



Spatiotemporal and Hydrogeological Assessment of Groundwater Flow and Vulnerability in Parts of the Benin Formation, Akwa Ibom State, Southeastern Nigeria

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Abstract

Groundwater flow dynamics and vulnerability assessment are critical for sustainable water management in parts of the Benin Formation, Southeastern Nigeria, where groundwater is the primary potable water source. However, uncontrolled exploitation, poor borehole siting, and contamination risks necessitate a detailed understanding of groundwater flow patterns and vulnerability. This study applies geospatial techniques to analyze groundwater flow patterns and assess aquifer vulnerability in parts of the Benin Formation, Southeastern Nigeria. Sustainable groundwater management is crucial due to increasing water demand, uncontrolled borehole siting, and contamination risks. A total of 23 borehole Static Water Level (SWL) measurements, lithologic logs from 11 sites, and Digital Elevation Models (DEMs) were analyzed to model groundwater flow. GIS-based hydrological modeling and vulnerability mapping were applied to assess contamination risk. Results indicate a predominant northwest-to-southeast groundwater flow, influenced by topography, hydraulic gradients, and lithology, with secondary flows towards the Imo and Cross Rivers. Recharge zones were delineated in Oruk Anam, Essien Udim, and Ukanafun, while discharge areas were identified near Ibesikpo Asutan and Ikot Ekpene. Vulnerability mapping reveals higher contamination risks in shallow aquifers within agricultural and industrial zones, necessitating urgent groundwater protection. These findings provide critical insights into groundwater sustainability, emphasizing the need for recharge zone protection, sustainable extraction policies, and pollution control measures to ensure long-term groundwater security.

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1.0 Background of Study

Fresh water is a finite and yet vulnerable resource, essential to sustain life, development and the environment, thus its exploration, evaluation and careful management remains a key factor in development planning. Ninety seven percent (97 percent) of global water is seawater with just 3 percent of freshwater. Of this fresh water, only 13 percent is accessible, making about 0.4 percent of the global water resources. More than 2 billion people in the world today are affected by water shortages in over 40 countries and this population is fast on the increase. Beyond quantity, the quality of our fresh water is also of huge concern, with half the population of the developing countries exposed to polluted water sources that increase incidence of some diseases like diarrhea, typhoid, cholera and guinea worm (Al Fry, 2005). Over exploitation of groundwater in many areas is also of growing concern, and in coastal environments, this has led to saline intrusions from the marine environment (Adepelumi *et al.*, 2009). The development of groundwater resources within the Benin Formation, in some southeastern parts of Nigeria has been faced with several problems especially the limited availability of a hydrogeological and hydro-geophysical database for reference and planning purposes. Subsurface exploration and research within this region have mainly enabled exploitation of groundwater for domestic and industrial uses. More information is needed on the Hydrogeological and Hydro-geophysical characteristics of the area. These will help in providing more detailed description of the Sub-surface lithology, Hydrostratigraphic units, Aquifer yield and other characteristics. The analysis of these data will also show the available groundwater resources and what is recoverable as well as addressing the questions around the current level of abstraction and groundwater sustainability. Besides, with

increasing water demand following the rapid growth of communities and expanding needs for water, which translates to more dependence on groundwater, there is need for detailed study and in-depth understanding of the hydrogeology of the study area. This project work is expected to assemble and update the existing hydrogeological information in the study area using Geographic Information System (GIS) technique and borehole information. This would allow for the effective management and future development of the groundwater resources of the study area.

2.0 Location and Geology of the Study Area

The study area lies between 5°19'N and 4°36'N and longitudes 7°27'E and 8°19'E and covering about 4,080.5km² (Figure 1). It is located within the sub-equatorial climatic region of Nigeria with a total annual rainfall of more than 300 to 400cm and temperature ranges from 25°C to 28°C with elevation ranging between 0m and 110m above sea level. The Western Sector of the Lower Cross River Basin is mainly made of the Alluvium in the coastal areas while the rest of the environment is Benin Formation (Wright, 1966; Nyong, 1995). This study will focus mainly on the segment covered by the Benin Formation.

2.1 Geologic Setting

The geology of the study area as indicated in Figure 1 is underlain by late Cretaceous to Quaternary sediments. The lowermost sediment is lateritic sandstone with minor shale of the Maastrichtian Nsukka Formation. Throughout the Paleocene to Early Eocene, a thick shale intercalated with sandstone and limestone was deposited (Imo Shale Formation) (Reyment, 1965), while in the middle of the Eocene semi-consolidated sandstone, siltstone and minor shale were deposited (Bende Ameki Formation). Since the Miocene-Oligocene grit and sand with

intercalations of clay and lignite beds were deposited constituting the Ogwashi-Asaba Formation. Overlying this formation is a thick sequence of gravel, sand, silt, and clay constituting the Benin Formation also known as the Coastal Plain Sands and alluvial ridges.

