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ORIGINAL ARTICLE

Groundwater facie analysis in the upper Cross River basin, southeast Nigeria

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Abstract The study area lies between latitudes 6°02′N and 6°24′N, and longitudes 8°00′E and 8°16′E. The area is underlain by Abakaliki shale which belongs to Asu River Group of Albian age. The study determines different water types (facies) via analysis of major ion concentration of water samples using spectrophotometer of HACH DR/2010 series. Twenty (20) water samples were collected and analyzed. The laboratory results were further induced to statistical evaluations using Aqua Chem, and it showed that the groundwater of the area is hard and fresh. The results can be classified into five hydrochemical facies, namely Ca–Mg–Cl–$S0_4$, Ca–Mg–HCO_3–Cl–SO_4, Ca–Mg–HCO_3, Na–K–HCO_3 and Na–K–Cl–SO_4, all of which are dominantly alkaline water. Static water level was measured from hand-dug wells to determine hydraulic heads which delineated local potentiometric surface. Flow directions were deduced, and it showed isolated system of groundwater movement. Such localized pattern of water occurrence can be attributed to the underlying shaley aquiclude across the area. The hydraulic head info was correlated with facie analysis to interpret groundwater recharge zones.

Keywords Cross River basin · Groundwater facie · Aquifers · Asu River shales

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Introduction

Upper Cross River basin is an extension of Cross River hydrogeological basin to the southeastern Nigeria. It comprises Abakaliki town and some surrounding mineralized villages. The area is groundwater problematic due to the underlying aquiclude-forming shales of Asu River Group of Albian age (Offodile 2002). However, fractures where formed, produce isolated and prolific aquifers with consequent non-regional flow system and thus yielding to different facie zones. According to Okogbue and Ukpai (2013), groundwater terrain of the area has been degrading due to mineralization of major ions, heavy metals and other trace elements. Therefore, the study determined the lithogenic significances (environmental impacts) of chemical elements that quantified to different groundwater types (facies), natural environments of origin according to Kevin (2005) and their physical flow pattern. The importance of this study is that groundwater resource origins were identified. The origin, however, enabled authors to define recharge and discharge zones. These zones will assist groundwater management programs in the future.

Geographical and hydrographical locations

The study area lies within latitudes 6°02′–6°24 north and longitudes 8°00′–8°16′E. The topography of the area is defined by the scattered pyroclastic hills in the Abakaliki town and an upland in the mineralized Ameka village. Generally, the terrain is rolling and undulating. Abakaliki area is located in the hydrographical Cross River basin (Fig. 1) and falls within Niger south hydrological area. The climate is humid and tropical with a marked dry season (November–March) and wet season (April–October). The vegetation is characterized by grasslands, shrubs and

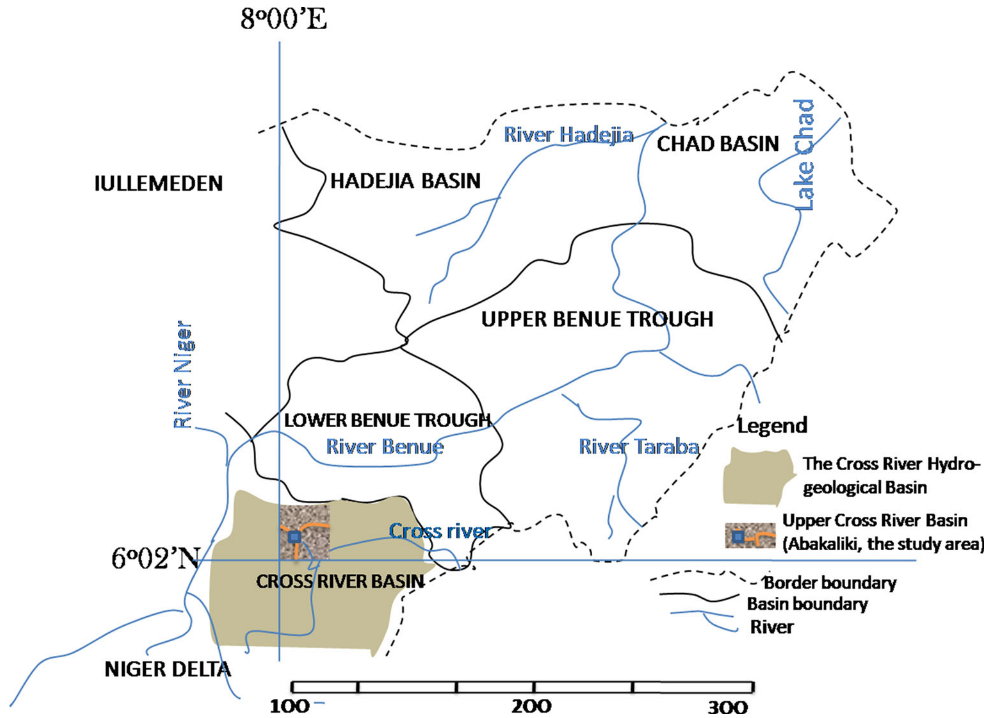

Fig. 1 Hydrogeographical map of some Nigerian River basins showing the study area

