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Aquifer characterization and subsurface geology of the Ewohimi–Ewatto–Igueben–Ubiaja Axis Edo State Nigeria

Edore Festus Omozeje[1*], Nosa Samuel Igbinigie[2] and Osakpolor Marvellous Omorogieva[3]

*Correspondence:
Edore Festus Omozeje
edore.omozeje@physci.uniben.edu; profzeje@gmail.com
[1]Department of Hydrology / Hydrogeology, Benin-Owena River Basin Development Authority, Kilometer 24, Benin-Sapele Road, Obayantor, Benin City, Edo State, Nigeria
[2]Department of Geology, Faculty of Physical Sciences, University of Benin, Benin City, Edo State, Nigeria
[3]Department of Marine Geology, Faculty of Physical Sciences, Nigeria Maritime University, Okerenkoko, Delta State, Nigeria

Abstract

An integrated geophysical, geological, and hydrogeological study was conducted along parts of the Ewohimi–Igueben–Ubiaja axis in Edo State, Nigeria, to characterize the aquifer systems and delineate zones of groundwater occurrence. Vertical electrical soundings, geological mapping, and correlation of borehole logs were used to delineate a multi-aquifer system comprising perched, unconfined, semi-confined, and confined aquifers at depths ranging from 30 to 300 m. Six to nine geoelectric layers were identified, consisting mainly of clay, sand, lignite, and sandstone units. Lignite horizons encountered at depths of 20–143 m were found to contribute to circulation losses and pipe clogging during drilling operations. Pumping tests yielded transmissivity values of 8.626–35.564 m^2/day and discharge rates of 17.33–44.6 m^3/h, confirming the productivity of the deeper aquifers. Groundwater contour and stream hydrograph analyses indicated baseflow contributions exceeding 70%, demonstrating active groundwater–surface water interactions. The study provides improved understanding of the subsurface stratigraphy and groundwater dynamics of the area and establishes a scientific basis for sustainable groundwater exploration and management.

Keywords Vertical electrical sounding, Hydrostratigraphy, Multi-aquifer system, Pumping test, Transmissivity, Niger Delta Basin

1 Introduction

Groundwater remains one of the most dependable sources of freshwater for socio-economic development in many rural and peri-urban communities because it can be developed directly at the point of demand. It supplies water for domestic, agricultural, and industrial activities in rural, peri-urban, and urban settlements. Despite its widespread occurrence, groundwater development is often constrained by geological and hydrogeological complexities that influence the distribution, accessibility, and productivity of aquifers.

Groundwater occurs in the subsurface within both unsaturated and saturated zones. The unsaturated (vadose) zone comprises the soil-water, intermediate, and

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capillary-fringe zones, whereas the saturated zone contains water that completely fills interconnected pores, voids, and fractures within geological formations. Depending on the hydrogeological setting, groundwater in the saturated zone may occur in perched, unconfined (water-table), leaky, or confined aquifers [6, 18, 21]. The occurrence, recharge, storage, and movement of groundwater are governed primarily by the interaction between geological and climatic conditions. While climate controls the availability of recharge through precipitation, the geological framework determines aquifer geometry, hydraulic properties, and groundwater-flow pathways. Consequently, both the quantity and quality of groundwater resources reflect the combined influence of these controlling factors [13].

Lithological characteristics play a fundamental role in controlling the occurrence and productivity of aquifers. Variations in rock type, texture, and structural features control porosity, permeability, and hydraulic connectivity, thereby influencing groundwater storage, movement, and geochemical evolution through water–rock interactions [4]. Within the Ewohimi–Igueben–Ubiaja axis, several unsuccessful groundwater development attempts have been reported, leading some studies to suggest that the area has limited groundwater potential and is increasingly dependent on surface-water sources for potable supply.

Electrical resistivity methods are widely employed for groundwater investigations in both sedimentary and crystalline terrains. In sedimentary environments, they are particularly effective for delineating permeable sandy aquifers, whereas in basement complexes they are commonly used to identify weathered zones and fractured bedrock that serve as groundwater reservoirs [2, 14, 15].

Despite numerous groundwater investigations within the study area, sustainable groundwater development remains a significant challenge. Most previous studies relied principally on Vertical Electrical Sounding (VES) to characterize subsurface conditions. Although VES provides valuable information on subsurface resistivity variations, interpretations based solely on surface geophysical data may be uncertain in heterogeneous sedimentary environments where sandstone, clay, and lignite can exhibit overlapping resistivity signatures. Consequently, integrating surface resistivity data with borehole lithological logs, drillers' records, and borehole geophysical logs is essential for improving the reliability of lithological interpretation and aquifer characterization.

However, the hydrostratigraphic framework of the Ewohimi–Igueben–Ubiaja axis remains inadequately constrained because previous investigations have not comprehensively integrated surface geophysical data with borehole lithological and geophysical data. The heterogeneous interbedding of sandstone, clay, and lignite within the Ogwashi-Asaba and Ameki Formations produces complex resistivity responses that hinder the reliable identification, correlation, and delineation of productive aquifer units. Consequently, uncertainties persist regarding the depth, thickness, lateral extent, and hydraulic significance of groundwater-bearing horizons, contributing to repeated borehole failures and conflicting assessments of the groundwater potential of the area. Addressing this knowledge gap requires the development of an integrated hydrostratigraphic framework that combines surface resistivity data with direct subsurface geological information.

The study area is situated within the Niger Delta Basin, where groundwater occurrence is principally controlled by the Ogwashi-Asaba and Ameki Formations. These formations comprise heterogeneous successions of sandstone, clay, sand, and lignite that

require detailed geoelectric and hydrogeological characterization. Sandstone constitutes more than 55% of the lithological succession and forms the principal groundwater-bearing unit within the area [17].

The objectives of this study are therefore to:

i. conduct comprehensive surface geophysical investigations using VES;
ii. determine the depth and thickness of productive groundwater-bearing horizons;
iii. delineate lateral and vertical facies variations; and.
iv. develop an integrated hydrostratigraphic framework through the correlation of surface resistivity data with borehole geophysical and lithological logs.

2 Study area

The study area is bounded by latitudes 6° 25′ N–6° 40′ N and longitudes 6° 12′ E–6° 30′ E. Figure 1 shows the location of the study area, which is bordered to the east by the plains of the Niger River hydrological system and to the west by the Ossiomo River drainage basin. The southern part of the area is underlain by the Coastal Plain Sand (Benin Formation), whereas the northern part is bordered by the hills of Ubiaja and Ukhuesan, which extend eastwards towards the communities of Oria and Onogholo.

Elevation varies considerably across the study area, ranging from approximately 96 m at Emu and Uokhuen, located within the valley of the Utor River, to over 250 m at Igueben and Ekehken. Covering an area of approximately 606 km², the study area comprises notable towns and villages, including Ewohimi, Ewatto, Igueben, Ugbegun, and Okhordua. These settlements are connected by a network of access roads. The study area also extends marginally into Delta State. The area is characterized by persistent potable water scarcity for industrial, agricultural, and domestic purposes; consequently, most

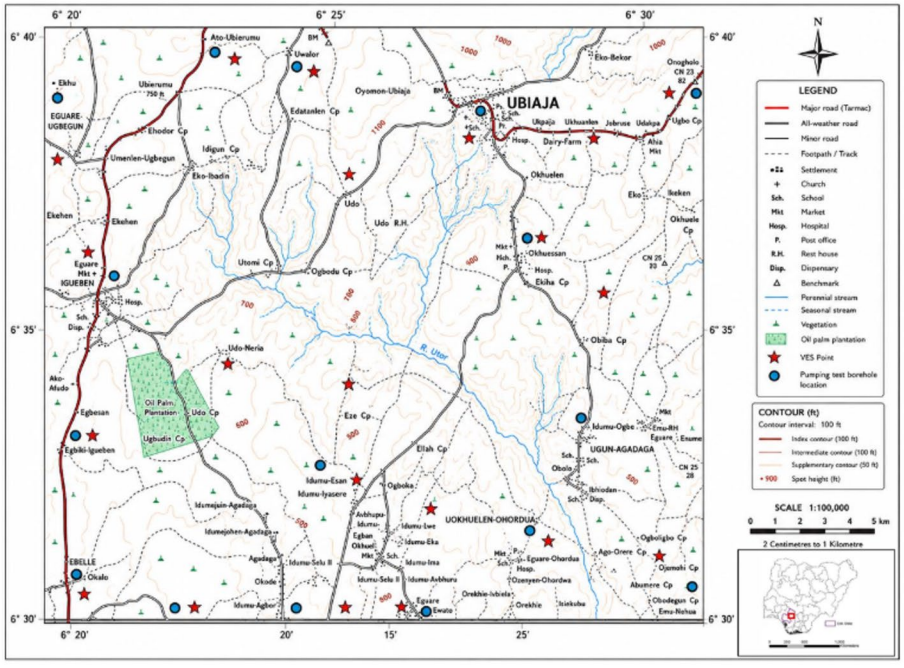


Fig. 1 Map of the study area showing VES points, borehole locations, rivers and streams. (Adapted from Federal surveys Nigeria, 1979)

inhabitants rely on rainwater harvesting, hand-dug wells, and rivers and streams for their daily water supply.

