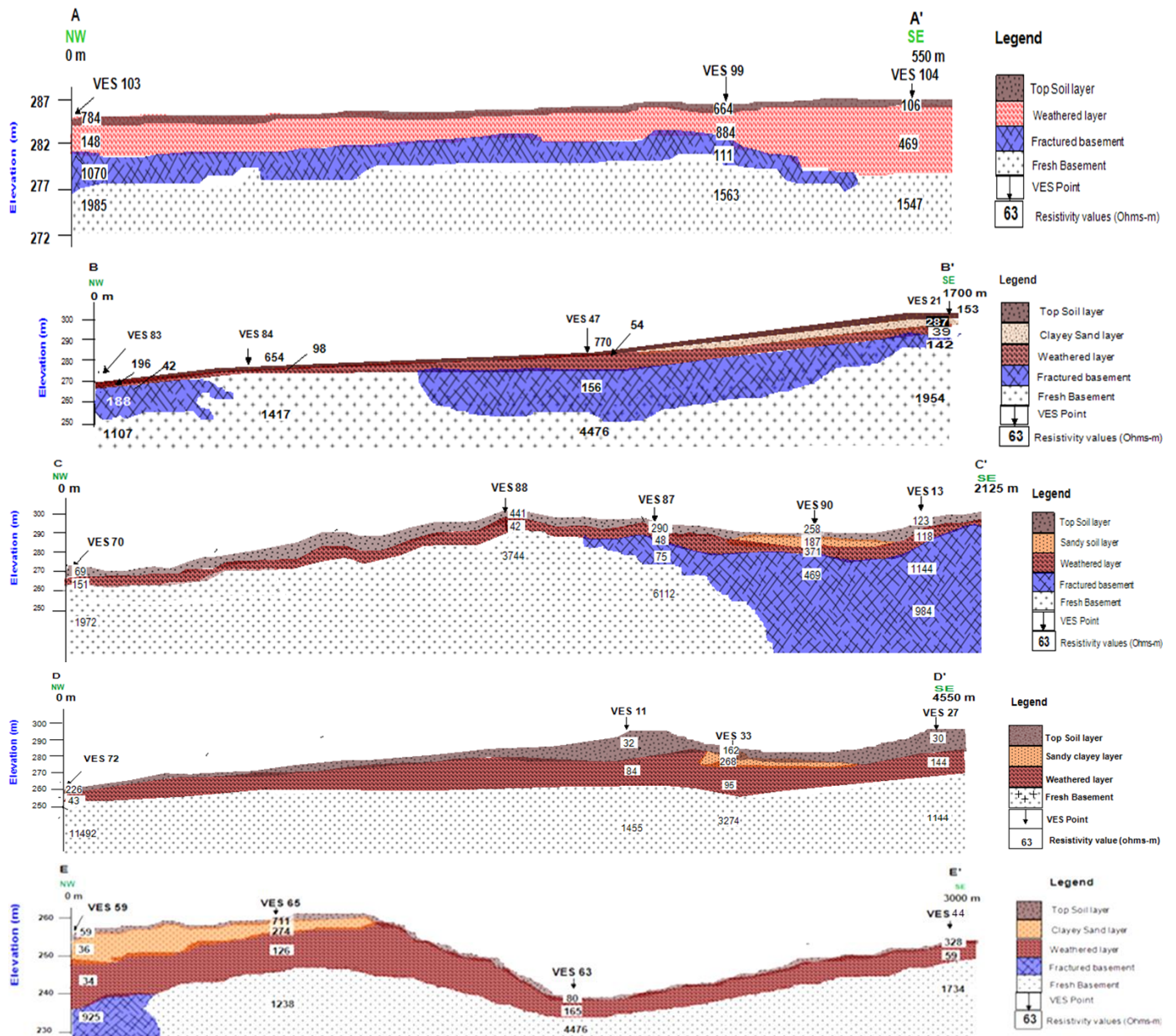


Figure 8: Geoelectric sections showing subsurface layer parameters along NW-SE profiles: (A) A-A'; (B) B-B'; (C) C-C'; (D) D-D'; and (E) E-E'.

far north, and the extreme northeastern flank. Overall, taking lineament density into account, the study area presents a generally positive outlook for groundwater exploitation.

3.3.2. Aquifer resistivity factor

Aquifer resistivity is a measure of an aquifer unit's qualitative response to the passage of an electric current. The magnitude of water saturation in any rock unit is closely related to its resistivity, which plays a vital role in this study. Aquiferous units in hard rocks are qualitatively categorized into two classes: weathered basement and fractured basement aquifers depending on the magnitude of their resistivity values [4, 42].

A notable characteristic of the Shadadi area was that boreholes are frequently constructed to draw from both aquifer types

at once within the same location. As widely recognized in basement hydrogeology, resistivity tends to vary inversely with GWP—lower resistivity in non-clayey unconsolidated and consolidated rock materials reflects greater GWP, whereas higher resistivity suggests the reverse [4]. This well-documented relationship provided the rationale for assigning the resistivity values used in the present classification (Figure 10(b)).

