



## **Integrated Geophysical, Hydrogeological, and Hydrogeochemical Assessments of Groundwater Potentials in Ini Local Government Area, Northern Akwa Ibom State, Nigeria**

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### **Abstract**

This study presents an integrated geophysical, hydrogeological, and hydrogeochemical assessments of groundwater potential in Ini Local Government Area of northern Akwa Ibom State, Nigeria. Electrical resistivity survey using vertical electrical sounding (VES) method was conducted at 25 locations to evaluate aquifer potential. Hydrogeological assessments were carried out to determine aquifer parameters, while hydrochemical analyses used Piper trilinear diagrams, cross plots and multivariate statistical techniques to assess groundwater quality and facies classification. The 3-layer geoelectric model was characterized with top layer resistivity ranging from 139.8 (VES 4) to 974.20  $\Omega\text{m}$  (VES 7), thickness between 1.4 (VES 22) and 12.4 m (VES 18). First aquiferous layer with resistivity values in the range of 9 (VES 22) to 3023.3  $\Omega\text{m}$  (VES 10) and thicknesses from 35.6 (VES 14) to 100.5 m (VES 13). The second aquifer has resistivity in the range 25.8 (VES 23) to 2006.4  $\Omega\text{m}$  (VES 4) and unresolved thickness. The 4-layer geoelectric models has the top layer underlain by an aquiferous layer with resistivity and thickness in the range 23.4 (VES 1) to 1274.6  $\Omega\text{m}$  (VES 20) and 3.2 (VES 17) to 54.1 m (VES 6). The next layer hosts with resistivity and thickness ranges of 258.6 (VES 17) – 2666.4  $\Omega\text{m}$  (VES 20) and 43.6 (VES 1) – 82.7 m (VES 9) hosts an aquifer. The fourth layer with unresolved thickness had resistivity values in the range 19.3 (VES 1) – 2358.9  $\Omega\text{m}$  (VES 3) hosts an aquifer. Eleven viable locations (VES 6, 7, 8, 9, 10, 16, 17, 18, 19, 20, and 22) were identified as promising for groundwater exploitation, with values indicating fair to good aquifer potential. Elevation and static water level mean values are  $92.72 \pm 47.11$  m and  $37.46 \pm 19.7$  m, respectively. Groundwater reserves varied between  $575.00 \times 10^6$  and  $18082 \times 10^6$  m<sup>3</sup> and regional groundwater flow direction is from West to East. The hydraulic conductivity, K and the transmissivity, T values averaged 0.78 m/day and 49.60 m<sup>2</sup>/day, respectively. Average Fe concentration of  $1.66 \pm 0.39$  mg/L exceeded MAL of 0.37 mg/L, while average Mn concentration of  $2.81 \pm 0.47$  mg/L exceeded MAL of 0.2 mg/L attributable to natural geogenic sources. Water is safe for irrigation uses. The hydrochemical facies is classified into the Ca-Mg-HCO<sub>3</sub>-Cl and Mg<sup>2+</sup>+Ca<sup>2+</sup>-Cl+HCO<sub>3</sub><sup>-</sup> water types attributed to carbonate and magnesium weathering. Gibb`s diagram showed TDS as a function of  $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$  and  $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ , supporting the dominance of rock weathering for surface and groundwater and evaporation process for contaminated water samples. Cross plots based on chloroalkaline indices CA I and CAII showed forward ion exchange. Factor analysis and

multivariate statistical analysis showed loadings suggestive of silicate and carbonate weathering. This study provides critical insights into groundwater suitability for domestic and agricultural uses to support sustainable water resource development given the complex geology of the study area. Preliminary geophysical investigations are recommended before borehole drilling to minimize failure risks.

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## 1.0 Introduction

The Sustainable Development Goal (SDG) target 6.1 calls for universal and equitable access to safe and affordable drinking water. Drinking water from an improved source is available when needed and free from faecal and priority chemical contamination (WHO, 2006). The availability and quality of groundwater resources have been affected by human and natural activities, e.g., infrastructural developments and climate change activities. Groundwater serves as a primary source of drinking water and irrigation in northern Akwa Ibom State. However, groundwater quality is influenced by a combination of natural geochemical processes and anthropogenic activities, such as agricultural practices, industrial waste disposal, and inadequate sanitation systems. Evaluating groundwater quality through hydrochemical characterization is crucial for sustainable water management (Appelo & Postma, 2005; Todd & Mays, 2005). The availability of groundwater for drinking and agricultural purposes in many regions of the world is a problem due to over-exploitation and contamination of groundwater aquifers (Subba Rao et al., 2012; Bouderbala et al., 2016). Globally, rural communities, particularly in developing nations including Nigeria, have as one of the major problems the lack of

adequate potable water supply for domestic use. This is the scenario in several areas, including Ini LGA in Akwa Ibom State, because some of the existing water wells which initially produced water have dried up, diminished in yield or produced unsafe water. The funds lost or wasted on such projects would have been properly utilized if suitable drill sites or depths were recommended from detailed hydrogeological or geophysical studies. This is the rationale for this research study on aquifer delineation and hydrochemistry. A greater percentage of rural communities in Nigeria depend on unimproved sources of water for drinking and domestic purposes, and statistics show that just about 75% of boreholes in Nigeria are functional. A quarter of the public water points break down in their first year of completion. About 21% of water points in Nigeria are seasonal, and 47% of boreholes in Nigeria are contaminated with *E. coli*. Two-thirds of boreholes drilled in Nigeria were done without sub-surface investigation (FMWR, 2021). The study was conducted in the Ini Local Government Area (LGA). The area was selected based on existing hydrogeological challenges, including groundwater depletion, water table variations, and concerns about water quality in northern Akwa Ibom state. Data was obtained from borehole

investigations, geophysical surveys, well tests, and laboratory analyses. This integrated methodology enhances the accuracy of groundwater resource assessments by correlating geophysical anomalies with hydrogeological and hydrochemical parameters (Fetter, 2018; Thomas *et al.*, 2020). The results provide empirical data to guide sustainable groundwater resource management and policy formulation for water supply planning. The aim of this study is to Integrate geophysical, hydrogeological and hydrogeochemical assessments for sustainable groundwater resources management in Ini LGA of Akwa Ibom state. The objectives are as thus:

- To delineate the aquifers in the study area using geological and geoelectrical techniques.
- To determine the aquifer parameters based on geoelectrical parameters and hydrogeological data.
- To determine the regional groundwater chemical types, identify the major ion sources and identify the controlling factors influencing the geochemical evolution of the water bodies in the study areas.
- To develop a hydrogeoelectrical model and provide recommendations for sustainable groundwater management in the study areas.

## 2.0 Description of geological and hydrogeological settings

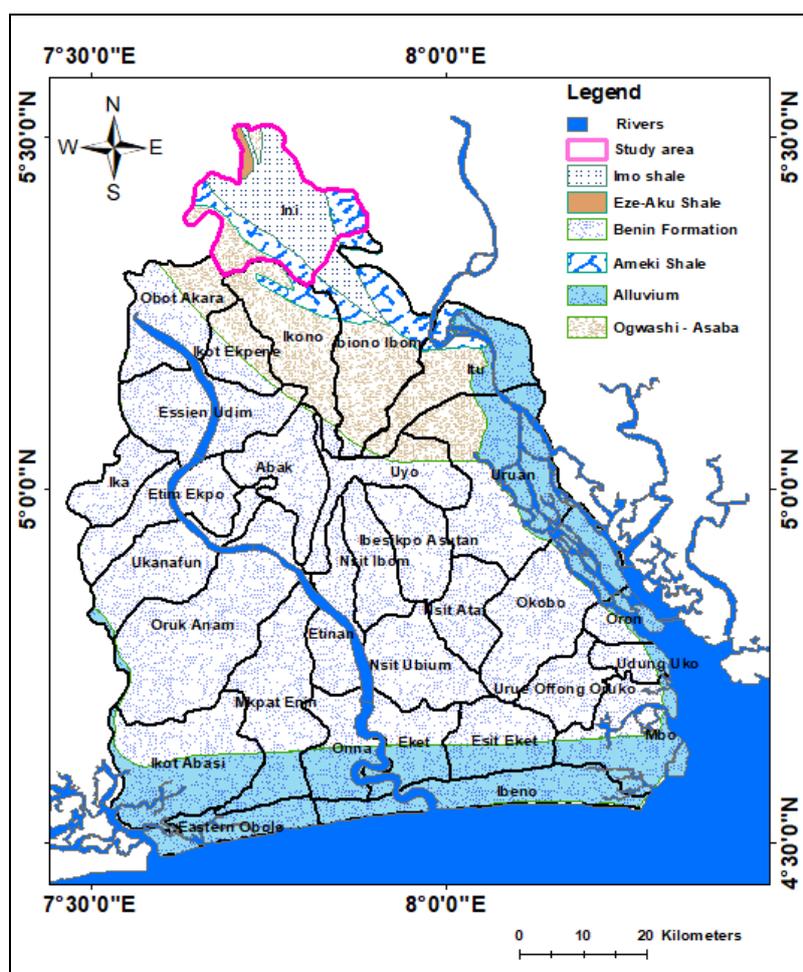
Akwa Ibom State lies within latitude  $4.9057^{\circ}$  N and longitude  $7.8537^{\circ}$  E and covers an estimated land area of 8,420 km<sup>2</sup>. It is limited to the south by the Atlantic Ocean and, in the north, west and east, by Abia, Imo and Cross Rivers. The study area in Ini LGA of Akwa Ibom State (Fig. 1) is located within latitude  $5.40000^{\circ}$  N and longitude  $7.73333^{\circ}$  E (Aniedi *et al.*, 2019). The terrain is virtually flat to gently undulating, sloping generally in the direction of the southern part of the state. Elevation is from about 100 to 120 m within the

zone. The shale is bluish to dark grey in colour. It is fissile and flat lying. The upper part grades into a mixture of clay and shale and finally into light brownish grey to reddish brown clay. Akwa Ibom State is underlain by sedimentary formations of Late Tertiary and Holocene ages (Short & Stauble, 1967). Deposits of recent alluvium and beach ridge sands occur along the coast and the estuaries of the Imo River and Qua Iboe River, and also along the floodplains of creeks. Inland, a greater part of the state consists of coastal plain sands, now weathered into lateritic layers, especially in Ini, Ikono, Etinan, Ikot Ekpene, and Itu LGAs. Geologically, Akwa Ibom State is underlain by two main rock types, which are sandstone and mudstone, with some limestone and clay/shale formations. The geology of northern Akwa Ibom State is primarily influenced by the Tertiary to Quaternary formations of the Niger Delta Basin. The dominant lithology includes coastal plain sands, clayey sands, and laterites. The Benin Formation, which is the primary groundwater-bearing unit, consists of highly porous and permeable sandstones interbedded with clay lenses (Short & Stauble, 1967).

Geologically, northern Akwa Ibom is part of the Niger Delta which occupies more than 80% of the study area is made up of Akata Formation (Shales intercalated with sands and siltstone), the Agbada Formation (Sands and Sandstones, intercalated with shales) in the middle and the Benin Formation (coarse-grained sands with minor intercalation of clays) at the top (Short & Stauble, 1967; Murat, 1972). However, Benin Formation, Bende Ameki Group and Imo shales are partly exposed in the study areas. Akwa Ibom State covers a total land area of about 6,900 km<sup>2</sup>, encompassing the Qua Iboe River Basin, the western part of the lower Cross River Basin and the eastern part of the Imo River Basin. The state has an oceanfront which spans a distance of 129 km from Ikot Abasi in the west to Oron in the southeast (Udom, 2004). In the northeastern part of the state, the subsurface geomaterials in the Benin Formation, which include clay and shale, are porous and capable

of absorbing water slowly but cannot discharge water in appreciable quantity into a well. The pores of these formations are not interconnected and are only porous but not permeable (Uduak & Ini, 2012). On the basis of geologic succession, four main hydrostratigraphic units have been delineated for the entire state (Esu *et al.*, 1999). These include three aquiferous units designated as

upper, middle and lower sand aquifers, in increasing geologic age and depth of burial. The middle aquifer is the most extensive and is separated from the lower sand aquifer by the Imo shale aquitard. These units are thoroughly discussed in chronological order from the youngest using illustrated drilled holes compiled for some existing groundwater wells by Esu *et al.* (1999) and Edet (1993).



**Fig. 1:** Geological map of Akwa Ibom State showing the study area

The hydrology of Akwa Ibom State is defined by a network of rivers, streams, and wetland systems, which significantly influence groundwater recharge. The major rivers in the state include the Cross River, Imo River, and Ikpa River, all of which contribute to surface water flow and aquifer recharge (Ekpo *et al.*, 2017). Hydrogeologically, Akwa Ibom State consists of unconfined to semi-confined aquifers, primarily hosted within the Benin Formation. The aquifer systems are recharged through precipitation, river seepage, and

infiltration of surface water. The groundwater table ranges between 5 and 20 meters below the surface, depending on the location and seasonal variations. The transmissivity values for the aquifers across the Niger Delta region range from  $1.05 \times 10^{-3}$  to  $11.3 \times 10^{-2}$  m<sup>2</sup>/s, while the coefficient of storage varies between  $1.07 \times 10^{-4}$  and  $3.53 \times 10^{-4}$ , and specific capacity values lie between 19.01 and 139.8 m<sup>3</sup>/d/m drawdown. These values suggest that the aquifers have very good capacity to transmit groundwater. The specific capacity of a well is its yield per

unit drawdown, usually expressed in  $\text{m}^3/\text{hr}/\text{m}$  of drawdown. (Abam & Nwankwoala, 2020). The presence of localized clay beds results in variation in water availability, particularly in areas with lower permeability. The most important aquifers in the Niger Delta are the Deltaic and Benin Formations. Most of the boreholes in the northern parts of the Niger Delta tap unconfined aquifers. In most of these boreholes the geological sequence consists of continuous sandy formations from top to bottom. However, some aquifers occur under confined conditions, resulting in artesian flows. The area is characterized by a humid tropical climate with two seasons, namely, the wet or rainy season and the dry season (Iloje, 2001). The rainy season is from May to October, and the dry season extends from November to April.