2.2 Hydrogeologic Setting

The area has three major hydrostratigraphic units including the Alluvial Deposit, Coastal Plain Sand and Lower Sand Aquifers. The Coastal Plain Sand aquifer is the most extensive and is separated from the Lower Sand aquifer by

the Imo Shale aquiclude. The aquifer is composed of sand, gravel, and sandstone with clay intercalations (Edet, 1993). The thickness of the aquifer varies between 35m in the north and 200 m in the south. The aquifer is considered to be semi-confined or unconfined, especially in the southern parts of the area. The main groundwater flow direction is from north to south into the Atlantic Ocean. There are also variations in the northeast-southwest and northwest-east directions into the Imo River and the Cross River (Esu *et al.*, 1999)

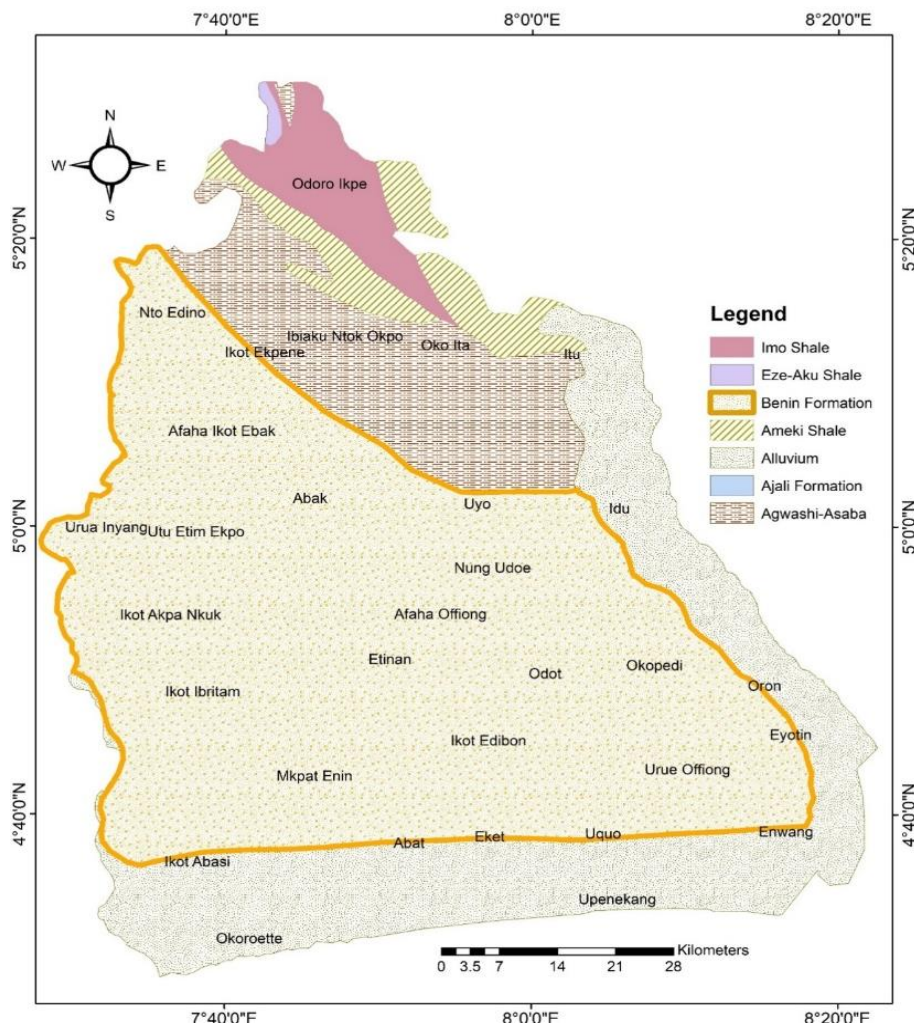


Fig. 1: Geologic Map of Akwa Ibom State highlighting the study area

3.0 Materials and Methods

3.1 Materials

The data analysis for this study involved the use of a combination of geophysical, geospatial, and computational tools to ensure accurate

interpretation of subsurface characteristics. The materials utilized in this research include resistivity meters for field data acquisition, geospatial software for mapping and

visualization, and specialized geophysical software for data modeling and interpretation.

i. Resistivity Meter

The resistivity meter was the primary instrument used for data acquisition. This electronic device measures the electrical resistivity of subsurface materials, which is crucial for identifying variations in lithology and groundwater-bearing formations (Telford *et al.*, 1990). Electrical resistivity methods have been widely used in hydrogeophysical studies for delineating aquifer properties, identifying clay-rich layers, and estimating groundwater potential (Reynolds, 2011). The Schlumberger and Wenner electrode configurations are among the most common electrode arrangements used in resistivity surveys for groundwater investigations, as they provide insights into vertical and lateral resistivity variations (Loke, 2000).

ii. ArcGIS and ArcScene – for Spatial Analysis
ArcGIS and ArcScene were used for spatial data analysis, georeferencing, and visualization of groundwater flow patterns. Geographic Information Systems (GIS) have become indispensable in hydrogeological studies, as they facilitate the integration of geophysical, geological, and hydrogeological datasets for spatial analysis (Jenson & Domingue, 1988). The use of ArcGIS allowed for the creation of thematic maps displaying variations in groundwater depths, aquiferous zones, and resistivity values, which are essential for groundwater management and decision-making (Fetter, 2001).

