Nigerian Journal of Technology (NIJOTECH)
Vol. 43, No. 3, September, 2024, pp.557 - 567
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://doi.org/10.4314/njt.v43i3.19

INTEGRATION OF GEOSPATIAL AND GEOPHYSICAL DATA FOR ASSESSING BOREHOLE CONDITIONS AT THE UNIVERSITY OF ILORIN, NORTH-CENTRAL, NIGERIA

AUTHORS:
A. A. Fatoyinbo[1], K. S. Ishola[2,*], C. J. Okolie[3], O. E. Daramola[4], I. A. Hamid-Mosaku[5], O. A. Ipadeola[6], I. D. Arungwa[7], C. O. Ogbeta[8], and S. E. Erharhaghen[9]

AFFILIATIONS:
[1,2,9]Department of Geosciences, Faculty of Science, University of Lagos, Nigeria.
[3,4,5]Department of Surveying and Geoinformatics, Faculty of Engineering, University of Lagos, Nigeria.
[6]Department of Surveying and Geoinformatics, Faculty of Environmental Sciences, University of Ilorin, Nigeria.
[7]Department of Surveying and Geoinformatics, School of Environmental Sciences, Federal University of Technology, Owerri, Nigeria.
[8]Department of Surveying and Geoinformatics, College of Environmental Sciences, Bells University of Technology, Ota, Nigeria.

***CORRESPONDING AUTHOR:**
Email: kishola@unilag.edu.ng

ARTICLE HISTORY:
Received: 05 February, 2024.
Revised: 17 August, 2024.
Accepted: 25 August, 2024.
Published: 20 September, 2024.

KEYWORDS:
Boreholes, Groundwater, Lineaments, Geographic information system, Remote sensing.

ARTICLE INCLUDES:
Peer review
DATA AVAILABILITY:
On request from author(s)

EDITORS:
Chidozie Charles Nnaji

FUNDING:
None

HOW TO CITE:
Fatoyinbo, A. A., Ishola, K. S., Okolie, C. J., Daramola, O. E., Hamid-Mosaku, I. A., Ipadeola, O. A., Arungwa, I. D., Ogbeta, C. O., and Erharhaghen, S. E. "Integration of Geospatial and Geophysical Data for Assessing Borehole Conditions at the University Of Ilorin, North-Central, Nigeria", *Nigerian Journal of Technology*, 2024; 43(3), pp. 557 – 567; *https://doi.org/10.4314/njt.v43i3.19*

Abstract
Even with pre-drilling geophysical surveys, the failure rates and suboptimal productivity of some boreholes within the University of Ilorin (UNILORIN) are a cause for concern. This present study investigated the hydrogeological capability and potentiality of some borehole sites at the university. To achieve this, an inventory of 47 boreholes with an existing lineament density map and Groundwater Potential Zonation (GWPZ) map of Ilorin South Local Government Area were integrated. These boreholes were categorized based on the lineament density, and groundwater potentiality. The results showed that 96% of the sampled boreholes were sited on zones of low groundwater potential (LGWP) while 4% were on zones of moderate groundwater potential (MGWP). Also, 17% of the boreholes coincided with zones of moderate lineament density, 83% of boreholes coincided with zones of low lineament density and no borehole was found to coincide within areas of high lineament density. The findings suggested that 83% of these boreholes (39 units) were drilled due to exigencies (e.g., cost consideration, proximity to facilities etc.) while only 17% of these boreholes (8 units) were drilled on account of scientific necessity or after the appropriate geoscientific evaluation was done. The findings in this study will benefit stakeholders and practitioners in water resource management in building robust models and databases at both regional and local levels.

1.0 INTRODUCTION
With the rising population, the earth's available water resources have witnessed increased usage, and inevitable water scarcity might be looming [1, 2]. Groundwater is a water resource that is replenished by rainfall variability, alleviates growing water scarcity, contributes to food security and regional growth as well, and mitigates the risks resulting from the effects of climate change on the hydrological cycle [3]. Before 1970, there was low infrastructural development in sub-Saharan Africa, and populations clustered around the wetlands because the outskirts and hinterlands had no water for survival; the only source of groundwater was from natural springs and artesian wells [4, 5], and also from shallow hand-dug wells within the regolith that gave water supplies, and abandoned after failing to yield [6, 7]. With the advent of technology, however, advanced drilling tools became accessible and affordable. This resulted in people migrating from the core clusters to the outskirts and hinterlands, but issues with wildcat and abortive boreholes continued unabatedly [4, 5].

In the past, borehole designs and completion have been taken for granted with the consequence that many have either failed to yield optimally or dried up. Several boreholes have been appraised in different geological settings to identify the causes of their failures [7, 8]. Borehole failure arises when a borehole that has been successfully drilled, subsequently fails to deliver sufficient yield of safe water throughout the year. According to [7], the causes of borehole failures include: tapping water from an aquiclude (i.e., a geological formation that absorbs and holds water but does not transmit it at a sufficient rate or it is impermeable to flow of water but does not yield water e.g., clay and shale), seasonal fluctuations in water level, improper casing of the overburden and pump failure. Other factors that may cause premature failure include poor quality siting, borehole design, drilling and completion, inadequate supervision, and inappropriate contracts [9 - 14]. During the last four decades, when deep exploration techniques were deployed for near-surface investigations, wildcats and abortive boreholes had become a thing of the past [15, 16]. Although the introduction of hydro-geophysics reduced wildcats and abortive boreholes to a certain extent [16, 17], more advanced point-scale geophysical techniques have since been introduced such as electrical methods, e.g., Vertical Electrical Soundings (VES) or depth sounding, and electromagnetic methods (e.g., Time Domain Electromagnetics and Frequency Domain Electromagnetics). Considering the need for improved water supplies, it is imperative to develop mechanisms and strategies to enhance the quality of water and borehole construction.