3.3.3. Overburden thickness factor

The overburden includes unconsolidated materials that loosely overlie the consolidated basement geology. It comprises both the weathered layer and loosely-held sediments overlying the fresh crystalline basement complex. Terrain having unfractured rocks nestled within the crystalline basement complex depends very

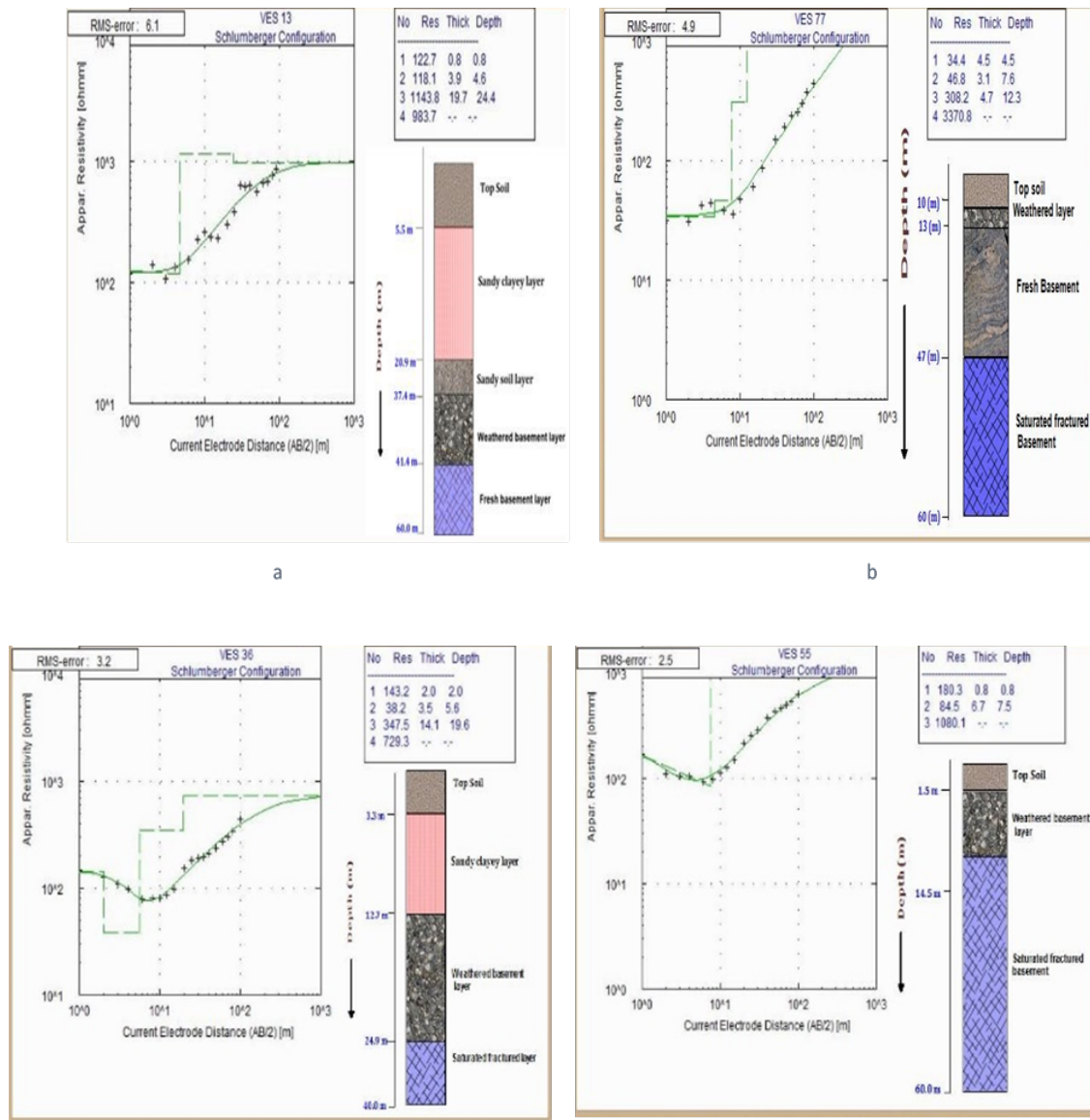


Figure 9: Correlations between sounding models and adjoining or neighbouring borehole lithologic logs: (a) sounding model at 8°53'10.5" N, 007°13'32.2" E and borehole at 8°53'6.7" N, 007°12'52.7" E, central Shadadi; (b) sounding model at 8°53'9.5" N, 007°12'26.3" E and borehole at 8°54'03.1" N, 007°12'49.8" E, northern Shadadi; (c) sounding model at 8°52'15.6" N, 007°13'9.6" E and borehole at 8°52'15.6" N, 007°13'6.2" E, southeastern study area; and (d) sounding model at 8°54'1.0" N, 007°10'45.4" E, northwestern study area.

