https://doi.org/10.5281/zenodo.23204758

Integrated Hydrogeophysical Assessment of Groundwater Flow Dynamics and Aquifer Potential in the Crystalline Basement Terrain of Felele, Southwestern Nigeria

Victoria *O. Olagoke[1]*,* ***Oluwasanmisire*** *C. Ajayi[1],* ***Enovwo*** *E. Odjegba[1],* ***Taiwo*** *O. Adekola[1],* ***Samson*** *A. Adeniyi[1] and* ***Henry*** *T. Awosika[2]*

ORCID: 0000-0001-7336-5658

Abstract

Groundwater is an important source of water supply in many urban areas underlain by crystalline Basement Complex rocks, where groundwater occurrence is strongly influenced by weathering and fracturing. This study assessed groundwater flow dynamics and relative aquifer potential in Felele, Ibadan, southwestern Nigeria, using integrated hydrogeological and geoelectrical investigations. Field investigations were conducted in June 2024 using groundwater-level measurements from 15 wells and boreholes and Vertical Electrical Sounding (VES) at eight locations using the Schlumberger electrode configuration. Hydraulic heads were calculated from measured groundwater levels and ground elevations, while VES data were interpreted using partial curve matching and WINRESIST software. Hydraulic-head values ranged from 139.45 to 178.38 m above mean sea level, indicating a predominant groundwater-flow pattern from the higher-head northeastern sector towardss the lower-head western and southwestern sectors. The geoelectrical results revealed heterogeneous subsurface conditions comprising topsoil, lateritic and clayey materials, weathered basement, fractured basement and fresh crystalline basement. Aquifer resistivity ranged from 32.20 to 234.00 Ωm, while interpreted aquifer thickness and overburden thickness varied considerably across the study area. VES 5 exhibited the most favourable groundwater-prospect conditions, with an interpreted aquifer thickness of 46.70 m, overburden thickness of 52.38 m and interpreted fractured basement. VES 2 showed comparatively less favourable conditions. The integrated results provide a site-specific assessment of groundwater flow and relative aquifer prospectivity and can support the prioritisation of locations for further groundwater investigation and development in Felele.

Keywords

Basement Complex, Felele, Groundwater flow, Hydrogeophysics, Vertical Electrical Sounding

Introduction

Groundwater is a vital freshwater resource that supports domestic, agricultural, and industrial activities worldwide, particularly in developing countries where increasing population growth, urbanisation, and climate variability continue to place pressure on surface-water resources (Fetter, 2001; Freeze & Cherry, 1979; Todd & Mays, 2005; UNESCO, 2022). In Nigeria, groundwater serves as an important source of water supply, particularly in urban and peri-urban areas where public water infrastructure may not adequately meet water demand.

Within the Basement Complex terrains that dominate much of southwestern Nigeria, groundwater

[1] *Department of Water Resources Management and Agrometeorology, College of Environmental Resources Management, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria*

[2] *Department of Earth Sciences, Adekunle Ajasin University, Akungba-Akoko, Ondo State, Nigeria*

occurrence is largely controlled by weathered regolith, fractured basement zones, joints, and faults because crystalline rocks generally possess limited primary porosity and permeability (Olorunfemi & Fasuyi, 1993; Wright, 1992). Consequently, groundwater occurrence is commonly associated with weathered overburden and fractured basement zones that provide secondary porosity and permeability for groundwater storage and movement.

Recent investigations across southwestern Nigeria have demonstrated the effectiveness of hydrogeophysical techniques for groundwater exploration and aquifer characterisation. Studies in Ibadan, Akure, Ado-Ekiti, and other Basement Complex environments indicate that groundwater occurrence is strongly influenced by weathering intensity, overburden thickness, fracture development, and lithological variability (Akintorinwa et al., 2020; Bayewu et al., 2017; Doro et al., 2023; Osinowo & Arowoogun, 2020). Electrical resistivity methods, particularly Vertical Electrical Sounding (VES), have also proven useful for delineating aquifer geometry, weathered zones, and fractured basement formations that constitute important groundwater-bearing horizons in crystalline terrains (Koefoed, 1979; Zohdy et al., 1974).

Despite increasing groundwater investigations within southwestern Nigeria, studies integrating groundwater-flow dynamics with detailed geoelectrical characterisation remain limited in Felele, Ibadan. Furthermore, increasing urbanisation and groundwater abstraction within the area underscore the need for site-specific groundwater-resource assessment. The relatively localized spatial coverage of this study is therefore deliberate, as it permits detailed investigation of groundwater-level variations and subsurface heterogeneity within Felele rather than attempting to generalise groundwater conditions across the wider Ibadan metropolis.