In evaluating boreholes, techniques such as hydrogeological surveys, water quality testing, borehole logging, field measurements, and data integration and modeling are commonly used [18]. Hydrogeological surveys include aquifer testing and geophysical methods to understand subsurface conditions. Water quality testing involves chemical and isotopic analysis to ensure safe drinking water. Borehole logging, including geophysical and video logging, inspects the condition of boreholes, while field measurements monitor water levels and flow rates. Geospatial techniques are particularly important due to their ability to integrate various data types into a unified spatial framework. They facilitate multi-scale analysis, planning and site selection, risk assessment and hazard mapping, drilling optimization, monitoring borehole conditions, and post-drilling analysis. Several authors have utilized geospatial techniques for assessing borehole failure, and potential groundwater locations [18 - 21]. In a recent study, [18] utilized remote sensing, spatial and geophysical modeling, and real recharging capabilities to identify suitable areas for groundwater exploitation in dry coastal areas. In another study, [22] developed a triangulation approach for groundwater potential evaluation using geospatial technology and multi-criteria decision analysis (MCDA) in Edo State, Nigeria. The study leveraged geospatial and borehole data to establish a zone with high groundwater potential.

According to [14], the practical realities of borehole drilling provision in Africa, have received inadequate attention by researchers, although there is recent research on the causes of borehole failures. The University of Ilorin (UNILORIN), North-central Nigeria has an existing tripartite water regime consisting of municipal water from the Asa and Agba dams, a mini university dam completed to augment the municipal water with River Oyun being the main source [23, 24], and a few dispersed water boreholes on the university landmass. Despite this seemingly composite water regime aimed at eradicating water insecurity, there are still cases of water scarcity within and around the university. The municipal water is not reliable, and the dam is vulnerable to seasonal variability. There is the possibility of fractured basements at certain points along the dam bank from a depth of about 10 m downward acting as zones of anomalous seepage which can be inimical to the continuous water retention of the dams [25]. In a related study, [26] showed that the university's dam has about twenty of its thirty baffle blocks damaged causing the dam to experience structural collapse from seepages through its foundation.

There are concerns that the groundwater which should be the most reliable component of the existing water regime is also not very productive and dependable despite claims that geophysical surveys were carried out before the boreholes were drilled. However, [27] indicated that there was no serious water problem in the region because the availability seemed higher than the present use. This is inconsistent with reality and the results of numerous studies which show that some parts of the region are highly water-stressed [28 - 30]. This present work integrates geospatial and geophysical data to investigate the rationale behind the drilling of boreholes within the University of Ilorin landmass. In light of this, two possible rationales were defined: (i) scientifically guided/geoscientific motive (i.e., due to scientific necessity and after appropriate geophysical evaluation), and (ii) exigent circumstances (i.e., constrained by cost, proximity etc). The main contribution of this study is the integration of geospatial and geophysical data for retrospective validation and post-development (i.e., post-drilling) evaluation of boreholes. This presents a unique way of investigating borehole failures, drilling optimization and post-drilling analysis.

2.0 LOCATION AND GEOLOGY OF THE STUDY AREA

The University of Ilorin (UNILORIN) has an areal extent of about 15,000 hectares (150 sq. km) with geographic coordinates between longitudes 4°39'E to 4°42'E and latitudes 8°27'N to 8°29'N covering the most active area on the landmass [31]. It is characterized by dry and wet seasons with a mean annual temperature ranging from 30°C to 36°C and exhibiting the double maxima pattern [28, 32]. Figure 1 is a geological map of Nigeria showing the study area. The average depth to water table in the area is 30 – 55 m. The geology belongs to the Precambrian-to-lower Paleozoic age and is often believed to be an extension of the south-western basement complex [29, 30, 33, 34]. Major rocks constituents of the Precambrian crystalline basement include migmatites, metasediments (schists, quartzites, and metavolcanic), late-stage minor pegmatites, Pan-African older granites, aplitic intrusives, and gneisses [33]. Ilorin is situated on the undifferentiated Precambrian basement complex of granitic strains and metamorphic origin [29, 35].

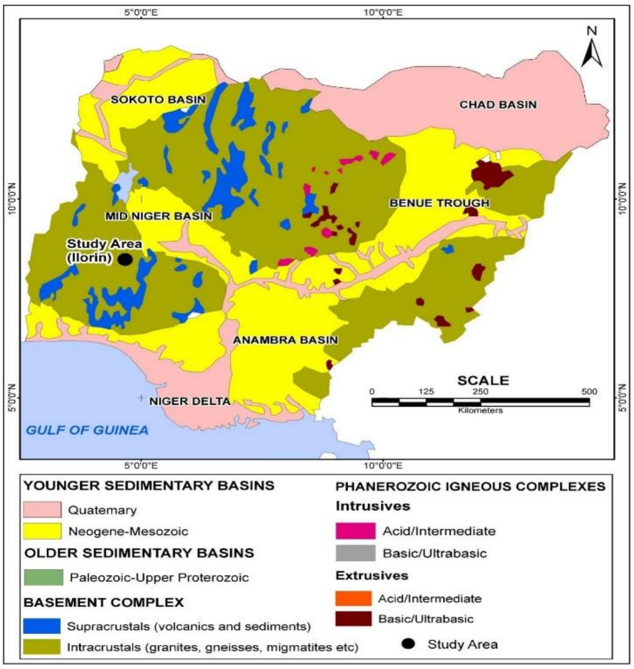

Figure 1: Geological map of Nigeria showing the study area. Adapted from [39]

Though the rocks were emplaced in Precambrian times, they have undergone many processes of metamorphism and magmatic intrusion and they now comprise some sedimentary rocks [35]. The rock types are characterized by two forms of aquifers which are the deeply fractured aquifers (fractured basements) and shallow porous aquifers (freshly weathered basements) and are majorly overlain with lateritic soil cover [28, 36 - 38]. A recent report noted that the fractured basement aquifers are more prevalent than the freshly weathered basement aquifers, and are mostly localized and disconnected occurring either as unconfined or semi-confined aquifers [29]. The structural fabrics are mainly north-south trending fractures dominated by southerly plungings (6° - 10°) anticlinorium with westerly dipping limbs [28, 35]. These types of rock deposits are weak and therefore readily yield to agents of erosion [32]. The elevation map derived from the 30 m Shuttle Radar Topography Mission digital elevation model (Figure 2) shows an approximate elevation range of 274 – 450 m in Ilorin South.