much on overburden thickness. Locally, areas with extensive overburden coupled with a thin layer or absence of clay and pronounced effective porosity have been recognized to have high GWP. Evaluation of the overburden thickness map indicates that the overburden thickness ranges from 3.3 to 40.3 m in Shadadi, with a mean value of 12.21 m. Overburden depth of more than 17.1 m was considered thick with comparative GWP than areas having less than 17.1 m. The overburden thickness map (Figure 10(c)) reveals that areas having a considerable thickness of weathered residuum are domiciled in the western and eastern flanks. Lesser depths are scattered around the centre, northern, and southeastern areas.

3.3.4. Drainage density factor

A higher drainage density denotes the presence of multiple streams situated in close proximity within a given geographical zone. This implies that precipitation events particularly yields voluminous allocation of water into numerous tributaries, whose combined discharge ultimately empties into the ocean. As a consequence, the water has limited migratory opportunities to recharge the water table beneath. Some researchers agree that a closely spaced drainage (higher drainage density) will result in a low GWP, and a reduced density of river channels will result in a greater potential for groundwater [12, 43]. The natural layout of Shadadi's drainage network is largely dendritic, which bears the characteristics of an area with similar rock types, with a planar or slightly tilted bed, and an extensively undulating topographic

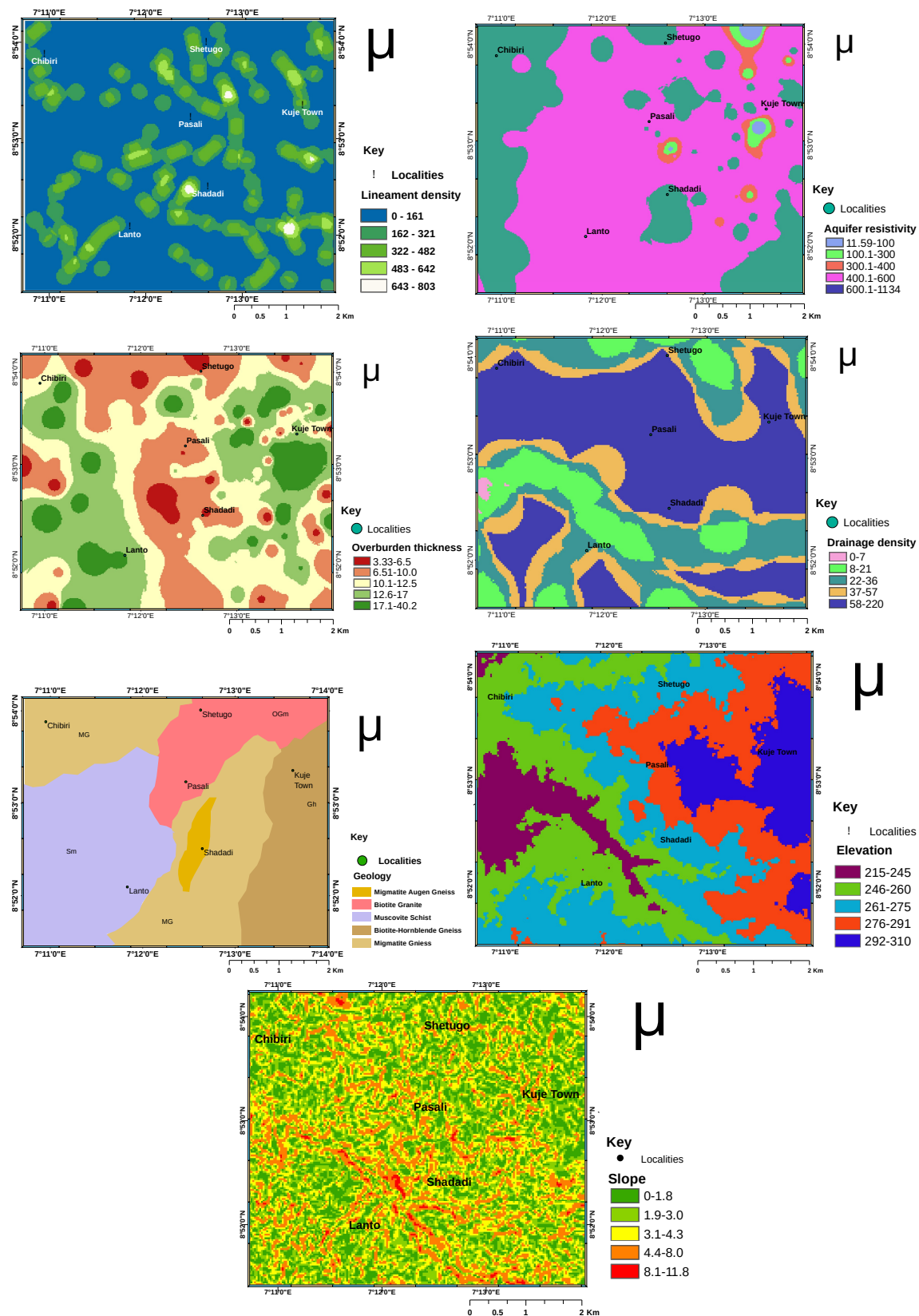


Figure 10: Classified spatial thematic maps of the factors influencing GWP in Shadadi: (a) lineament density; (b) aquifer resistivity; (c) overburden thickness; (d) drainage density; (e) lithology; (f) elevation; and (g) slope.