The study area and its immediate surroundings lie within the tropical rainforest belt of Nigeria and experience two major seasons: the dry and rainy seasons [10]. The dry season generally extends from November to March, whereas the rainy season occurs from April to October, with a brief dry spell in August, commonly referred to as the "little dry season" [10]. The average annual rainfall recorded in the area over the past 10 years is approximately 1,606.46 mm, with an observable declining trend in rainfall [1]. Evapotranspiration has been estimated at more than 1,400 mm [17]. The study area is characterized by elevated terrain, with elevations locally exceeding 250 m above sea level. Despite the generally gentle surface relief, the landscape is dissected by deep valleys associated with perennial and ephemeral streams and other drainage features.

Groundwater development is generally more successful in valley bottoms and other low-lying areas than in elevated terrain because these locations commonly correspond to areas of groundwater discharge, where the water table is relatively shallow. The convergence of subsurface flow towards valleys, coupled with favourable hydraulic gradients, can enhance groundwater accumulation and increase the likelihood of encountering productive aquifers at economically feasible drilling depths. In contrast, upland areas and plateau surfaces typically have deeper water tables and thicker unsaturated zones, often requiring deeper drilling to intercept productive aquifer horizons. Consequently, boreholes constructed in valley settings may have a higher probability of success and can often be completed at shallower depths than those located on elevated terrain. This relationship underscores the significant influence of geomorphology on groundwater exploration and development in the study area [17].

2.1 Hydrology and hydrogeology

The study area is drained by the River Ella and its tributaries, which are perennial. Streams that generally flow southeastward from the plateau scarp originate from springs in southern Ubiaja and between Ekpon and Ewohimi, where the perched and water-table aquifers intersect the ground surface. These streams are generally clear and are sustained by continuous groundwater seepage. Numerous perennial streams and springs emerge along the valley margins where groundwater intersects the land surface [17]. The River Ella and Iyagun River are prominent hydrological features of the area and, together with their tributaries, constitute the major drainage network. Several unsuccessful attempts at groundwater development have been reported in the area, suggesting challenges associated with groundwater exploration and development.

2.2 Geology of the study area

The geologic formations recognized in the study area are the Ameki Formation, Asaba-Ogwashi Formation, and the Benin Formation [5, 7, 11, 13, 16, 17, 19].

Most recently, the NGSA reported the existence of the Awgu Shale and Ajali Sandstone in the area [8]. The Ogwashi-Asaba Formation consists of fine- to coarse-grained, white and multicoloured sands; white, grey, pinkish, or dark grey clays; black carbonaceous clays; and lignite. The sands and clays are ferruginized in some horizons.

The Ameki Formation underlies the Ogwashi-Asaba Formation and is of Middle Eocene age. It comprises a series of highly fossiliferous grey-green sandy clays with

calcareous concretions and white clayey sandstones [11]. The formation consists of a lower lithological group with fine- to medium-grained sandstone and intercalations of calcareous shale and thin shelly limestone, and an upper lithological unit with coarse- to medium-grained, cross-bedded sandstone, bands of fine grey-green sandstone, and sandy clay.

Plunging southward below the Ameki Formation is the Imo Shale, which is Paleocene in age. It consists of thick, blue-black clayey shale and exhibits lateral variation into sandstone in some areas [11]. Resting conformably on the Ogwashi-Asaba Formation is the Benin Formation. Its sediments include yellowish to whitish sands with gravelly and pebbly units. The sands are coarse-grained, locally fine-grained, and sometimes poorly sorted, cross-bedded sandstone [19]. Lenticular clays, lignite, and shales occur in some areas, where they confine small but moderately yielding aquifers [12].

At the surface, the study area is underlain by the Ogwashi-Asaba Formation, which is in turn underlain by the Ameki Formation (Fig. 2). The cross-bedded sandstone observed in several outcrops within the area is not diagnostic of the Ajali Formation. Although such structures are characteristic of Ajali deposits, they also commonly develop within the Ameki and Ogwashi-Asaba Formations under fluvial-deltaic conditions [11]. Integration of field observations with borehole logs and geoelectric sections indicates that these units contain significant interbeds of lignite and clay, a lithological association that differs from the predominantly friable, quartz-rich sandstone characteristic of the Ajali Formation [20].

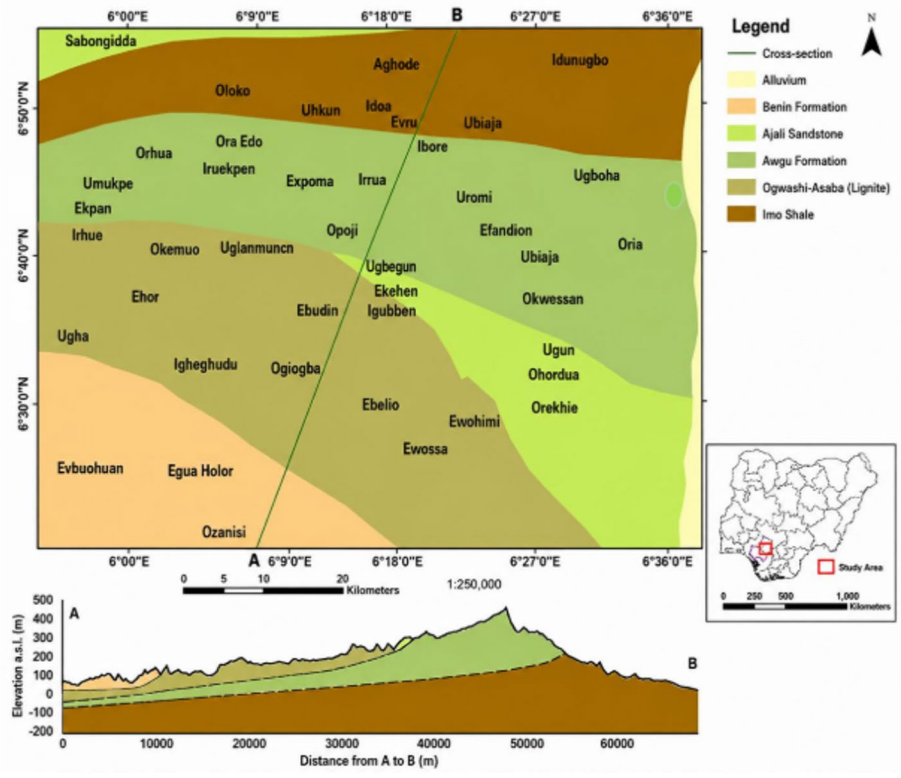


Fig. 2 Geologic map of the study area and environs (After NGSA [8])

3 Materials and methods

3.1 Study design and data sources

This study adopts an integrated hydrogeological and geophysical approach that combines field investigations, geological mapping, and hydrological analyses to characterize aquifer systems and groundwater occurrence.

A comprehensive review of existing literature, including geological and mineral resource maps of Edo State [7–9] and relevant regional studies, was undertaken to establish the geological and hydrogeological framework of the study area.

Both primary and secondary datasets were utilized, including lithological logs from productive and non-productive boreholes, drilling records, feasibility reports, groundwater-level data, streamflow measurements, and rainfall records obtained from relevant agencies and field investigations. These datasets were integrated to assess subsurface heterogeneity and groundwater dynamics.

3.2 Geological and hydrogeological field investigations

Field reconnaissance surveys were conducted to map surface geological features and identify representative outcrops within and around the study area. Lithological logs from multiple boreholes were compiled and correlated to assess vertical and lateral variations in subsurface lithology.

The lithological log data were used to construct borehole correlation panels, stratigraphic columns, and fence diagrams, providing insights into aquifer geometry and continuity. Supporting field measurements were carried out using standard geological equipment, including a Brunton compass, GPS device, and measuring tape.

3.3 Geophysical data acquisition

Geophysical investigations were conducted using electrical resistivity methods to delineate subsurface stratigraphy and aquifer units. Vertical Electrical Sounding (VES) surveys were conducted in most communities within the study area using ABEM Terameter SAS 1000 and SAS 4000 instruments with the Schlumberger electrode array configuration.

A total of 24 VES stations were occupied across the study area and strategically located in areas with documented borehole success and failure to capture subsurface variability. The current electrode spacing (AB/2) extended to 600 m, providing adequate depth of investigation for groundwater exploration. Measurements were acquired using progressively increasing electrode spacing to ensure sufficient depth of penetration and resolution. The field data were analysed using IP2WIN and Interpret VES 2.0 software.

3.4 Geophysical data processing and interpretation

Field resistivity data were initially subjected to quality control through visual inspection of the sounding curves to identify outliers and inconsistencies. The data were subsequently interpreted using iterative forward and inverse modelling techniques implemented in IP2WIN and Interpret VES 2.0 software.

Initial layer parameters were derived through curve matching and subsequently refined by inversion to minimize the root mean square (RMS) error between observed and calculated resistivity values. The interpretation employed standard layered-earth

models, with resistivity and thickness parameters constrained by available borehole lithological data.

The generated geoelectric sections were correlated with lithological logs to enhance the reliability of the interpretation. Fence diagrams and three-dimensional subsurface models were further developed using RockWorks software to visualize stratigraphic continuity and aquifer distribution.

3.5 Pumping test analysis

Pumping tests were conducted on selected boreholes to determine aquifer hydraulic properties, including transmissivity. Both field-conducted and archived pumping-test data obtained from the Benin-Owena River Basin Development Authority were utilized.

The tests were performed under constant-discharge conditions, with pumping durations of at least 23 h to ensure an adequate aquifer response. Recovery data were also recorded following cessation of pumping. Drawdown data were analysed using the Cooper–Jacob straight-line method, assuming confined or unconfined aquifer conditions [3]. The applicability of these assumptions was evaluated based on the lithological and geophysical interpretations.