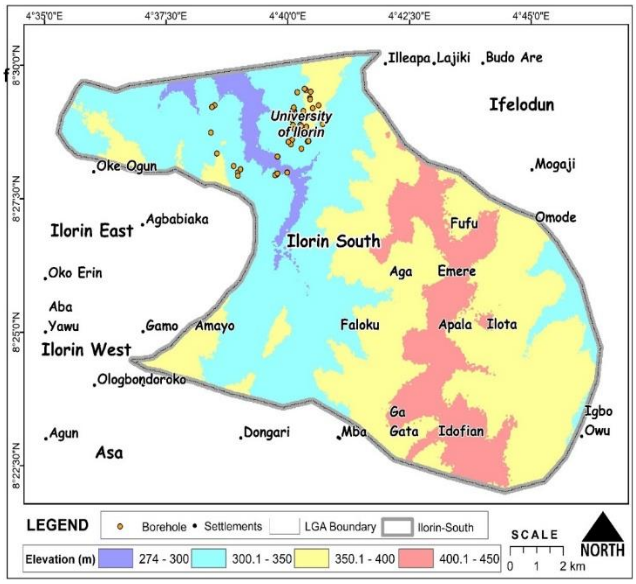

Figure 2: Elevation map of Ilorin South

3.0 MATERIALS AND METHODS

Figure 3 shows the workflow diagram of the methodology which comprises data acquisition, data processing and analysis, and presentation of results. The stages are explained in the following sections.

3.1 Data Acquisition and Processing

The datasets used for this study included the geographic coordinates and inventory of the boreholes within UNILORIN, courtesy of the UNILORIN Works Department; a Groundwater Potential Zonation map (GWPZ) with details [40]; and Landsat 8 multispectral imagery acquired from the United States Geological Surveys (USGS) which was used to generate the lineaments. The datasets and their characteristics are displayed in Table 1.

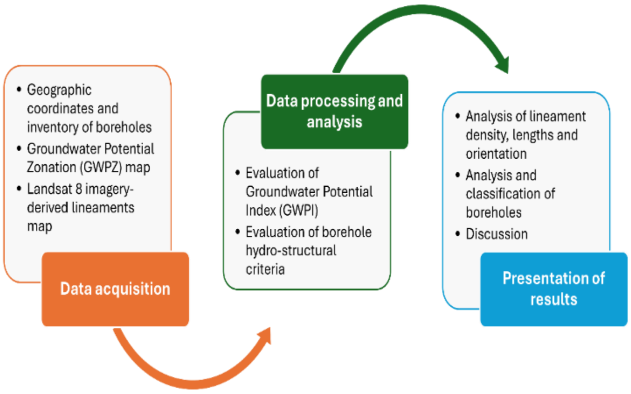

Figure 3: Workflow diagram of the methodology

Table 1: Characteristics of datasets used for this study

Data	Source	Year
Landsat 8 imagery (path 190, row 054)	NASA/USGS	31st March 2019
Borehole coordinates and inventory	UNILORIN Works Department	
Groundwater potential zonation (GWPZ) map	[40]	2022

The GWPZ map was generated using the Analytical Hierarchical Process (AHP) technique [41 – 46]. In the AHP technique, the relative importance of groundwater influencing factors (e.g., drainage density, lineament density, land cover, soil type, annual rainfall, slope, and geomorphology) was determined based on the expertise of groundwater management experts (some of whom were knowledgeable about the study area). After averaging their responses from a questionnaire survey, a pairwise comparison was done for the AHP model. The importance of the thematic layers in estimating groundwater potential is briefly summarised below:

1. Geomorphology: Geomorphology is very important in modeling groundwater potential as it affects other factors such as slope, drainage density and infiltration rate.
2. Lineament density: Lineaments are faults and fractures that cause secondary porosity and permeability to increase. They serve as channels for the movement and accumulation of groundwater.
3. Slope: Slope is important for understanding water flow direction and it influences water infiltration and runoff rates.
4. Land cover: It involves groundwater infiltration rate, soil moisture and the distribution of surface water are subject to the type of land cover.
5. Rainfall: Rainfall is an important hydro-meteorological variable that affects groundwater recharge and the process of surface runoff. Short duration and high intensity rainfall results in less infiltration while long duration and low intensity rainfall leads to more infiltration
6. Soil: Soils differ in their permeabilities and physical characteristics (soil texture). Soil influences surface runoff and groundwater infiltration and percolation.
7. Drainage: Drainage density has significant impact on groundwater availability. Drainage density is estimated as the ratio of stream lengths by basin area. Low drainage density implies high infiltration and increase in groundwater potential.

Subsequently, the sub-classes of the thematic layers were ranked and combined in a weighted overlay operation within ArcGIS software. The result was the GWPZ map which was reclassified into three classes: high, moderate, and low groundwater potential. The groundwater potential index (GWPI) was estimated from the integration of the total normalized weights for the layers (Equation 1).

$$GWPI = Dd_w Dd_{w_i} + Ld_w Ld_{w_i} + LULC_w LULC_{w_i} + SC_w SC_{w_i} + AR_w AR_{w_i} + S_w S_{w_i} + Gm_w Gm_{w_i} \quad (1)$$

Where, Dd: Drainage density; Ld: Lineament density; $LULC$: land cover; SC: Soil class; AR: Annual rainfall; S: Slope; Gm: Geomorphology; Dd_w is the normalized weight of the thematic layer; and w_i is the normalized weight of sub-layer classes.

For the lineaments extraction, the Landsat image spatial frequency was enhanced with a 5 x 5 directional convolution filter applied in ENVI software in the four principal directional angles: N-S, NW-SE, NE-SW, and E-W [47]. The convolution resulted in an output image with enhanced brightness values. The enhanced image was then transferred to PCI Geomatica software version 2018 for edge-detection, thresholding, and curve extraction for lineaments extraction. Following the extraction, the lineaments were converted to ESRI shapefile format. Further details of the GWPZ generation (Figure 4), the GWPI calculations and the lineaments extraction (Figure 5) have been discussed in [40].

To analyse the lineament orientations (magnitude and direction), the Landsat-derived lineaments were imported into RockWorks software for preparation of rose diagrams. Further analysis was also done using lineament density maps (Figure 5) which were prepared using the line density tool in the ArcGIS Spatial Analyst toolbox. Finally, the boreholes were overlaid on the GWPZ map, and lineament map for analysis.