surface with extremely low reliefs (Figure 10(d))

3.3.5. Lithology thematic map

Geology constituted a principal factor in the appraisal of hydric potential, and significantly influences its spatial spread and avail-

ability in the study site. The groundwater retention abilities of different lithologic types are positively correlated with their degree of weathering and secondary porosity. Consequently, rock units that exhibit high resistance to weathering are expected to have negligible presence of secondary channels, such as fractures and joints, which facilitate water infiltration from the surface to the subsurface. This will have a negative impact on GWP. On the other hand, the least resistant rock unit to weathering will be a repository of a good quantity of groundwater due to the availability of secondary fractures, and porosity. In this study, the various lithologic units were weighed, ranked, and categorized taking into account their level of hydrogeological relevance using their relative resistance to weathering, degree of fracturing, and individual pulverized product of the weathering process. Geologically, Shadadi comprises muscovite schist, coarse to medium-grained biotite granite, biotite-hornblende gneiss, and migmatite gneiss. Particularly, rocks having the least resistance to environmental factors, and also possessing a considerable degree of fracturing, and yielding non-clayey material as a product of weathering, were ranked the most in this study. Conversely, the most resistant rocks to weathering, alongside those churning out clayey materials as pulverized products of weathering, were ranked the least (Figure 10e).

3.3.6. Elevation factor

In the study area, high-altitude areas have low groundwater possibilities, while low-altitude regions have a higher likelihood due to gravitational forces playing a significant role in driving water downstream. The implication is that high-altitude areas would not be the best fit for siting boreholes due to the high cost of water extraction [12] [44]. Shadadi's elevation ranges from 215 to 310 m above sea level. Analysis of Figure 10(f) clearly shows that areas centred in Shadadi community and the eastern zone are the topographic high, while low-land areas are scattered around the northern, western, and southern flanks. Lower topography zones were attributed a significant weight, since they are generally considered platforms for groundwater storage in contrast to the higher topographic zones which were ranked lower.

3.3.7. Slope factor

The significance of the slope angle in regulating the percolation of surface water into the groundwater is notable, as it holds a crucial role in this hydrological process. Typically, regions characterized by steep topography are correlated with higher water velocity, and a heightened potential for runoff which invariably leads to reduced infiltration rates [45]. Here, a heterogeneous slope angle is observed in Shadadi and its environs. It fluctuates between 0° and 11.8° with a notable slope angle concentration observed around 0, and 3.8 (Figure 10(g)). In the central portion of Shadadi and even towards the south, higher slope values specifically ranging from 6° to 11.8° are clustered. Pockets of high-angle slope are scattered around the study area. This slope inclination aligns with regions where rapid overland runoff manifest with less percolation time. Chibiri, Shetugo and some parts of Kuje communities are areas where slope values fell below 6° with an attendant positive prospect for groundwater.

3.4. ASSIGNMENT OF WEIGHTS TO CRITERIA

The contribution and influence of each thematic factor on the GWP of Shadadi were found to be markedly disproportionate. Consequently, relative weights were assigned to define the hydric contribution level of each individual criterion using Saaty's scale (Table 1), and the resulting weighted numerical values were subsequently employed as input parameters in the overlay analysis. Tables 2 and 3 shows the pairwise comparison between the competing variables, and their sub-class categorization. From the normalization of the assigned weight, the comparison matrix indicated that the overburden thickness takes the highest normalized weight of 0.37, making it the most sensitive for

GWP within this study area. Accordingly, the next most influential themes are elevation (0.25), slope (0.20), lithology (0.08), aquifer resistivity (0.05), lineament density (0.03) and drainage density (0.02). According to some researchers [4, 12], it is absolutely crucial that the consistency ratio for a 7x7 matrix be equal to or less than 10 % for the pairwise comparison to be valid. For this study, 0.037 was the computed consistency ratio.