### 3.0 Methodology

The study adopts an integrated approach to assessing groundwater potential, integrating geophysical, geological, hydrogeological and hydrogeochemical techniques. This approach ensures a comprehensive evaluation of the subsurface characteristics, aquifer parameters, and water quality within the study area (Ekanem *et al.*, 2024; Udosen *et al.*, 2024). Other parts of the state had been studied by the use of geoelectrical, geological, hydrogeological and hydrogeochemical methods (Edet 1993; Edet and Ntekim 1996; Esu *et al.*, 1999; Ajayi & Umoh, 1998; Edet & Okereke 2001; George *et al.*, 2015a, b, c; Edet *et al.*, 2014; Edet, 2017). Water quality was analyzed in the laboratory according to the Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines to assess potability suitability (Ayers & Westcot, 1994). The groundwater samples from 10 boreholes labelled SP1-SP10 in Ini LGA were analyzed for major cations, anions and coliforms using

standard methods for examining water and wastewater by APHA (2017).

### 3.1 Geoelectric techniques

Geophysical techniques were used to map subsurface structures and identify potential groundwater-bearing formations (Asfahani *et al.*, 2023). SSR-MP-ATS model of (IGIS) Resistivity meter and its accessories to measure to electrical resistivity of the subsurface. Electrodes were used as the contact points for current to pass into the ground. Cables and clips were utilized to connect resistivity meter to the electrodes. A power source (battery) provided the required power for the survey. Other survey tools such as measuring tapes, compasses were utilized for precise positioning. Garmin channel 12 GPS kit was used to obtain elevations and coordinates for the all locations. The geophysical survey utilized the Vertical Electrical Sounding (VES) method with the Schlumberger electrode configuration for 25 locations conducted with the maximum current electrode spacing (AB/2) at 300m (Table 1). With this spacing, the expected depth of penetration varied between 100m and 300m due to clay/shale layers acting as membrane to current penetration. Twenty-five (25) VES measurements were made in the study area and quantitative interpretations of the geoelectrical data were made by considering the variations in the apparent resistivity for each electrode separation while the point of interest was kept constant. Master curves were used to obtain the resistivity ( $\rho$ ) and thickness (h) of each geoelectric layer (Zohdy *et al.*, 1974). A data logger was utilized for recording the generated data for future processing and interpretation. WinResist software was utilized for 1D profile modelling, and computer-aid interpretation, which helped in obtaining a better resolution of the thicknesses and resistivities of the different geologic layers (Edet & Okereke, 1997).

**Table 1:** VES locations at Ini LGA

VES No.	Location	Coordinate (°)		Elevation (m)
		N	E	
1	Ikot Atim Ikot Uko- Ubienkene Road	5.34094	7.69525	111.00
2	Nkari	5.35483	7.67888	109.00
3	Nkari 2	5.37588	7.67047	126.00
4	Mbente, Nkari	5.40566	7.65719	104.00
5	Ikot Uko, Nkari	5.40972	7.64269	113.00
6	Itak Ikot Obio Ise	5.31877	7.68025	131.00
7	Ini-Obot Akara boundary	5.31186	7.67052	127.00
8	Mbiabong junction	5.33686	7.69725	142.00
9	Mbiakpa Ibakasi	5.34783	7.72030	105.00
10	Odoro Ikpe	5.35327	7.74088	126.00
11	Nna Enin, Ikpe	5.37433	7.75833	42.00
12	Ikpe Ikot Nkon, by the hospital	5.39908	7.76841	28.00
13	Ogu Itu Mbonuso	5.42963	7.76841	29.00
14	Ogu Itu Mbonuso 2	5.45386	7.74791	47.00
15	Itu Mbonuso	5.48766	7.71469	192.00
16	Ikporom, Itu Mbonuso	5.50038	7.70047	100.00
17	Itu Mbauzo, Abia state	5.48586	7.68380	113.00
18	Mkpu, Itu Mbonuso	5.48905	7.71097	90.00
19	Nchan Ebua	5.48183	7.71361	96.00
20	Nchan Ebua 2	5.48544	7.72141	108.00
21	Ebo	5.46522	7.71008	96.00
22	Itak Ikot Obio Ise 2	5.31877	7.68025	131.00
23	Mbiabet Ikot Udo	5.33736	7.80955	22.00
24	Nkana, Ikpe	5.37505	7.84516	21.00
25	Obot Mme	5.41116	7.84516	47.00

$$T = Kh \quad (3)$$

### 3.1.1 Estimation of aquifer parameters from geophysical data

To complement areas lacking direct boreholes estimates of aquifer parameters, surface resistivity data was deployed based on the principles of electric and groundwater flow. The examined parameters are expressed in the following equations:

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (1)$$

S = Longitudinal conductance (in Siemens),  $h_i$  (m) = thickness of layer and  $\rho_i$  ( $\Omega\text{m}$ ) = apparent resistivity of the aquiferous layer

$$Tr = \sum_{i=1}^n \rho_i h_i \quad (2)$$

Tr = Transverse resistance ( $\Omega\text{m}^2$ ) which is a product of the apparent resistivity and thickness of the aquiferous layer

where T, K, are aquifer transmissivity and hydraulic conductivity. From results of surface resistivity measurements, Dar Zarrouk parameters were computed according to Maillet (1947), Bhattacharya and Patra (1968) and Asfahani (2016) in Equations 1, 2 and 3. A relationship between aquifer transmissivity, transverse resistance and longitudinal conductance has been established (Niwas & Singhal, 1981). Therefore, equations 1, 2 and 3 in Dar Zarrouk parameters can be combined to give equations 4, 5 and 6 (Massoud et al., 2010):

$$T = (K\sigma R) \quad (4)$$

where R = Transverse resistance and  $\sigma$  is water electrical conductivity (Siemens/m or  $\mu\text{S}/\text{cm}$ ).

$$T = \left( \frac{K}{\sigma} \right) C \quad (5)$$

where C= longitudinal conductance and

$$K = \frac{T}{h} \quad (6)$$

In areas of similar geological and water quality characteristics, the product  $K\sigma$  will remain fairly constant (Niwas & Singhal, 1981; Mbonu *et al.*, 1991; Onuoha & Mbazi, 1988; Tizro *et al.*, 2010). Therefore, if K values are known from the pumping test and  $\sigma$  from the resistivity measurements, it is possible to calculate transmissivity and its variations over the entire aquifer.

### 3.1.2 Groundwater reserve estimation

The total amount of groundwater reserve (GR in  $m^3$ ) for the hydrogeological zones was determined as follows (Edet & Okereke, 2014):

$$GR = Atn \quad (7)$$

where A is the area  $m^2$ , t is the saturated thickness of the aquifer obtained from geoelectric sounding and water level measurements in m and n porosity in %.

### 3.2 Geologic and hydrogeologic techniques

A system of geological and hydrogeological investigation was carried out on 7 boreholes in 7 LGA's of northern Akwa Ibom state for the purpose of comparison. Lithological logs were collected to complement the geophysical studies, decipher the aquifer materials and static water levels. Aquifer parameters were determined using geoelectrical results and standard pumping test.

### 3.3 Hydrochemical techniques

Field measurements taken during the study include; geographic coordinates and elevation using the GPS Garmin type 76 kits. The groundwater samples from 10 boreholes labelled SP1-SP10 (Table 2) were analysed for major cations and anions using standard methods for examination of water and wastewaters by APHA (2017). To study the physical, chemical and bacteriological water qualities of the groundwater within the area, to

determine the dominant cations and anions and their influence on the area, compare the results of the study with international specification (NSDWQ, 2007) in order to determine their suitability for domestic, irrigation and industrial use.

#### 3.3.1 Hydrochemical facies

Hydrochemical plots included Piper diagram and Gibbs Cross Plots are used to simulate the hydrochemical processes operating in the groundwater system and shows the relative concentrations of the different ions from the individual samples based on average values for each location within the area of study. It also permits the cations and anion compositions of characterizing the various groundwater types within the area. The Piper's (Piper 1944) trilinear diagram is one of the most common methods for presenting hydrochemical facies (Back & Hanshaw 1965).

#### 3.3.2 Multivariate statistics

Pearson moment correlation analysis and factor analysis was employed to understand the degree of association of the physico-chemical parameters. Correlation describes the size and direction of the linear relationship between two contiguous variables and ranges in value from -1 to +1. When one variable increases as the 2<sup>nd</sup> increases, correlation is positive while if the variables vary in opposite direction correlation is negative (Kalaivani & Krishnaveni, 2015). Factor analysis explains the correlations between sample observations in the field. The technique reduces a large number of variables into smaller dataset without the loss of information (Williams *et al.*, 2010).

### 4.0 Results and discussions

Twenty-five (25) VES measurements and 10 water samplings made in the study area are displayed on the geological map in Fig 2. Table 3 gives a summary of the VES numbers, layer resistivity values, number of layers, thicknesses and depth to aquifer in the study area. Table 4 give the following information about the VES stations: the field name of the station; the

geographical location of each station; the number of geological layers present at the subsurface of each station; the resistivity of these layers; the thickness of each layer, the total depth of each layer from the surface and

the lithology. The VES locations in the study area generally fit 3 layers of A ( $\rho_1 > \rho_2 > \rho_3$ ), K ( $\rho_1 < \rho_2 > \rho_3$ ) and H ( $\rho_1 > \rho_2 < \rho_3$ ) and 4 layers of HK ( $\rho_1 > \rho_2 < \rho_3 > \rho_4$ ) and QH ( $\rho_1 > \rho_2 > \rho_3 < \rho_4$ ) types (Tables 3 & 4).

**Table 2:** Borehole locations and coordinates for water quality analysis in the study area

Sampling point	Location Name	Coordinates		Elevation (M)
		Latitude (N)	Longitude (E)	
SP 1	Etok Nkwot (Filling station)	5.33805	7.71083	124.36
SP 2	Odoro Ikpe	5.38277	7.76472	84.14
SP 3	Asanting Utit Ikpe	5.35666	7.74388	89.00
SP 4	Itak	5.31694	7.705	117.96
SP 5	Mbiabong Ik. Udofia	5.32277	7.68833	130.15
SP 6	Etok Nkwot <sub>2</sub>	5.33861	7.70583	120.09
SP 7	Nsit Ikpe <sub>1</sub>	5.36694	7.73638	99.97
SP 8	Nsit Ikpe <sub>2</sub>	5.37166	7.71805	101.19
SP 9	Ananamong Itu Mbunuso	5.47027	7.72111	93.88
SP 10	Ikot Essien Itu Mbunuso	5.47027	7.72916	100.88

#### 4.1 Hydrogeoelectrical layers

The 3-layer geoelectric model is characterized by VES locations 2, 4, 5, 7, 10, 13, 14, 18, 19, 21, 22, 23, 24 and 25 in the study area (Tables 3 & 4). The top layer with resistivity ranging from 139.8 (VES 4) to 974.20  $\Omega\text{m}$  (VES 7). This layer represents unsaturated overburden composed of fine-medium grained, clayey, silty, lateritic sand. The thickness of this layer varied between 1.4 (VES 22) and 12.4 m (VES 18) and does not constitute any water bearing medium. Underlying this layer is the first aquiferous layer with resistivity values in the range of 9 (VES 22) to 3023.3  $\Omega\text{m}$  (VES 10) with thicknesses in the range 35.6 (VES 14) to 100.5 m (VES 13). Lithologically, this layer represents silty, clayey, gravelly, fine-coarse sand and gravels. Within this layer are some conductive zones. Underlying the first

aquiferous layer is the second aquifer with resistivity in the range 25.8 (VES 23) to 2006.4  $\Omega\text{m}$  (VES 4) and unresolved thickness. The

layer is composed of clayey, silty fine-coarse sand.

The 4 - layer geoelectric models were encountered at VES locations 1, 3, 6, 8, 9, 11, 12, 15, 16, 17 and 20 in the study area (Tables 3 & 4). The first layer reveals top soil composed of dry loose silty, sandy, clayey, gravelly materials with thickness and resistivity in the range 0.6 to 3.6 m and 180.1 to 2107  $\Omega\text{m}$  and is of no hydrogeologic significance. The top layer is underlain by slightly conductive layer with resistivity and thickness in the range 23.4 to 1274.6  $\Omega\text{m}$  and 3.2 to 54.1 m constituting the first aquifer. Lithological data showed that the layer is composed of clayey, silty, gravelly saturated sand. The second layer is followed by a conductive layer with resistivity and thickness of 258.6 – 2666.4  $\Omega\text{m}$  and 43.6 – 82.7 m and is composed of saturated clayey, silty, sand and constitutes the second aquifer in the study area. The fourth layer with unresolved thickness had resistivity values in the range 19.3 – 2358.9  $\Omega\text{m}$  and constitutes the third aquifer which is not currently exploited and is composed of gravelly, silty, clayey sand.