3.6 Hydrological measurements and analysis

Hydrological monitoring was conducted along the Utor River channel, where continuous water-level and temperature data were recorded using a Van Essen pressure logger installed at Ebu. The monitoring site was selected because it captures flows from both the Ella and Iyagun Rivers, which drain the study area. Monitoring was conducted for approximately 18 months. The Van Essen pressure logger recorded hourly stage measurements automatically, and the data were downloaded periodically using a computer. Discharge measurements were obtained twice monthly at the monitoring station using a Valeport current meter to capture variations in flow conditions. Stage–discharge relationships (rating curves) were developed from the field measurements and used to generate continuous discharge hydrographs.

Baseflow separation was performed on the hourly discharge data using the Minimum Method. This technique identifies the lowest discharge values within a specified time window (2N days, where N is determined by the basin area) and connects these values to define the baseflow hydrograph. The method was selected because of its consistency and reduced subjectivity compared with manual graphical techniques. Rainfall data corresponding to the monitoring period were incorporated to assess recharge patterns and their influence on groundwater and streamflow dynamics.

3.7 Data integration and visualization

All datasets were integrated within a geospatial and modelling framework to ensure consistency in interpretation. Geological, geophysical, and hydrological data were synthesized to develop a conceptual hydrogeological model of the study area.

Spatial analysis and map generation were carried out using Global Mapper 23 Pro, while Surfer 16 was used for contouring and surface modelling. The integration of multiple data sources improved the robustness of the interpretations and reduced uncertainty in the delineation of aquifer systems.

4 Results

4.1 Overview of integrated datasets

The findings of this study are presented through an integrated set of geophysical and hydrogeological outputs, comprising VES-derived geoelectric sections, a summary of VES data and interpretations, a regional geoelectric cross-section, borehole correlation logs, a stratigraphic fence diagram, a depth-to-aquifer map, a baseflow separation chart, pumping-test results, a table of borehole and aquifer parameters, and groundwater equipotential maps. Together, these datasets provide a comprehensive characterization of the subsurface geological framework, lithological succession, aquifer geometry, and groundwater flow regime across the Ubiaja–Ewatto–Ewohimi axis.

4.2 Depth to productive aquifer

The depth to the main productive aquifer varies across the study area. The results are illustrated using several complementary datasets, including VES curves and geoelectric sections (Figs. 3, 4, 5, 6, 7 and 8), a summary of VES data and interpretations (Table 1), a geoelectric cross-section (Fig. 9), borehole correlation logs (Figs. 10, 11 and 12), a stratigraphic fence diagram (Fig. 13), a depth-to-aquifer map (Fig. 14), and groundwater equipotential maps (Fig. 15). These datasets collectively provide a detailed characterization of subsurface lithology, aquifer geometry, and groundwater flow within the Ubiaja–Ewatto–Ewohimi axis.

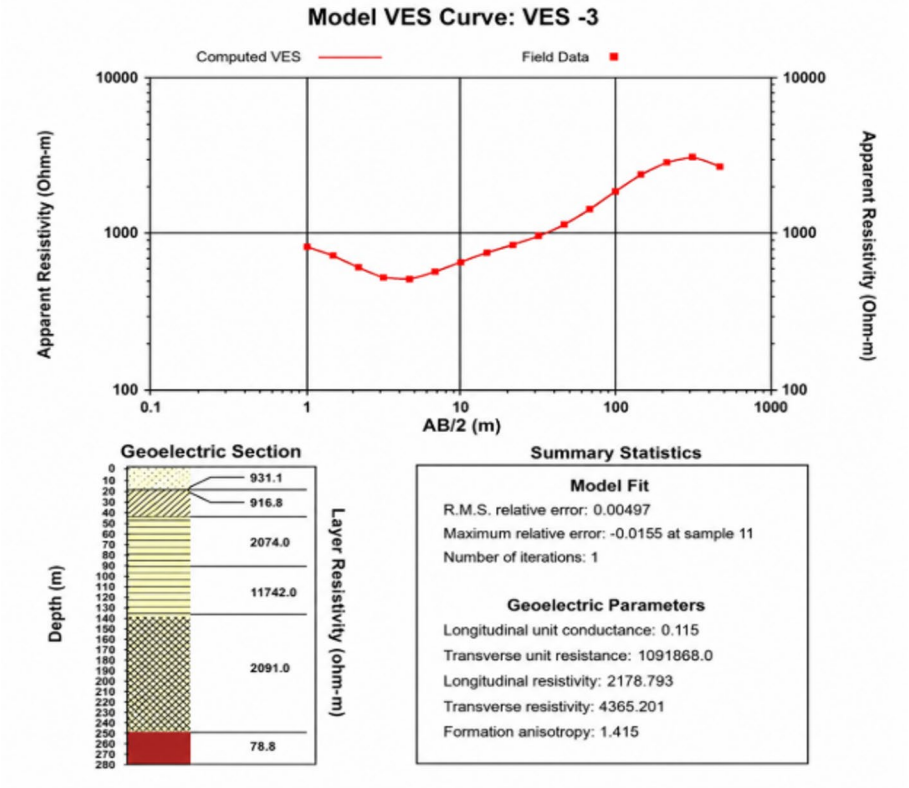


Fig. 3 Ewohimi VES curve/geoelectric section

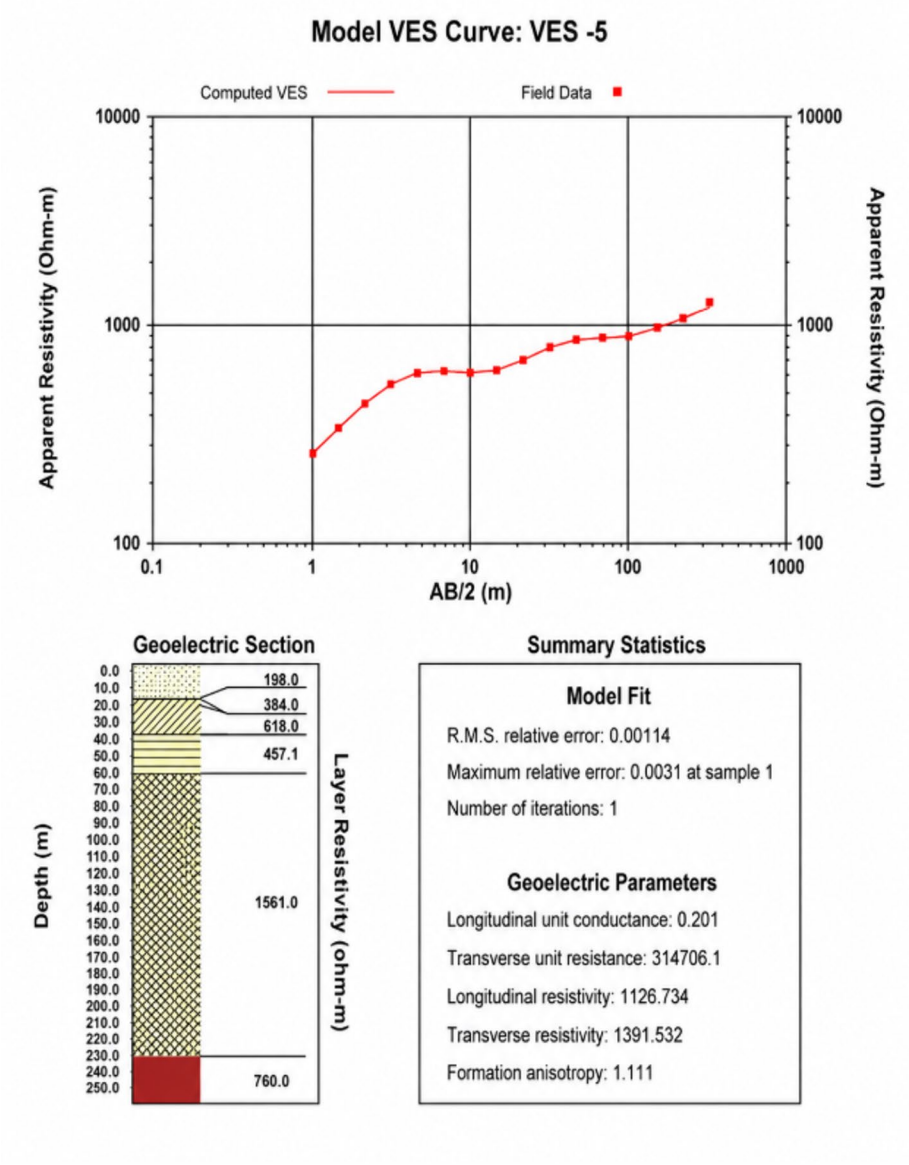


Fig. 4 Ewatto VES curve/geoelectric section

Groundwater depth varies spatially across the study area (Fig. 14), ranging from approximately 69 to 150 m. Shallow aquifer occurrences (69–120 m) are observed in Uokhuen, Uburubu, Orekhie, and parts of Emu and Ulogua–Okhordua. In contrast, deeper aquifer occurrences (120–150 m) are recorded in Okaigben, Ewatto, Okhordua, and Ugun. The depth-to-aquifer map (Fig. 14) reveals a systematic spatial pattern, with shallower aquifer occurrences generally associated with low-lying areas and deeper occurrences found in relatively elevated terrain.

4.3 Lithological characteristics and hydrostratigraphy

Lithological logs (Figs. 10, 11 and 12) indicate a heterogeneous sedimentary sequence comprising alternating sand, sandy clay, clay, and lignite units. Lignite intercalations occur at varying depths across parts of the study area and are commonly associated with reported drilling challenges [16].