scanty trees. The area is drained by Iyokwu River from northcentral, Abia River from northwest, both joining with Ebonyi River. The Ebonyi River then drains other river systems in the area and flows southwards, forming a trellis drainage pattern that stretches beyond the study area to Cross River (Fig. 2).

Geology and mineralization

Offodile (2002) reported that Asu River Group, Albian in age and subdivided into three formations, comprises essentially of over 200 m bluish gray to olive brown shales and sandy shales, fine-grained micaceous and calcareous sandstones and some limestones. There are also some dykes, sills and igneous intrusives associated with the group. The group underlies Abakaliki area, dipping northwestwards and southeastwards in the northern and southern parts, respectively, with strike direction along the axis of Abakaliki anticlinorium-aftermath uplift formed during Santonian tectonic episode of post-Albian that trends northeast–southwest (Fig. 3). According to Reyment (1965), intrusion took place during the post-Albian time which deformed the shale of the area, creating different geologic structures, some of which have mineralizing properties. Thus, the shale of Asu River Group was faulted, fractured and weathered in many places which were identified during field mapping in the course of this study. Many of these structures formed lodes in the study area. Among the lodes are Enyigba main lode, Ameri and Ameka lodes. The mineral lodes/veins are made up of galena (PbS), sphalerites (ZnS), siderite ($FeCo_3$) and the subordinate chalcopyrite ($CuFeS_2$) and marcasite (FeS_2).

Materials and methods

Proposed sample locations were visited with the aid of a topographic map of the area which showed the access roads, and information gathered was compiled as regards the names of the locations where the samples would be collected (Table 1). Water sample collection from boreholes commenced the next day after reconnaissance. A Global Positioning System (GPS) of Garmin eTrex model was used to locate each sampled point by measuring latitudes and longitudes of the sampled location. A total of 20 samples were collected from different locations spread across the study area: 16 from boreholes, 3 from hand-dug wells and 1 from the town water supply reservoir. The reservoir sample was collected in order to compare the difference in elemental composition of the pipe-borne water with the groundwater. Each sample was collected using a clean 1-l plastic water bottle and labeled according to the location name. Each plastic bottle was rinsed with the same water to be sampled before the collection to avoid any contamination from the bottle. Physical parameters such as the electrical conductivity (EC) and temperature relevant to the study were measured in situ using a portable WTW LF 90 conductivity meter. Dips and strikes were measured using a Brunton compass, depths to groundwater levels in 21 hand-dug wells were measured using a 100-m tape while the