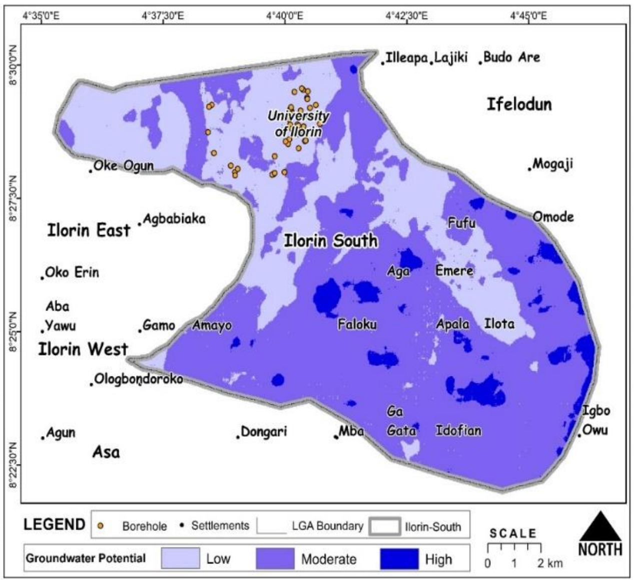

Figure 4: Groundwater Potential Zones Map (GWPZ) of Ilorin South with the location of boreholes. Adapted from [40]

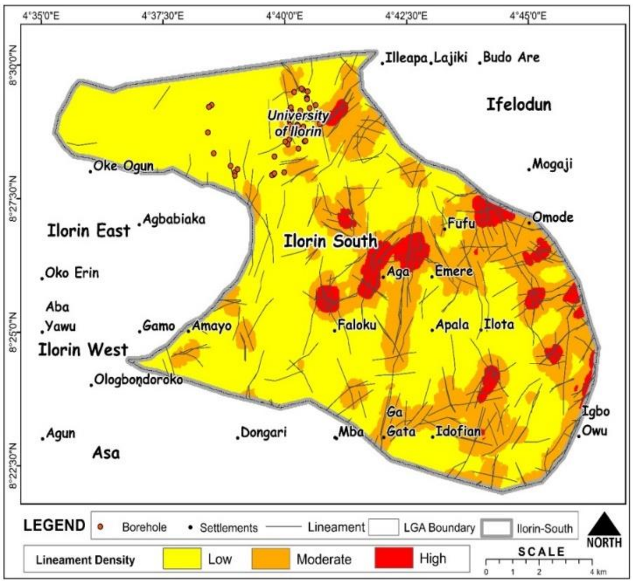

Figure 5: Lineament density map with the location of boreholes. Adapted from [40]

3.2 Analysis of Borehole Characteristics and Drilling Motives

At this stage, the borehole coordinates were overlaid on the GWPZ map to determine the degree of coincidence for a retrospective zonation. This was done to ascertain the claim made by the UNILORIN Works Department that geophysical surveys were carried out before the commencement of borehole drilling exercise. This involved both quantitative and qualitative analyses to understand the motive of drilling the existing boreholes. The rationales were categorized into two classes: (i) Geoscientific (i.e., after geoscientific evaluation and based on scientific necessity), and (ii) Exigent (i.e., due to cost consideration, proximity to other facilities etc.). The quantitative approach adopted in the groundwater potential indexing was contained in [48] while subjective criteria were selected for the qualitative analysis.

In this study, a borehole was adjudged to be "Exigent" if it is found out that the borehole is either functional or dysfunctional and the borehole coincides with low lineament density even if it falls within a zone of either moderate or high groundwater potential. On the contrary, a borehole was adjudged to be "Geo-scientific" if the borehole is either functional or dysfunctional and it coincides with moderate lineament density even if it falls within a zone of low groundwater potential. Priority was given to the lineament density because although other thematic controlling factors (e.g., soil type, slope, rainfall, and land cover) contribute to the recharge of groundwater in basement complex terrain, it is the surficial lineaments (i.e., subsurface faults and fractures) that determine the subsurface flow of percolated water, retention, and storage [33, 49 - 52]. Thus, in a situation where there is a dearth of structural geological features (i.e., lineaments, joints, faults, fractures, etc.), it does not matter whether there is infiltration or not, because in the basement complex, the lineament is prime. Table 2 and Table 3 show the quantitative indices and the subjective criteria used for determining the motive behind drilling boreholes respectively. The borehole status is categorised as either functional (F) or dysfunctional (D), while the lineament density and GWPZ are both categorised as either low (L) or moderate (M). These three criteria (borehole status, lineament density and GWPZ) were integrated to determine the likely rationale for drilling the boreholes.

Table 2: Groundwater Potential Index (GWPI) classification [48]

GWPI	Potential Implication
< 0.4	Very poor
0.4 - 0.5	Poor
0.5 - 0.6	Moderate
0.6 - 0.7	Good
0.7 - 0.8	Very Good
> 0.8	Excellent

Table 3: Hydro-structural criteria for determination of drilling motives

Borehole Status	Lineament Density (LD)	GWPZ	Criteria (St, LD and GWPZ)	Rationale
Functional	L or M	L or M	FLL or FLM FML or FMM	Exigent Geoscientific
Dysfunctional	L or M	L or M	DLL or DLM DML or DMM	Exigent Geoscientific

Where, F is Functional, D is Dysfunctional, L is Low, M is Moderate

3.2.1 Assumptions

The following assumptions were made:

(i) Classifying unconfirmed boreholes as functional (F)**:** The reason was that four (4) unconfirmed boreholes were under construction at the time of the survey and detailed geophysical surveys would have been conducted, as appropriate, before siting the boreholes. Hence, it was assumed that they would be functional on completion.

(ii) Ignoring high groundwater potential zones in the criteria: UNILORIN being a point of interest within Ilorin South had no borehole that coincided within the high GWPZ. Thus, the mention of a high zone in the criteria was unnecessary.

(iii) The status of the boreholes classified as functional (F) and dysfunctional (D) does not take into consideration any aquifer characteristics and/or hydraulic properties.