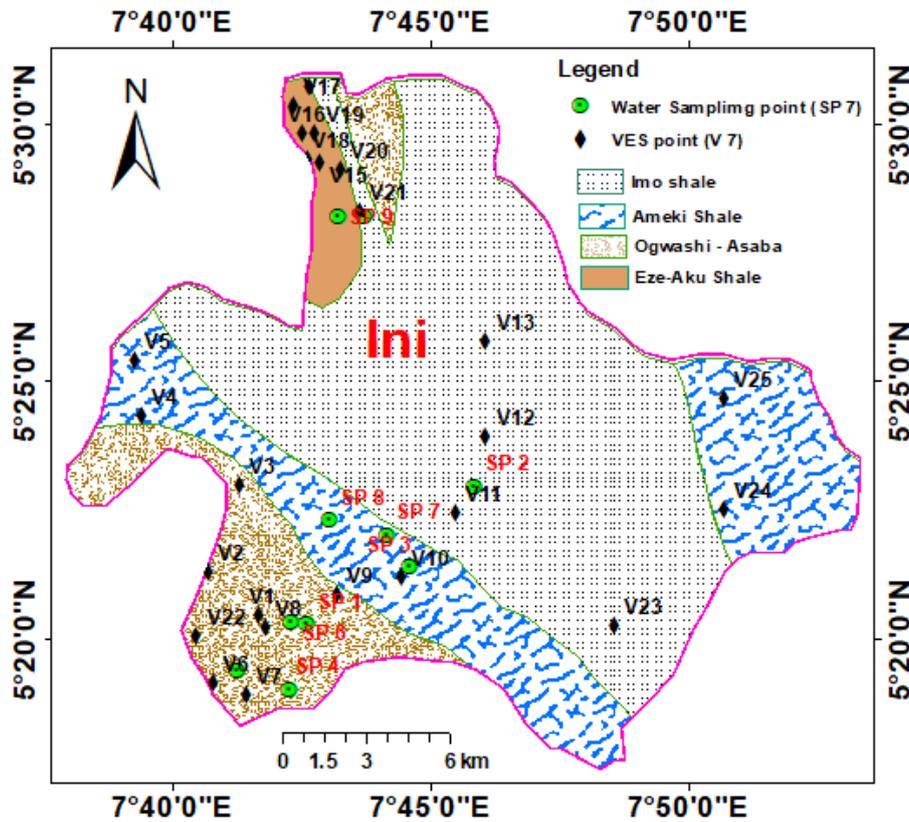


Fig. 2: Geological map of study area showing the 25 VES points and 10 water sampling points

Table 3: Goelectrical layer of apparent resistivity and thickness from interpretation of goelectrical sounding for the study area

VES No.	No. of Layers	Curve Type	Layer Resistivity ( $\Omega\text{m}$ )				Layer Thickness (m)			Layer Depth (m)		
			$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	$h_1$	$h_2$	$h_3$	$d_1$	$d_2$	$d_3$
1	4	HK	209.1	23.4	394.3	19.3	2.6	9.3	43.6	2.6	11.9	55.6
2	3	K	335.7	2099.0	1325.2		4.2	94.6		4.2	98.8	
3	4	KH	1346.9	1811.4	970.5	2358.9	2.0	35.8	59.2	2.0	37.8	97.0
4	3	A	139.8	1077.6	2006.4		6.4	82.8		6.4	89.2	
5	3	K	147.9	1671.2	726.1		5.9	95.9		5.9	101.7	
6	4	QH	1504.5	1124.7	277.9	612.4	2.3	54.1	49.8	2.3	56.4	106.2
7	3	K	692.7	2368.1	1462.7		7.3	85.8		7.3	93.1	
8	4	HK	614.9	154.1	2055.8	723.9	1.1	9.1	81.2	1.1	10.2	91.4
9	4	HK	691.6	322.4	1962.1	514.4	1.3	7.4	82.7	1.3	8.8	91.5
10	3	K	200.1	3023.3	709.6		2.1	82.3		2.1	84.4	
11	4	HK	2107.9	160.5	708.7	222.1	2.0	12.3	76.9	2.0	14.3	91.2
12	4	HK	802.1	144.6	557.2	121.6	2.3	11.6	69.0	2.3	13.9	83.0
13	3	H	521.7	107.8	566.6		3.2	100.5		3.2	103.7	
14	3	H	212.1	25.8	467.0		1.7	35.6		1.7	37.3	
15	4	HK	1794.9	318.3	1584.1	512.8	3.0	30.0	70.4	3.0	33.0	103.4
16	4	HK	1556.6	204.8	678.8	195.1	1.7	7.9	80.0	1.7	9.5	89.5
17	4	KH	180.1	750.1	258.6	694.3	0.6	3.2	81.2	0.6	3.8	85.0
18	3	K	682.2	2817.8	1282.0		12.4	77.2		12.4	89.6	
19	3	K	644.5	2437.8	1123.7		3.9	94.2		3.9	98.2	
20	4	HK	1746.7	1274.6	2666.4	617.6	3.6	18.4	60.0	3.6	22.1	82.0
21	3	H	240.3	39.7	869.5		2.0	77.2		2.0	79.2	
22	3	H	143.3	9.0	255.3		1.4	37.1		1.4	38.5	
23	3	K	974.2	2471.6	25.8		1.8	70.0		1.8	71.8	
24	3	K	899.1	1467.0	372.3		2.4	46.9		2.4	49.3	
25	3	H	198.4	28.1	470.9		2.9	51.0		2.9	53.9	
<b>Minimum</b>			<b>139.80</b>	<b>9.00</b>	<b>25.80</b>	<b>19.30</b>	<b>0.60</b>	<b>3.20</b>	<b>43.60</b>	<b>0.60</b>	<b>3.80</b>	<b>55.60</b>
<b>Maximum</b>			<b>2107.90</b>	<b>3023.30</b>	<b>2666.40</b>	<b>2358.90</b>	<b>12.40</b>	<b>100.50</b>	<b>82.70</b>	<b>12.40</b>	<b>103.70</b>	<b>106.20</b>

Mean	743.49	1037.31	951.10	599.31	3.20	49.21	68.55	3.20	52.42	88.71
Standard Deviation	603.948	1711.485	682.367	632.945	2.528	34.076	13.635	2.528	35.497	13.416

**Table 4:** VES summary with number of layers and lithology of the study area

VES No.	No. of Layers	Curve Type	Resistivity ( $\Omega\text{m}$ )	Thickness (m)	Depth (m)	Lithology
1	4	HK	209.1	2.6	2.6	Top soil
			23.4	9.3	11.9	Shale Formation
			394.3	43.6	55.6	Fine grained sand with minor clay intercalation
			19.3			Shale Formation
2	3	K	335.7	4.2	4.2	Top soil
			2099.0	94.6	98.8	Compacted lateritic sand
			1325.2			Coarse grained sand
3	4	KH	1346.9	2.0	2.0	Top soil
			1811.4	35.8	37.8	Compacted lateritic sand
			970.5	59.2	97.0	Fine sand
			2358.9			Gravelly sand
4	3	A	139.8	6.4	6.4	Top soil
			1077.6	82.8	89.2	Coarse grained sand
			2006.4			Gravelly sand
5	3	K	147.9	5.9	5.9	Top soil
			1671.2	95.9	101.7	Compacted lateritic sand
			726.1			Fine sand
6	4	QH	1504.5	2.3	2.3	Top soil
			1124.7	54.1	56.4	Coarse grained sand
			277.9	49.8	106.2	Fine grained sand with minor shale intercalation
			612.4			Poorly sorted medium grained sand
7	3	K	692.7	7.3	7.3	Top soil
						Conglomerate of small, medium and coarse-grained sand with pebble intercalations
			2368.1	85.8	93.1	Gravelly sand
			1462.7			Gravelly sand
8	4	HK	614.9	1.1	1.1	Top soil
			154.1	9.1	10.2	Clayey sand
			2055.8	81.2	91.4	Gravelly sand
			723.9			Fine sand
9	4	HK	691.6	1.3	1.3	Top soil
			322.4	7.4	8.8	Sandy clay
			1962.1	82.7	91.5	Gravelly sand
			514.4			Fine grained sand with minor clay intercalations
10	3	K	200.1	2.1	2.1	Top soil
			3023.3	82.3	84.4	Gravelly sand
			709.6			Fine sand
11	4	HK	2107.9	2.0	2.0	Top soil
			160.5	12.3	14.3	Clayey sand
						Conglomerate of small, medium and coarse-grained sand with pebble intercalations
			708.7	76.9	91.2	Shale Formation
12	4	HK	802.1	2.3	2.3	Top soil
			144.6	11.6	13.9	Clayey sand
						Conglomerate of small, medium and coarse-grained sand with pebble intercalations
			557.2	69.0	83.0	Shale Formation
13	3	H	521.7	3.2	3.2	Weathered siltstone
						Conglomerate of small, medium and coarse-grained sand with pebble intercalations
			107.8	100.5	103.7	Shale Formation
14	3	H	212.1	1.7	1.7	Weathered siltstone
			25.8	35.6	37.3	Shale Formation
			467.0			Fine grained sand with minor clay intercalations

15	4	HK	1794.9	3.0	3.0	Weathered siltstone
			318.3	30.0	33.0	Sandstones
			1584.1	70.4	103.4	Gravelly sand
			512.8			Fine grained sand with minor clay intercalations
16	4	HK	1556.6	1.7	1.7	Top soil
			204.8	7.9	9.5	Small to medium grained sands
			678.8	80.0	89.5	Fine grained sand with clay intercalations
			195.1			Shale Formation
17	4	KH	180.1	0.6	0.6	Top soil
			750.1	3.2	3.8	Sandstones
			258.6	81.2	85.0	Sandy clay
			694.3			Fine grained sand with minor clay intercalations
18	3	K	682.2	12.4	12.4	Motley top soil
			2817.8	77.2	89.6	Gravelly sand
			1282.0			Saturated small to medium grained sand
19	3	K	644.5	3.9	3.9	Top soil
			2437.8	94.2	98.2	Gravelly sand
			1123.7			Saturated small to medium grained sand
20	4	HK	1746.7	3.6	3.6	Weathered sandstones
			1274.6	18.4	22.1	Mudstones
			2666.4	60.0	82.0	Gravelly sand
			617.6			Saturated medium to large grained sand
21	3	H	240.3	2.0	2.0	Top soil
			39.7	77.2	79.2	Shale Formation
			869.5			Fine grained sand
22	3	H	143.3	1.4	1.4	Top soil
			9.0	37.1	38.5	Shale Formation
			255.3			Sandy clay
23	3	K	974.2	1.8	1.8	Top soil
			2471.6	70.0	71.8	Gravelly sand
			25.8			Shale Formation
24	3	K	899.1	2.4	2.4	Top soil
			1467.0	46.9	49.3	Gravelly sand
			372.3			
25	3	H	198.4	2.9	2.9	Top soil
			28.1	51.0	53.9	Shale Formation
			470.9			Fine grained sand with minor clay intercalations

#### 4.1.1 Interpretation of representative geoelectric curves

For VES 6, Four (4) lithological units were interpreted in Fig. 3a. They include poorly sorted top soil (layers 1) which is about 2.3m thick, followed by 54.1m thick coarse grained sands (layer 2). This is followed by a layer of Fine grained sand with minor shale intercalations (3) which is about 49.8m in thickness. Layers 2 and 3 constitute the major aquifers in the area and lies between 56.4m (shallow) and 106.2m -  $\approx$  (medium). Curve is QH type (Fig. 3a).

For VES 9, four (4) lithological units were interpreted from the geophysical survey plot in Fig. 3b; They include wet lateritic top soil (layers 1) which is about 1.3m thick, followed by 7.4m thick of sandy clays (2). The underlying layers (3 and 4) consist of gravelly sands (82.7m) and and fine grained sand with minor clay intercalation respectively. Layer 3 constitutes the major aquifer in the area from a depth of 91.5m and it is an unconfined aquifer. Curve is HK type (Fig. 3b).

For VES 17, four (4) lithological units were interpreted from the geophysical survey plot in Fig. 3c; They include top soil (layer 1) of 0.6m, sandstones (layers 2) which is about 3.2m thick, followed by 81.2m thick of sandy clay (3). The underlying layers (4) consist of fine-grained sand with minor clay intercalation. Layer 4 hosts the aquifer unit is suitable for a mini water borehole that should be screened at 110m. Curve is KH type (Fig. 3c).

For VES 20, four (4) lithological units were interpreted from the geophysical plot in Fig. 3d They include weathered sandstone (layers 1) which is about 3.6m thick, followed by 18.4m thick mud stone (layer 2) and 60m of gravelly

sands (layer 3). The underlying layer 4 consists of saturated medium to large grained sand and constitutes the major aquifers from depth of 82m. Curve is HK type (Fig. 3d).