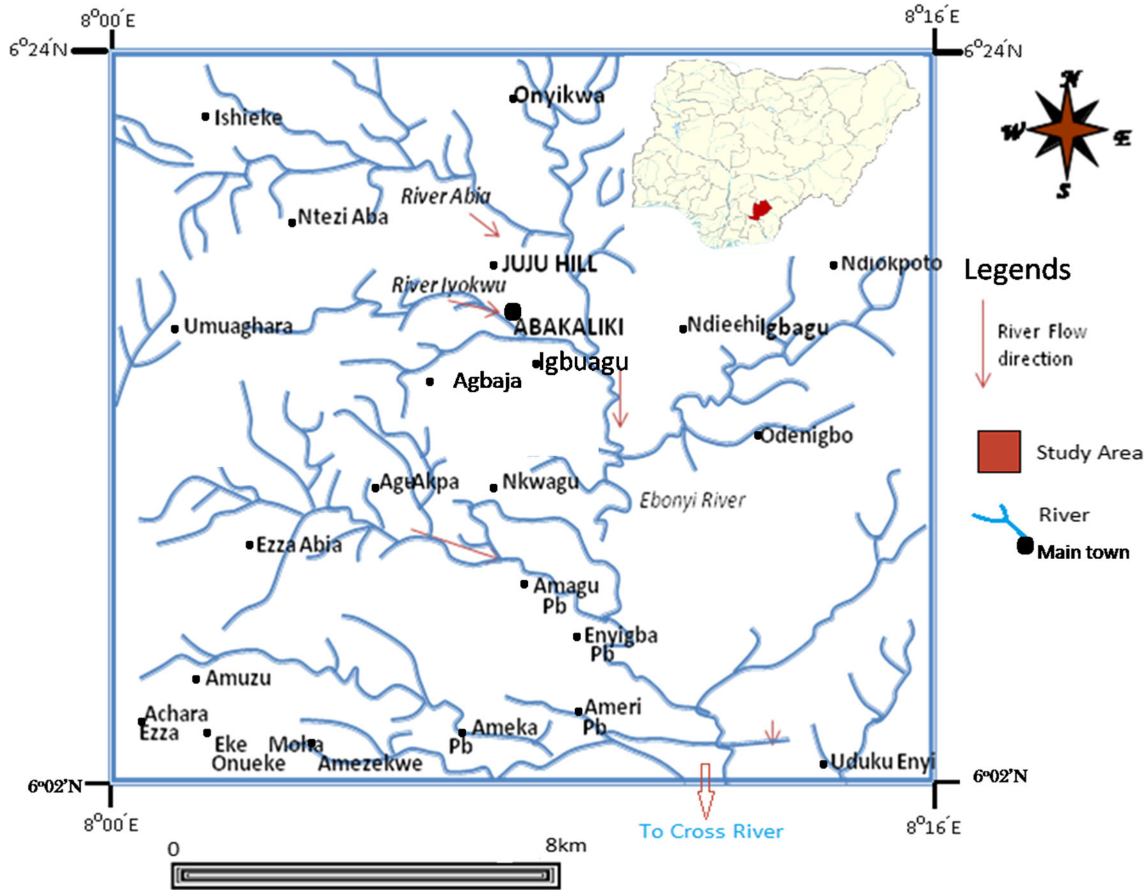

Fig. 2 Hydrological map of the study area showing local drainage system

elevation from mean sea level and location of each of the wells was measured using the GPS of Garmin eTrex model. The generated data went through further software analysis using Aqua Chem to determine hydraulic heads. The longitudes and latitudes measured were converted to coordinates in meters on a universal transverse mercator (UTM) using UTM calculator.

Note: The hydraulic head of each well is the difference of elevation and depth to water level in the well. Thus,

$$\text{Elevation (m)} - \text{Depth to water level (m)} = \text{Hydraulic head (m)}.$$

The samples were analyzed at Hydrochemistry laboratory of UNICEF assisted water and sanitation project office, Federal secretariat, Ibadan Nigeria. Ions were analyzed using spectrophotometer of HACH DR/2010. The laboratory results were further induced to statistical evaluations to produce a Piper diagram. A resistivity meter was used for vertical electrical sounding (VES) data acquisition. The raw VES data were processed using appropriate constants and were presented as sounding curves which are obtained by plotting graph of apparent resistivity versus half-current electrode spacing (1/2AB) on double logarithmic graph sheets.

Results and discussion

The hydraulic heads as presented in Table 2 are emplaced in Fig. 4. As shown in the figure, the highest static water level is at the central part of the map and the lowest at the northeastern. The hydraulic head data were further used to produce a 3-D surface map (Fig. 5) showing recharge zones indicated by cone-like uplifts, which when correlated with Fig. 4 reflects elevations of higher static water level. Under steady-state condition, the elevation at any point on the water table equals the energy heads (Todd 1980). Therefore, the higher energy heads in the study area are inferred as permeable weathered zones where infiltration flow is more prominent. The flow lines lie perpendicular to water table contours as depicted in Fig. 4. The figure also showed that flow directions are variable, indicating non-regional groundwater flow. According to Kevin (2005), the occurrence of groundwater and the distribution of aquifers, aquicludes and aquitards in a region are determined by lithology (geologic strata in terms of rock composition and texture), stratigraphy (rock sequence and links between various deposits), and the structures (folds, faults, joints and fractures) of the geologic strata present. From