This study integrates hydrogeological and geoelectrical techniques to evaluate groundwater-flow dynamics and relative aquifer potential within Felele, Ibadan, southwestern Nigeria. The specific objectives are to determine groundwater-flow direction using hydraulic-head analysis, characterise subsurface lithology and aquifer geometry through electrical resistivity investigations, evaluate relative groundwater prospectivity, and integrate hydrogeological and geoelectrical datasets for improved groundwater-resource assessment. The study contributes site-specific information that can support further groundwater investigation and development in Basement Complex environments.

Literature Review

Groundwater occurrence in crystalline Basement Complex terrains is strongly influenced by the thickness and composition of the weathered overburden and by the development of fractures within the underlying basement. Early hydrogeophysical investigations in southwestern Nigeria demonstrated the usefulness of electrical resistivity sounding for delineating weathered and fractured zones and for supporting groundwater development decisions (Okhue & Olorunfemi, 1991; Olayinka & Olorunfemi, 1992; Olorunfemi & Fasuyi, 1993). These studies established the importance of geoelectrical parameters such as overburden thickness, weathered-layer characteristics, and basement fracturing in groundwater assessment.

Subsequent studies have applied integrated geophysical and multicriteria approaches to groundwater-potential evaluation. Bayewu et al. (2017) demonstrated the use of geophysical criteria for evaluating groundwater potential in southwestern Nigeria, while Babatunde et al. (2022) applied a multicriteria evaluation approach to integrate geoelectrical parameters for groundwater-potential mapping in Ibadan. Preeja et al. (2011) also demonstrated the application of weighted multicriteria approaches to groundwater-potential-zone mapping. Such approaches provide a basis for combining multiple groundwater-controlling factors rather than relying on a single geoelectrical parameter.

More recent investigations around Ibadan have emphasized the spatial heterogeneity of crystalline basement aquifers and the need to integrate hydrogeological and geophysical information when evaluating groundwater resources (Doro et al., 2023; Osinowo & Arowoogun, 2020). However, the present study focuses specifically on Felele and combines groundwater-level observations with VES-derived parameters and a weighted Groundwater Potential Index to examine both groundwater-flow conditions and relative groundwater prospectivity at a localized scale. This provides a site-specific perspective that complements broader groundwater-potential assessments within the Ibadan region.

Study Area

The study area is located at Felele, Ibadan, Oyo State, southwestern Nigeria, between latitudes 7°17′N and 7°19′N and longitudes 3°52′E and 3°54′E (Figure 1). Felele lies within the southwestern part of the Ibadan metropolis and has experienced rapid urbanisation accompanied by increasing groundwater abstraction for domestic and commercial purposes.

The elevation of the study area ranges from

approximately 148 to 188 m above mean sea level. Geologically, the area is underlain by Precambrian Basement Complex rocks comprising migmatite-gneiss, granite gneiss, quartzite, and associated intrusive bodies (Rahaman, 1988). Groundwater occurrence is largely associated with the weathered regolith and fractured basement horizons, which constitute the principal groundwater-bearing units within Basement Complex environments.

The study area experiences a tropical climate characterised by distinct wet and dry seasons. The wet season generally extends from March to October, while the dry season occurs from November to February. Mean annual rainfall is approximately 1,200–1,500 mm, while mean temperatures generally range from about 24 to 32 °C (Eruola et al., 2012). The drainage pattern is predominantly dendritic, consistent with the geological and topographic setting of the Basement Complex terrain (Doro et al., 2023; Rahaman, 1988).

Although the study covers a relatively localized area within Felele, the scale was selected to permit detailed investigation of spatial variations in groundwater levels, hydraulic head, subsurface lithology, aquifer geometry, and groundwater prospectivity. The study is therefore intended as a site-specific assessment of groundwater conditions within Felele rather than a regional characterisation of the entire Ibadan metropolis.

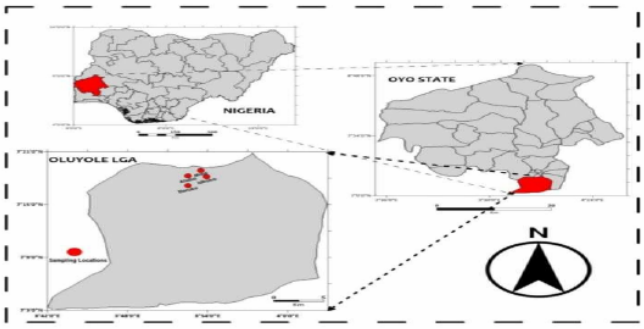


Figure 1. Location map of Felele, Ibadan, Oyo State, southwestern Nigeria showing the distribution of VES stations and groundwater monitoring wells used for hydrogeological investigations.