#### 4.1.2 Hydrogeoelectrical profiles

A north-south cross section was taken through VES locations 15, 9, 8, 7 and 19, where 3 layers were demarcated in the south and four layers in the north (Fig. 4). The top layer (A) with resistivity in the range 614.9 (VES 8) to 175.9  $\Omega\text{m}$  (VES 15) represents the top soil (fine-coarse grained clayey, silty sand) with no hydrogeologic significance. Underlying this layer is a conductive layer ( $B_1$ ) at VES 15, VES 9 and VES 8 in the north and resistivity layer ( $B_2$ ) at VES 7 and VES 19 in the south which does not hold any prospect for groundwater at VES 15, VES 9 and VES 8 due relatively shallow depth (7.4 – 30m) and composed of clayey fine sands. The layer at VES 7 and VES 19 with thicknesses in the range 85.8 – 94.2m is composed of medium-coarse gravelly sand constitutes the first aquifer in the southern parts of the study area. The third layer (C) has resistivity in the range 1123.7 (VES 19) and 2055.8  $\Omega\text{m}$  at VES 8 is composed of medium-coarse sands and constitute the first aquifer in the north and second aquifer in the area. Below the aquiferous layer (C), is a fairly conductive layer (D) at VES 15, VES 9 and VES 8. The values of resistivity for this layer varies between 512.8 (VES 15) and 723.9  $\Omega\text{m}$  at VES 8. Depth to top of this layer vary from 91.4 (VES 8) to 103.4 m at VES 15. Since no drilling has been recorded in this layer (D), the inferred materials of this layer are fine-medium sand and constitute the second aquifer in the north.

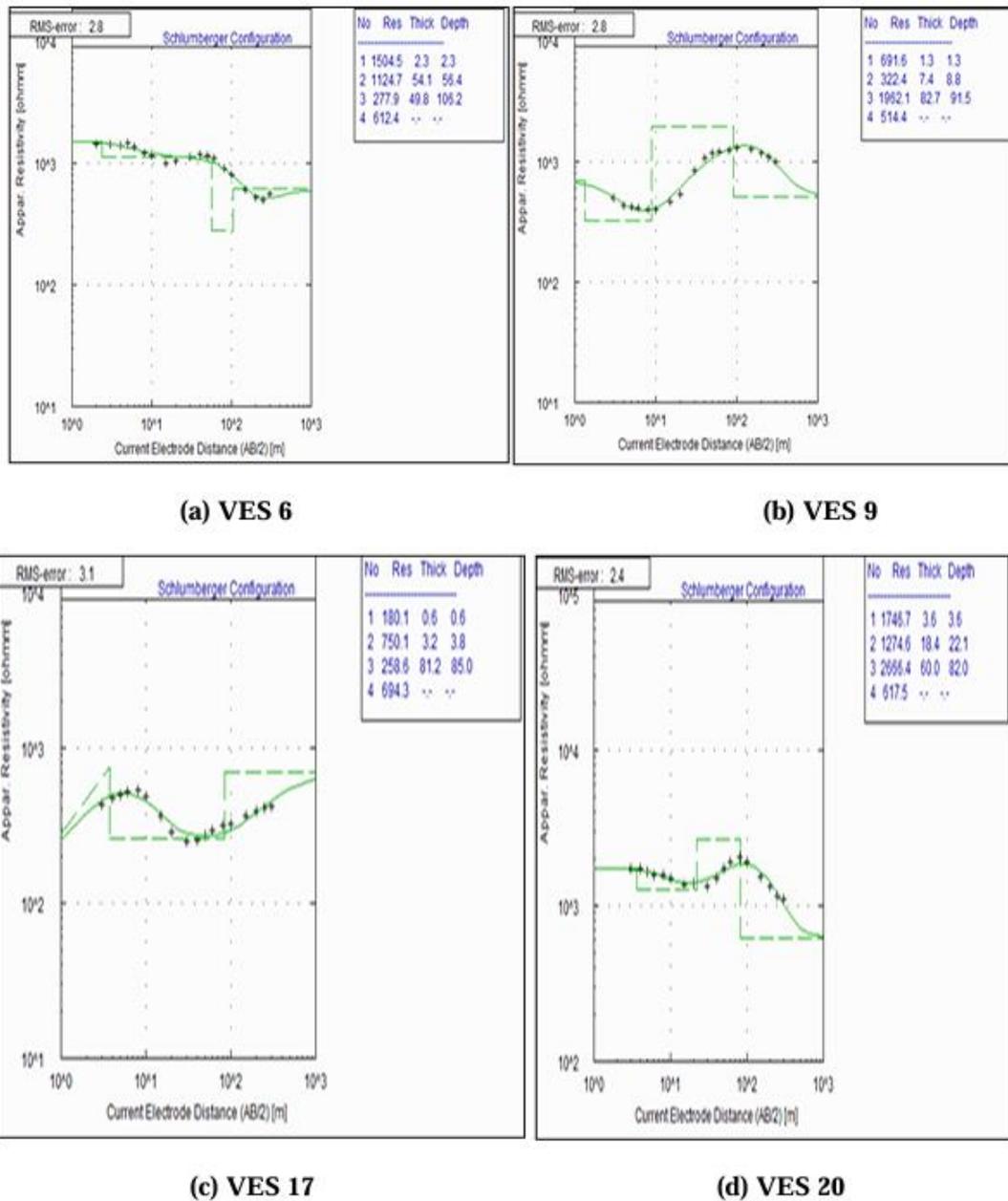


Fig. 3: Profile illustrating four selected interpreted 1D models of (a) VES 6, (b) VES 9, (c) VES 17, (d) VES 20 of the VES data in the study area

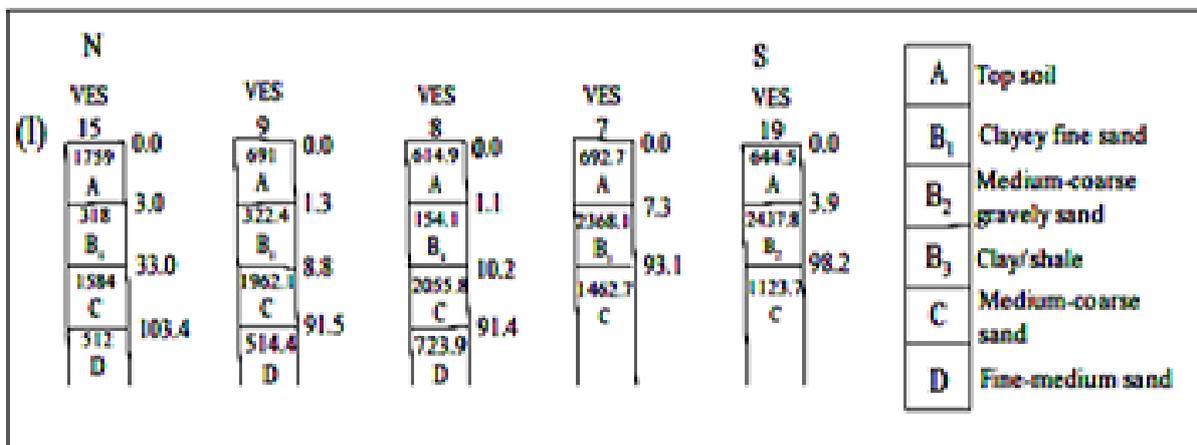


Fig. 4: Hydrogeoelectrical section of study area

### 4.1.3 Hydrogeoelectrical models

A proposed hydrogeoelectrical model for the area is presented in Table 5.

### 4.2 Hydrostratigraphy

Lithologically, this group consists of alternating clays, lateritic clays, sandy clays, fine to coarse sands, clayey sands, clayey gravels, lignite, and shales (Ikot Abia IN1, Mbio Oku Ikot-Odung IN2, Itan Idoro IN3, Ndiya Etok IN4 and Mbiabet Ikot Efa IN5). The clay horizons and lenses disturb the vertical and lateral continuity of aquifers and locally produce multi-aquifer systems (Fig. 5). The identification of hydrostratigraphic units in this group (6) is very complicated due to the distribution of different types of sediments. In the delimitation of

hydrostratigraphic units, lithologic, geophysical and hydraulic data are used. The thickness of the saturated zone varies from 6m to 200m. Depth to the top of the saturated zone varies between 2m at Mbio Oku Ikot Edung (IN2) to about 190m at Mbiabet Ikot Abia (IN1). The saturated thickness depends on mainly be seasonal fluctuations and rate of withdrawal. The static water level, SWL varies between 20m at Odoro Ikpe (IN4) to 47m at Ndiya Etok (IN5). The mean value of 5 locations is about 122.35 m (Table 6). Pumping and static water level tests were conducted in 7 LGA's in northern Akwa Ibom state (Fig. 6) and available relevant data are used for a comparative analysis presented in Table 7.

**Table 5:** Hydrogeoelectrical model for the study area

Model	Layer	Resistivity ( $\Omega\text{m}$ )	Thickness (m)	Description	Aquifer
3 Layer	1	139.8 - 974.2	1.4 - 6.4	Overburden, unsaturated (fine-medium grained, clayey, silty, lateritic sand)	
	2	9.0 - 3023.3	35.6 - 100.5	Fine-coarse/gravelly sand silty, clayey	1
	3	25.8 - 2006.4		Fine-coarse sand, clayey	2
4 Layer	1	180.1 - 2107.9	0.6 - 3.6	Overburden, unsaturated (fine-medium-coarse grained, clayey, silty, lateritic sand)	
	2	23.4 - 1274.6	3.2 - 54.1	Fine-medium sand silty, clayey	1
	3	258.6 - 2666.4	43.6 - 82.7	Fine-medium-coarse grained sand silty	2
	4	19.3 - 2358.9		Fine-medium-coarse grained sand gravelly, clayey, silty	3

**Table 6:** Well locations for hydrostratigraphic sections in the study area

Code	LGA	Location	Elevation (m)	SWL (m)
IN1	Ini	Mbiabet Ikot Abia	100.00	46.00
IN2		Mbio Oku Ikot Edung	105.00	46.00
IN3		Itan Idoro	110.00	43.00
IN4		Ndiya Etok	120.00	20.00
IN5		Mbiabet Ikot Efa	107.00	47.00
<b>Statistics</b>	<b>Ini</b>	<b>Min</b>	<b>83.00</b>	<b>20.00</b>
		<b>Max</b>	<b>225.40</b>	<b>47.00</b>
		<b>Mean</b>	<b>122.35</b>	<b>40.40</b>
		<b>SD</b>	<b>7.43</b>	<b>11.50</b>

### 4.2.1 Aquifer parameters

Pumping and static water level tests were conducted in 7 LGA's in northern Akwa Ibom

state, including the study area (Fig. 6). All the boreholes are located in the northern part of the state noted for its complex geology regarding

groundwater availability. The justification for the comparison is based on the heterogeneity of the formations located therein and used to

identify those areas with favourable aquifer parameters.

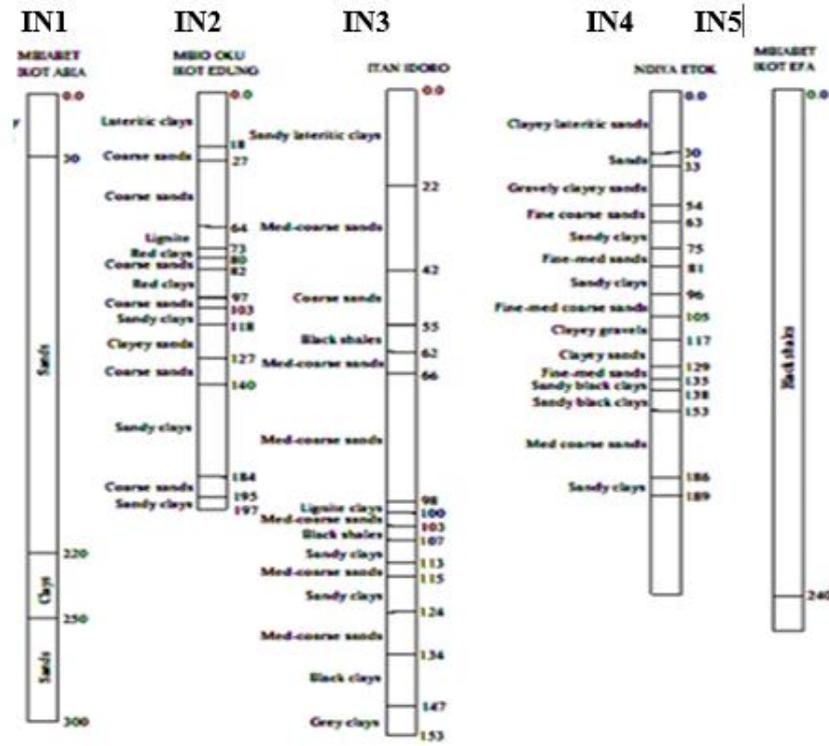


Fig. 5: Hydrostratigraphic section through parts of the study area

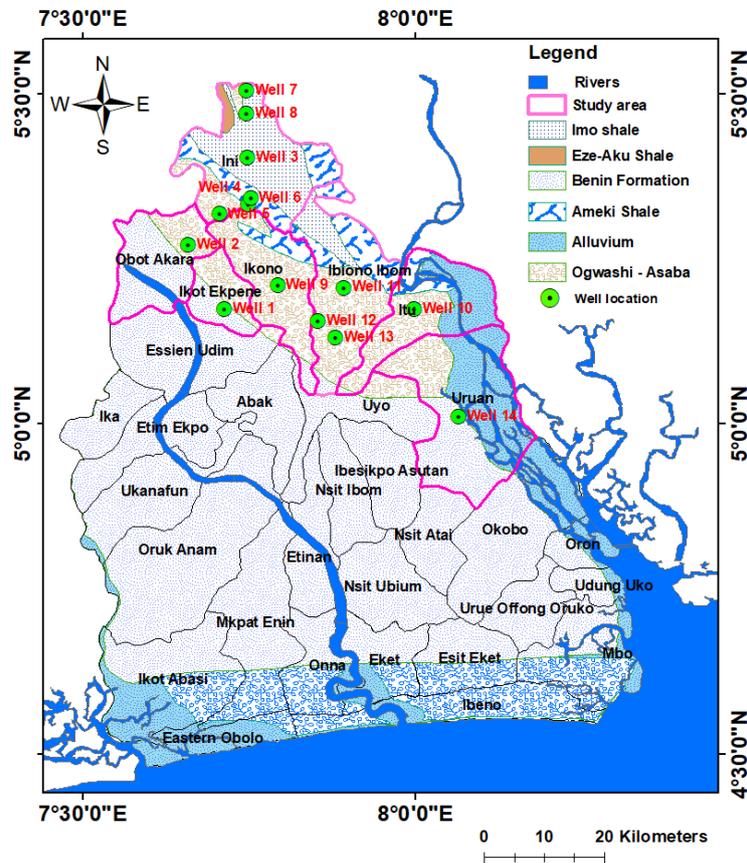


Fig. 6: Geological map of Akwa Ibom State showing 7 LGA's sites in northern Akwa Ibom state for pumping and static water level tests