iv. WINRESIST, RES2D, and INTERPEX – for Geophysical Analysis

WINRESIST, RES2D, and INTERPEX were used for processing, modeling, and inversion of resistivity data. These software tools are widely applied in hydrogeophysical studies to derive resistivity-depth profiles and visualize subsurface layers (Loke, 2000). WINRESIST is particularly effective in one-dimensional resistivity inversion, while RES2D is used for

two-dimensional resistivity imaging, allowing for a more detailed representation of subsurface structures (Griffiths & Barker, 1993). INTERPEX software was also employed to enhance the accuracy of geophysical interpretations, aiding in the identification of aquifer boundaries and lithological variations (Zohdy *et al.*, 1974).

3.2 Methodology

3.2.1 Vertical Electrical Sounding (VES)

Data for this study were collected from 80 VES stations distributed across the study area at approximately 10 km intervals. Each VES survey provided resistivity data that were used to estimate the depth to the water table and identify the subsurface structure. The resistivity measurements were obtained using the Schlumberger electrode configuration, which allows for deeper penetration into the subsurface.

3.2.2 Borehole and Lithological Data

In addition to the VES data, borehole logs from Essien Udim, Oruk Anam, Ibesikpo Asutan, and Ika were collected and analyzed. These logs provided information on the depth to the water table, aquifer thicknesses, and lithology. The borehole data were crucial for calibrating the resistivity results and correlating the geophysical data with actual geological formations.

3.2.3 Topographic Data and Digital Elevation Model (DEM)

Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM) to generate a Digital Elevation Model (DEM) of the study area. The DEM provided detailed information on surface features and was essential for delineating groundwater flow directions, recharge zones, and discharge areas. The DEM resolution was **30 meters**, providing sufficient detail for the analysis.

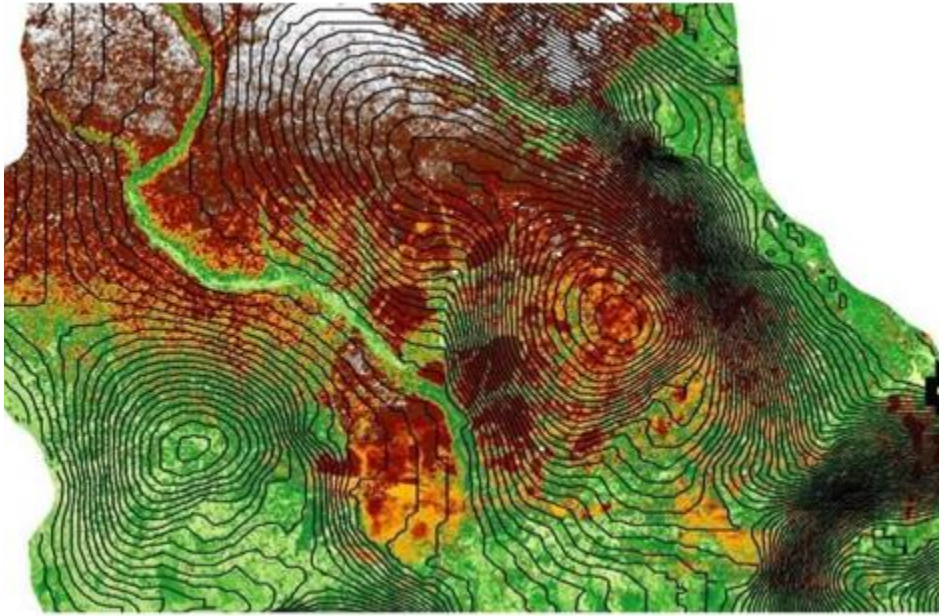


Fig. 2: Excerpt of DEM with sample contour lines extracted - Source of data: Alos Palsar 2006

3.2.4 Geospatial Analysis in ArcGIS

The geospatial analysis was conducted using ArcGIS 10.8 software. The key steps in the analysis are described below.

3.2.4.1 Groundwater Flow Mapping

A groundwater flow map was generated using the Flow Direction tool in ArcGIS. This tool calculates the direction of groundwater flow from each cell in the DEM to its steepest downslope neighbor. The input for this analysis included the water table data from VES stations and boreholes. Using these data, a continuous water table surface was interpolated using the Kriging method, which accounts for spatial autocorrelation in the data (Ahmed & Carpenter, 2003). The result was a detailed map showing groundwater flow vectors and gradients.

3.3 Extraction of Gaining Streams and springs

The extraction and study of gaining streams and springs play a crucial role in hydrogeological investigations, particularly in understanding groundwater-surface water interactions, assessing water availability, and ensuring sustainable management of water resources. Gaining streams receive additional water from groundwater inflow, while springs emerge when

groundwater naturally surfaces due to pressure or geological structures. The presence and behavior of these features provide essential insights into the underlying hydrogeological processes that govern groundwater movement and discharge.