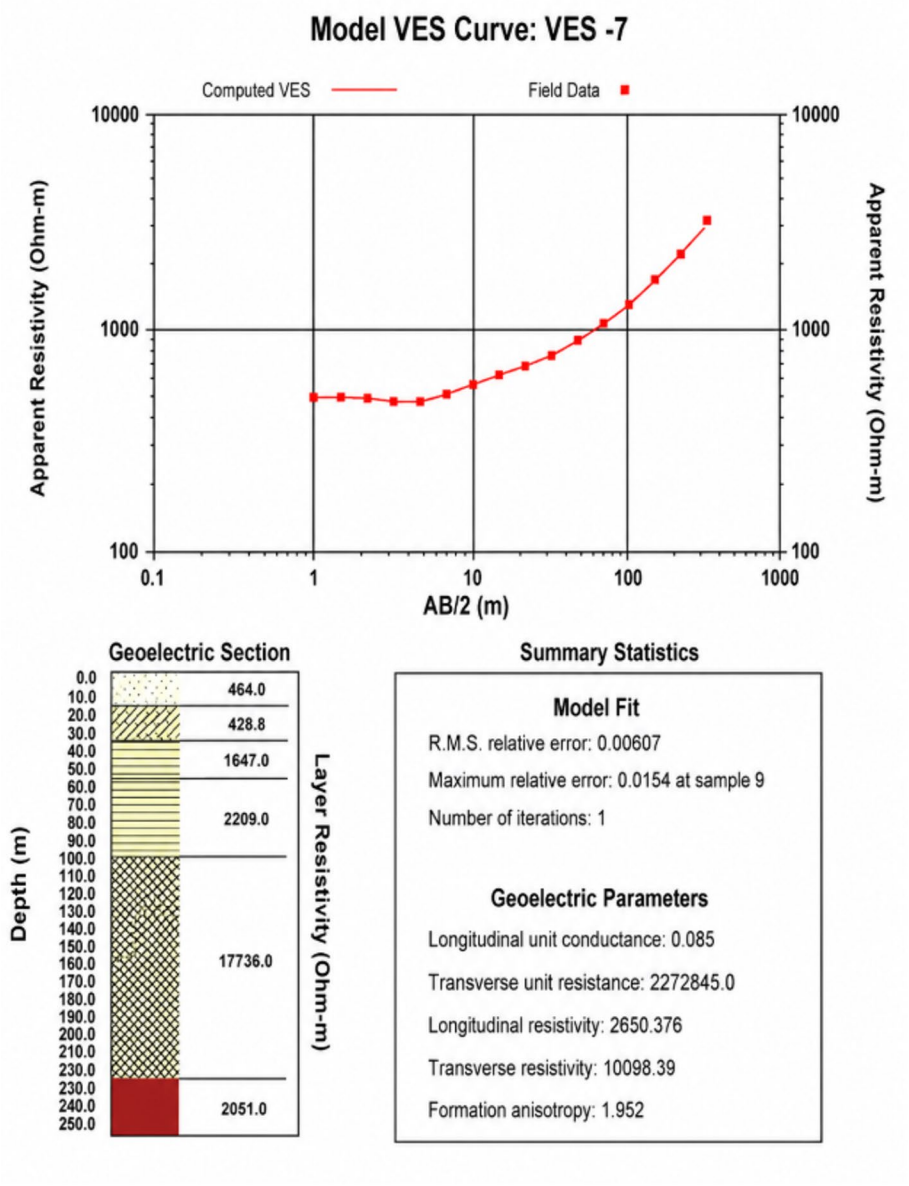


Fig. 5 Igueben VES curve/geoelectric section

Clay lenses and sandy clay units occur at multiple stratigraphic levels and exhibit lateral discontinuity. In the geoelectric curves/sections (Figs. 3, 4, 5, 6, 7 and 8), these units are represented by relatively low-resistivity layers separating more resistive sandy units. The stratigraphic fence diagram (Fig. 13) illustrates the vertical and lateral variability of these units and delineates the principal aquifer horizons.

4.4 Surface water discharge and baseflow contribution

Measured discharge in the Ella River ranges from 7.717 to 15.621 m^3/s, while discharge in the Iyagun River ranges from 3.984 to 6.894 m^3/s. Hydrograph separation of the Utor River hydrograph at Ebu indicates that baseflow contributes more than 70% of the total stream discharge (Fig. 16). The discharge hydrograph derived from the stage–discharge

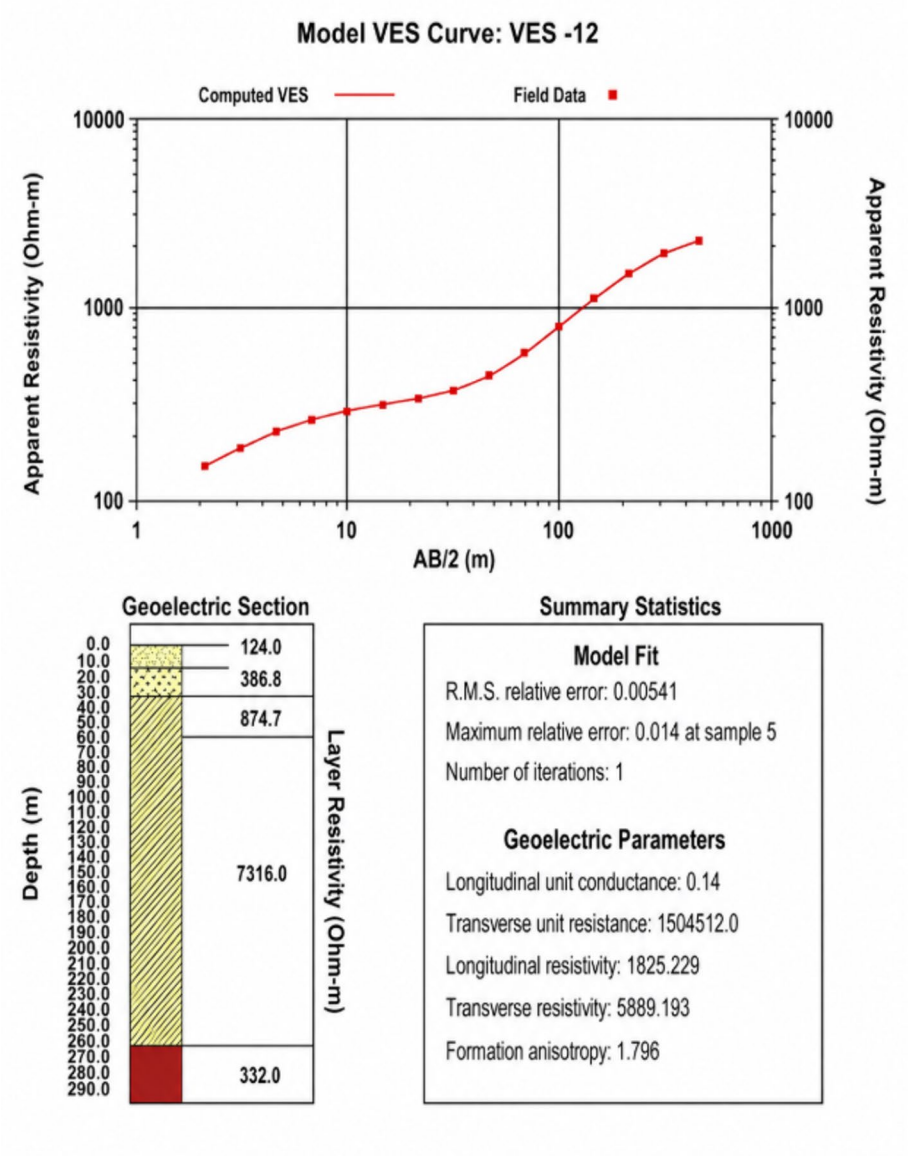


Fig. 6 Ogwa VES curve/geoelectric section

relationship shows relatively stable flow conditions throughout the year, consistent with sustained groundwater input, and yields a calculated baseflow index (BFI) of 76%.

Calculating the base flow Index (BFI)

$$\text{Total Volume}\,(V_{total}): \text{Approximately}\ 1.29 \times 10^9 m^3$$

$$\text{Baseflow Volume}\,(V_{base}): \text{Approximately}\ 0.98 \times 10^9 m^3$$

$$\text{Baseflow Index (BFI)}: \ V_{base}/V_{total} = 0.98 \times 10^9 m^3/1.29 \times 10^9 m^3 = 0.76\,(76\%)$$

4.5 Aquifer parameters

Pumping-test results from selected boreholes indicate transmissivity values ranging from 8.626 to 35.564 m^2/day (Table 2). Borehole discharge rates range from 17.33 to 44.60 m^3/h under sustained pumping conditions. Hand-dug wells tapping shallow