Methodology

Hydrogeological Investigation

Field investigations were conducted in June 2024 to evaluate groundwater levels, hydraulic-head distribution, and groundwater-flow dynamics within the study area. Fifteen groundwater points comprising hand-dug wells and boreholes were selected for groundwater-level measurements. Geographic coordinates and ground elevations were determined using a handheld Global Positioning System (GPS) receiver. Depth-to-water measurements were obtained using a water-level indicator. The 15 locations were selected to provide spatial coverage across the principal sectors represented in the study, including Itesiwaju Estate (Maje), Idiroko, Ataba, and Eleruku, thereby allowing comparison of hydraulic-head conditions across the study area.

Hydraulic head was calculated from ground elevation and depth to the water table using:

where:

H = hydraulic head (m),

E = ground elevation (m), and

D = depth to water table (m).

The calculated hydraulic-head values were subsequently imported into ArcGIS Pro 3.0 (Environmental Systems Research Institute, 2024) for spatial interpolation and generation of groundwater-contour maps and groundwater-flow-direction maps. The hydrogeological data used for hydraulic-head determination are presented in Table 1.

Table 1. Hydrogeological Data Used for Hydraulic Head Determination

oP4	Location	Longitude (°E)	Latitude (°N)	Elevation (m)	Depth to Water (m)	Hydraulic Head (m)
P1	Itesiwaju Estate (Maje)	3.893245	7.315568	172	8.20	163.80
P2	Itesiwaju Estate (Maje)	3.891420	7.313785	162	3.95	158.05
P3	Idiroko Well P1	3.895809	7.310372	178	6.45	171.55
P4	Idiroko Well P2	3.897405	7.311180	188	9.62	178.38
P5	Idiroko Well P3	3.896521	7.309870	178	5.20	172.80
P6	Idiroko Well P4	3.896315	7.308147	185	8.50	176.50
P7	Ataba Borehole P1	3.875491	7.304163	161	8.50	152.50
P8	Ataba Well P1	3.875644	7.304305	148	8.55	139.45
P9	Ataba Borehole P2	3.876315	7.300750	155	4.14	150.86
P10	Ataba Well P2	3.878892	7.300947	165	9.70	155.30
P11	Eleruku Well P1	3.873867	7.283614	151	7.20	143.80
P12	Eleruku Well P2	3.873016	7.285415	161	6.80	154.20
P13	Eleruku Well P3	3.875397	7.285961	156	7.30	148.70
P14	Eleruku Well P4	3.878768	7.287662	163	6.42	156.58
P15	Eleruku Well P5	3.876231	7.286973	156	7.62	148.38

Geoelectrical Investigation

Vertical Electrical Sounding (VES) was conducted at eight locations within the study area using the Schlumberger electrode configuration to characterise subsurface lithology and aquifer geometry. The apparent resistivity of the subsurface layers was determined from the measured potential difference and injected current using the appropriate geometric factor for the Schlumberger array. The Schlumberger configuration and resistivity-sounding interpretation follow established procedures for electrical sounding investigations (Koefoed, 1979; Zohdy et al., 1974).

The field VES data were interpreted using partial curve matching and subsequently processed using WINRESIST software to determine the apparent resistivity and thickness of the interpreted subsurface layers. The interpreted VES curves included H, QH, HKH, and KHKH types. The resulting layer parameters were used to identify the major subsurface units and to characterise the weathered and fractured basement zones that may constitute groundwater-bearing horizons. The interpretation procedure is consistent with established approaches to applied electrical geophysics (Reynolds, 2011).

Groundwater Potential Index Development

The Groundwater Potential Index (GPI) was developed from seven parameters derived from the Vertical Electrical Sounding (VES) interpretation: weathered layer thickness, weathered layer resistivity, depth to aquifer top, overburden thickness, VES curve type, presence of fractured basement, and number of permeable layers. These parameters were selected to represent variations in subsurface conditions that

influence groundwater occurrence and storage within the Basement Complex terrain.

Each parameter was assigned a score ranging from 0 to 100 based on established thresholds applicable to Basement Complex environments. The scoring criteria were based on previous hydrogeophysical studies, including Olayinka and Olorunfemi (1992), Olorunfemi and Fasuyi (1993), Okhue and Olorunfemi (1991), and Bayewu et al. (2017). The seven parameters were assigned weights of 0.25, 0.15, 0.15, 0.15, 0.10, 0.10, and 0.10, respectively. The GPI was calculated using the Weighted Linear Combination (WLC) approach, in which the standardised score of each parameter was multiplied by its assigned weight and the resulting weighted scores were summed to obtain the composite GPI value (Babatunde et al., 2022; Malczewski, 1999; Preeja et al., 2011).

The resulting GPI values at the eight VES locations ranged from 72 to 88. The GPI represents a relative assessment of groundwater prospectivity and should not be interpreted as a direct prediction of borehole yield because pumping-test data and measured borehole yields were not available. The High, Moderate, and Low groundwater-potential descriptions reported for the individual VES stations in Tables 2 and 3 are qualitative interpretations of the VES-derived aquifer conditions and should not be interpreted as numerical GPI classes.