**Table 7:** Aquifer parameters based on pumping test for the study area and environs

LGA	Code	Lat N (°)	Long E (°)	Static water level (m)	Discharge (Q) (m <sup>3</sup> /day)	Drainage density (DD) (m)	Transmissivity (T) (m <sup>2</sup> /day)	Hydraulic conductivity(K) (m/day)	Specific capacity (SC) (m <sup>3</sup> /day/m)	Storativity (S)
<b>Ikot Ekpene</b>	Well-1	5.1744	7.7145	10.62	259.68	9.57	323.40	2.53	48.51	0.003893
<b>Obot Akara</b>	Well-2	5.2712	7.6599	19.26	1171.20	2.95	126.74	9.95	38.98	0.002721
<b>Ini</b>	Well-3	5.4042	7.7488	15.98	1039.20	5.09	79.27	0.78	47.04	0.008289
<b>Ikono</b>	Well-4	5.2104	7.7940	13.98	443.76	6.13	477.00	18.20	44.85	0.003574
<b>Itu</b>	Well-5	5.1738	7.9991	7.34	414.48	7.38	484.53	5.25	30.30	0.002817
<b>Ibiono Ibom</b>	Well-6	5.2070	7.8931	7.34	416.16	11.99	413.78	13.28	46.17	0.005432
<b>Uruan</b>	Well-7	5.0110	8.0660	15.62	519.60	1.65	248.07	3.78	16.94	0.009869

Table 8 presents the values of aquifer transverse resistance (R) and aquifer longitudinal conductance (C) computed from equations 1 and 2 and T from equations 3, and 5. The parameter  $K\sigma$  which is constant for the aquifer was estimated for well locations well-3. This was combined with transverse resistance

values from other locations without pumping test data to determine the hydraulic conductivity and transmissivity of the aquifer. The hydraulic conductivity, K values averaged 0.78 m/day and the transmissivity values in the range of 23.4 – 66.92 m<sup>2</sup>/day (average 49.60 m<sup>2</sup>/day) for the study area.

**Table 8:** Estimated aquifer parameters obtained from VES data for the study area

No	Parameter/location	Ini							
	VES No	3	3	7	8	9	15	15	
	Aquifer No	1	2	1	1	1	1	2	
1	average field hydraulic conductivity, K (m/day)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
2	transmissivity (m <sup>2</sup> /day)	79.27	79.27	79.27	79.27	79.27	79.27	79.27	79.27
3	aquifer resistivity, $\rho_a$ ( $\Omega$ m)	1811.4	970.5	2368.0	2055.8	1962.1	318.0	1584.0	
4	aquifer thickness, t (m)	35.80	59.20	85.80	81.20	82.70	30.00	70.40	
5	aquifer longitudinal conductance, C ( $\Omega^{-1}$ )	0.02	0.06	0.04	0.04	0.04	0.09	0.04	
6	aquifer transverse resistance, R ( $\Omega$ m <sup>2</sup> )	64848.12	57453.6	203174.4	166931	162265.7	9540	111513.6	
7	$\sigma = 1/\rho$ (Siemens per metre (S/m))	0.001	0.001	0.000	0.000	0.001	0.003	0.001	
8	K/ $\sigma$ value (m <sup>2</sup> day <sup>-1</sup> S <sup>-1</sup> )	1412.892	756.99	1847.04	1603.524	1530.438	248.04	1235.52	
9	$K\sigma$ (Siemens per day (Sday <sup>-1</sup> ))	0.000	0.001	0.000	0.000	0.000	0.002	0.000	
10	transmissivity of aquifer, T (m <sup>2</sup> /day)	27.924	46.176	66.924	63.336	64.506	23.4	54.912	
11	hydraulic conductivity of aquifer K (m/day)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78

Remarks:  $\sigma$  electrical conductivity (Siemens/m)

#### 4.2.2 Static water level and groundwater flow direction

The elevation of water level ranged between 17.80 m above mean sea level (amsl) and 108.2 with mean of 66.10±39.06 m in the study area. Average recorded SWL values for Ini was

30.74±21.66 (Table 9). Limited static water level (SWL) data from Well-4, 5, 6, 7 and 8 in the study area in Fig. 6 shows that, the SWL varied between 20 and 48 m with mean of 40.84±11.71 m. Absolute water level (AWL)

varied between 35 and 100 m with a mean of  $63.16 \pm 23.65$  for the study area (Table 9).

**Table 9:** Static water level from pumping tests on boreholes in the study area

Code	Location	Coordinates		Elevation (m)	SWL (m)	AWL (m)
		Lat (N)	Long (E)			
Well-4	Ibam Edet	5.333611	7.750278	100.00	46.00	54.00
Well-5	Iton Idoro	5.319	7.707	110.00	45.20	64.80
Well-6	Odoro Ikpe	5.34225	7.753806	120.00	20.00	100.00
Well-7	Ikpe Ikot Nkon Ibiaku Ntok	5.505	7.748	107.00	45.00	62.00
Well-8	Okpo	5.470028	7.747417	83.00	48.00	35.00
Statistics	Min			<b>83.00</b>	<b>20.00</b>	<b>35.00</b>
	Max			<b>120.00</b>	<b>48.00</b>	<b>100.00</b>
	Mean			<b>104.00</b>	<b>40.84</b>	<b>63.16</b>
	SD			<b>13.77</b>	<b>11.71</b>	<b>23.65</b>

Elevation of water level ranged from 20.10 m to 136.50 m with a mean of  $92.72 \pm 47.11$ , SWL values ranged from 2.30 m to 47.00 m with a mean of  $37.46 \pm 19.7$ , AWL value ranged from 17.80 m to 89.50 m and a mean of  $55.26 \pm$

31.17 for the study area (Table 10). The regional groundwater flow direction obtained from 5 wells as shown in Fig. 7 is from West to East in the study area. The flow is from area of high elevation towards the lowest elevation point at GFA1 which acts as a sink.

**Table 10:** Well data for regional groundwater flow direction in the study area

Code	Location	Longitude	Latitude	Elevation (m)	SWL (m)	AWL (m)
GFA1	Ikpe Ikot Nkan	7.8006	5.4003	20.10	2.30	17.80
GFA2	Ibiaku Ntok Okpo	7.7475	5.4669	130.00	47.00	83.00
GFA3	Ibam Edet	7.9002	5.3336	100.00	46.00	54.00
GFA4	Ikot Udofia	7.6836	5.3336	136.50	47.00	89.50
GFA5	Nko	7.7669	5.2836	77.00	45.00	32.00
Statistics	Min			<b>20.10</b>	<b>2.30</b>	<b>17.80</b>
	Max			<b>136.50</b>	<b>47.00</b>	<b>89.50</b>
	Mean			<b>92.72</b>	<b>37.46</b>	<b>55.26</b>
	SD			<b>47.11</b>	<b>19.67</b>	<b>31.17</b>

#### 4.2.3 Groundwater reserve estimation

With an estimated area of 514,080,000 m<sup>2</sup> for the study area and an average porosity of 35% (Freeze & Cherry, 2010) the groundwater reserves varied between  $575.00 \times 10^6$  and  $18082 \times 10^6$  m<sup>3</sup> for the study area. This suggest enormous amount of groundwater that can be sustainably developed, especially for the rural residents.

#### 4.2.4 Groundwater quality for drinking

The univariate statistical summary values of the physicochemical and microbiological parameters and heavy metals of groundwater resources in the study area are compared with those of the WHO (2006) in Table 11. The standard deviation (SD) exhibited low variations (< 5) in all the parameters indicating that the water might not have been affected by different hydrochemical processes. The

physicochemical parameters and heavy metals limits (MAL) of WHO (2006) in Table 11. in the water are below the maximum admissible

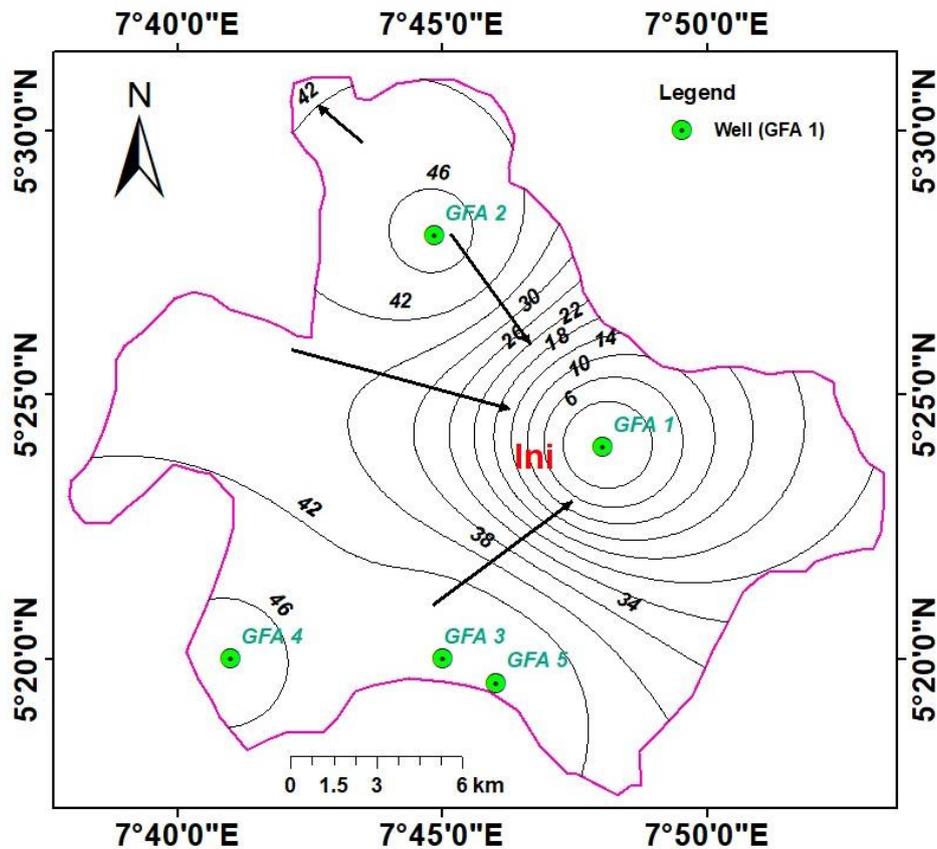


Fig. 7: Contour map showing groundwater flow direction in the study area

The mean values of groundwater temperature were  $29.25 \pm 0.3$  and fall within the ambient temperature levels of 22 to 29°C (Stumm & Morgan, 1981). The mean pH values of groundwater were found to be  $4.9 \pm 1.1$  falls within 6 to 8 range of pH in natural water (Thakre et al., 2010) and is classed as slightly acidic ( $\text{pH} < 6$ ). Electrical conductivity (EC) is a measure of total dissolved solids (TDS), and dissolved salts in water and general quality of water had mean values of  $163.14 \pm 0.77$   $\mu\text{S}/\text{cm}$ . The mean values (in mg/L) of TDS were  $79.05 \pm 3.62$ . EC and TDS values were below the maximum admissible limit (MAL) of 1500  $\mu\text{S}/\text{cm}$  and 1000 mg/L. The mean value of total hardness (TH) was  $83.56 \pm 1.98$  and on the basis of TH ( $< 500$  mg/L) all the water samples are soft and suitable for drinking and domestic use. Sodium and Potassium occur naturally in water

due to seawater intrusion (Edet, 2021; Edet & Okereke, 2001, 2022) and silicate weathering (Edet, 2018).