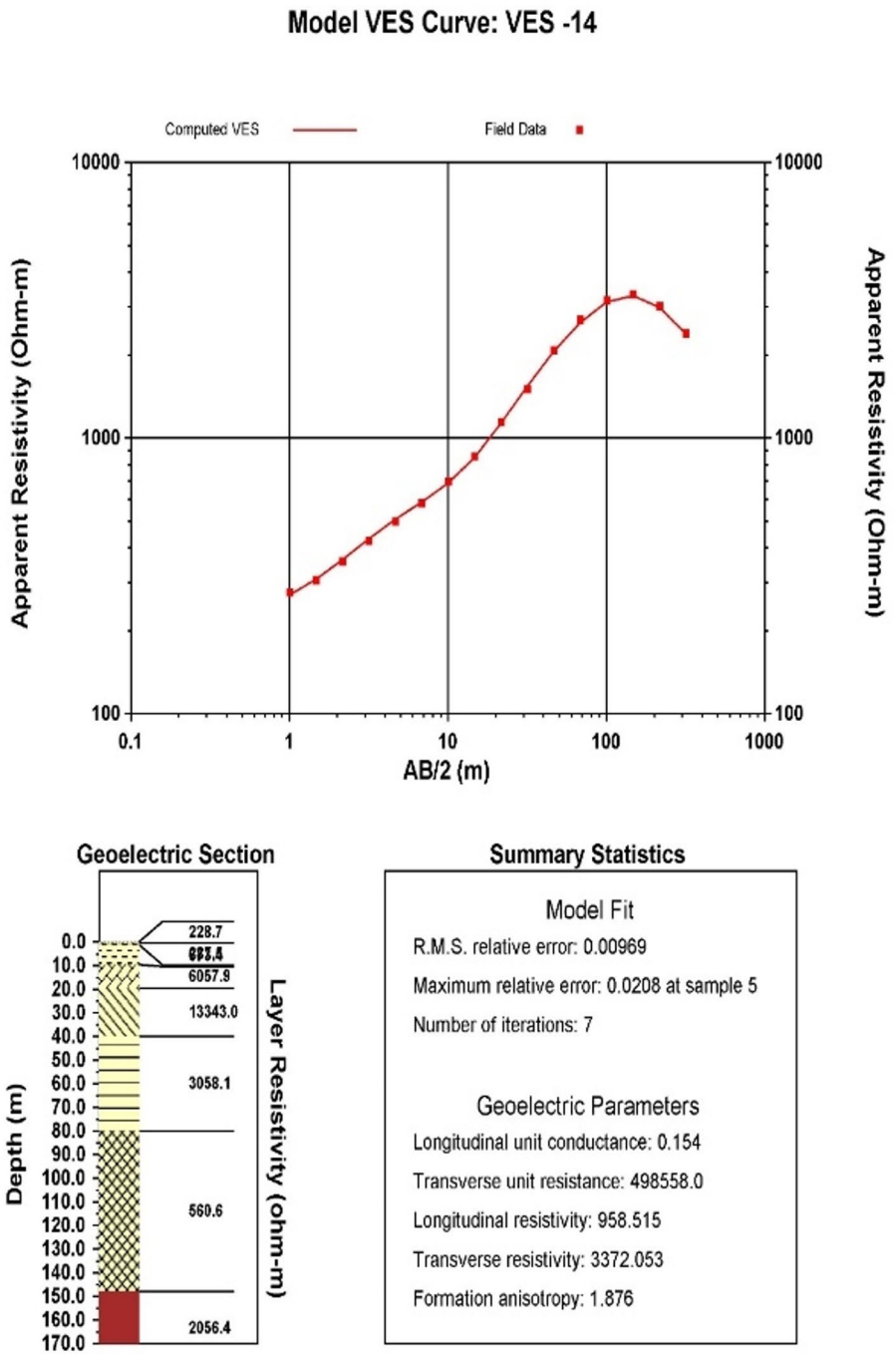


Fig. 7 Ugbegun VES curve/geoelectric section

perched aquifers exhibit variable productivity across the study area. Higher productivity is observed in Igueben, Ebudin, Ugbegun, Ebelle, Ubiaja, and Ewossa, whereas relatively low yields and, in some locations, an absence of perched aquifer conditions characterize Ewohimi, Ewatto, and Okhordua in the southeastern section of the study area. This spatial pattern may be related to the location of these communities within or adjacent to river valleys, where shallow groundwater associated with perched aquifers may preferentially discharge into the surface drainage network, thereby contributing to streamflow through baseflow. Consequently, a substantial proportion of groundwater may be

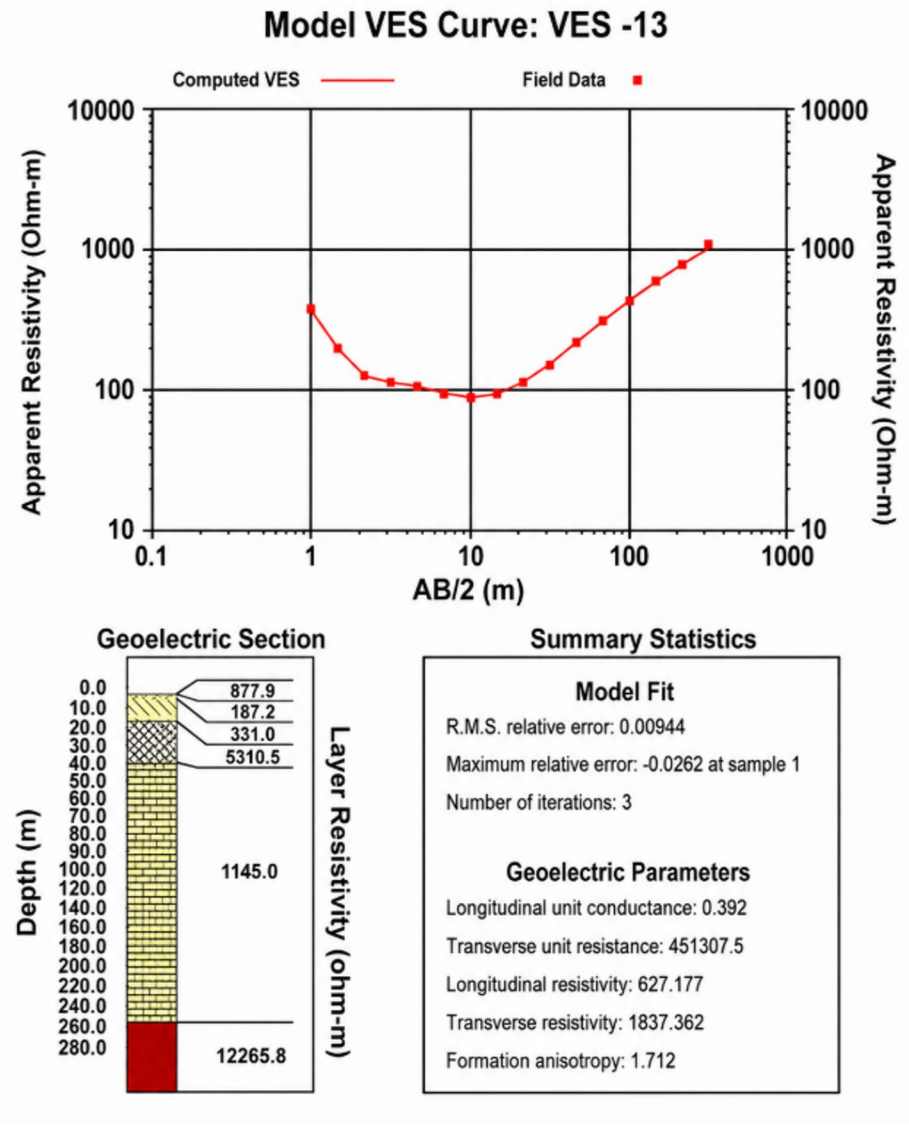


Fig. 8 Ubiaja VES curve/geoelectric section

discharged into the stream network, thereby reducing the volume available for abstraction from the perched aquifer. The groundwater equipotential map (Fig. 15) indicates a regional groundwater-flow direction toward the major river channels.

5 Discussion

5.1 Geological settings and stratigraphic interpretation

Regionally, the study area occurs within a sedimentary succession that is stratigraphically related to formations of the adjacent Anambra Basin and Niger Delta Basin. The Ogwashi–Asaba Formation, of Oligocene–Miocene age, forms part of the Niger Delta sedimentary succession, whereas the Upper Maastrichtian Ajali Formation is associated with the Anambra Basin [11, 19]. These formations represent distinct stratigraphic units deposited under contrasting depositional conditions and consequently exhibit different lithological characteristics. The eastern extension of the study area is associated with the Ogwashi–Asaba, Nsugbe, and Nanka Formations, with the Nsugbe Formation

Table 1 Summary of the VES data/interpretation

Probe point	Location on the map	Depth (m)	Thickness (m)	Resistivity ρ (Ωm)	Lithology
VES 1	Ewohimi	0	0–18	372.4	Laterite, clayey
		18	18–25	967	Sand
		25	25–50	451	Clay
		50	50–230	1561.0	Sand, clay, lignite, saturated at base
		230	230–250	498.5	Sand, saturated
VES 2	Uokhuen	0	0–15	132.2	Laterite, clayey
		15	18–26	987	Sand
		26	26–50	125.3	Clay
		50	55–210	1661.0	Sand, lignite, Saturated sand
		210	210–250	598.5	Sand, saturated
VES 3	Ewohimi	0	0–15	332.2	Laterite, clayey
		15	18–26	987	Sand
		26	26–55	461	Clay
		55	55–210	1661.0	Sand, clay and lignite. Saturated at the base
		210	210–250	598.5	Sand, saturated
VES 4	Ewatto	0	0–16	267	Laterite, clayey
		16	16–25	988	Sand
		25	25–54	457.1	Clay
		54	54–225	1561.0	Sand, clay and lignite. Saturated
		225	225–250	760.0	Sand, saturated
VES 5	Ewatto	0	0–16	257	Laterite, clayey
		16	16–25	918	Sand
		25	25–54	357.2	Clay
		54	54–225	1461.0	Sand, clay and lignite. Saturated
		225	225–250	618.0	Sand, saturated
VES 7	Igueben	0	0–20	464	Laterite, clayey
		20	20–51	1647	Sand
		51	51–110	2209	Sandy, lignite
		110	110–227	17,736	Sand, Saturated at the base
		227	227–250	25,111	Sandstone, dry
VES 8	Ubiaja	0	0–12	877.9	Laterite, sandy
		12	12–20	687.2	Clayey sand
		20	20–50	9310	Sandy, lignite
		50	50–227	1145	Sand, clay, Saturated at the base
		227	227–280	12,265	Sandstone, dry
VES 9	Okhordua	0	0–18	577.3	Laterite, sandy
		18	18–45	387.1	Clayey sand
		45	45–110	966	Sandy, lignite, saturated at the base
		110	110–220	845	Sand
		220	220–250	565	Sand, saturated
VES 10	Ebelle	0	0–9	126	Laterite, clayey
		9	9–20	386.0	Sand
		20	20–50	774	Sandy
		50	50–260	516	Sand, clay, saturated at the base
		260	260–290	212	Clay
VES 12	Ogwa	0	0–10	124.0	Laterite, clayey
		10	10–22	386.0	Sand
		22	22–55	874.7	Sandy
		55	55–260	736.2	Sand, lignite and clay. Saturated at base
		260	260–290	332.0	Sand, saturated