The interpreted geoelectrical parameters and qualitative groundwater-potential classifications for the eight VES stations are summarised in Table 2.

Table 2. Summary of Geoelectrical Parameters and Qualitative Groundwater Potential

The corresponding lithological sequences and their hydrogeological significance are presented in Table 3.

VES Station	Aquifer Unit	Aquifer Resistivity (Ωm)	Interpreted Aquifer Thickness (m)	Overburden Thickness (m)	Qualitative Groundwater Potential
1	Weathered Basement	45.20	23.50	29.27	Moderate
2	Weathered Basement	32.60	14.50	16.41	Low
3	Weathered/Fractured Basement	59.50	16.20	21.96	Moderate
4	Weathered Basement	48.55	19.65	24.47	Moderate
5	Fractured Basement	234.00	46.70	52.38	High
6	Weathered/Fractured Basement	75.70	11.20	22.05	Moderate
7	Weathered Basement	42.10	14.00	25.17	Moderate
8	Weathered Basement	32.20	15.60	33.32	Moderate

Table 3. Lithological Interpretation of VES Stations

VES Station	Layer Sequence	Interpreted Lithology	Hydrogeological Significance
VES 1	Topsoil → Lateritic Layer → Weathered Basement → Fresh Basement	Moderately weathered basement terrain	Moderate qualitative groundwater potential associated with appreciable weathering thickness
VES 2	Topsoil → Clayey Weathered Layer → Fresh Basement	Thin weathered basement over shallow bedrock	Low qualitative groundwater potential associated with limited storage capacity
VES 3	Topsoil → Lateritic Layer → Weathered Basement → Fractured Basement → Fresh Basement	Weathered and fractured basement aquifer system	Moderate qualitative groundwater potential supported by interpreted basement fracturing
VES 4	Topsoil → Lateritic Layer → Weathered Basement → Fresh Basement	Moderately developed weathered zone	Moderate qualitative groundwater potential associated with weathering thickness
VES 5	Topsoil → Weathered Basement → Fractured Basement → Fresh Basement	Thick weathered and fractured basement aquifer	High qualitative groundwater potential associated with substantial aquifer thickness, thick overburden and interpreted basement fracturing
VES 6	Topsoil → Lateritic Layer → Weathered Basement → Fractured Basement → Fresh Basement	Fractured basement aquifer system	Moderate qualitative groundwater potential supported by secondary porosity associated with weathering and fracturing
VES 7	Topsoil → Clayey Sand → Weathered Basement → Fresh Basement	Weathered basement aquifer	Moderate qualitative groundwater potential associated with moderate storage conditions
VES 8	Topsoil → Clayey Sand → Weathered Basement → Fresh Basement	Thick weathered basement aquifer	Moderate qualitative groundwater potential associated with relatively thick overburden

Spatial Interpolation and Mapping

The calculated GPI values for the eight VES locations were spatially interpolated using Surfer 25.0. The Kriging interpolation method was used to generate the continuous GPI surface and produce the groundwater-potential map. The GPI values at the VES locations ranged from 72 to 88. The value of 71 displayed at the lower end of the map legend represents a boundary extrapolation produced during gridding and does not correspond to an actual calculated GPI value at any of the VES stations.

The hydraulic-head measurements from the 15 groundwater points were used to represent the spatial distribution of hydraulic head and infer the predominant local groundwater-flow direction from areas of relatively higher hydraulic head towards areas of lower hydraulic head. The hydrogeological and geoelectrical interpretations were subsequently considered together to provide an integrated assessment of groundwater conditions within the study area.

Results and Discussion

Hydraulic Head Distribution and Groundwater Flow Dynamics

The spatial distribution of hydraulic head within the study area is presented in Figure 2.

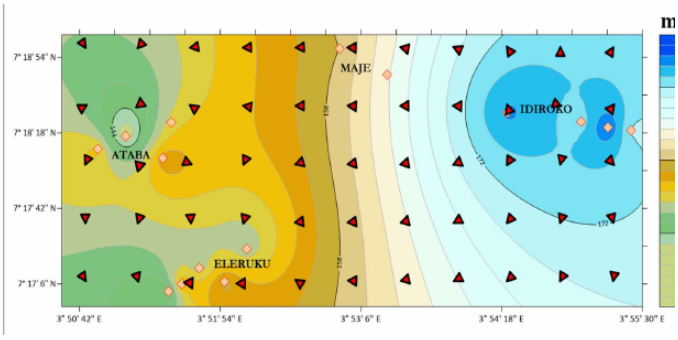


Figure 2. Spatial distribution of hydraulic head within the study area showing variations in hydraulic head.

The measured hydraulic-head values range from 139.45 to 178.38 m above mean sea level. The highest hydraulic head was recorded at Idiroko Well P2 (178.38 m), while the lowest occurred at Ataba Well P1 (139.45 m), giving a maximum hydraulic-head difference of 38.93 m. The relatively higher hydraulic-head values occur mainly in the eastern and northeastern parts of the study area around Idiroko, whereas lower values occur towards the western and southwestern sectors around Ataba and Eleruku.