3.5. GROUNDWATER POTENTIAL MAP

The GWP index for Shadadi was calculated as $GWP = \sum_i W_i X_i$, where W_i is the normalized weight assigned to each thematic layer and X_i is the corresponding subclass score derived from Table 2 and Table 3. This expression was implemented in ArcGIS 10.3 to generate the GWPM. The GWPM (Figure 11) shows that very high and high potential zones are concentrated primarily in the western, northwestern, and eastern regions, while areas in the northeast are predominantly of moderate GWP. Parts of the central, northern, and southern regions were identified as low- and moderate-GWP zones. In terms of area coverage, the results of the weighted overlay analysis indicated that the moderate zone occupied the largest proportion, accounting for 60.5% or 17.72 km². The high yield, low, very high, and very low zones followed, accounting for 23.8%, 14.9%, 0.7%, and 0.1%, respectively, which equated to 6.98 km², 4.37 km², 0.21 km², and 0.02 km² in areal coverage (Table 4). The predictive performance of the GWPM was evaluated using borehole yield data from 49 drilled boreholes in the Shadadi area (Table 5). The computation of the kappa statistic using the confusion matrix (Table 6) is as follows:

Using the confusion matrix in Table 6, the observed agreement was

$$P_o = \frac{43}{49} = 0.8776,$$

and the expected agreement by chance was

$$P_e = \frac{(1 \times 1) + (7 \times 9) + (31 \times 29) + (10 \times 10)}{49^2} = 0.4427.$$

Therefore,

$$K = \frac{0.8776 - 0.4427}{1 - 0.4427} \approx 0.78.$$

3.6. DISCUSSION

Our investigation corroborates the capacity of thematic refinement and integration, as exemplified in previous research [19], in optimising the identification of successful water borehole drilling points in the Shadadi area. The findings highlight the

Table 1: Saaty's pairwise comparison scale and interpretation [33].

Strength of significance	Definition	Explanation
1	Equally important	The research design is influenced equally by two criteria.
3	Moderate importance	There is a slight preference for one criterion over the other.
5	Strong importance	Preference for one criterion is notably stronger than for the alternative.
7	Very strong or demonstrated importance	The superiority of one criterion over another is demonstrated in practice.
9	Extremely important	One factor is unequivocally prioritized over the other, indicating the greatest degree of preference.
2, 4, 6, 8	Intermediate values between adjacent judgments	Used when compromise is needed.

Table 2: Subclass ranges, ratings, and associated hydrological parameters.

Hydrological parameter	Subclass range	GWP yield class	Subclass rating (1–5)	AHP weight (%)
Lineament density	0–161	Very low	1	3
	162–321	Low	2	
	322–482	Moderate	3	
	483–642	High	4	
	643–803	Very high	5	
Aquifer resistivity	11.59–100	Very high	5	5
	101–300	High	4	
	301–400	Moderate	3	
	401–600	Low	2	
	601–1142	Very low	1	
Overburden thickness	3.33–6.5	Very low	1	37
	6.51–10	Low	2	
	10.1–12.5	Moderate	3	
	12.6–17	High	4	
	17.1–40.2	Very high	5	
Drainage density	0–7	Very high	5	2
	8–21	High	4	
	22–36	Moderate	3	
	37–57	Low	2	
	58–220	Very low	1	
Lithology	Migmatite augen gneiss	Very low	1	8
	Biotite granite	Low	2	
	Muscovite schist	Very high	5	
	Biotite-hornblende gneiss	Moderate	3	
	Migmatite gneiss	High	4	
Elevation	215–245	Very high	5	25
	246–260	High	4	
	261–275	Moderate	3	
	276–291	Low	2	
	292–310	Very low	1	
Slope	0–1.8	Very high	5	20
	1.9–3.0	High	4	
	3.1–4.3	Moderate	3	
	4.4–8.0	Low	2	
	8.1–11.8	Very low	1	

pivotal role of each theme in influencing GWP delineation, providing a nuanced understanding that complements and expands upon existing research. The dominance of the moderate GWP zone across 60.5% of Shadadi reflects the heterogeneity typical of Precambrian basement terrain, where aquifer occurrence is controlled by localized weathering and fracturing rather than laterally continuous formations. These outcomes correspond with

previous studies [4, 12, 37]. The concentration of low-yield boreholes in the central Shadadi community aligns with the mapped muscovite schist and shallow overburden, indicating limited fracture development and rapid runoff on higher slope gradients. In contrast, the high to very high potential zones in the western and northwestern sectors correspond to areas of greater lineament density and thicker weathered residuum, suggesting en-

Table 3: Pairwise comparison matrix and weight determination using the AHP technique [46] and Saaty's scale [33]. Number of comparisons: 21; principal eigenvalue: 7.294; consistency ratio: 0.037; eigenvector solution: 5 iterations.