4.0 RESULTS AND DISCUSSION

Most boreholes fall in the low groundwater potential zone meaning that the zone is least favourable to groundwater exploitation (Figure 4). Lineaments are significant in groundwater potential mapping since they are linear features and weak zones that serve as channels for groundwater movement and accumulation. Figure 5 simply suggests that the UNILORIN area generally has low lineament density, and there is a high probability that subsurface fractures (like fissures and joints) that would have served as groundwater repositories do not exist in that area. Figure 6 presents a rose diagram of the identified lineaments, showing the major lineaments developments in the study area, while Figure 7 presents the distribution of the lineament lengths. Figure 6 shows that the mean ray (red line with double arrow) is in the NE-SW direction. This can be supported by the lineament density map that shows several rectilinear alignments oriented in the NE-SW direction. The NW-SE is also another trending direction. The geology which is the hard rock/ basement complex of granitic strain is a naturally difficult zone for groundwater exploration. Table 4 shows the classification of the probable motives for the drilling of 47 boreholes based on their coincidences on the lineament density and GWPZ maps. Of the 47 boreholes, 35 (74 %) are functional, 8 (17 %) are dysfunctional while the status of 4 (9 %) are unconfirmed. This implies that 45 units of sampled boreholes within UNILORIN were built on zones of low groundwater potential, while 2 were built on zones of moderate groundwater potential.

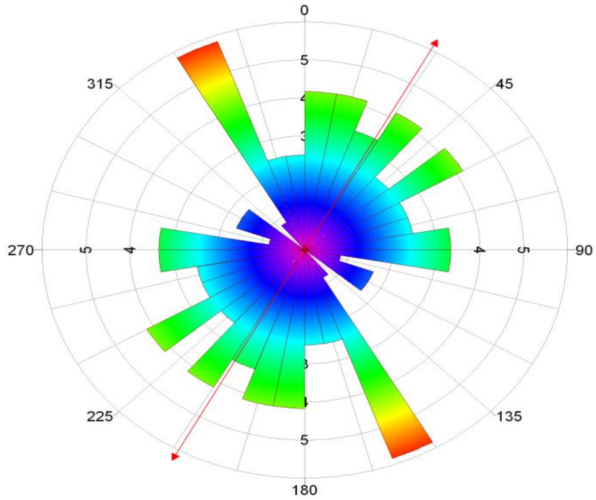

Figure 6: Rose diagram of the Landsat-derived lineaments

Generally, Ilorin South LGA can be said to have moderate groundwater potential and it is expected that areas around Ilota, Apala, Emere, Omode (at the flanks), Ga Gata, Idofian, and Faloku should not witness scarcity of water. The moderate-to-high groundwater potentiality of these areas agrees with the findings of [27]. In their studies, it was suggested that there was no serious water shortage in the whole of the North-central region (Ilorin inclusive) since availability seems higher than the present use. Moreover, [40] have shown that most of the aforementioned areas are either bare lands or covered by vegetation except Ga Gata, Ilota, and some parts of Idofian which have sparse built-up areas with little demand for industrial and home use. On the contrary, the UNILORIN landmass, Amayo, Ganmo, Ile Apa, Ologbondoroko, and Oke Ogun areas fall principally on the low-to-moderate potential zone.

This might be the prime reason UNILORIN and its environs have been experiencing water issues and might be connected with the lack of data to guide decision-making regarding where to site boreholes in that region. Regarding coincidence with lineaments and lineament density, 8 (17%) of the boreholes coincided with zones of moderate lineament density while 39 (83%) of the boreholes coincided with zones of low lineament density. Since lineaments are surficial expressions of subsurface groundwater depositional structures like faults and fractures [33, 50, 51], it means that most boreholes within UNILORIN will produce sub-optimally because there are no enough subsurface groundwater reservoirs to withstand massive groundwater extraction, thereby making aquifers in the zone vulnerable to a quick and easy drawdown. Figure 8 shows the statistics of the sampled boreholes, the level of their coincidence with the lineament density, and the classes of groundwater potential zones they belong.

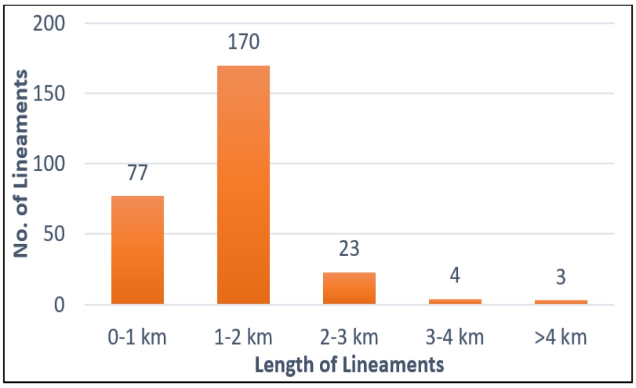

Figure 7: Distribution of lineaments in the study area

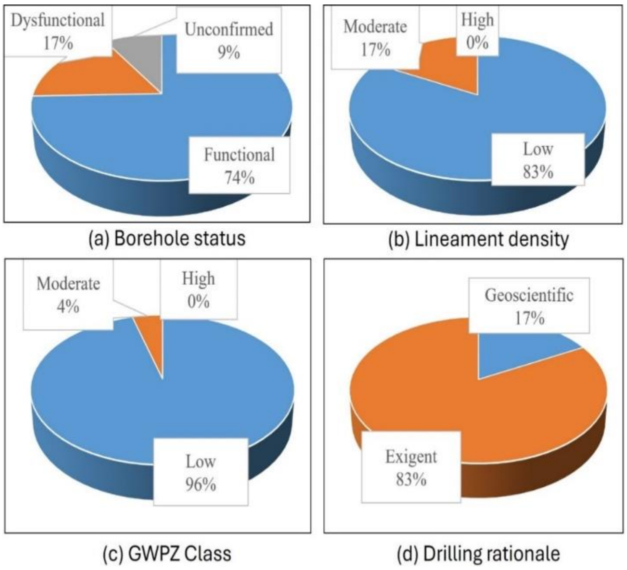

Figure 8: The percentage distribution of (a) borehole status (b) lineament density (c) Groundwater potential zones, and (d) drilling rationale