The mean concentration of sodium (mg/L) was  $6.65 \pm 0.39$  and of potassium  $3.58 \pm 0.23$ . The concentrations of sodium and potassium were found to be within the MAL of 200 and 12 mg/L. Average concentration of  $\text{Ca}^{2+}$  (in mg/L) was  $16.80 \pm 0.74$  and of  $\text{Mg}^{2+}$  was  $11.29 \pm 1.19$  and were found to be within the MAL of 75 and 150 mg/L. Chloride occurs naturally in water of all types and elevated concentration could be due to runoff of inorganic fertilizer, sewage discharge (Lkr et al. 2020), sea water intrusion (Edet & Okereke 2001, Edet, 2021) and halite dissolution (Edet and Okereke 2002). The average concentration of  $\text{Cl}^-$  was  $18.49 \pm 0.93$  mg/L and was below the MAL of 250 mg/L. The average concentrations of bicarbonate

recorded was  $8.58 \pm 0.63$  mg/L and found to be within the MAL of 600 mg/L. Sulphate occurs naturally in water due to weathering of country rock, leachate, air deposition and industrial waste water (Lkr *et al.*, 2020).

The mean concentration (in mg/L) of  $\text{SO}_4^{2-}$  recorded in the different water types was  $12.36 \pm 0.77$  and were within MAL value of 250 mg/L. Nitrate is found in water as a result of fertilizer runoff and waste disposal and ingestion of water with high nitrate may results in high risk of methemoglobinemia (Mukherjee & Singh, 2021, 2022; Etesin *et al.*, 2023). The

average concentration (in mg/L) of nitrate was  $4.39 \pm 0.44$  and was below the MAL of 45 mg/L. The concentration of coliform in groundwater averaged  $0.02 \pm 0.03$  cfu/ml are within the WHO MAL of 0.00 cfu/ml, however, 40% of the groundwater samples were not within this limit in the study area. Fe concentration ( $\mu\text{g/L}$ ) averaged  $1.66 \pm 0.39$ , higher than MAL of 0.37 mg/L, which attributable to natural geogenic sources. Mn concentration averaged  $2.81 \pm 0.47$  and all samples had higher concentration than MAL of 0.2 mg/L, which attributable to natural geogenic sources.

**Table 11:** Statistical summary of the physicochemical parameters and heavy metals for groundwater in study area

Parameter	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6	SP 7	SP 8	SP 9	SP 10	Min	Max	Mean	SD	WHO (2011)
Temp ( $^{\circ}\text{C}$ )	29.4	29	28.9	29.6	29.3	29.1	29.5	29.7	29.2	28.8	28.80	29.70	29.25	0.30	-
pH	6.7	7.1	6.6	6.9	7.6	7	6.1	7.3	6.8	7.5	6.10	7.60	6.96	0.45	6.5-8.5
EC ( $\mu\text{S/cm}$ )	163.7	161.5	162.7	162.5	163.3	164.1	163.2	163.9	162.9	163.6	161.50	164.10	163.14	0.77	1500
TDS (mg/L)	77.4	76.5	77.2	78.1	79.2	80.1	72.3	82.5	85.1	82.1	72.30	85.10	79.05	3.62	1000
Total Hardness (mg/L)	83.3	82.5	86.1	80.5	81.3	85.3	86.5	82.7	84.3	83.1	80.50	86.50	83.56	1.98	500
$\text{Na}^+$ (mg/L)	6.6	6.7	7.1	6.3	6.9	7.3	6.1	6.5	6.8	6.2	6.10	7.30	6.65	0.39	200
$\text{K}^+$ (mg/L)	3.65	3.53	3.74	3.15	3.82	3.23	3.81	3.71	3.61	3.58	3.15	3.82	3.58	0.23	12
$\text{Ca}^{2+}$ (mg/L)	16.8	15.9	17.5	16.1	17.4	17.9	16.3	16.5	17.6	16	15.90	17.90	16.80	0.74	75
$\text{Mg}^{2+}$ (mg/L)	10.06	12.5	10.01	11.07	13.15	11.34	10.5	9.87	12.67	11.71	9.87	13.15	11.29	1.19	150
$\text{Cl}^-$ (mg/L)	18.6	19.2	17.5	18.7	18.9	19.8	17.3	17.1	18.3	19.5	17.10	19.80	18.49	0.93	250
$\text{HCO}_3^-$ (mg/L)	8.8	7.9	8.75	8.2	9.25	9.58	8.13	9.03	7.56	8.57	7.56	9.58	8.58	0.63	600
$\text{SO}_4^{2-}$ (mg/L)	12.9	11.8	13.1	12.3	11.3	12.6	13.7	11.3	12.5	12.1	11.30	13.70	12.36	0.77	250
$\text{NO}_3^-$ (mg/L)	4.51	3.78	4.65	4.87	3.98	4.24	4.18	5.23	4.47	4.03	3.78	5.23	4.39	0.44	50
Fe (mg/L)	1.2	1.76	1.95	1.57	2.02	1.13	1.38	2.36	1.42	1.84	1.13	2.36	1.66	0.39	0.3
Mn (mg/L)	2.61	3.12	2.23	2.17	3.58	2.93	2.48	2.81	3.42	2.71	2.17	3.58	2.81	0.47	0.2
Coliform (cfu/ml)	0	0.01	0.06	0.03	0	0	0.08	0	0	0	0.00	0.08	0.02	0.03	10

#### 4.2.5 Groundwater quality for irrigation

The summary statistics of irrigation indices and suitability for irrigation are given in Tables 12 and 13 respectively.

##### Electrical conductivity

Electrical conductivity (EC) is often used to assess the salinity of water (Massoud *et al.*, 2022). The values for the study area varied as follows: 161.50 and 164.10  $\mu\text{S/cm}$  for the

study area (Table 12) revealing that 100% of the groundwater samples have EC values < 250  $\mu\text{S/cm}$  which reflects no restriction for irrigation (Table 13).

##### Sodium adsorption ratio

Sodium adsorption ratio (SAR) compares the percentage of sodium ions in water to calcium and magnesium ions. SAR is inversely proportional to the rate of water

percolation in soil (Massoud *et al.*, 2022).  
From the equation;

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad (8)$$

The average values of SAR were  $0.31 \pm 0.02$  meq/L for the study area (Table 12) indicating that these samples are appropriate for irrigation ( $SAR < 10$ ) in Table 13.

### Percent Sodium

From the equation;

$$Na\% = \frac{Na + K}{Ca + Mg + Na + K} \quad (9)$$

The average values of %Na were  $17.72 \pm 0.86$  meq/L for the study area (Table 12) indicating that these samples are appropriate for irrigation (Table 13).

### Residual sodium carbonate

Residual sodium carbonate (RSC) was used to assess the dangerous impact of  $HCO_3^-$  and  $CO_3^-$  on irrigation water quality (Aghazadeh & Mogaddam 2010) and measure the effects of  $HCO_3^-$  and  $CO_3^-$  on soil and crop development (Massoud *et al.*, 2022). From the equation;

$$RSC = (Co_2 + HCo_3) - (Ca + Mg) \quad (10)$$

The average RSC values were -1.64 meq/L to -1.36 meq/L with an average of  $-1.46 \pm 0.10$  meq/L for the study area (Table 12). This indicates safe irrigation water (Table 13).

### Magnesium hazard

From the equation;

$$MH = \frac{(Mg^{2+})}{(Ca^{2+} + Mg^{2+})} \quad (11)$$

The average magnesium hazard (MH) values were  $52.46 \pm 2.7$  meq/L for the study area (Table 12) indicating that these groundwater samples are appropriate for irrigation. However, 70% of the groundwater samples are not suitable for irrigation (Table 13).

### Permeability index

From the equation;

$$PI = \frac{(100 \times Na^+ + \sqrt{HCO_3^-})}{(Ca^{2+} + Mg^{2+} + Na^+)} \quad (12)$$

The average Permeability index (PI) values were  $40.93 \pm 1.67$  meq/L for the study area (Table 12) indicating that these groundwater samples are appropriate for irrigation (Table 13).

**Table 12:** Irrigation indices

LGA	Code	EC	SAR	%Na	RSC	MH	PI
Ini	SP 1	163.7	0.32	18.55	-1.36	49.69	42.99
	SP 2	161.5	0.31	17.29	-1.51	56.46	40.36
	SP 3	162.7	0.34	19.21	-1.41	48.55	42.13
	SP 4	162.5	0.30	17.11	-1.41	53.14	41.65
	SP 5	163.3	0.31	16.90	-1.64	55.49	38.09
	SP 6	164.1	0.33	17.95	-1.50	51.10	41.41
	SP 7	163.2	0.29	17.73	-1.39	51.51	41.09
	SP 8	163.9	0.31	18.71	-1.36	49.66	42.37
	SP 9	162.9	0.30	16.77	-1.62	54.28	38.08
	SP 10	163.6	0.29	16.97	-1.44	54.69	41.13
Statistics	Min	<b>161.50</b>	<b>0.29</b>	<b>16.77</b>	<b>-1.64</b>	<b>48.55</b>	<b>38.08</b>
	Max	<b>164.10</b>	<b>0.34</b>	<b>19.21</b>	<b>-1.36</b>	<b>56.46</b>	<b>42.99</b>
	Mean	<b>163.14</b>	<b>0.31</b>	<b>17.72</b>	<b>-1.46</b>	<b>52.46</b>	<b>40.93</b>
	SD	<b>0.77</b>	<b>0.02</b>	<b>0.86</b>	<b>0.10</b>	<b>2.74</b>	<b>1.67</b>

**Table 13:** Classification of groundwater for irrigation use (Massoud *et al.*, 2022)

Parameter	Range		No
			Ini
<b>EC</b>	< 250	Excellent	10
	250-750	Good	
	750-2250	Permissible	
	>2250	Doubtful	
<b>SAR</b>	<10	Excellent	10
	10-18	Good	
	18-26	Doubtful	
	>26	Unsuitable	
<b>%Na</b>	<20	Excellent	10
	20-40	Good	
	40-80	Moderate	
	>80	Unsuitable	
<b>RSC</b>	<1.25	Good	10
	1.25-2.5	Doubtful	
	>2.5	Unsuitable	
<b>MH</b>	<50	Suitable	3
	>50	Unsuitable	7
<b>PI</b>	<80	Good	10
	80-100	Moderate	
	>100	Poor	

### 4.3 Hydrochemical facies

Plotting of the analytical results on a Piper diagram (Fig. 8) revealed that the hydrochemical facies of the different water types are classified into two groups (Table 14). The first group is the calcium-magnesium-bicarbonate-chloride (Ca-Mg-HCO<sub>3</sub>-Cl) water type. Twenty percent of the samples in the study area fall within the first group (Massoud *et al.*, 2022). These facies are attributed to carbonate weathering and Base Exchange. The second group is Magnesium-Calcium-Chloride-Bicarbonate (Mg<sup>2+</sup>+Ca<sup>2+</sup>-Cl<sup>-</sup>+HCO<sub>3</sub><sup>-</sup>). The group consists of 80% of groundwater from the study area and signifies magnesium weathering (Mukherjee & Singh, 2022).

#### 4.3.1 Sources of ions

Using the ionic ratios with respect to Cl<sup>-</sup> is normally used to assess the atmospheric contribution of dissolved ions in water (Singh *et al.*, 2005). The average Na<sup>+</sup>/Cl<sup>-</sup> and K<sup>+</sup>/Cl<sup>-</sup> for marine sources are 0.85 and 0.0176, respectively. The average Na<sup>+</sup>/Cl<sup>-</sup> is 0.92±0.10

and K<sup>+</sup>/Cl<sup>-</sup> is 0.28±0.04. This suggests low contributions from atmospheric and marine sources and indicates high level of contributions from rock weathering (Singh *et al.*, 2005). The plot of the data on Gibb's diagram (Gibbs, 1970) showing total dissolved solids (TDS) as a function of Na<sup>+</sup>/(Na<sup>+</sup>+Ca<sup>2+</sup>) and Cl<sup>-</sup>/(Cl<sup>-</sup>+HCO<sub>3</sub><sup>-</sup>), also support the dominance of rock weathering for surface water and groundwater and evaporation process for contaminated water samples (Fig. 9).