S/N	Criterion	Priority	Rank	(+)	(-)	1	2	3	4	5	6	7	Weight
1	Elevation	24.70 %	2	7.00 %	7.00 %	1.00	3.00	2.00	0.50	6.00	9.00	8.00	0.25
2	Lithology	7.60%	4	2.40 %	2.40 %	0.33	1.00	0.20	0.14	2.00	5.00	3.00	0.08
3	Slope	20.40%	3	8.10 %	8.10 %	0.50	5.00	1.00	0.50	3.00	9.00	8.00	0.20
4	Overburden thickness	37.20%	1	11.00 %	11.00 %	2.00	7.00	2.00	1.00	9.00	9.00	9.00	0.37
5	Aquifer resistivity	4.70%	5	1.10 %	1.10 %	0.17	0.50	0.33	0.11	1.00	2.00	2.00	0.05
6	Drainage density	2.30%	7	0.80 %	0.80 %	0.11	0.20	0.11	0.11	0.50	1.00	0.50	0.02
7	Lineament density	3.10%	6	0.80 %	0.80 %	0.13	0.33	0.13	0.11	0.50	2.00	1.00	0.03

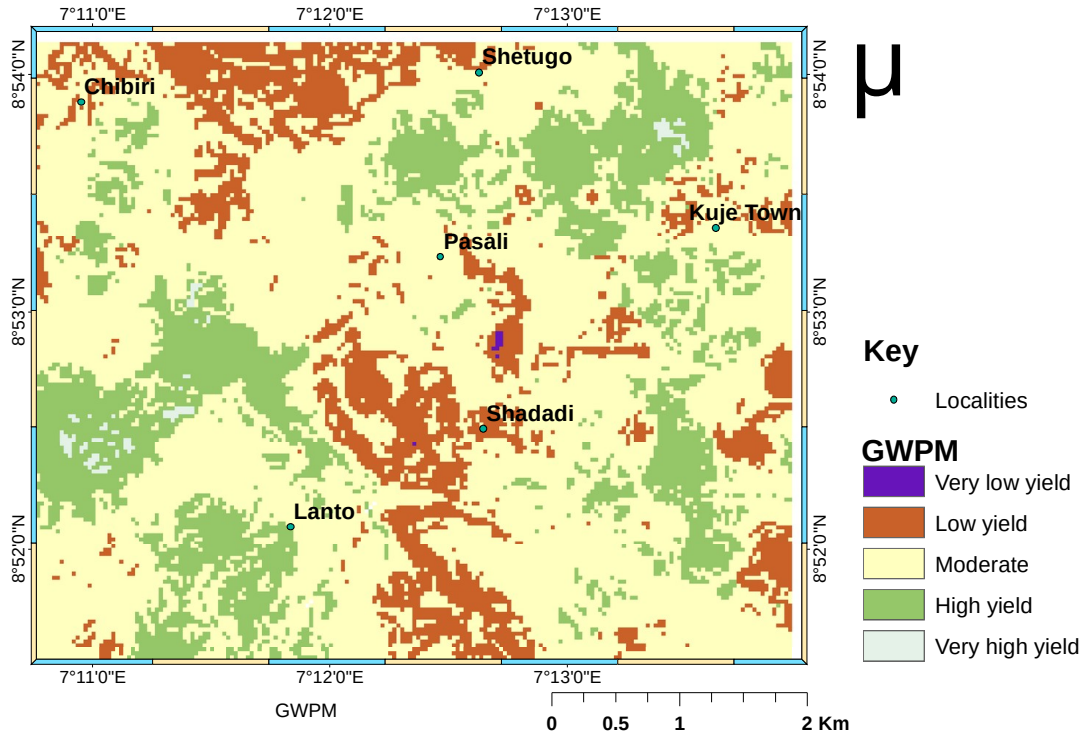


Figure 11: GWPM of Shadadi showing the distribution of the different yield categories.

Table 4: Groundwater prospective zones in Shadadi.

Prospective zone	Area (km ²)	Coverage (%)
Very low yield	0.02	0.1
Low yield	4.37	14.9
Moderate yield	17.72	60.5
High yield	6.98	23.8
Very high yield	0.21	0.7

hanced secondary porosity and storage capacity. This strong spatial correspondence between predicted zones and observed borehole yields, underscored by a Cohen's kappa of 0.78 indicating substantial agreement, confirms that integrating structural, topographic, and geophysical parameters substantially improves targeting accuracy compared to single-method approaches.

In relation to the local geology, the results of the geospatial analysis showed that the muscovite schist, biotite-hornblende gneiss, biotite granite, and the deeply weathered migmatite gneiss located in Chibiri community constitute high- and moderate-potential zones in contrast to the exposed, and unfractured migmatite gneiss, ubiquitous towards the south from the central zone in Shadadi community, which constitutes a low-groundwater-potential lithology. Drawing upon the deductions

made from both the geoelectrical data inversion analysis presented in the geoelectric section, and corroborated by the representative lithologic logs, four to five distinct subsurface layers: topsoil, sandy-clay, weathered basement, fractured basement, and fresh basement are delineated. The aquiferous zone was found to be confined to the weathered and fractured basement layers, with average depth ranging from 15 m in the northern and western regions, and up to 60 m in the southern and northeastern regions. These results are comparable to those of [42] for a groundwater investigation in the southwestern part of the study area and [47] for the Keffi area of central Nigeria. The geophysical investigation also revealed that the high concentration of structural controls was found to be the explanation for the prolific yields of boreholes drilled in the north-west, south, and northeastern sections, while the considerably thick weathered residuum coupled with shallow fractures accounts for the good yield of boreholes in the northeast and central part of the Shadadi area.