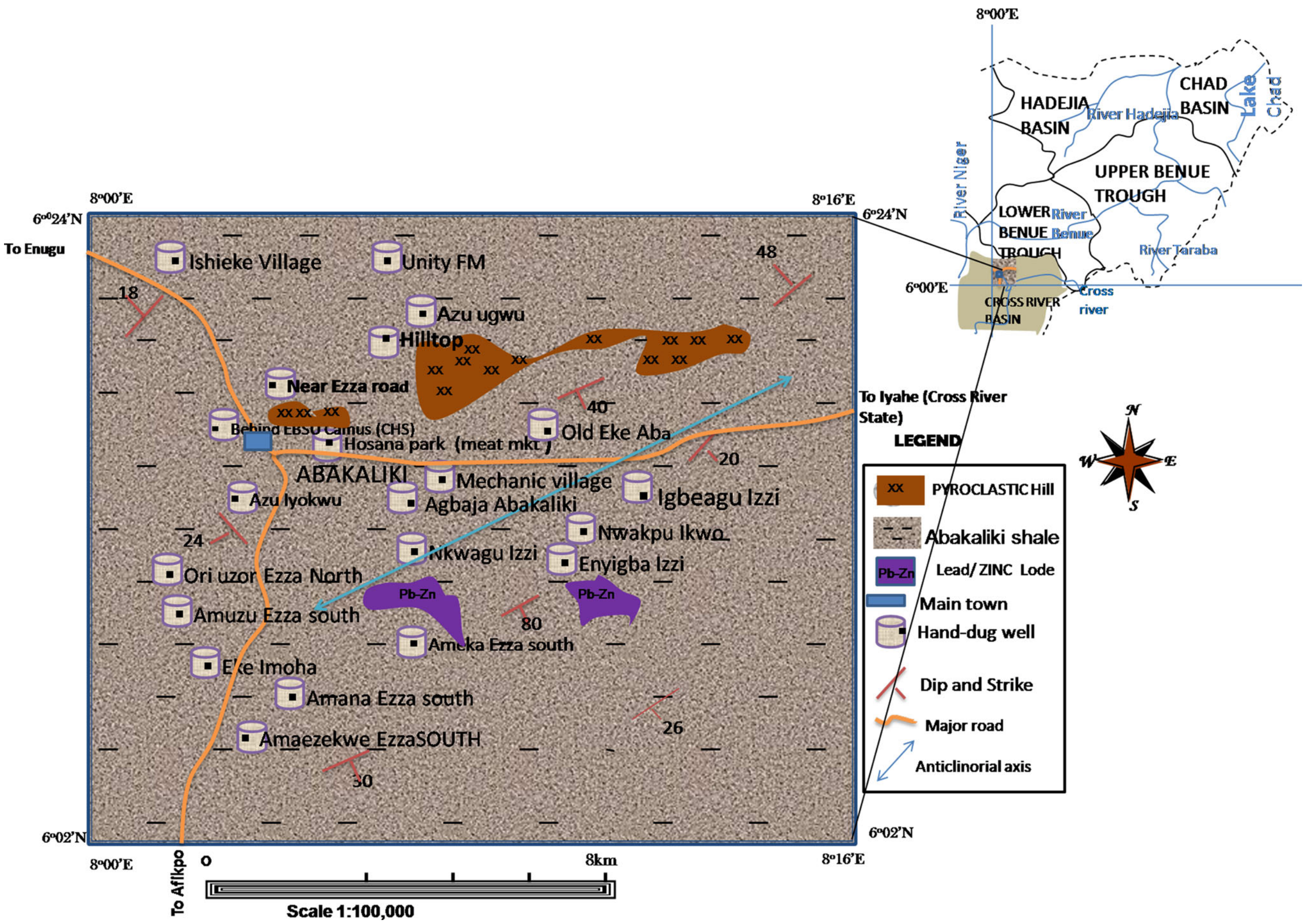

Fig. 3 Local geologic map of the study area showing locations of hand-dug wells for water level measurements

analytical results of VES data presented in Fig. 7, the aquifers of the study area are influenced by the structures formed from fractures/weathered zones, while shales of the Asu River Group and the intercalated mudstone layers formed the aquicludes and aquitards, respectively (Table 3). The table showed that underground water contains soil water which correlates with the unsaturated zone and groundwater which correlates with the saturated zone. The latter was used as a criterion for the static water levels measured in the area, which flow system is localized due to intermingled shale and mudstone beds that confined groundwater flow to different restricted environments. This means, therefore, that the hydrogeology of the area is determined by the geology.