Jankowski & Acworth (1997) used the plot of Na<sup>+</sup>/Cl<sup>-</sup> versus Cl<sup>-</sup> to estimate the contribution of evaporation process. Hence Fig. 10a clearly revealed that the trend of Na<sup>+</sup>/Cl<sup>-</sup> versus Cl<sup>-</sup> as almost horizontal, indicating contributions from evaporation to chemistry of groundwater. The plot of Ca<sup>2+</sup>+Mg<sup>2+</sup> against HCO<sub>3</sub><sup>-</sup>+SO<sub>4</sub><sup>2-</sup> will be close to 1:1 if the weathering of calcite, dolomite and gypsum are dominant reactions in the system (Cerling *et al.*, 1989; Fisher & Mullican 1977). The plot of Ca<sup>2+</sup>+Mg<sup>2+</sup> against HCO<sub>3</sub><sup>-</sup>+SO<sub>4</sub><sup>2-</sup> (Fig. 10b), show the data fall

above the theoretical line (1:1). This suggests contributions from carbonate source and demanding the required portion of the  $\text{HCO}_3^- + \text{SO}_4^{2-}$  to be balanced by the alkaline (Singh *et al.*, 2013). The stoichiometry of carbonate weathering demands that  $\text{Ca}^{2+} + \text{Mg}^{2+}$  be equal to  $\text{HCO}_3^-$ . The plot of  $\text{Ca}^{2+} + \text{Mg}^{2+}$  against  $\text{HCO}_3^-$  (Fig. 10c) shows excess of  $\text{Ca}^{2+} + \text{Mg}^{2+}$

relative to  $\text{HCO}_3^-$  for all samples and demand excess positive charge of  $\text{Ca}^{2+} + \text{Mg}^{2+}$  should be balanced by  $\text{HCO}_3^-$  provided by silicate weathering. The concentration of  $\text{Na}^+ + \text{K}^+$  for all water samples are in excess over chloride (Fig. 10d), suggesting that most of the alkalis ( $\text{Na}^+$ ,  $\text{K}^+$ ) originate from weathering of sodic ( $\text{Na}^+$ ) and (potassic ( $\text{K}^+$ ) plagioclase feldspars.

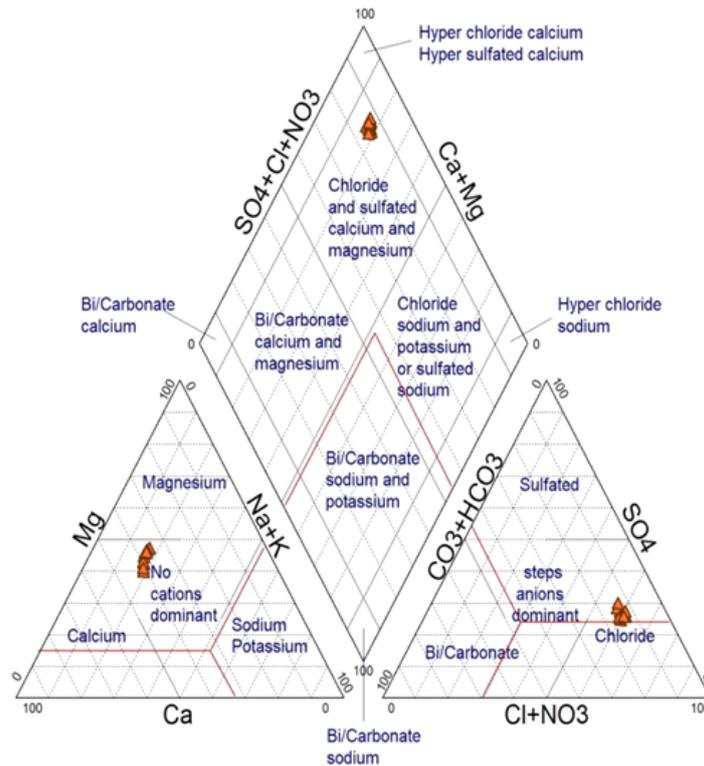
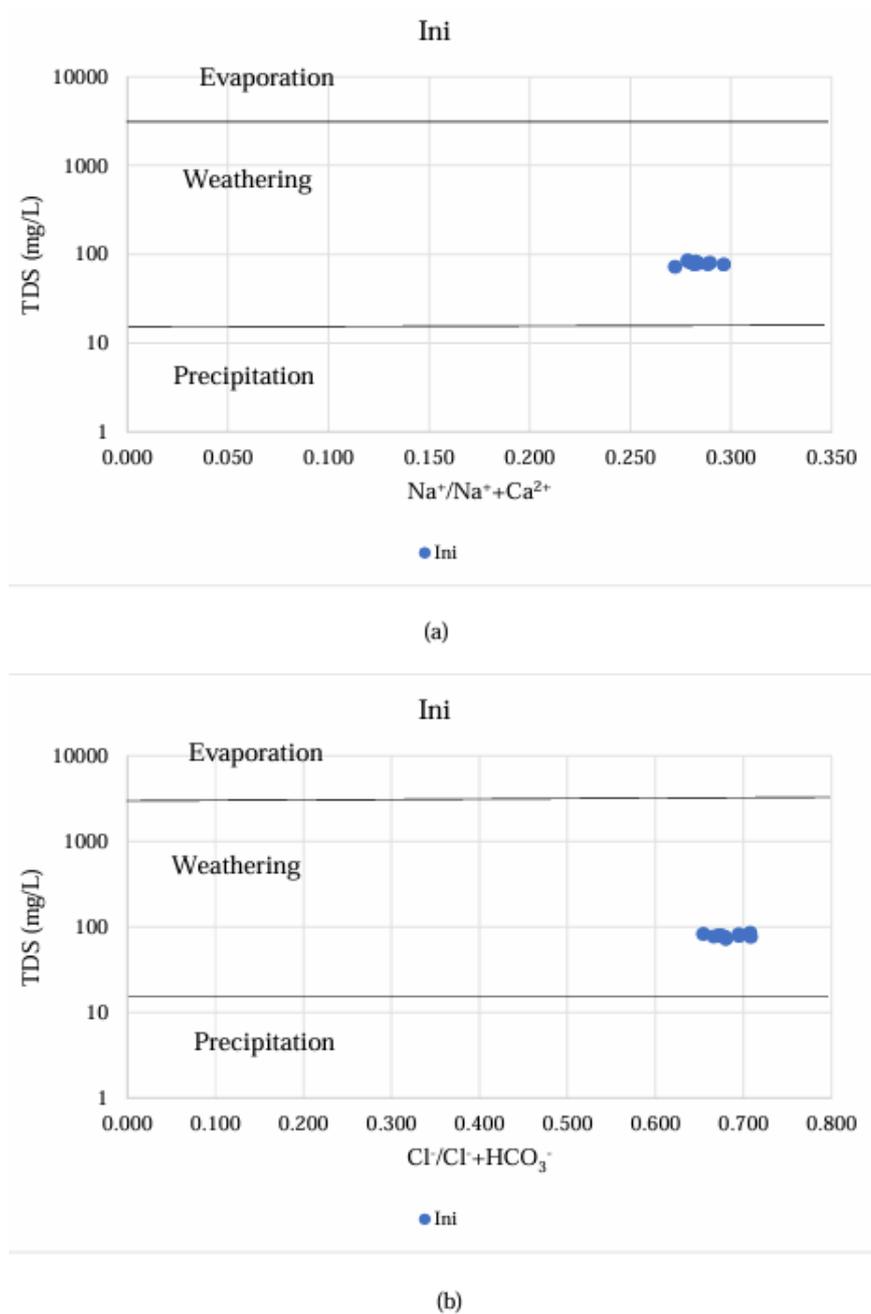


Fig. 8: Piper diagram plot for groundwater from the study area

Table 14: Hydrochemical facies of groundwater in Ini LGA

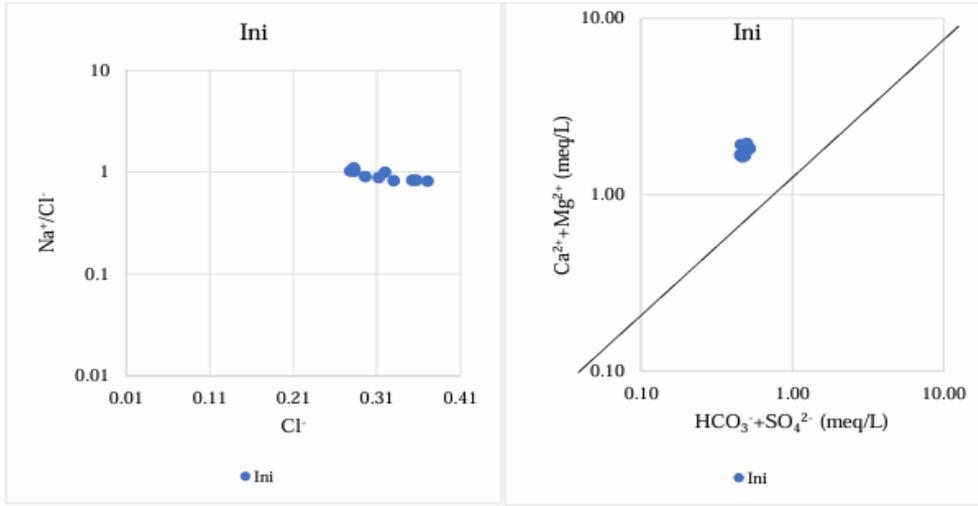
Code	Facies	Group
SP 1	$\text{Ca}^{2+} - \text{Mg}^{2+} - \text{HCO}_3^- - \text{Cl}^-$	1
SP 2	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 3	$\text{Ca}^{2+} - \text{Mg}^{2+} - \text{HCO}_3^- - \text{Cl}^-$	1
SP 4	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 5	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 6	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 7	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 8	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 9	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2
SP 10	$\text{Mg}^{2+} - \text{Ca}^{2+} - \text{Cl}^- - \text{HCO}_3^-$	2



**Fig. 9:** Gibbs diagram for the groundwater (a) TDS vs  $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$  and (b) TDS vs  $\text{Cl} / (\text{Cl} + \text{HCO}_3^-)$

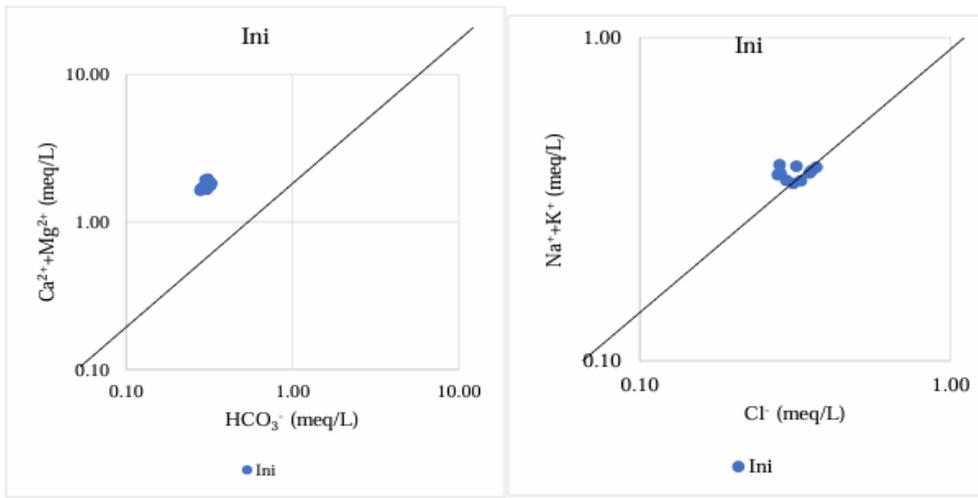
The composition of water derived from carbonate weathering are characterized by higher concentrations of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  and have  $\text{Ca}^{2+}/\text{Na}^+$ ,  $\text{Mg}^{2+}/\text{Na}^+$  and  $\text{HCO}_3^-/\text{Na}^+$  as 50, 10 and 120 respectively (Gaillardet *et al.*, 1999). However, lower values are expected from silicate weathering due to low solubility of  $\text{Na}^+$  relative to  $\text{Ca}^{2+}$ . The chemical composition assigned to silicate end member for  $\text{Ca}^{2+}/\text{Na}^+$ ,  $\text{Mg}^{2+}/\text{Na}^+$  and  $\text{HCO}_3^-/\text{Na}^+$  is 0.35, 0.24 and 2, respectively (Gaillardet *et al.*, 1999). The geochemical data of this study

plotted on the bivariate diagram of  $\text{Mg}^{2+}/\text{Na}^+$  against  $\text{Ca}^{2+}/\text{Na}^+$  and  $\text{HCO}_3^-/\text{Na}^+$  against  $\text{Ca}^{2+}/\text{Na}^+$  relating carbonate and silicate end members, indicate silicate weathering as the main process (Figs. 10 e and 10 f). Also, the plot of TDS versus  $\text{Na}^+$  shown in Fig. 10g shows  $\text{Na}^+$  increasing as TDS and thus in addition to silicate weathering, it might be related to human activities such as sewage, domestic waste, drains from dumpsites (Williams *et al.*, 1999; Choi *et al.*, 2005).