Table 4: Analysis and classification of the Boreholes

Borehole Status	**No.**
Dysfunctional	8
Functional	35
Unconfirmed	4
GWPI Summary	**Value**
Minimum	0.21
Maximum	0.29
Average	0.23
GWPZ Class	**No.**
Low	45
Moderate	2
Lineament Density	**No.**
Low	39
Moderate	8
Drilling Rationale	**No.**
Geoscientific	8
Exigent	39

5.0 CONCLUSIONS

In this study, the integration of geospatial and geophysical data as well as analysis as proven to be an effective tool for geophysicists in the design and determination of sampling areas for borehole development. Geospatial data makes it more convenient to manage large-scale geophysical projects with several datasets and to build a comprehensive database. On issues concerning water, it has become necessary to deploy essential tools and techniques in order to proffer lasting solutions. For the first time in the study area (UNILORIN), this study empirically established the nexus between failed boreholes, lineaments and groundwater potential zones. Consequently, this gives an indication of possible solutions to the issues of failed boreholes. Furthermore, the complementary role of geospatial data with geophysics technique in the quest for sustainable water management policies has been highlighted. Regarding the rationale for drilling of boreholes, there is a higher probability that most of the boreholes were built based on exigencies (i.e., from a resource-based consideration and for logistics such as cost and proximity).

Owing to population growth, adequate water supply is becoming a challenge in the study area. As a result, the study area cannot depend solely on one source of supply (groundwater, municipal, or school dam) to meet the demands. The existing tripartite water configuration (combination of boreholes, municipal water, and dam) must be improved upon and maybe in the near future, the university management can begin to look at the possibility of a managed aquifer recharge (MAR) system which is a safe and reliable way to store and treat accumulated waters in nature's largest reservoir (i.e., subsurface geological structures). It must be mentioned that the study did not account for temporal changes in groundwater levels, rainfall patterns, or other dynamic environmental factors that could affect borehole functionality and groundwater potential over time.

6.0 ACKNOWLEDGEMENTS

The authors acknowledge the support of Prof. C. O Akoshile (Physics Department, UNILORIN and former Director, UNILORIN Renewable Energy Centre – UREC) and Dr. T. O Lawal (Physics Department, UNILORIN). Also, appreciation goes to Late Prof P. C. Nwilo of the University of Lagos (UNILAG) Surveying and Geoinformatics Department for giving the researchers free access to the Department's Remote Sensing and Photogrammetry laboratory and the facilities. We acknowledge Late Prof A.O Olawepo (Physics Department, UNILORIN) for his mentorship and advice on this project and Mr. H. A Yussuf (Physics Department, Kinsey College of Education, Ilorin). Special thanks also to Samuel Akinnusi and Hamed Olanrewaju (Surveying & Geoinformatics Department, UNILAG). We acknowledge the assistance of Chibueze Janet Onyinye in the generation of rose diagrams of the lineaments. Ultimately, we say a big thanks to the Director of the University of Ilorin Works Department for giving information about details of some of the school infrastructures especially in connection to water resources.

7.0 CONFLICT OF INTERESTS

The authors declare no conflict of interest.

8.0 AUTHORS CONTRIBUTIONS

AF: Conceptualisation, data processing and analysis, manuscript preparation, review and editing. KI: Supervision, manuscript review and editing. CO: Data processing and analysis, visualization, manuscript review and editing. OD: Data processing and analysis, visualization. IAH-M: Project design, manuscript editing. OAI: Manuscript review and editing. IA: Manuscript review and editing. CO: Manuscript review and editing. SE: Manuscript editing.

REFERENCES

[1] Ahner, B. "Assessing Groundwater Stress: An Approach of Measuring Groundwater Stress based on Sub-national statistical data", IGRAC, Westvest 7, 2013. The Netherlands.

[2] Anuforom, C. A. "Induction Lecture of Nigeria Academy of Science", *Nigeria Meteorological Agency*, Oshodi, Lagos-Nigeria, 2013.

[3] IGRAC "Adapting to Climate Change in the SADC Region through Water Security – A focus on Groundwater", International Groundwater Resources Assessment Centre, 1st SADC Groundwater Conference, South Africa, 2018.

[4] Foster, S., Tuinhof, A. and Garduño, H. "Groundwater development in sub-Saharan Africa. A strategic overview of Key issues and major needs". *Sustainable groundwater management, lessons from practice, Case profile collection*, (15), 2006. The World Bank Publication, Washington DC, USA

[5] Adelana S.M.A and MacDonald A.M. "Groundwater Research Issues in Africa"; In MacDonald Alan, Abioye T.A (eds), *Applied Groundwater Studies in Africa*, Leiden, The Netherlands, CRC Press 1-7 (IAH Selected Papers on Hydrogeology 13), 2008.

[6] Jones, H.A. and Hockey, R.D. "The geology of part of S Nigeria". *Geological Survey of Nigeria Bulletin*. 31, 101, 1964.

[7] Ajayi, O. and Abegurin, O.O. "Borehole Failures in Crystalline Rocks of South-Western Nigeria". *GeoJournal*, vol. 34, no. 4, pp 397-405, 1994.

[8] Adiat, K.A.N., Nawawi, M.N.M., Abdullah, K. "Application of multicriteria decision analysis to geoelectric geologic parameters or spatial prediction of groundwater resources potential aquifer evaluation". *Pure and Applied Geophysics*. vol. 170, pp 453 – 471, 2013.

[9] Anscombe, J. "East Mangochi Rural Water Supply and Sanitation project (EMRWSS) Premature Failure of Hand Pumps", *Unpublished Consultancy Report*; GITEC Consult GmbH: Cologne, Germany, 2004.

[10] Chowns, E. "Community management: The limits of institutional design and collective action". In *Proceedings of the International Research Society for Public Management (IRSPM) Conference*, Panel I103, Birmingham, UK, 31 March 2015.

[11] Bonsor, H.C., Oates, N.P., Chilton, P.J., Carter, R.C., MacDonald, A.M., Calow, R., Alwo, R., Wilson, P., Tumutungire, M., Bennie, M. "A Hidden Crisis: Strengthening the Evidence Base on the Sustainability of Rural Groundwater Supplies: Results from a Pilot Study in Uganda"; OR/15/019; British Geological Survey: Nottingham, UK, 2015.