This spatial variation indicates that groundwater movement is influenced by differences in hydraulic head within the study area. The higher-head conditions around Idiroko represent areas of relatively greater hydraulic potential, while the lower-head conditions around Ataba and Eleruku represent areas towards which groundwater is expected to move. The 38.93 m value represents a difference in hydraulic head and should not be described as a hydraulic gradient, since hydraulic gradient requires consideration of both head difference and separation distance.

The observed spatial pattern is consistent with the general behaviour of groundwater systems in crystalline Basement Complex terrains, where groundwater movement may be influenced by topography, weathering, and subsurface geological heterogeneity. Similar relationships between hydrogeological conditions and groundwater flow have been reported in southwestern Nigeria, including the Ibadan area (Bayewu et al., 2017; Doro et al., 2023).

Groundwater Flow Direction

Based on the spatial distribution of hydraulic head, groundwater-flow direction was interpreted from areas of relatively higher hydraulic head towards areas of lower hydraulic head. The resulting predominant local groundwater-flow pattern is shown in Figure 3.

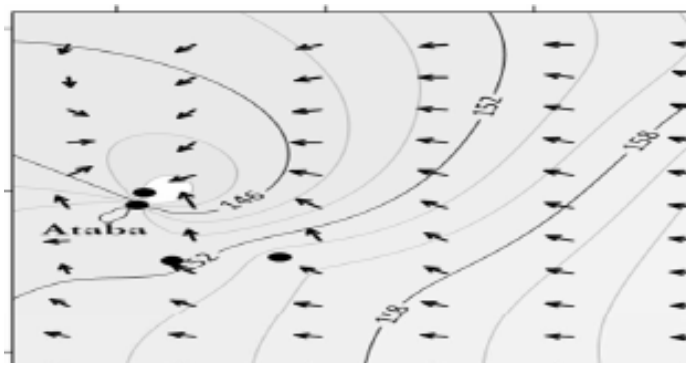


Figure 3. Predominant local groundwater-flow direction inferred from the spatial distribution of hydraulic head in the study area.

The flow-direction map indicates a general movement from the eastern and northeastern sector around Idiroko towards the western and southwestern parts of the study area around Ataba and Eleruku. The consistency between the hydraulic-head distribution and the flow-direction pattern indicates that spatial differences in hydraulic potential exert an important control on groundwater movement within the study area.

The location-based pattern is particularly evident when the monitoring points are considered together with the mapped head distribution. The Idiroko area contains the highest measured heads, including 178.38 m at P4, while the Ataba and Eleruku areas generally contain lower head values. This spatial relationship supports the interpretation of groundwater movement towards the western and southwestern sectors.

However, the hydraulic-head data alone do not provide sufficient evidence to designate Idiroko unequivocally as a recharge zone or Ataba and Eleruku as discharge zones. Such interpretations would require additional information such as recharge estimates, groundwater-level monitoring through time, hydrochemical evidence, or detailed hydrogeological investigations.

The observed flow pattern agrees generally with findings from other Basement Complex environments in southwestern Nigeria, where groundwater movement is influenced by variations in hydraulic head and geological conditions (Bayewu et al., 2017; Doro et al., 2023).

Geoelectrical Characterisation of the Subsurface

The geoelectric lithological section (Figure 4) shows the vertical variation in the interpreted subsurface units across the eight VES stations, including topsoil, lateritic materials, weathered

basement, fractured basement and fresh crystalline basement.

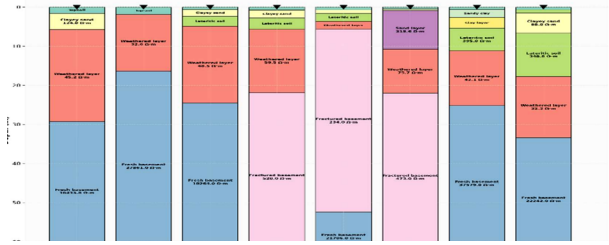


Figure 4. Geoelectric Lithological Section Across the Study Area.

The interpreted geoelectrical parameters revealed considerable subsurface variability across the study area. Aquifer resistivity values range from 32.20 to 234.00 Ωm, while interpreted aquifer thickness varies from 11.20 to 46.70 m. Overburden thickness ranges from 16.41 to 52.38 m based on the values presented in Table 2. The geoelectrical interpretation identifies a heterogeneous subsurface sequence comprising topsoil, lateritic materials, clayey sand, weathered basement, fractured basement, and fresh crystalline basement.