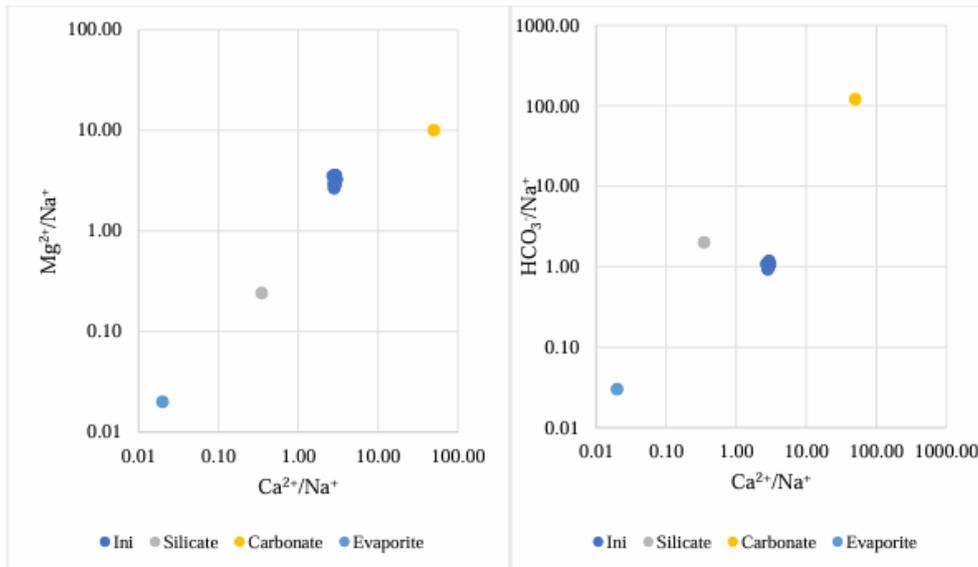
(a)

(b)



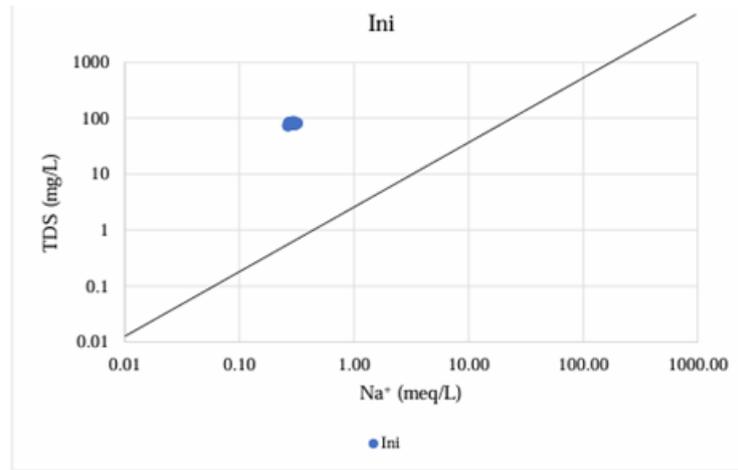
(c)

(d)



(e)

(f)



(f)

**Fig. 10:** Cross Plots between ions (a)  $\text{Na}^+/\text{Cl}^-$  versus  $\text{Cl}^-$  (b)  $\text{Ca}^{2+}+\text{Mg}^{2+}$  versus  $\text{HCO}_3^-+\text{SO}_4^{2-}$  (c)  $\text{Ca}^{2+}+\text{Mg}^{2+}$  versus  $\text{HCO}_3^-$ . (d)  $\text{Na}^++\text{K}^+$  versus  $\text{Cl}^-$  (e)  $\text{Mg}^{2+}/\text{Na}^+$  versus  $\text{Ca}^{2+}/\text{Na}^+$  (f)  $\text{HCO}_3^-/\text{Na}^+$  versus  $\text{Ca}^{2+}/\text{Na}^+$  and (g) TDS versus  $\text{Na}^+$  for groundwater in Ini LGA.

### 4.3.2 Ion exchange

Computed values of indices from equations based on chloroalkaline indices (CA I), Schoeller (1977):

$$CAI-1 = \frac{[\text{Cl}^- - (\text{Na}^+ + \text{K}^+)]}{\text{Cl}^-} \quad 13$$

$$CAI-2 = \frac{[\text{Cl}^- (\text{Na}^+ + \text{K}^+)]}{(\text{SO}_4^{2-} + \text{HCO}_3^- + \text{NO}_3^-)} \quad 14$$

Groundwater samples in this study showed prevalence for ion exchange (Table 15, Fig. 11).

**Table 15:** Type of ion exchange in the study area

Code	CAI 1	CAI 2	Type of Ion exchange
SP 1	-0.34	-0.14	Forward ion exchange
SP 2	-0.08	-0.04	Forward ion exchange
SP 3	-0.43	-0.18	Forward ion exchange
SP 4	-0.13	-0.06	Forward ion exchange
SP 5	-0.07	-0.04	Forward ion exchange
SP 6	-0.25	-0.11	Forward ion exchange
SP 7	-0.22	-0.10	Forward ion exchange
SP 8	-0.35	-0.15	Forward ion exchange
SP 9	-0.08	-0.05	Forward ion exchange
SP 10	-0.09	-0.04	Forward ion exchange

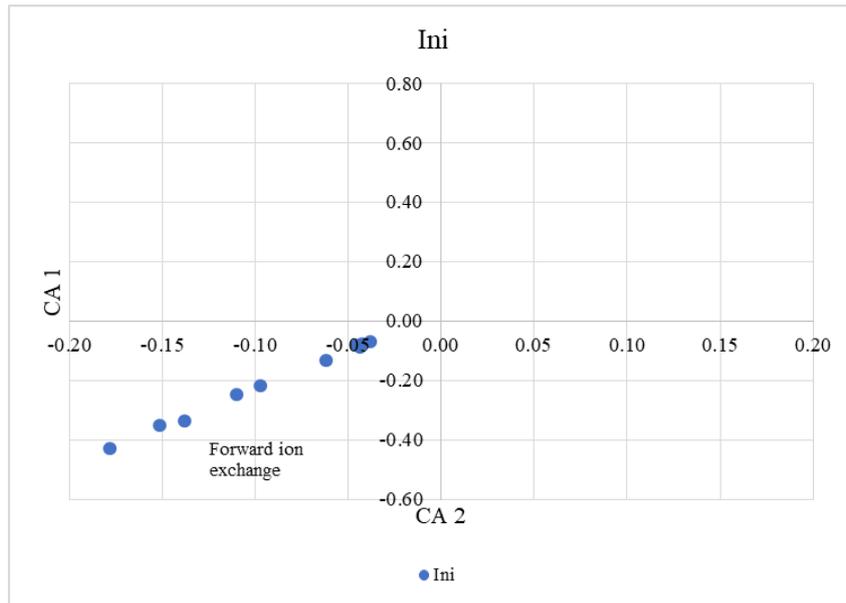


Fig. 11: Plot of CA 1 versus CA 2 showing forward ion exchange

4.4 Multivariate statistical analysis

4.4.1 Pearson moment correlation analysis

The interrelationships among different water quality parameters for the different water types of the study area were studied by means of Pearson moment correlation analysis and given in Table 16. Correlation coefficients  $\geq 0.70$  were regarded as significant correlation. EC displayed strong positive correlation with  $\text{HCO}_3^-$ . This indicates that the process enriching this element might be the same (Ciner et al.,

2020). pH shows negative correlation with TH and  $\text{SO}_4^{2-}$  implying that their enrichment might be related to common process of TH and  $\text{SO}_4^{2-}$ . The correlation between  $\text{Na}^+$  and  $\text{Ca}^{2+}$  is due to ion exchange. The following pairs of strong correlation were also observed: negative correlation between  $\text{Mg}^{2+}$  and  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and Fe, while positive correlation was observed between  $\text{Mg}^{2+}$  and Mn. Negative correlation is due to different sources of element.

Table 16: Correlation matrix for groundwater

	Temp	EC	TDS	pH	TH	$\text{Na}^+$	$\text{K}^+$	$\text{Ca}^{2+}$	$\text{Mg}^{2+}$	Cl <sup>-</sup>	$\text{HCO}_3^-$	$\text{SO}_4^{2-}$	$\text{NO}_3^-$	Fe	Mn
Temp	1.000														
EC	0.213	1.000													
TDS	-0.127	0.312	1.000												
pH	-0.197	0.146	0.589	1.000											
TH	-0.295	0.208	-0.262	<b>-0.674</b>	1.000										
$\text{Na}^+$	-0.372	0.070	0.229	0.140	0.226	1.000									
$\text{K}^+$	-0.007	0.084	-0.152	-0.082	0.293	-0.116	1.000								
$\text{Ca}^{2+}$	-0.168	0.376	0.316	-0.047	0.391	<b>0.836</b>	0.057	1.000							
$\text{Mg}^{2+}$	-0.346	-0.347	0.306	0.490	-0.372	0.188	-0.062	0.116	1.000						
Cl <sup>-</sup>	-0.506	-0.015	0.205	0.494	-0.331	0.258	-0.573	0.042	0.583	1.000					
$\text{HCO}_3^-$	0.023	<b>0.689</b>	0.047	0.384	0.002	0.459	-0.019	0.422	-0.240	0.184	1.000				
$\text{SO}_4^{2-}$	-0.086	0.022	-0.531	<b>-0.910</b>	<b>0.758</b>	-0.093	0.029	0.128	-0.447	-0.250	-0.238	1.000			
$\text{NO}_3^-$	0.608	0.284	0.271	-0.139	-0.082	-0.080	-0.120	0.064	<b>-0.665</b>	-0.603	0.109	-0.032	1.000		
Fe	0.044	-0.105	0.231	0.543	-0.343	-0.096	0.421	-0.228	-0.012	-0.378	0.139	<b>-0.659</b>	0.263	1.000	
Mn	-0.138	0.022	0.463	0.514	-0.215	0.351	0.247	0.347	<b>0.794</b>	0.327	0.020	-0.550	-0.456	0.093	1.000

#### 4.4.2 Factor analysis

To further investigate the potential sources of the elements in the different water types, factor analysis (FA) was used to identify the most significant loadings. The results of factor analysis (FA) are presented in Table 17. Five factors with eigen value  $> 1$  were extracted from R-mode FA. The FA of the water quality indicated that the chemistry of the different water types in the study area is controlled by geogenic processes and anthropogenic activities. Considering the loadings in this study, factor loadings  $> 0.70$  were considered significant and loadings  $< 0.70$  were considered insignificant. In Ini LGA, Factor 1 explains

28.87% having significant loadings for pH and negative loadings for TH and  $\text{SO}_4^{2-}$ . This group loading indicates geologic processes through prevalence of weathering. Factor 2 explains approximately 19.51%. The factor is loaded with temperature and  $\text{NO}_3^-$ , which is linked to anthropogenic sources. Factor 3 explains 18.03. This factor (3) is loaded with  $\text{Na}^+$  and  $\text{Ca}^{2+}$ . The high positive loading for this factor is due to ion exchange. Factor 4 explains 11.88% of variance. The factor is negatively loaded with  $\text{K}^+$ . Factor 5, which account for the variance of 7.85% is loaded with EC and  $\text{HCO}_3^-$  and is suggestive of silicate and carbonate weathering.

**Table 17:** Factor Loadings for groundwater

LGA	Ini				
	Factor 1	2	3	4	5
Temp	0.075	<b>-0.764</b>	-0.186	0.005	-0.063
EC	0.004	-0.277	0.280	0.015	<b>0.732</b>
TDS	0.600	-0.207	0.545	0.147	-0.041
pH	<b>0.929</b>	0.230	0.049	0.049	0.255
TH	<b>-0.810</b>	0.091	0.316	-0.297	0.142
$\text{Na}^+$	-0.005	0.219	<b>0.780</b>	0.086	0.261
$\text{K}^+$	-0.055	0.075	0.044	<b>-0.949</b>	0.002
$\text{Ca}^{2+}$	-0.157	0.004	<b>0.924</b>	-0.009	0.247
$\text{Mg}^{2+}$	0.492	0.615	0.291	0.115	-0.448
$\text{Cl}^-$	0.290	0.659	0.078	0.670	0.128
$\text{HCO}_3^-$	0.171	0.007	0.196	0.014	<b>0.935</b>
$\text{SO}_4^{2-}$	<b>-0.979</b>	-0.010	-0.021	0.056	-0.047
$\text{NO}_3^-$	0.034	<b>-0.965</b>	0.037	0.014	0.129
Fe	0.622	-0.178	-0.194	-0.612	0.097
Mn	<b>0.535</b>	<b>0.391</b>	<b>0.558</b>	<b>-0.169</b>	<b>-0.228</b>
Eigenvalue	<b>4.330</b>	<b>2.927</b>	<b>2.704</b>	<b>1.782</b>	<b>1.177</b>
% Total variance	<b>28.866</b>	<b>19.515</b>	<b>18.029</b>	<b>11.882</b>	<b>7.846</b>
Cumulative eigen value	<b>4.330</b>	<b>7.257</b>	<b>9.961</b>	<b>11.744</b>	<b>12.921</b>
Cumulative %	<b>28.866</b>	<b>48.381</b>	<b>66.410</b>	<b>78.292</b>	<b>86.137</b>

#### 5.0 Conclusion

Groundwater in Ini LGA is largely suitable for drinking and irrigation, though localized contamination from nitrates, iron and manganese necessitates targeted intervention.

The study confirms the presence of significant groundwater reservoirs in the study areas, with moderate to high groundwater potential. However, localized contamination necessitates targeted intervention strategies.

### 5.1 Key recommendations

Conducting aquifer vulnerability assessments and collecting additional data on aquifer parameters will enhance understanding of groundwater dynamics in the study area. The establishment of groundwater protection zones is recommended to prevent contamination, along with regular water quality monitoring to detect trends in hydrochemical variations. Implementing proper well-spacing strategies can help prevent over-extraction of groundwater resources. Public awareness campaigns on safe agricultural practices and improved sanitation are also essential to protect water quality. Additionally, further isotopic analyses are suggested to trace contamination sources and refine hydrogeochemical models. The integration of geophysical, hydrogeological, and hydrochemical data provides a robust framework for the sustainable management of groundwater resources in the region.

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