Locally, Shadadi community is located at the centre of the region having an overburden thickness of less than 10 m, The low-GWP areas are therefore characterized by very high drainage density, very high gradient, low lineament density, high resistivity

Table 5: Validation dataset showing borehole depth, yield, and concordance between field-observed and GWPM-projected yield classifications in Shadadi.

Borehole	Longitude	Latitude	Depth	Yield ($\text{m}^3 \text{ day}^{-1}$)	Observed class	GWPM class	Description
BH-1	7.22558333	8.8891111	110	74	Low	Low	Agreement
BH-2	7.206077	8.886143	100	94	Moderate	Moderate	Agreement
BH-3	7.204833	8.872889	120	50	Low	Low	Agreement
BH-4	7.217972	8.883806	50	81	Moderate	Moderate	Agreement
BH-5	7.201972	8.883639	50	84	Moderate	Moderate	Agreement
BH-6	7.221056	8.894306	100	121	High	High	Agreement
BH-7	7.21769	8.875111	120	140	High	Moderate	Disagreement
BH-8	7.230278	8.873889	115	97	Moderate	Low	Disagreement
BH-9	7.207306	8.885972	60	98	Moderate	Moderate	Agreement
BH-10	7.214583	8.890019	80	90	Moderate	High	Disagreement
BH-11	7.208333	8.896222	50	139	High	High	Agreement
BH-12	7.210667	8.900111	40	90	Moderate	Moderate	Agreement
BH-13	7.212528	8.899778	35	98	Moderate	Moderate	Agreement
BH-14	7.230919	8.871917	40	90	Moderate	Moderate	Agreement
BH-15	7.217306	8.88575	70	93	Moderate	Moderate	Agreement
BH-16	7.206945	8.874945	100	99	Moderate	Moderate	Agreement
BH-17	7.207194	8.883194	70	87	Moderate	Moderate	Agreement
BH-18	7.211139	8.876083	70	91	Moderate	Low	Disagreement
BH-19	7.230222	8.8895	70	97	Moderate	Low	Disagreement
BH-20	7.221111	8.8836944	150	63	Low	Low	Agreement
BH-21	7.212944	8.89775	80	91	Moderate	Moderate	Agreement
BH-22	7.229278	8.896833	80	87	Moderate	Moderate	Agreement
BH-23	7.231278	8.890139	70	81	Moderate	Moderate	Agreement
BH-24	7.200222	8.884028	100	96	Moderate	Moderate	Agreement
BH-25	7.204333	8.890417	80	88	Moderate	Moderate	Agreement

Table 5 continued

Borehole	Longitude	Latitude	Depth	Yield ($\text{m}^3 \text{ day}^{-1}$)	Observed class	GWPM class	Description
BH-26	7.199944	8.885472	60	86	Moderate	Moderate	Agreement
BH-27	7.1945	8.898056	60	90	Moderate	Moderate	Agreement
BH-28	7.2119722	8.8802222	140	Abortive	Very low	Very low	Agreement
BH-29	7.206944	8.896944	50	125	High	High	Agreement
BH-30	7.207889	8.887333	99	91	Moderate	Moderate	Agreement
BH-31	7.202778	8.877806	70	90	Moderate	Moderate	Agreement
BH-32	7.212278	8.892694	80	96	Moderate	Moderate	Agreement
BH-33	7.213556	8.898917	60	89	Moderate	Moderate	Agreement
BH-34	7.211361	8.895667	80	120	High	High	Agreement
BH-35	7.203778	8.890417	60	90	Moderate	Moderate	Agreement
BH-36	7.216694	8.879583	90	95	Moderate	Moderate	Agreement
BH-37	7.211306	8.894139	100	97	Moderate	Moderate	Agreement
BH-38	7.231694	8.883778	90	137	High	High	Agreement
BH-39	7.225861	8.872972	50	144	High	High	Agreement
BH-40	7.222	8.874472	70	87	Moderate	Moderate	Agreement
BH-41	7.227028	8.878944	50	143	High	High	Agreement
BH-42	7.223472	8.883722	80	94	Moderate	Moderate	Agreement
BH-43	7.227139	8.872917	70	90	Moderate	Moderate	Agreement
BH-44	7.228154	8.868537	100	149	High	High	Agreement
BH-45	7.226778	8.869639	70	111	High	High	Agreement
BH-46	7.22622	8.890889	110	50	Low	Low	Agreement
BH-47	7.23225	8.8912778	120	30	Low	Moderate	Disagreement
BH-48	7.2046667	8.8845833	110	60	Low	Low	Agreement
BH-49	7.2128611	8.8814722	140	19	Low	Low	Agreement

Table 6: Confusion matrix for field-observed and GWPM-projected yield classes.