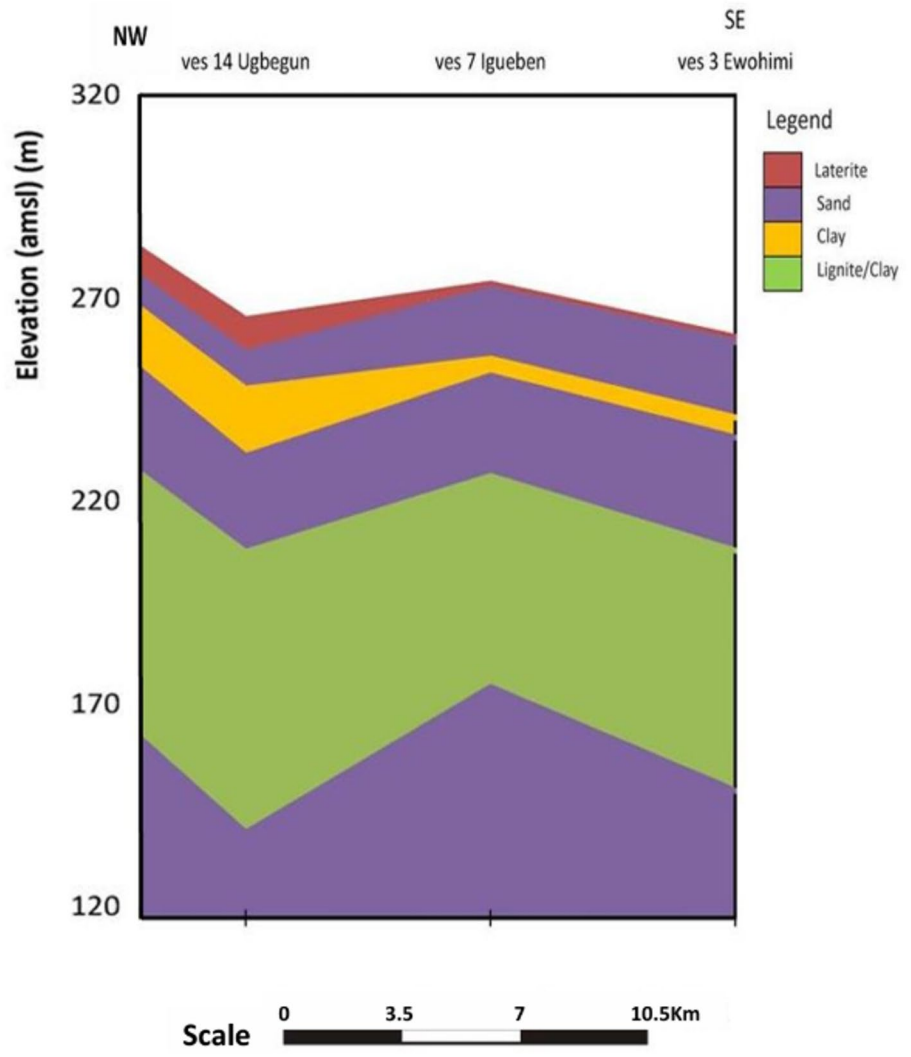


Fig. 9 Geo-electric cross section NW–SE section

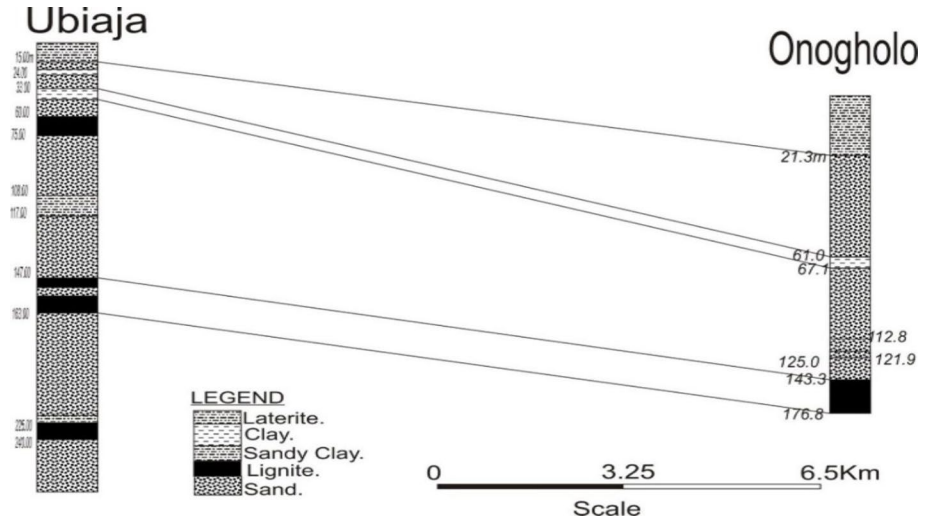


Fig. 10 Correlation of borehole logs from Ubiaja–Onogholo (W–E)

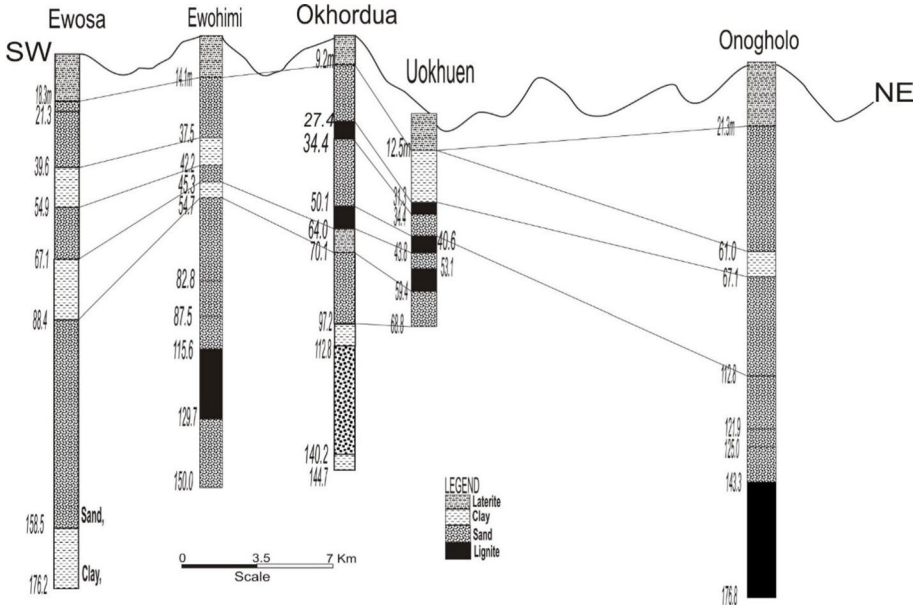


Fig. 11 Correlation of borehole logs from Ewossa–Onogholo [16]

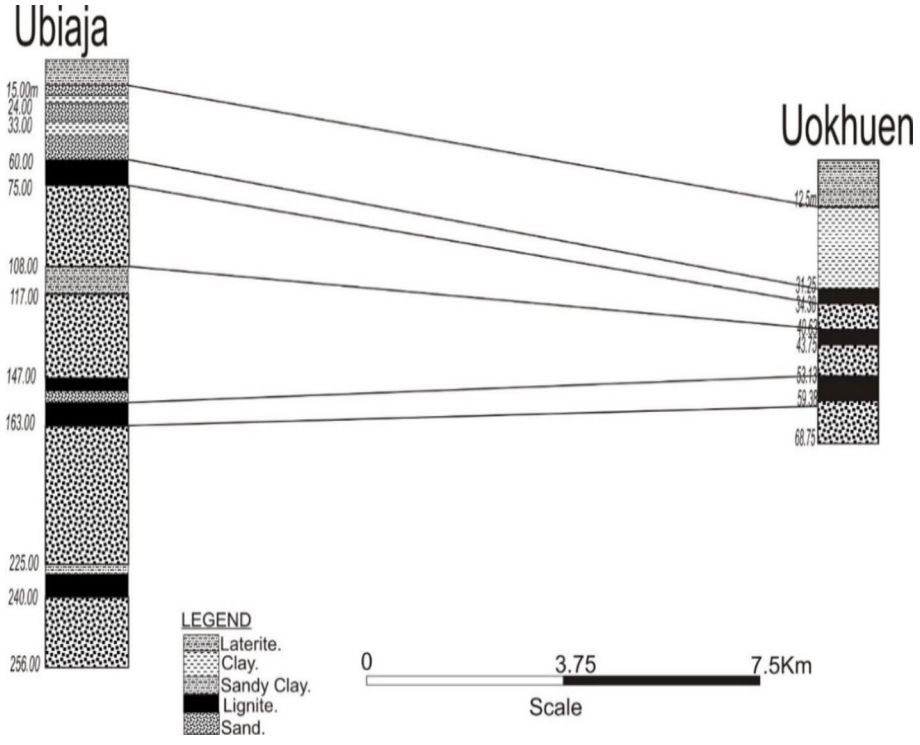


Fig. 12 Correlation of borehole logs from Ubiaja to Uokhuen

and Nanka Sands regarded as lateral equivalents of the Ameki Formation. This regional stratigraphic continuity supports the correlation of the sedimentary succession in the study area with the Ameki–Ogwashi–Asaba framework. The occurrence of cross-bedded sandstone in outcrops within the study area is therefore not, by itself, diagnostic of the Ajali Formation. Although cross-bedding is a characteristic sedimentary structure of the Ajali Formation, it is not unique to this formation; similar structures may also