[12] Furey, S. "Handpumps: Where Now? A Synthesis of Online Discussions (2012–2014)"; Rural Water Supply Network; Skat Foundation: St. Gallen, Switzerland, 2014.

[13] Liddle, E. F. R. "Review of Handpump-Borehole Implementation in Uganda"; OR/18/002; British Geological Survey: Nottingham, UK, 2018.

[14] Danert, K., Adekile, D. and Canuto, J.G. "Striving for Borehole Drilling Professionalism in Africa: A Review of a 16-Year Initiative through the Rural Water Supply Network from 2004 to 2020". *Water*, 2020, *12*, 3305. https://doi.org/10.3390/w12123305

[15] Hubbard, S. S. and Linde, N. "Hydrogeophysics"; Lawrence Berkeley National Laboratory, California Digital Library, University of California, 2011.

[16] Deng Ya-ping, SHI Xiao-qing and WU Ji-chun. "Applications of Hydrogeophysics in Characterization of Subsurface Architecture and Contaminant Plumes", *Journal of*

Groundwater Science and Engineering, vol. 4, no. 4, pp. 354-366, 2016.

[17] Binley, A., Hubbard, S.S., Huisman, J.A., Revil, A., Robinson, D.A., Singha, K. and Slater L.D. "The Emergence of Hydrogeophysics for improved understanding of Surface Processes over Multiple Scales", *Water Resources Research*, 51, 3837-3866, 2015. DOI:10.1002/2015WR017016

[18] Elewa, H. H., Nosair, A. M., Ibrahim, A., Zelenakova, M., Pietrucha-Urbanik, K., Habib, H. M., Abdel Moneam, N. A., Ragab, R. M. and Ramadan, E. M. "Use of remote sensing, spatial and geophysical modeling, and real recharging capabilities to identify suitable areas for groundwater exploitation in dry coastal areas", *Journal of Environmental Management*, 363, 121243, 2024. https://doi.org/10.1016/j.jenvman.2024.121243

[19] Abdelouhed, F., Ahmed, A., Abdellah, A., Yassine, B. and Mohammed, I. "Using GIS and remote sensing for the mapping of potential groundwater zones in fractured environments in the CHAOUIA-Morocco area". *Remote Sensing Applications: Society and Environment*, 23, 100571, 2021. https://doi.org/10.1016/j.rsase.2021.100571

[20] Akinluyi, F. O., Olorunfemi, M. O. and Bayowa, O. G. "Application of remote sensing, GIS and geophysical techniques for groundwater potential development in the crystalline basement complex of Ondo State, Southwestern Nigeria". *Sustainable Water Resources Management*, vol. 7, no. 4, 2021. https://doi.org/10.1007/s40899-020-00486-5

[21] Oni, A. G., Adediran, T. A., Olorunfemi, M. O., Eniola, P. J. and Adewale, E. A. "Evaluation of the groundwater potential of Modomo Community in Ile-Ife, Southwest Nigeria, using integrated geophysical techniques". *Sustainable Water Resources Management*, vol. 6, no. 111, 2020. https://doi.org/10.1007/s40899-020-00467-8

[22] Ozegin, K. O. and Ilugbo, S. O. "A triangulation approach for groundwater potential evaluation using geospatial technology and multi-criteria decision analysis (MCDA) in Edo State, Nigeria". *Journal of African Earth Sciences*, 209, 105101, 2024. https://doi.org/10.1016/j.jafrearsci.2023.105101

[23] AbdulKadir, T. S. "Assessment of Morphological and Hydrological Parameters of Oyun River Basin Nigeria", *Ethiopian Journal of Environmental Studies and Management*, vol. 9, no. 4, pp. 470-480, 2016.

[24] Salami, A. W., Sule, B. F., Ayanshola, A. M, Bilewu, S. O and Ajiboye, T. K. "Evaluation of Sustainable Hydropower Potential of UNILORIN and Asa Dams in Ilorin, Kwara State, Nigeria", *Journal of Sustainable Development in Africa*, vol. 18, no. 3, pp. 127-140, 2016.

[25] Olasunkanmi, N.K., Olatunji, S., Akoshile, C.O. and Nwankwo L.I. "Geoelectrical Assessment of University of Ilorin Dam Axis", *Archives of Physics Research*, vol. 3, no. 3, pp. 221-231, 2012.

[26] Olukanni, D.O., Adedeji A.A. and Salami, A.W. "Assessment of Selected Dams in Kwara State, Nigeria", *USEP: Journal of Research Information in Civil Engineering* vol.14, no. 2, 2017.

[27] Salami, A.W., Aremu, A.O. and AbdulRaheem, K.A. "Water Resources Development and Management in North-Central Nigeria: Challenges and Solution"; *Proceedings of the 1st Regional Workshop Organized by the National Water Capacity Building Network, North-Central Regional Center (NWRCBNet – NC)*, University of Ilorin, 3rd & 4th December 2013.

[28] Fawale, O., Nwankwo, L.I., Oladipo, O.I. and Lawal T.O. "Geo-Electrical Evaluation of Aquifer Characteristics and Groundwater Potential in Sango-Kulende Area, Ilorin, Nigeria", *Journal of Applied Sciences, Information and Computing*, vol.1, no.1, pp. 41 - 48, 2020.

[29] Olatunji, J.A., Awojobi, M.O., Olasehinde, D.A., Akinrinmade, O.A. and Olasehinde P.I. "Electrical Resistivity Investigation of the Groundwater Potential in parts of Kwara State Polytechnic, Ilorin, Nigeria", *Global Journal of Pure and Applied Sciences*, vol. 23, pp. 157 - 166, 2020.

[30] Olatunji, J. A., Omonona, O. V. and Odediran, O. A. "Aquifer Characterization using evidences from Hydro-geophysical Data: A Case of Ilorin Crystalline Basement Complex, South-Western Nigeria", *International Journal of Research and Innovation in Applied Sciences*, vol V, issue 1, pp. 118-127, 2017.

[31] Olasehinde, P. I. and Raji, W. O. "Geophysical Studies of Fractures of Basement Rocks at University of Ilorin, Southwestern Nigeria: Application to Groundwater Exploration", *Water Resources*, 17, 3-10, 2007.