One of the fundamental reasons for extracting gaining streams and springs is to understand the connectivity between aquifers and surface water bodies. These features act as indicators of groundwater discharge, demonstrating how groundwater contributes to streamflow, particularly during dry seasons when baseflow sustains river ecosystems (Winter et al., 1998). The study of these systems helps to delineate groundwater recharge and discharge zones, offering a clearer picture of the regional hydrological balance. Additionally, assessing the extent of groundwater contribution to surface water bodies enhances the ability to predict changes in water availability due to natural variability or human activities (Sophocleous, 2002).

Gaining streams and springs are also valuable for evaluating groundwater flow and aquifer potential. Since they emerge as a result of groundwater discharge, their location, flow rate,

and chemical composition provide information about the characteristics of the subsurface aquifers. Hydrogeologists use these features to determine groundwater gradients, estimate flow velocities, and infer the permeability and transmissivity of aquifers (Freeze & Cherry, 1979). The study of gaining streams can also reveal aquifer sustainability, as continuous groundwater discharge suggests that recharge

mechanisms are maintaining balance with extraction rates. In regions where groundwater depletion is a concern, declining discharge from gaining streams and springs can serve as an early warning signal of aquifer over-extraction (Scanlon et al., 2006). Fig. 3 shows the extraction of gaining streams and springs within the area of study.

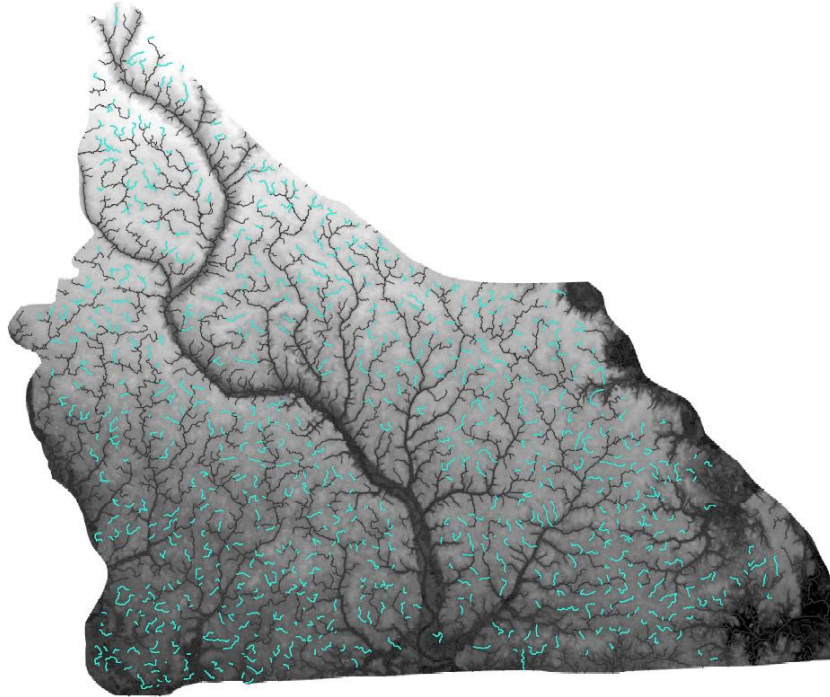


Fig. 3: Extraction of Gaining Streams and Springs - Source of data: Alos Palsar 2006

3.4 Extraction of Groundwater Elevation point data from gaining streams and boreholes

The extraction of elevation point data for gaining streams and springs is essential in hydrogeological and hydrological studies, particularly in understanding groundwater-surface water interactions, delineating flow paths, and assessing aquifer dynamics. Elevation data provide a crucial spatial reference for determining the direction of groundwater flow, the relationship between recharge and discharge zones, and the influence of topography on groundwater emergence in the form of springs and gaining streams. One of the primary reasons for extracting elevation point data is to establish the hydraulic gradient, which governs the movement of groundwater. Groundwater flows

from areas of higher hydraulic head to lower hydraulic head, and elevation data allow for the accurate mapping of these gradients (Freeze & Cherry, 1979). By analyzing the elevation differences between recharge zones, groundwater levels, and discharge points such as springs and gaining streams, researchers can infer groundwater flow directions and estimate flow velocities. This information is critical for understanding the connectivity between aquifers and surface water bodies, helping to predict how water moves through the subsurface and where it naturally discharges.

Elevation data are also fundamental in delineating watersheds and defining groundwater catchment areas. Springs and gaining streams often occur in specific

geomorphological settings where groundwater intersects the land surface due to geological structures or topographic lows. Extracting elevation point data helps in identifying these areas, allowing for better hydrogeological mapping and classification of different discharge zones (Winter et al., 1998). Furthermore, elevation data are useful in assessing how changes in land use, such as urbanization or deforestation, may impact groundwater recharge and surface water contributions.