Facie analysis and groundwater classifications

Table 4 presents results of the hydrochemical analysis, indicating that 50 % of the water resources are alarming with pollution of total dissolved solids (TDS) when compared with WHO (2004) standard limit, especially around Enyigba area where the concentration falls within brackish range of 1020 mg/l. Similarly, total hardness ranges from 21 to 228 mg/l as $CaCO_3$, with the lowest in representative samples 4 and 18. The mean concentration of the total hardness is 124 mg/l which falls between 75 and 150 mg/l range of water hardness prescription according to Sawyer and McCarty (1967). The table shows the concentrations of major ions from laboratory results in milligram per liter (mg/l) and was converted to milliequivalent per liter (meq/l) (Table 5) purposefully for the groundwater facie evaluation. It was done by dividing the valence (ionic charge) of each major element with its atomic or formula weight; the dividend was used as the converting factor (Table 6) which is multiplied by the concentration in ppm or mg/l to get the meq/l. The concentrations of ions in meq/l were used to plot Piper trilinear diagram according to Ahiarakwem (2004), as developed by Piper (1944). The Piper diagram (Fig. 6) identified five hydrochemical facies, labeled A to E, whereby the facies were presented where projections from the cation and anion triangles intersect on the diamond shape of the Piper trilinear diagram. According to Freeze and Cherry (1979), a hydrochemical facie is a distinct zone that has cations and anions concentrations

Table 1 Locations for water sampling

Sample no	Sample code	Location name	Source
1	Ameka 1	Near the abandoned mine site	BH
2	Amagu	General Hospital Amagu	BH
3	Ameri 1	Abandoned mine site	HW
4	Enyigba 1	Abandoned mine site	BH
5	Enyigba 2	Community primary school Enyigba	BH
6	Abakaliki 9	Agbaja	BH
7	Abakaliki 8	Mechanic site	BH
8	Abakaliki 2	Mile 50 hospital Abakaliki	BH
9	Igbeagu	Defunct Teachers training college Igbeagu-izzi	BH
10	Nkwagu	Central school Nkwagu	HW
11	Ameri 2	Ameri village play ground	BH
12	Ameka 2	Village play ground	BH
13	Abakaliki 1	Ishieke campus-EBSU	BH
14	Abakaliki 4	EBSU teaching Hospital	BH
15	Abakaliki 3	CHS campus-EBSU	BH
16	Abakaliki 11	Near Uzana motor park (meat market)	HW
17	Abakaliki 7	Azu-Ugwu	BH
18	Abakaliki 5	Water works (town water reservoir)	PW
19	Abakaliki 6	College of Agricultural campus-EBSU	BH
20	Abakaliki 10	Nkaliki	BH

BH bore hole, *PW* pipe-borne water, *HW* hand-dug well

Table 2 Results of groundwater level measurements surveyed from hand-dug wells

S/no.	Location name	Hydraulic heads (m)	Longitudes (East)	Latitudes (north)
1	Hill top	31	008°07′104″	06°21′ 778″
2	Meat Mkt	33	008°06′ 973″	06°19′ 914″
3	Azu-Ugwu	32	008°07′ 291″	06°20′ 730″
4	Mechanic site	34	008°07′ 931″	06°18′ 111″
5	−X	28	008°10′976″	06°18′578″
6	Azu-Iyokwu	40	008°04′508″	06°16′ 578″
7	Near Ezza rd.	36	008°05′710″	06°19′866″
8	EBSU, CHS	32	008°04′ 973″	06°19′914″
9	Ishieke village	37	008°03′569″	06°22′ 206″
10	Unity Fm (mile 50)	34	008°06′609″	06°22′102″
11	Nkwagu Izzi	46	008°07′ 556″	06°15′ 313″
12	Orizor, Ezza	38	008°02′116	06°16′122
13	Amuzu Ezza	40	008°02′557″	06°12′ 632″
14	Eke Imoha Mkt	30	008°03′634″	06°10′326″
15	Amaezekwe	38	008°04′835″	06°09′476″
16	Amana, Ezza	26	008°05′687″	06°09′776″
17	Ameka-Ezza	40	008°06′814″	06°09′620″
18	Amagu, Ikwo	30	008°09′ 396″	06°12′ 776″
19	Enyigba, Izzi	42	008°08′396″	06°12′ 784″
20	Igbagu, Izzi	28	008°12′696″	06°19′ 557″
21	Agbaja-Abakaliki	29	008°08′ 947″	06°19′529″