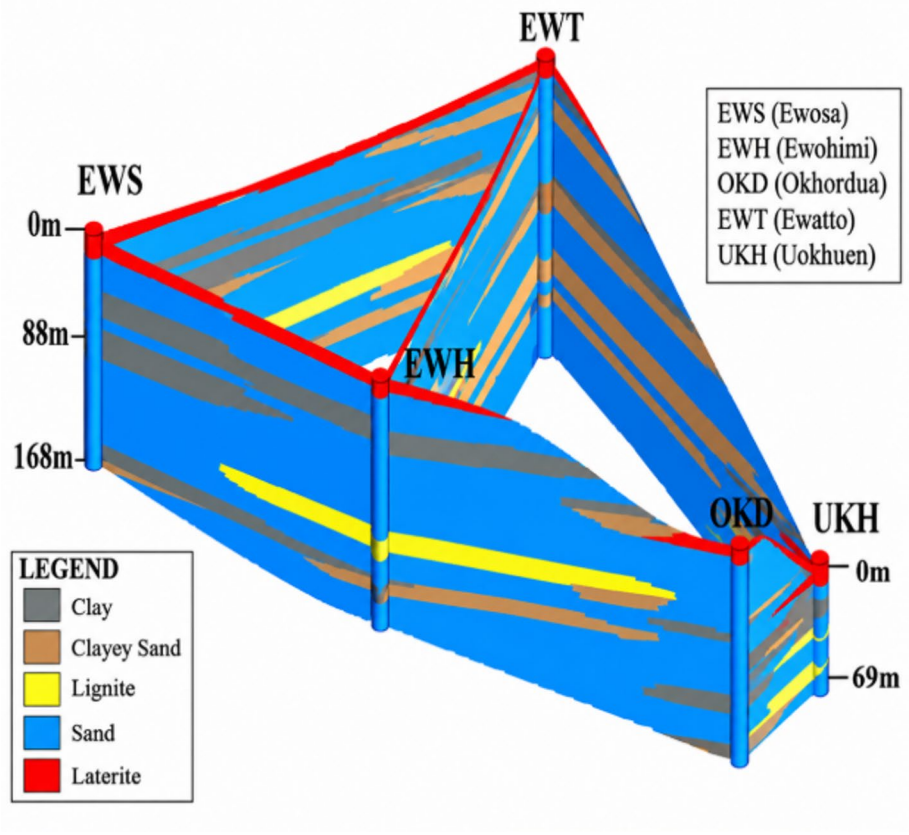


Fig. 13 Stratigraphic model of the study area (Ewossa, Ewatto, Ewohimi, Okhordua and Uokhuen)

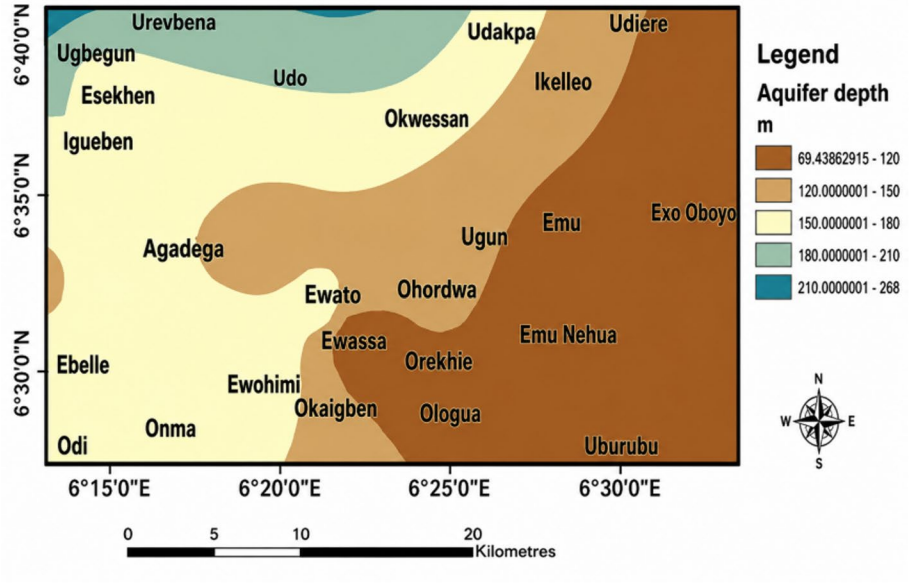


Fig. 14 Depth to main aquifer in the study area (Adapted after [16])

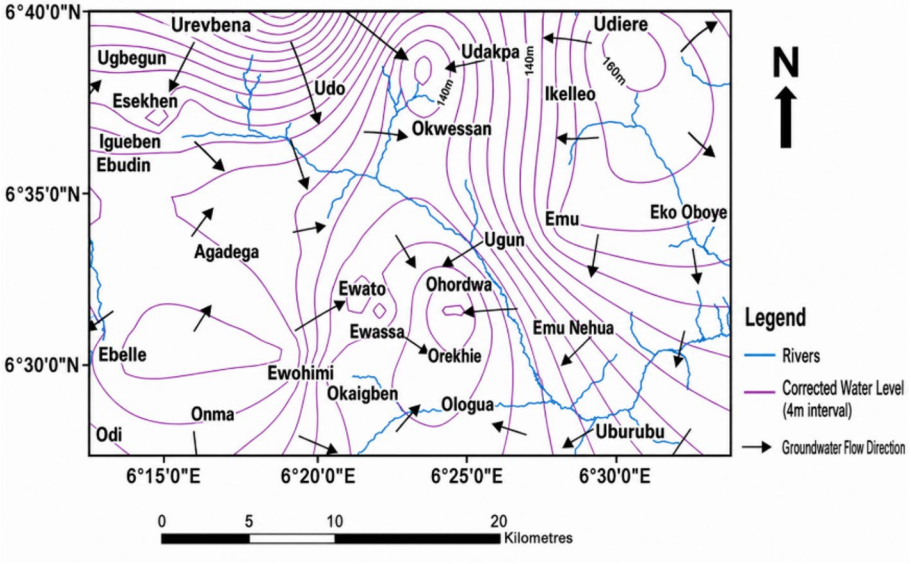


Fig. 15 Groundwater equipotential lines and flow direction

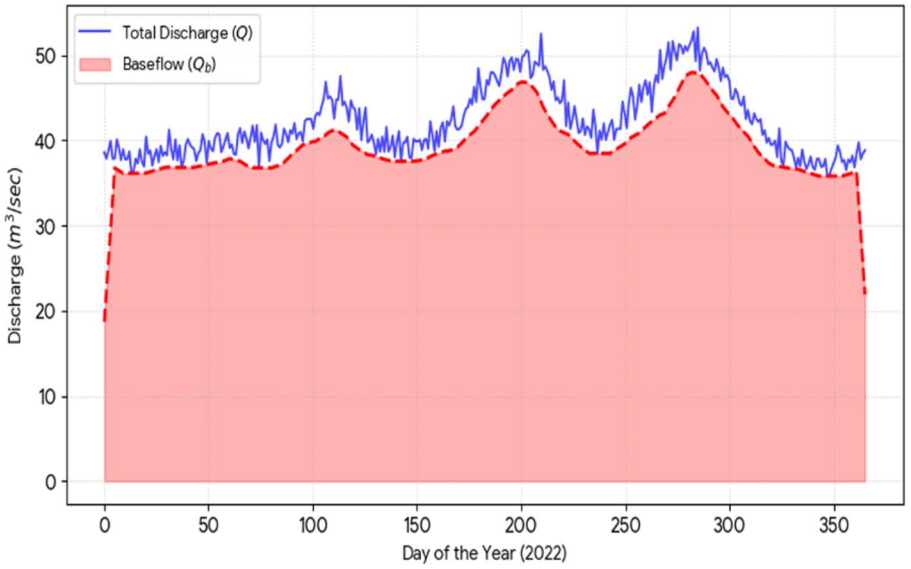


Fig. 16 Base flow separation showing the total streamflow (blue) and the calculated base flow (red)

develop in the Ameki and Ogwashi–Asaba Formations under fluvial to deltaic depositional conditions. Consequently, the identification of cross-bedding alone is insufficient to assign the observed sandstone units to the Ajali Formation, and lithological associations, stratigraphic relationships, and supporting borehole and geoelectric evidence should be considered in their interpretation.

Field evidence, supported by borehole and geoelectric data, shows that these cross-bedded units are interbedded with lignite and clay horizons. These lithological associations are inconsistent with the typically clean, friable sandstones characteristic of the Ajali Formation.