The integration of elevation data with hydrological models enhances the ability to simulate groundwater-surface water interactions under varying conditions. Digital Elevation Models (DEMs) derived from extracted elevation points are widely used in GIS-based hydrological modeling to predict surface runoff, groundwater recharge potential, and streamflow patterns (Jenson & Domingue, 1988). These models help in identifying critical areas where groundwater discharge plays a significant role in maintaining stream baseflow, especially during

dry periods when precipitation is limited. Understanding these relationships is vital for water resource management, ensuring that surface water bodies remain ecologically functional and that groundwater reserves are sustainably utilized.

Additionally, elevation data contribute to the assessment of groundwater vulnerability and flood risk. In regions where gaining streams and springs serve as the primary water sources, changes in elevation and topography can influence water availability. For example, shifts in groundwater levels due to over-extraction or climate change can alter the locations and discharge rates of springs, potentially leading to reduced water availability in dependent ecosystems and communities (Taylor *et al.*, 2013). Elevation data are also useful in identifying areas prone to flooding due to rising groundwater levels, helping in disaster preparedness and mitigation planning. Fig. 4 shows the Groundwater elevation point extracted from gaining streams and springs.

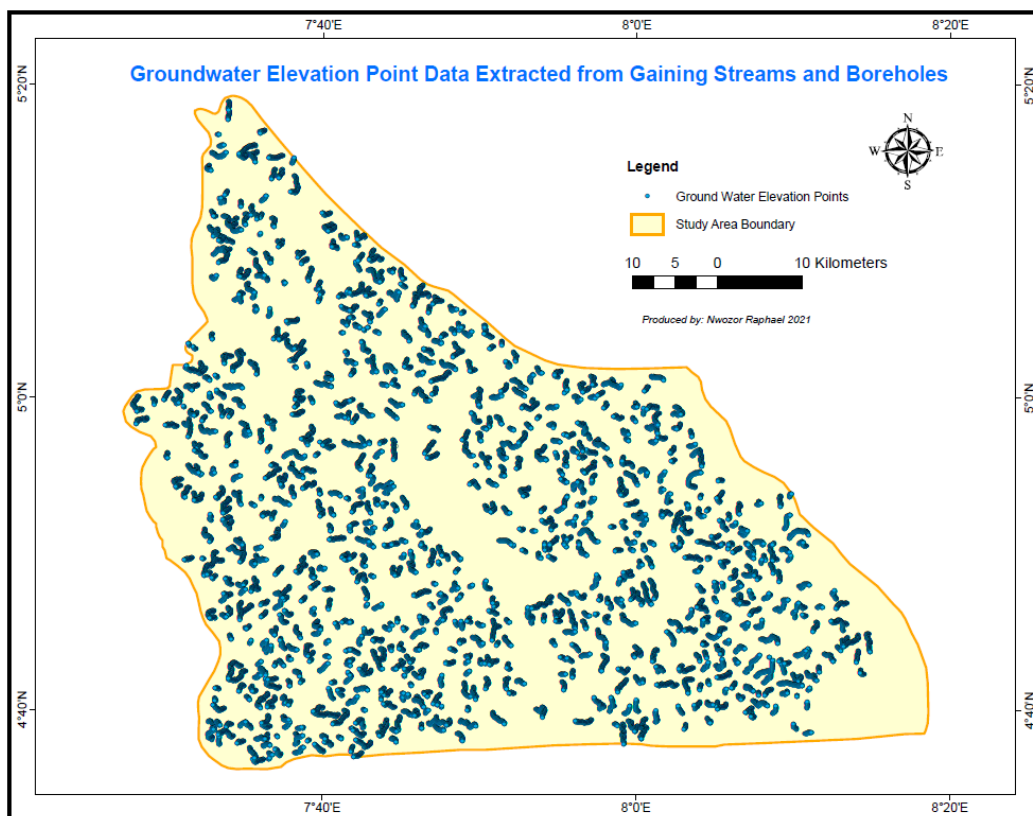


Fig. 4 Groundwater Elevation Point Data Extracted from Gaining streams and Boreholes

3.4 Recharge and Discharge Zone Identification

Recharge zones were identified by analyzing areas of high flow accumulation in the DEM. These zones were characterized by shallow water tables and steep topography, where surface water is likely to infiltrate and replenish groundwater. Discharge zones were located in low-lying regions, typically near rivers such as the Imo and Cross Rivers, where groundwater intersects the surface and contributes to river baseflow.

4.0 Results

The Benin Formation, primarily composed of continental sands and gravels, is a major aquifer system within the Niger Delta. This formation exhibits high porosity and permeability, which are critical for groundwater storage and flow. The electrical resistivity survey data provides valuable insights into the subsurface lithology and groundwater potential of the study area.