X = Location name not verified

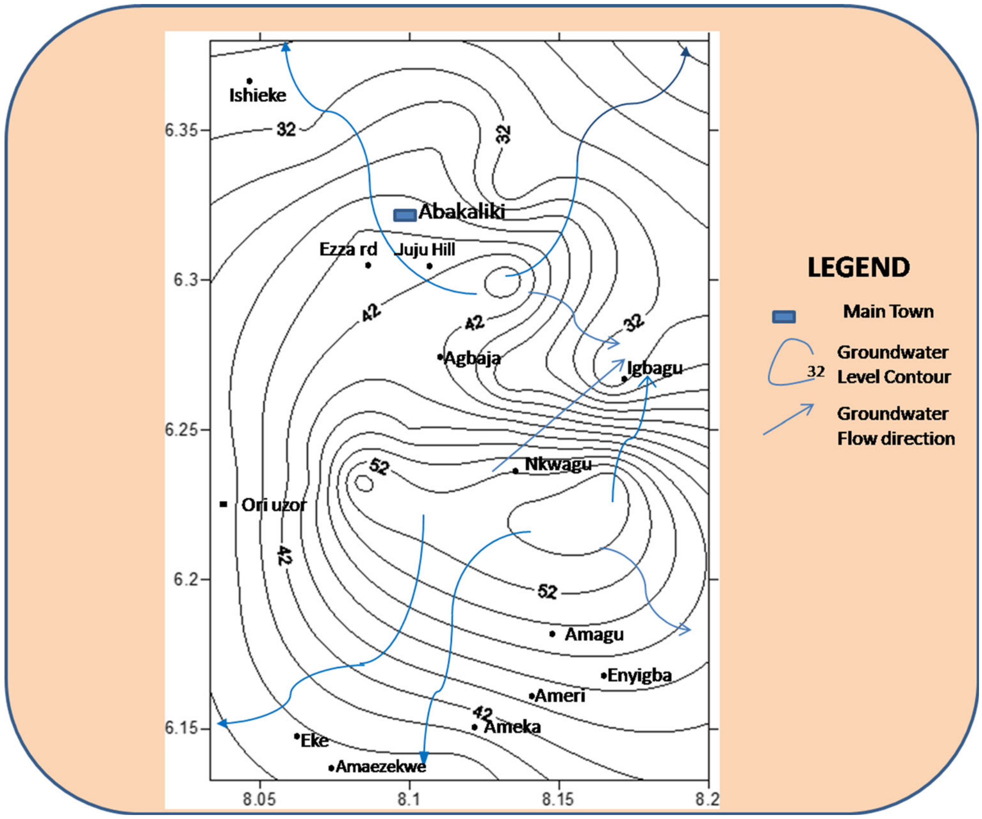

Fig. 4 Water table map of the area showing local groundwater flow directions

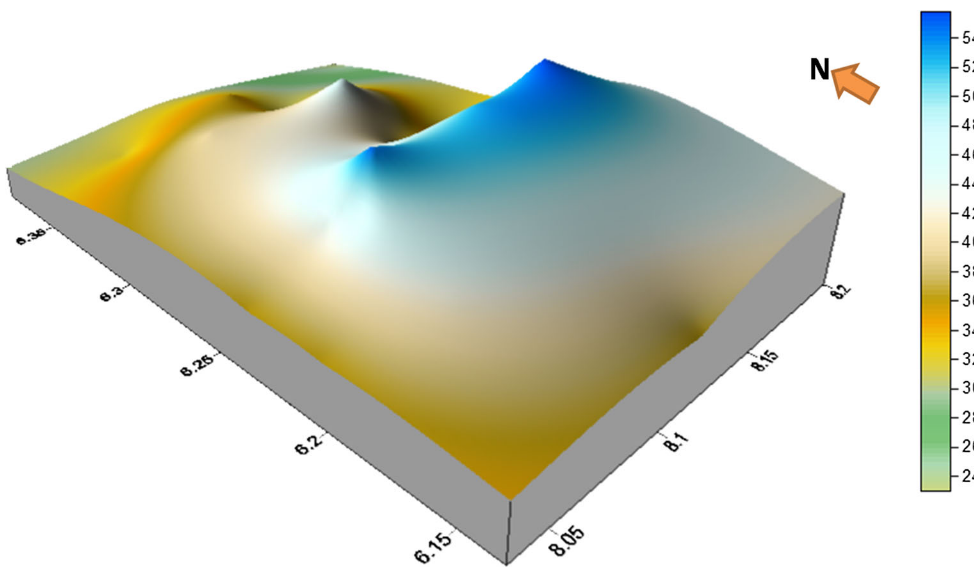

Fig. 5 Terrain model of the study area depicting groundwater recharge zones

describable within defined composition category. These were derived from four end zones of the diamond shape. The facies represent water types in the study area and are named as follows:

Type (A): $Ca–Mg–Cl–SO_4$ facie.
Type (B): $Ca–Mg–HCO_3–Cl–SO_4$ facie.
Type (C): $Ca–Mg–HCO_3$ facie.
Type (D): $Na–K–HCO_3$ facie.
Type (E): $Na–K–Cl–SO_4$ facie