The variation in resistivity and layer thickness reflects differences in lithology, weathering development, and the occurrence of interpreted fractured basement zones. In crystalline Basement Complex terrains, the fresh basement generally has limited primary porosity, whereas weathering and fracturing can generate secondary porosity and permeability that permit groundwater storage and movement. The interpreted weathered and fractured basement units therefore constitute the principal groundwater-bearing horizons identified in the study.

The results are consistent with previous hydrogeophysical investigations in southwestern Nigeria. Bayewu et al. (2017) demonstrated the usefulness of geophysical methods for identifying groundwater-bearing weathered and fractured basement zones, while Akintorinwa et al. (2020) emphasized the importance of weathering thickness and basement fracturing in groundwater evaluation. Doro et al. (2023), working within the Ibadan crystalline basement environment, similarly demonstrated the strong influence of subsurface heterogeneity on groundwater occurrence.

Lithological Interpretation and Aquifer Geometry

The lithological interpretation derived from the VES data and presented in Figure 4 and Table 3 indicates considerable vertical and lateral variation in subsurface conditions. The interpreted VES curve types include H, QH, HKH, and KHKH, reflecting variations in the resistivity structure of the subsurface. The interpreted sequences include weathered basement and, at some locations, fractured basement overlying fresh crystalline basement.

Among the investigated stations, VES 5 exhibits the most favourable interpreted aquifer geometry. It has an aquifer resistivity of 234.00 Ωm, an interpreted aquifer thickness of 46.70 m, and an overburden thickness of 52.38 m, with an interpreted fractured basement unit. The combination of substantial overburden development, relatively thick aquiferous material, and interpreted basement fracturing provides a stronger basis for its favourable groundwater classification than resistivity alone.

In contrast, VES 2 is characterised by an aquifer resistivity of 32.60 Ωm, an interpreted aquifer thickness of 14.50 m, and an overburden thickness of 16.41 m. The relatively thin aquiferous zone and limited overburden development, together with the presence of shallow fresh basement, indicate comparatively less favourable groundwater conditions.

The remaining VES locations exhibit intermediate combinations of weathering, interpreted aquifer thickness, overburden development, and basement fracturing and were consequently classified qualitatively as having moderate groundwater potential. These variations demonstrate the heterogeneous nature of Basement Complex aquifers, where groundwater occurrence can change considerably over relatively short distances. Similar spatial heterogeneity has been documented in groundwater investigations across southwestern Nigeria (Akintorinwa et al., 2020; Doro et al., 2023).

Groundwater Potential Assessment

The spatial distribution of the interpreted groundwater-potential conditions across the study area is presented in Figure 5.

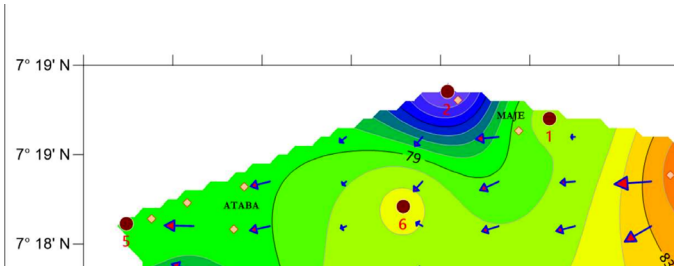


Figure 5. Groundwater Potential Map of the Study Area.

The spatial distribution of the Groundwater Potential Index (GPI) is presented in Figure 5. The GPI was derived from seven VES interpretation

parameters: weathered layer thickness, weathered layer resistivity, depth to aquifer top, overburden thickness, curve type, fractured basement presence, and number of permeable layers. Each parameter was scored on a 0–100 scale and combined using the Weighted Linear Combination approach with weights of 0.25, 0.15, 0.15, 0.15, 0.10, 0.10, and 0.10, respectively.

The calculated GPI values at the eight VES locations range from 72 to 88, indicating spatial variation in relative groundwater-potential conditions within the study area. Higher GPI values represent locations where the combined characteristics of the evaluated VES parameters provide comparatively more favourable groundwater conditions, whereas lower values indicate comparatively less favourable combinations of the evaluated parameters.

VES 5 has a relatively thick interpreted aquifer of 46.70 m, substantial overburden thickness of 52.38 m, and interpreted fractured basement, providing supporting geological evidence for favourable groundwater prospectivity. In contrast, VES 2 has an interpreted aquifer thickness of 14.50 m and overburden thickness of 16.41 m, together with shallow fresh basement, indicating comparatively less favourable conditions.

The GPI map therefore provides a spatial representation of groundwater prospectivity based on the combined interpretation of multiple VES parameters rather than reliance on a single geoelectrical parameter. The mapped pattern should be interpreted as a relative indication of groundwater prospectivity rather than a direct measure of borehole yield. Confirmatory drilling, borehole logging, and pumping tests would be required to establish actual aquifer productivity at individual locations. The value of 71 shown on the map legend results from boundary extrapolation during Kriging and does not represent an actual calculated GPI value at any VES location.