4.1 Groundwater Flow Patterns

The groundwater surface elevation of the project area was generated using groundwater elevation

data from 35 borehole points and 832 gaining stream points as shown on Table 1. The groundwater surface elevation for each of these boreholes was extracted by subtracting the SWL value from the surface elevation value for each of the points. Using the groundwater level elevation (Z) for every point in space with X and Y values representing the geographic coordinate of borehole points and the groundwater level raster (digital elevation model) of the project location and was interpolated using the kriging tool on ArcGIS and applying the spherical semivariogram model. The groundwater level contour for the study area was developed using the spatial analyst tool on ArcGIS. The results of the groundwater flow analysis are summarized in Table 1. The predominant flow direction in the study area is from north to south, with secondary flow patterns oriented towards the Imo River and Cross River. The flow velocities varied across the study area, with higher velocities in the northern upland areas and lower velocities in the southern lowlands.

Table 1: Summary of Groundwater Flow Characteristics

Location	Flow Direction	Flow Velocity (m/day)	Primary Discharge Areas
OrukAnam	North to South	1.5	Cross River
EssienUdim	North to South	1.8	Imo River
IbesikpoAsutan	East to West	1.2	Imo River
IkotEkpene	East to West	1.1	Cross River
Ukanafun	North to South	2.0	Cross River

Fig. 4 illustrates the flow vectors across the study area, highlighting the major flow directions and areas of convergence. By mapping the depth to the top of the aquifer across the study area, a groundwater flow direction was inferred (figure 4). Generally, groundwater flow was observed to move from higher to lower elevations, consistent with regional topographic gradients. The flow direction was predominantly towards the

southeast, influenced by the geological and topographical characteristics of the Niger Delta. The identified flow direction towards the southeast (figure 5) aligns with regional hydrological patterns and offers insights into potential recharge and discharge areas. Understanding the spatial distribution and flow direction of groundwater is crucial for effective water resource management.

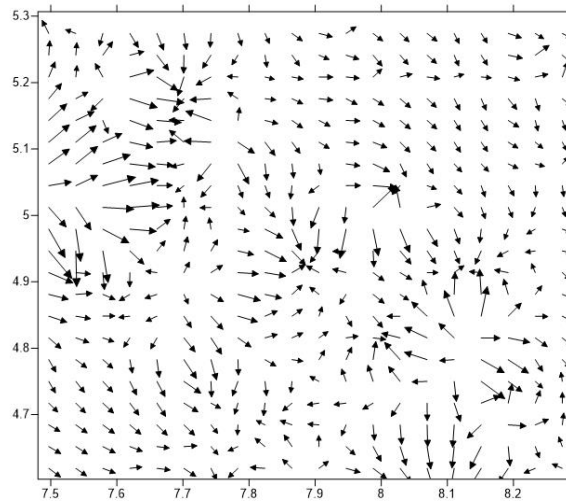


Fig. 4: Groundwater flow direction within the study area

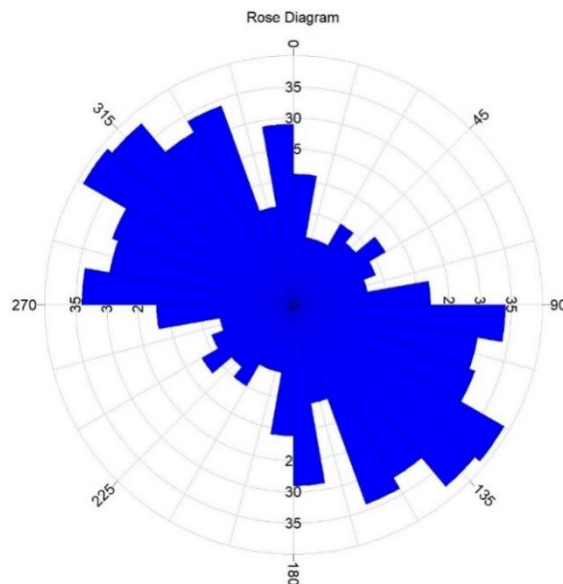


Fig. 5: Rose diagram indicating the predominant groundwater flow direction

4.2 Recharge and Discharge Zones in the Study Area

In the northwest part of the study area, locations such as Ikot Ebak, Ibesit Numj, Ikot Oruk Anam, and Ntak Ibesit Oruk Anam exhibit moderate aquifer depths ranging from 48 to 53 meters. These relatively consistent depths suggest stable groundwater conditions with less pronounced recharge or discharge activities. However, areas with slight variations in water table depths might still contribute to localized recharge zones where surface water infiltrates to replenish the groundwater. As we move towards the central part of the study area, including places like Technical College Mkpato Enin, Abak Oko, and

Ukwo Eket, the depth to the aquifer tends to increase, reaching up to 68 meters in some locations. This increase in depth indicates potential discharge zones where groundwater might be moving upwards, contributing to surface water bodies or sustaining wetland ecosystems. The presence of deeper aquifers in this region suggests areas where groundwater storage is substantial and the potential for groundwater extraction is higher. Further southeast, in areas such as Ikot Akpan Obio Okot Etinan, Usaka Annang Obot Akara, and Mbiabon Ikot Ntem Uyo, the depth to the aquifer shows significant variability, ranging from as shallow as 33 meters to as deep as 109 meters.