From Fig. 6, type A ($Ca–Mg–Cl–SO_4$) constitutes 25 % of the water samples. It includes samples 7,10,14,16 and 19. It has appreciable amounts of chloride ion (Cl^-), sulfate ion (SO_4^-) and alkaline earth metal ions (Mg^{2+} and Ca^{2+}). Sulfate is a characteristic of water from atmospheric precipitation (Davis and De Wiest 1966) while chloride-rich water indicates brine origin (Todd 1980). In that case,

Table 3 VES result at Mgboejiogu street, Near Ezza road, Abakaliki and driller's log/well cuttings description from the surveyed borehole (N06°203′, E008°055′)

Layer	Thickness (M)	App resistivity (Ω m)	Inferred lithology	Description	Drilling log analysis	
					Depth (m)	Lithology
1	0.69	1243.9	Overburden	Topsoil	4	Overburden sandy–clay laterite
2	1.87	1042.6	Compact clay (mudstone)	Aquitard	10	Humid mudstone
3	3.92	947.2	Humid shale formation with mudstone	Soil water	12	Sandstone lenses
4	9.28	832.7	Fractured shale	Aquiclude	23	Dark-gray shale (fissured, not prolific)
5	28.21	544.3	Weathered shale	Aquifer	30	H_2O saturated zone
6	101.20	1388.9	Unweathered Shale	Aquiclude	80	Hard bedrock

Table 4 Results of chemical parameters of water samples studied

Sample number	Sample location	Pb (mg/l)	Fe (mg/l)	Ca^{2+} (ppm)	Mg^{2+} (ppm)	Na^{+} (ppm)	K (ppm)	Cl^{-} (mg/L)	SO_4^{2} (mg/L)	HCO_3^{-} (mg/L)	NO_3^{-} (mg/L)	Total hardness (mg/L)	TDS (mg/l)	Ca hardness (mg/L)
1	Ameka 1	0.01	0.12	37.8	13.67	12.151	26.198	32	4	110	55.00	150	494	94
2	Amagu	0.007	0.05	24	2.19	12.136	20.986	30	15	40	55.88	69	195	60
3	Ameri 1	0.008	0.01	20	1.70	13.775	24.198	34	21	42	62.04	57	364	50
4	Enyigba 1	0.01	0.64	21	0.24	110.35	45.150	150	30	150	44.22	21	1020	20
5	Enyigba 2	0.005	0.81	32	4.64	9.741	18.741	24	13	70	85.67	99	422.5	80
6	Abakaliki 9	0.006	0.09	33	10.99	12.138	20.841	46	9	124	68.84	153	338	108
7	Abakaliki 8	0.011	0.02	24	1.47	9.981	19.216	98	21	28	35.20	66	734.5	60
8	Abakaliki 2	0.009	0.04	36	11.72	7.251	16.721	12	7	122	43.56	138	273	90
9	Igbeagu	0.009	0.67	35	8.55	9.081	31.081	24	58	92	35.64	233	748.5	100
10	Nkwagu	0.007	0.01	24	6.35	9.751	16.581	100	12	34	75.68	86	186	60
11	Ameri 2	0.005	0.98	32	9.77	11.241	27.342	16	15	82	66.08	120	403	80
12	Ameka 2	0.018	0.03	50	10.26	8.975	19.095	34	0	102	35.20	228	422.5	124
13	Abakaliki 1	0.007	0.18	27	0.24	12.136	27.986	12	7	38	31.68	69	195	68
14	Abakaliki 4	0.007	0.03	74	10.26	10.025	21.061	80	150	82	41.36	228	598	186
15	Abakaliki 3	0.009	0.12	40	2.44	10.841	24.181	8	3	100	28.60	110	473	100
16	Abakaliki 11	0.008	0.06	40	7.81	9.225	17.316	24	41	80	64.24	132	572	100
17	Abakaliki 7	0.009	0.78	32	9.77	10.92	25.097	20	21	68	38.28	120	188.5	80
18	Abakaliki 5	0.009	0.40	08	5.24	10.09	22.081	30	29	8	23.44	21	145	20
19	Abakaliki 6	0.007	0.02	34	12.21	9.981	27.198	50	96	20	51.48	200	325	150
20	Abakaliki 10	0.01	0.01	49	14.16	10.986	21.98	56	4	98	38.72	180	617.5	122

Offodile (2002) disclosed that brine springs issue out along the axis of the Abakaliki anticlinorium. The brine spring is likely the source of the chloride in this group. Therefore, type A facie is an indication of mixing groundwater environment where water from intermediate zones streamlined from recharge areas that have much influence of precipitation, dilutes salty water harbored in the Asu River sediment. This type of facie falls within the range of normal alkalinity according to Nton et al. (2007). The water type is localized within the Abakaliki town.