Integrated Hydrogeological and Geoelectrical Interpretation

The integration of the hydrogeological and geoelectrical datasets provides a site-specific understanding of groundwater occurrence and movement within Felele. The hydraulic-head measurements show a range of 139.45–178.38 m above mean sea level, with the predominant local groundwater-flow tendency directed from the higher-head eastern and northeastern sectors towards the lower-head western and southwestern sectors.

The geoelectrical results demonstrate that groundwater occurrence is associated primarily with the development of weathered and fractured basement zones. Locations with greater aquiferous thickness and substantial overburden development generally provide more favourable conditions for groundwater occurrence. The strongest combination of these characteristics occurs at VES 5, which has the thickest interpreted aquifer and overburden among the investigated VES stations and an interpreted fractured basement unit.

The integrated interpretation therefore indicates that groundwater conditions in Felele are controlled by the interaction of hydraulic-head distribution, weathering development, basement fracturing, aquifer geometry, and lithological variability. This agrees with previous studies in southwestern Nigeria, including investigations around Ibadan, which have demonstrated the importance of geological heterogeneity and secondary porosity in controlling groundwater occurrence in crystalline Basement Complex terrains (Akintorinwa et al., 2020; Bayewu et al., 2017; Doro et al., 2023).

The results also demonstrate why hydrogeological and geoelectrical information should be considered together when evaluating groundwater prospectivity in the study area. Hydraulic-head data provide information on the likely direction of groundwater movement, whereas the VES results provide information on subsurface conditions that may favour groundwater storage and transmission. Their integration therefore provides a stronger basis for prioritising locations for further groundwater investigation than either dataset considered independently.

Conclusion

This study integrated hydrogeological and geoelectrical investigations to assess groundwater-flow dynamics and relative aquifer prospectivity within the Basement Complex terrain of Felele, Ibadan, southwestern Nigeria. Hydraulic-head values from the investigated groundwater points ranged from 139.45 to 178.38 m above mean sea level, with the highest value recorded around Idiroko and the lowest at Ataba. The spatial distribution of hydraulic head indicates a predominant local groundwater-flow tendency from the eastern and northeastern parts of the study area towards the western and southwestern sectors, including Ataba and Eleruku.

The geoelectrical investigation revealed considerable subsurface heterogeneity, with interpreted aquifer resistivity ranging from 32.20 to 234.00 Ωm and interpreted aquifer thickness ranging from 11.20 to 46.70 m. The subsurface comprises topsoil, lateritic and clayey materials, weathered basement, fractured basement, and fresh crystalline

basement. The results indicate that groundwater occurrence is strongly influenced by the development and thickness of weathered and fractured basement zones, overburden thickness, and lithological variability.

Among the investigated VES stations, VES 5 exhibited the most favourable relative groundwater prospectivity, with an aquifer resistivity of 234.00 Ωm, an interpreted aquifer thickness of 46.70 m, an overburden thickness of 52.38 m, and an interpreted fractured basement unit. VES 2 showed comparatively less favourable conditions, characterised by an interpreted aquifer thickness of 14.50 m, overburden thickness of 16.41 m, and shallow fresh basement. The integrated interpretation therefore demonstrates the value of combining hydraulic-head information with geoelectrical characterisation for assessing groundwater occurrence and identifying locations that warrant further investigation in crystalline Basement Complex environments.

The groundwater-potential assessment presented in this study should be regarded as a relative assessment of groundwater prospectivity rather than a direct prediction of borehole yield, since pumping-test data and measured borehole yields were not available. Nevertheless, the integrated results provide useful site-specific information for prioritising locations for confirmatory groundwater investigations and sustainable groundwater-resource planning in Felele.

Recommendations

Based on the findings of this study, VES 5 should be prioritised for further groundwater investigation because of its favourable combination of interpreted aquifer thickness, substantial overburden development, and interpreted basement fracturing. However, borehole development at this location should be preceded by appropriate confirmatory investigations to establish the actual aquifer characteristics and groundwater yield. More generally, groundwater development within the study area should take into account the spatial variability of the Basement Complex aquifer, with priority given to locations characterised by relatively thick weathered or fractured zones rather than areas where fresh basement occurs at shallow depth.

Groundwater abstraction within the study area should be appropriately monitored, particularly as urbanisation and groundwater demand increase, to minimise the risk of excessive abstraction and support sustainable groundwater use. Pumping tests and borehole lithological logging should also be undertaken at selected prospective locations to determine aquifer transmissivity, storage characteristics, and actual borehole yield, and to provide field-based validation of the relative groundwater-potential classification obtained from the present study.

Future investigations should incorporate hydrochemical analyses to assess groundwater quality and improve understanding of the relationship between groundwater movement, subsurface lithology, and potential sources of contamination. In addition, periodic groundwater-level monitoring is recommended to improve understanding of seasonal and long-term variations in hydraulic-head distribution and groundwater-flow conditions within the study area.