This wide range of depths indicates dynamic groundwater conditions with both recharge and discharge zones. Shallow aquifer depths in locations like Ikot Akpan and Obio Okot suggest active recharge zones where surface water easily infiltrates the subsurface, replenishing the groundwater. In contrast, deeper aquifer depths in places like Usaka Annang and Mbiabon Ikot Ntem point towards potential discharge zones where groundwater might be contributing to rivers, lakes, or other surface water bodies.

The central and southeastern parts of the study area, with their significant variations in water table depths, highlight the complex hydrogeological interactions between surface water and groundwater. Areas with shallow aquifers are likely to experience higher recharge rates, especially during rainfall events, leading to increased groundwater levels. Conversely, regions with deeper aquifers might act as discharge zones where groundwater emerges to

sustain surface water systems, particularly during dry periods.

Overall, the study area exhibits a diverse range of groundwater conditions with distinct recharge and discharge zones identified by variations in water table depths. Understanding these zones is crucial for sustainable groundwater management as it helps in identifying areas suitable for groundwater extraction, regions requiring protection to maintain recharge rates, and zones where groundwater contributes to maintaining surface water ecosystems. These insights are essential for developing effective water resource management strategies and ensuring the long-term sustainability of groundwater supplies in the region. Recharge zones are crucial for replenishing groundwater resources and must be protected from over-extraction and contamination (Table 2). Table 3, shows the ground water discharge zones for the study area.

Table 2: Recharge Zone Characteristics

Community	Elevation (m)	Depth to Water Table (m)	Recharge Potential
Essien Udim	150	25	High
Ukanafun	120	18	Moderate
Oruk Anam	100	20	High

Table 3: Discharge Zone Characteristics

Community	Elevation (m)	Water Table Depth (m)	Discharge Potential
Ibesikpo Asutan	50	10	High
Ikot Ekpene	60	12	Moderate
Ukanafun	40	8	High
Ika	30	6	Very High

4.3 Depth to Aquifers

The depth to the top of aquifers (**figure 6**) varies significantly across the study area, ranging from as shallow as 16 meters (AK-019) to as deep as 109 meters (AK-073). This variation highlights the heterogeneous nature of the Benin

Formation. Generally, locations with shallower aquifers, such as AK-018 (19 meters) and AK-019 (16 meters), are more accessible and potentially more economical for groundwater extraction.

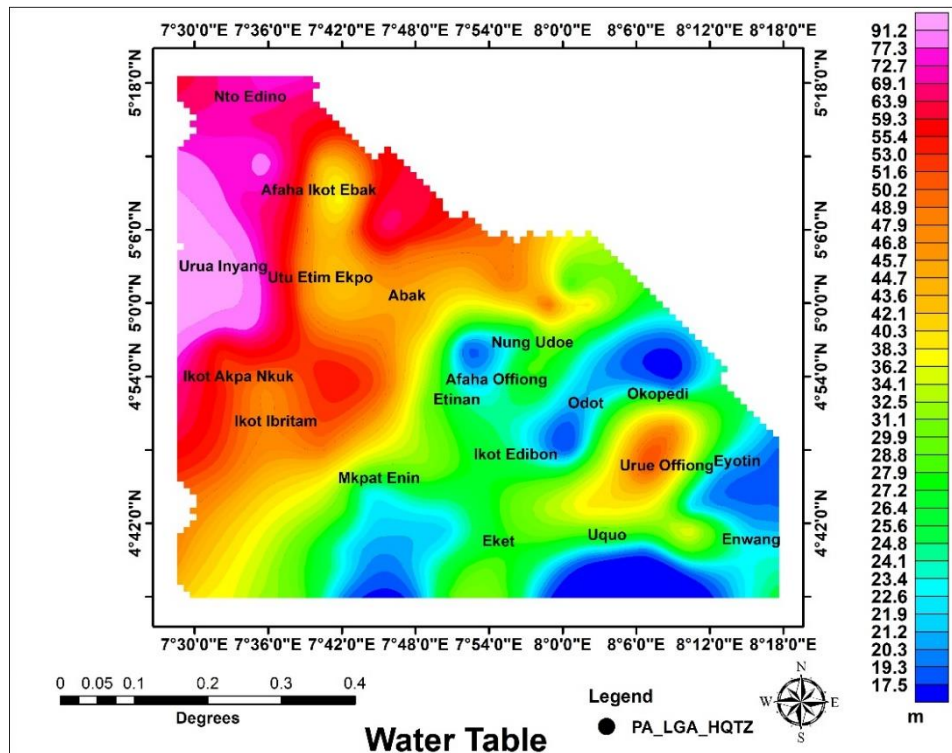


Fig. 6: Depth to water table within the study area

4.4 Groundwater Potential

The high resistivity zones with substantial depths suggest significant groundwater potential within the Benin Formation. The varying resistivity values at different depths indicate heterogeneous aquifer conditions, which can influence groundwater flow and storage. The presence of high resistivity layers interbedded with low resistivity layers suggests the existence of multiple aquifers and confining layers, which can impact groundwater extraction and management strategies. The resistivity variations also point to lithological heterogeneity within the formation, which is crucial for understanding mineral distribution and exploitation potential. The combination of

high and low resistivity layers indicates a complex depositional environment, with varying conditions that could influence mineral quality and quantity.