[32] Jimoh, H. I. "Predicting the factors of soil loss on different surfaces in Ilorin, Nigeria", *YOLDE*, vol. 1, no. 1, pp. 8-14, 1997.

[33] Akinluyi F. O., Olorunfemi, M. O. and Bayowa O. G. "Investigation of the Influence of Lineaments, Lineament Intersection and Geology and Geology on Groundwater Yield in the Basement Complex Terrain of Ondo State, Southwestern Nigeria", *Applied Water Science*, 8, 49, 2018. https://doi.1007/s13201-018-0686-X

[34] Rahaman, M. A. "Review of the Basement Geology of Southwestern Nigeria, Kogbe". C.A (Ed) Geol. Niger pp.36-56, 1976.

[35] Olasehinde, P. I., Virbka, P. and Esan, A. "Preliminary Results of Hydrogeological Investigations in Ilorin area, South Western Nigeria – Quality of Hydrochemical Analysis", *Water Resources Journal*, vol 9, pp. 51-61, 1998.

[36] Lawal, T. O., Sunday, J. A. and Fawole, O. "Impact of V.E.S in delineation of groundwater distribution and exploration in hard rock terrain", *International Journal of Advancement in Physics*, vol. 4, no. 1, pp. 30-35, 2012.

[37] Nwankwo, L. I. "2D Resistivity Survey for groundwater exploration in a hard rock terrain: A case of MAGDAS observatory UNILORIN, Nigeria", *Asian Journal of Earth Sciences*, vol. 4, no. 1, pp. 46-53, 2011. DOI: 10.3923/ajes. 2011.4653.

[38] Olawepo, A. O., Fatoyinbo, A. A., Ali, I. and Lawal, T. O. "Evaluation of groundwater potential and subsurface lithologies in UNILORIN quarters using resistivity method". *The African Review of Physics*, *8*, 2013.

[39] Akintola, A. I., Ikhane, P. R., Okunlola, O. A., Akintola, G. O. and Oyebolu, O. O. "Compositional Features of Precambrian Pegmatites of Ago-Iwoye Area, Southwestern Nigeria", *Journal of Ecology and Natural Environment*, vol. 4, no. 3, pp.71-87, 2012. DOI: 10.5897 /JENE11.112 ISSN: 2006-9847

[40] Ishola, K. S., Fatoyinbo, A. A., Hamid-Mosaku, A. I., Okolie, C. J., Daramola, O. E. and Lawal, T. O. "Groundwater potential mapping in hard rock terrain using remote sensing, geospatial and aeromagnetic data". *Geosystem and Geoenvironment* vol. 2, no. 1, (2022) 100107. https://doi.org/10.1016/j.geogeo.2022.100107

[41] Adiat, K. A. N., Nawawi, M. N. M. and Abdullah, K. "Assessing the Accuracy of GIS-Based Elementary Multi-Criteria Decision Analysis as a Spatial Prediction Tool – A Case of Predicting Potential Zone of Sustainable Groundwater Resources", *Journal of Hydrology*, 440-441, 75-89, 2012.

[42] Brunelli, M. "Introduction to the Analytic Hierarchy Process". *Springer Briefs in Operations Research*. P. 83. 978-3-319-12502-2 (electronic).10.1007/978-3-319-12502-2, 2015.

[43] Hamid-Mosaku, A. I. "Intelligent geospatial decision support system for Malaysian marine geospatial data infrastructure", (Unpublished doctoral dissertation). Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia, 2014.

[44] Hamid-Mosaku, I. A., Mahmud, M. R. and Mohd, M. S. "An evaluation of marine geospatial data infrastructure (MGDI) by delphi-analytic hierarchy process (AHP) approach". *Jurnal Teknologi*, vol. 78(6-12), pp. 57–68, 2016. DOI:10.11113/jt.v78.9233

[45] Reisi, M., Afzali, A. and Aye, L. "Applications of analytical hierarchy process (AHP) and analytical network process (ANP) for industrial site selections in Isfahan, Iran". *Environmental Earth Sciences*, vol. 77, no. 14, 537, 2018. DOI: 10.1007/s12665-018-7702-1

[46] Saaty, T. L. "What is the analytic hierarchy process?" In *Mathematical models for decision support*, pp. 109-121, 1988. Springer, Berlin, Heidelberg.

[47] Epuh, E. E., Okolie, C. J., Daramola, O. E., Ogunlade, F. S., Oyatayo, F. J., Akinnusi, S. A. and Emmanuel, E. I. "An integrated lineament extraction from satellite imagery and gravity anomaly maps for groundwater exploration in the Gongola basin". *Remote Sensing Applications: Society and Environment*, 20, 2020, Article 100346, 10.1016/j.rsase.2020.100346

[48] Srivastava P. K. and Bhattacharya A. K. "Groundwater Assessment through an integrated approach using Remote Sensing, GIS and Resistivity Technique: A case from a Hard Rock Terrain", *International Journal of Remote Sensing*, vol. 27,20, pp. 4599-4620, 2006. DOI: 10/1080/01431160600554983

[49] Ejepu, J. S, Olasehinde, P. I., Okhimamhe, A. A. and Okunlola, I. "Investigation of Hydrogeological Structures of Paiko Region, North-Central Nigeria Using Integrated Geophysical and Remote Sensing Techniques", *Geosciences*, vol. 7, 122, 2017. doi:10.3390/geosciences7040122.

[50] Mogaji, K. A., Aboyeji, O. S. and Omosuyi, G. O. "Mapping of Lineaments for Groundwater Targeting in the Basement Complex Region of Ondo State, Nigeria Using Remote Sensing and GIS Techniques", *Integrated Journal of Water*

Resources and Environmental Engineering, vol. 3, no. 7, pp. 150-160, 2011.
[51] Ogunmola, J. K., Ayolabi, E. A. and Olobaniyi, S. B. "Lineament Extraction from SPOT 5 and NIGERIASAT –X Imagery of the Upper Benue Trough, Nigeria", *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XL-1, ISPRS Technical Commission 1 Symposium, 17-20 November 2014, Denver, Colorado, USA.
[52] Sander, P. "Lineaments in Groundwater Exploration: A Review of Applications and Limitations"; *Hydrogeology Journal*, vol. 15, pp. 71-74, 2007.