Furthermore, the vertical and lateral facies relationships observed across the study area (Figs. 10, 11 and 12) indicate a heterogeneous sequence of sand, clay, and lignite,

Table 2 Pumping test data, borehole and aquifer parameter

S/*N*	Place	Borehole depth (m)	Yield (M^3/h)	Static water level (m)	Elevation (m)	Corrected water level (m)	Total draw down (m)	Specific capacity (l/min/m)	Transmissivity (m^2/day)	Aquifer thickness (m)	Hydraulic conductivity
1	Ewohimi	189	17.33	153.03	267.04	114.01	14.05	20.56	22.39	76.90	0.29
2	Ubiaja	189	24.56	149.82	261.13	111.31	20.42	20.05	5.99	60.00	0.10
3	Ebelle	213	16.08	106.25	283.15	179.90	16.08	28.30	8.63	51.70	0.17
4	Igueben	220	33.20	152.40	366.67	214.27	18.10	30.57	35.56	48	0.74
5	Ugbegun	198	44.6	165.20	302.94	137.74	12.20	60.93	21.30	45.00	0.47
6	Ewatto	210	30.10	156.36	286.46	126.10	10.30	50.01	15.02	70.00	0.21
7	Okhordua	161.3	22.4	84.40	185.21	101.17	9.40	36.06	36.44	35.48	1.03

which is more characteristic of the Ameki–Ogwashi–Asaba stratigraphic framework. Therefore, the identification of cross-bedding alone is insufficient to assign these units to the Ajali Formation, and their previous interpretation in this context is likely erroneous.

5.2 Topographic control on aquifer depth and productivity

The observed spatial variation in aquifer depth suggests a strong influence of topography on groundwater occurrence. Shallow aquifer zones are predominantly associated with low-lying areas, whereas deeper aquifer occurrences correspond to relatively elevated terrain.

This distribution reflects typical groundwater-flow behavior in sedimentary basin settings, where hydraulic gradients drive groundwater from recharge areas at higher elevations toward discharge zones in valleys. The groundwater equipotential lines and flow directions (Fig. 15) support this interpretation, showing convergence of groundwater flow toward river channels. This implies that drilling depths and success rates are likely to vary systematically with elevation, with potentially better groundwater prospects in topographic lows and transitional zones.

5.3 Hydrostratigraphic controls and drilling implications

The presence of lignite layers within the sedimentary sequence may explain the drilling complications reported in parts of the study area. Lignite horizons may contribute to circulation losses and pipe sticking, thereby influencing borehole success rates [16]. The identification of clay lenses and sandy clay units confirms the occurrence of perched and leaky aquifer systems. These discontinuous horizons create localized groundwater storage above the regional water table, thereby explaining the spatial variability in hand-dug well productivity. Communities with favorable perched-aquifer conditions record productive shallow wells, whereas areas lacking such hydrostratigraphic configurations exhibit limited shallow-well productivity.

5.4 Groundwater–surface water interaction

The high baseflow contribution (76%) indicates a strong hydraulic connection between groundwater and surface-water systems (Fig. 16). The dominance of baseflow suggests that river discharge is largely sustained by groundwater rather than direct surface runoff. This interpretation is corroborated by the groundwater equipotential map (Fig. 15), which shows flow directions oriented toward river channels, indicating that the rivers function as gaining systems. The agreement between hydrograph separation and hydraulic-gradient analysis provides consistent evidence of groundwater discharge into surface-water bodies. These findings highlight the important role of the aquifer system in sustaining perennial river flow within the study area.

5.5 Aquifer performance and groundwater development potential

The transmissivity values obtained (8.626–35.564 m^2/day) indicate moderate aquifer potential, consistent with the heterogeneous nature of the sedimentary formations (Fig. 17; Table 2). The recorded transmissivity values are 22.386 m^2/day at Ewohimi, 8.626 m^2/day at Ebelle, and 35.564 m^2/day at Igueben. The observed variation may be attributed to differences in borehole depth, well-completion methods, and aquifer properties, including porosity, permeability, and aquifer thickness. The corresponding

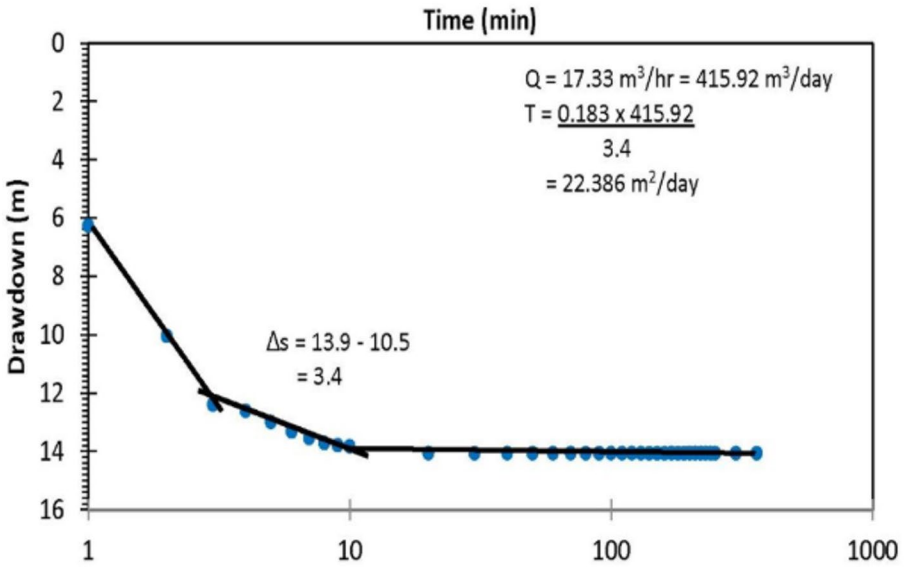


Fig. 17 Pumping test chart of Ewohimi borehole

borehole yields are 17.33 m^3/h at Ewohimi, 27.3 m^3/h at Ebelle, and 33.2 m^3/h at Igueben. These yields indicate that the main aquifer can support moderate to high abstraction rates under appropriate development and management conditions.

In contrast, perched aquifers have limited storage capacity and areal extent, resulting in variable and generally lower productivity. Their occurrence is controlled by localized hydrostratigraphic conditions rather than by regional aquifer continuity. From a groundwater development perspective, targeting the main aquifer system in areas with favorable aquifer thickness and depth—particularly within valley environments and along plateau margins—is likely to enhance borehole success rates and support long-term groundwater sustainability.

5.6 Integration of geophysical and borehole data

The integration of VES results and borehole lithological logs provides a consistent framework for subsurface interpretation. Low-resistivity zones identified in the VES sections generally correspond to clay-rich or saturated formations, whereas higher resistivity values are associated with sandy aquifer units.

6 Conclusion

This study presents an integrated hydrogeological, surface geophysical, and hydrological characterization of the Ubiaja–Ewatto–Ewohimi axis using electrical resistivity sounding, borehole lithological correlation, pumping-test analysis, and assessment of surface-water–groundwater interactions. The integrated interpretation provides a coherent understanding of aquifer distribution, hydraulic performance, and groundwater-flow dynamics within the study area.

The subsurface is characterized by a heterogeneous sedimentary sequence comprising sand, sandy clay, clay, and lignite intercalations associated with the Ameki and Ogwashi–Asaba Formations. These lithological variations exert strong control on groundwater occurrence, resulting in a multi-aquifer system comprising regional confined aquifers and localized perched aquifers.

Lignite and clay horizons act as semi-confining units, contributing to drilling challenges and influencing groundwater storage and movement. Depth to the main aquifer varies spatially from approximately 69 to 150 m, with shallower aquifer zones predominantly occurring in low-lying valley environments and deeper occurrences associated with elevated terrain. This distribution reflects the influence of topography and regional hydraulic gradients on groundwater occurrence and recharge–discharge processes.

Hydraulic analysis indicates that the main aquifer exhibits transmissivity values ranging from 8.626 to 35.564 m^2/day and supports borehole yields of 27.3–33.2 m^3/h under sustained pumping conditions. These results indicate moderate aquifer productivity and favorable groundwater development potential in areas with suitable lithological and hydrogeological conditions. In contrast, perched aquifers exhibit localized and variable productivity because of their limited continuity and dependence on discontinuous clay-bound horizons.

Hydrograph separation analysis of the Utor River indicates that baseflow contributes 76% of the total stream discharge, confirming substantial groundwater contribution to surface-water systems. This interpretation is further supported by groundwater equipotential mapping, which indicates groundwater-flow convergence toward river channels. Collectively, these findings indicate that the rivers function as gaining streams and are hydraulically connected to the regional aquifer system.

Overall, the integrated dataset demonstrates that groundwater occurrence and productivity within the study area are controlled by the combined effects of lithological heterogeneity, structural discontinuities, and topographic gradients. The most favorable zones for groundwater development occur within valley settings and along plateau margins, where aquifer thickness, hydraulic connectivity, and recharge conditions may be more favorable. The study provides a robust hydrogeological framework for sustainable groundwater exploration and management in the area.

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Benin-Owena River Basin Development Authority.

Author contributions
Author E. F conceived designed, carried out data collection, analysis of data, and drafting of the manuscript. Author N. S was responsible for interpretation of result. Author O. S is responsible for the review of the draft article while all author approved the final manuscript.

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Data availability
Data Availability StatementThe data that support the findings of this study are available from the corresponding author upon reasonable request. The data include borehole lithologic logs, geophysical resistivity logs, hydrostratigraphic correlation profiles, and drilling records obtained from relevant water resource agencies.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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