Actual \ Predicted	Very low	Low	Moderate	High	Total
Very low	1	0	0	0	1
Low	0	6	1	0	7
Moderate	0	3	27	1	31
High	0	0	1	9	10
Column total	1	9	29	10	49

values, and thin aquifer thickness, and are located in topographically higher terrain. In contrast, high-GWP areas are situated downstream and have a low resistivity value, low slope steepness, low drainage density, coupled with a considerable thickness of weathered residuum. In terms of area coverage, the results of the weighted overlay analysis indicated that the moderate zone occupied the largest proportion, accounting for 60.5% or 17.72 km². The high yield, low, very high, and very low zones followed, accounting for 23.8%, 14.9%, 0.7%, and 0.1%, respectively, which equated to 6.98 km², 4.37 km², 0.21 km², and 0.02 km² in areal

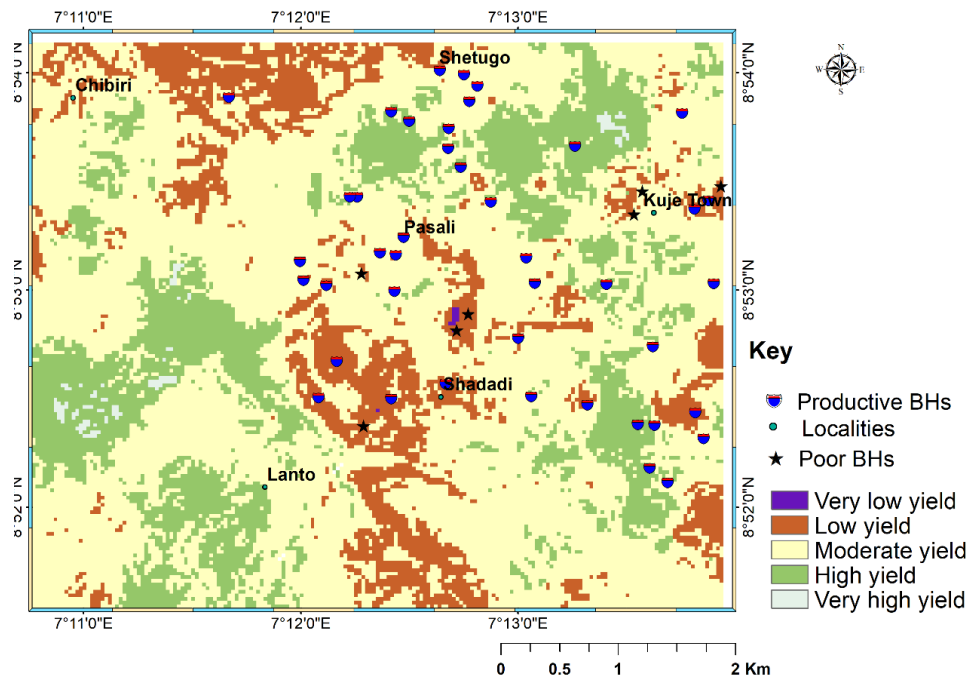


Figure 12: Selected drilled borehole data overlaid on the Shadadi GWPM to assess agreement or disagreement.

coverage (Table 4). Practically, future borehole siting should prioritize the western, northwestern, and isolated southeastern high-potential zones, while avoiding the central uplift where repeated drilling failures have been reported. A key limitation remains the uneven distribution of VES data in underdeveloped areas, which introduces uncertainty in the interpolated overburden and resistivity layers; infilling these gaps would further refine the model.

Validation of the GWPM in this study relied on hydrological data from 49 representative boreholes, draped over the model and displayed in Figure 12. A concentration of low yield boreholes in the central Shadadi area, along with an isolated low-yield borehole in the eastern low-yield zone, showed considerable agreement with the GWPM generated in this research. Furthermore, the measure of the extent of agreement between the GWPM and the data obtained relating to the drilled boreholes using Cohen's kappa coefficient, revealed a κ value of 0.78. The validation results confirm that the produced GWPM provides a reliable basis for groundwater exploration and borehole siting in the Shadadi area.

4. CONCLUSION

In this study, a GWPM for Shadadi and adjoining areas in central Nigeria was generated by integrating multiple groundwater-influencing factors using MCDA in a GIS environment. It was established that the northwestern, western, and some isolated portions of the southeastern part of Shadadi and environs, were delineated as areas of high groundwater potential on the GWPM. A cluster of low- to very-low-yield boreholes occurs within the low-yield zone in the central and slightly southern parts of the study area. The kappa statistic of 0.78 indicates substantial agreement between observed yield and the AHP-derived GWPM yield class. Overall, Shadadi and adjoining communities in central Nigeria have predominantly moderate to high groundwater potential.

DATA AVAILABILITY

All datasets generated in this study are available from the corresponding author upon reasonable request.

DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

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