4.5 Groundwater Vulnerability Analysis

The vulnerability analysis identified regions at high risk of groundwater contamination, particularly in areas with shallow water tables and permeable soils, which are prone to rapid infiltration of contaminants. Vulnerable areas were primarily located near agricultural and industrial zones in Oruk Anam, Ikot Ekpene, and Ibesikpo Asutan. Table 4 provides a summary of the groundwater vulnerability classification.

Table 4: Groundwater Vulnerability Classification

Community	Depth to Water Table (m)	Dominant Soil Type	Vulnerability Level
Oruk Anam	10	Sandy Loam	High
Ikot Ekpene	12	Coarse Sand	Moderate
Ibesikpo Asutan	8	Sandy Clay	High
Ukanafun	18	Sandy Loam	Low
Essien Udim	25	Clayey Sand	Low

5.0 Discussion

The results of this study reveal several important patterns in groundwater flow and vulnerability in the Benin Formation. The dominant north-to-south groundwater flow direction is consistent with regional topographic gradients, indicating that the subsurface hydrology is strongly influenced by surface elevation. Communities like Essien Udim, Oruk Anam, and Ukanafun are situated in key recharge areas where groundwater replenishment is most effective. Protecting these zones from over-exploitation and contamination is critical for the long-term sustainability of groundwater resources in the region. The discharge zones identified along the Imo River and Cross River play a vital role in maintaining the baseflow of these rivers, particularly during the dry season when surface water input is minimal. These findings suggest that any significant reduction in groundwater recharge in the upland areas could have detrimental effects on river flow and overall water availability in the region.

The vulnerability analysis indicates that certain communities, particularly those near Ibesikpo Asutan, Ikot Ekpene, and Oruk Anam, are at higher risk of groundwater contamination. These areas, with shallow water tables and permeable soils, are prone to rapid infiltration of pollutants, especially in agricultural and industrial zones. Implementing groundwater protection measures, such as buffer zones and regular monitoring, is recommended to safeguard the water quality in these vulnerable areas.

The analysis of the VES data set provides valuable insights into areas with significant variations in water table depths, indicating possible recharge or discharge zones within the study area. These zones are critical for understanding groundwater dynamics and managing water resources effectively.

In the northwest part of the study area, locations such as Ikot Ebak, Ibesit Numj, Ikot Oruk Anam, and Ntak Ibesit Oruk Anam exhibit moderate

aquifer depths ranging from 48 to 53 meters. These relatively consistent depths suggest stable groundwater conditions with less pronounced recharge or discharge activities. However, areas with slight variations in water table depths might still contribute to localized recharge zones where surface water infiltrates to replenish the groundwater.

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Overall, the study area exhibits a diverse range of groundwater conditions with distinct recharge and discharge zones identified by variations in water table depths. Understanding these zones is crucial for sustainable groundwater management as it helps in identifying areas suitable for groundwater extraction, regions requiring protection to maintain recharge rates, and zones where groundwater contributes to maintaining surface water ecosystems. These insights are essential for developing effective water resource management strategies and ensuring the long-term sustainability of groundwater supplies in the region.

6.0 Summary and Conclusions

This study has provided a comprehensive geospatial analysis of groundwater flow patterns, recharge and discharge zones, and groundwater vulnerability within the Benin Formation, Southeastern Nigeria. By integrating Vertical Electrical Sounding (VES) data, borehole records, and Digital Elevation Models (DEMs), the research successfully mapped dominant groundwater flow directions and identified critical hydrogeological zones. The findings indicate that groundwater predominantly flows from the north to the south, with secondary flow paths towards the Imo and Cross Rivers. Recharge zones were identified in upland areas, particularly around Essien Udim, Ukanafun, and Oruk Anam, where infiltration potential is high. Conversely, discharge zones were concentrated in low-lying regions near rivers, where groundwater resurfaces and contributes to baseflow. The vulnerability analysis highlighted that Oruk Anam, Ikot Ekpene, and Ibesikpo Asutan are at the highest risk of contamination due to shallow water tables, permeable soils, and human activities such as agriculture and industrialization.

The insights gained from this study are crucial for groundwater resource management in the Benin Formation. To ensure long-term sustainability, it is recommended that recharge zones be protected through land-use regulations that prevent over-extraction and contamination from agricultural runoff and industrial effluents. Implementing groundwater monitoring programs in vulnerable areas will enable early detection of contamination and fluctuations in water levels, allowing for timely intervention. Additionally, further research incorporating real-time monitoring systems and long-term hydrogeological assessments should be conducted to account for seasonal variations and climate change impacts on groundwater resources. These measures will enhance water security and sustainability, ensuring that groundwater remains a reliable source for communities within the Benin Formation.

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