Data Availability Statement

The datasets generated and analysed during this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, manuscript organisation, and improvement of scientific presentation. The authors reviewed, revised, and validated all content generated by the tool and take full responsibility for the accuracy, integrity, and originality of the published work.

References

Akintorinwa, O. J., Atitebi, M. O., & Akinlalu, A. A. (2020). Hydrogeophysical and aquifer vulnerability zonation of a typical basement complex terrain: A case study of Odode Idanre, southwestern Nigeria. Heliyon, 6(8), e04549. https://doi.org/10.1016/j.heliyon.2020.e04549

Babatunde, A. A., Ilugbo, S. O., Jemiriwon, E. T., Karram, A. A., Kolawole, A. A., & Taiwo, A. N. (2022). Hydrogeophysical investigation using electrical resistivity method within Lead City University Ibadan, Oyo State, Nigeria. International Journal of Earth Sciences Knowledge and Applications, 4(1), 51–62.

Bayewu, O. O., Oloruntola, M. O., Mosuro, G. O., Laniyan, T. A., Ariyo, S. O., & Fatoba, J. O. (2017). Geophysical evaluation of groundwater potential in part of southwestern Basement Complex terrain of Nigeria. Applied Water Science, 7(8), 4615–4632. https://doi.org/10.1007/s13201-017-0623-4

Doro, K. O., Adegboyega, C. O., Aizebeokhai, A. P., & Oladunjoye, M. A. (2023). The Ibadan Hydrogeophysics Research Site (IHRS)—An

observatory for studying hydrological heterogeneities in a crystalline basement aquifer in southwestern Nigeria. Water, 15(3), 433. https://doi.org/10.3390/w15030433

Environmental Systems Research Institute. (2024). ArcGIS Pro (Version 3.0) [Computer software].

Eruola, A. O., Ufoegbune, G. C., Makinde, A. A., & Nwaogazie, I. L. (2012). Climate change and its impacts on water resources in southwestern Nigeria. Journal of Sustainable Development in Africa, 14(7), 214–231.

Fetter, C. W. (2001). Applied hydrogeology (4th ed.). Prentice Hall.

Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice Hall.

Koefoed, O. (1979). Geosounding principles 1: Resistivity sounding measurements. Elsevier.

Malczewski, J. (1999). GIS and multicriteria decision analysis. John Wiley & Sons.

Okhue, E. T., & Olorunfemi, M. O. (1991). Electrical resistivity investigation of a typical basement complex area: The Obafemi Awolowo University campus case study. Journal of Mining and Geology, 27(2), 63–69.

Olayinka, A. I., & Olorunfemi, M. O. (1992). Determination of geoelectrical characteristics in Okene area and implications for borehole siting. Journal of Mining and Geology, 28(2), 403–412.

Olorunfemi, M. O., & Fasuyi, S. A. (1993). Aquifer types and the geoelectric/hydrogeologic characteristics of part of the central basement terrain of Nigeria (Niger State). Journal of African Earth Sciences, 16(3), 309–317. https://doi.org/10.1016/0899-5362(93)90051-Q

Osinowo, O. O., & Arowoogun, K. I. (2020). A multi-criteria decision analysis for groundwater potential evaluation in parts of Ibadan, southwestern Nigeria. Applied Water Science, 10, 228. https://doi.org/10.1007/s13201-020-01311-2

Preeja, K. R., Sabu, J., Jobin, T., & Vijith, H. (2011). Identification of groundwater potential zones of a tropical river basin (Kerala, India) using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing, 39(1), 83–94. https://doi.org/10.1007/s12524-011-0075-5

Rahaman, M. A. (1988). Recent advances in the study of the basement complex of Nigeria. In P. O. Oluyide, W. C. Mbonu, A. E. Ogezi, I. G. Egbuniwe, A. C. Ajibade, & A. C. Umeji (Eds.), Precambrian geology of Nigeria (pp. 11–43). Geological Survey of Nigeria.

Reynolds, J. M. (2011). An introduction to applied and environmental geophysics (2nd ed.). Wiley-Blackwell.

Todd, D. K., & Mays, L. W. (2005). Groundwater hydrology (3rd ed.). John Wiley & Sons.

UNESCO. (2022). The United Nations World Water Development Report 2022: Groundwater—Making the invisible visible. UNESCO Publishing.

Wright, E. P. (1992). The hydrogeology of crystalline basement aquifers in Africa. Geological Society, London, Special Publications, 66, 1–27. https://doi.org/10.1144/GSL.SP.1992.066.01.01

Zohdy, A. A. R., Eaton, G. P., & Mabey, D. R. (1974). Application of surface geophysics to ground-water investigations. U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 2, Chapter D1. https://doi.org/10.3133/twri02D1