Type B ($Ca–Mg–HCO_3–Cl–SO_4$) is the dominant water type in the study area and constitutes about 45 % of the water samples. It comprises samples 2, 5, 6, 9, 12, 13, 15, 17 and 20. It is an intermediate facie situated between the two end members of types A and C. Ca^{2+}, Mg^{2+} and HCO_3^{-} can be attributed to dissolution of carbonate mineral while SO_4^{-} dissolved from sulfide minerals, all of which can be influenced by recharging rainwater. For chloride ion, Cl^{-}, it is indicative of deepwater zone (Freeze and Cherry 1979). So, this group is between recharge zone and deepwater environment, somewhat hard, slightly acidic and weak alkaline water. It is likely an intermediate zone. This group is more prominent from the central to the southern part of the study area.

Type C ($Ca–Mg–HCO_3$) symbolizes water from recharge zone where carbonic acid formed due to reaction of CO_2 from organic matters and infiltrating water from rain in the unsaturated zone reacts with earth materials to release Ca^{2+}, Mg^{2+} and HCO_3^{-}. It constitutes about 15 % of the whole samples and comprises samples 1, 8 and 11.

Table 5 Results of hydrochemical analysis of the major ion concentrations in meq/l

Sample number	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3	SO_4^{2-}	Cl^{-}
1	1.85	1.12	0.33	0.67	1.80	0.08	0.99
2	1.18	0.18	0.53	0.54	0.83	0.51	0.85
3	0.98	0.14	0.60	0.62	0.69	0.43	0.96
4	1.05	0.02	4.80	1.15	2.46	0.62	3.53
5	1.57	0.38	0.42	0.48	1.15	0.27	0.68
6	1.65	0.90	0.48	0.53	2.03	0.00	1.30
7	1.18	0.12	0.43	0.50	0.46	0.44	2.80
8	1.76	0.96	0.32	0.43	2.00	0.87	0.34
9	1.75	0.70	0.51	0.80	1.51	1.21	0.68
10	1.18	0.52	0.42	0.43	0.056	0.25	2.82
11	1.57	0.80	0.49	0.70	1.34	0.31	0.45
12	2.43	0.84	0.39	0.49	1.67	0.00	0.96
13	1.33	0.02	0.53	0.72	0.62	0.15	0.34
14	3.65	2.06	0.45	0.54	1.37	3.125	2.26
15	1.96	0.20	0.47	0.11	1.64	1.78	0.23
16	1.96	0.64	0.40	0.44	1.31	2.60	0.68
17	1.57	0.80	0.48	0.64	1.11	0.44	0.56
18	0.39	0.48	0.44	0.57	0.13	0.60	0.85
19	1.70	1.00	0.43	0.70	0.33	1.77	1.41
20	2.39	1.16	0.48	0.56	1.61	1.13	1.58

Table 6 Conversion factors for major ions from ppm (or mg/l) to meq/l

Ion	Atomic number	Conversion factor
Ca^{2+}	40.08	0.04990
Mg^{2+}	24.31	0.08224
Na^{+}	22.99	0.04348
K^{+}	39.10	0.02556
HCO_3^{-}	61.02	0.01639
SO_4^{2-}	96.02	0.02082
Cl^{-}	35.45	0.02820

This type of water is characterized by hardness due to carbonate effect, dominated by alkaline earth metals (Ca, Mg) and weak acid of bicarbonate (Nwankwo 1988). The facie is found around the old mine areas (Ameka 1 and Ameri 2) and toward Ishieke village near Ebonyi State University (EBSU) faculty of education campus.

Type D (Na–K–HCO_3) constitutes about 5 % of the study area and involves only sample 4. It is alkaline water, which might have evolved through cation exchange process from the weathered zone of the Abakaliki shale, probably dominated by clayey soil (cation exchanger) within the shale of Asu River group. The exchange reaction could be as follows:

$$\frac{1}{2}Ca^{2+} + Na \cdot X \rightarrow 1/2\ Ca \cdot X + Na^{+}$$

where Ca^{2+} is taken up from the water to the cation exchange material (X) which in exchange releases Na^{+} to the groundwater, resulting in a Na–HCO_3 water type. This reaction causes more dissolution of carbonate minerals as a result of increased affinity of the water to replace the lost Ca^{2+}, thereby releasing more HCO_3^{-} and subsequently raising the pH, and making the groundwater alkaline. The water type is interpreted as groundwater on transit due to the prevalence of the cation exchange process. The water type is found at Enyigba in the southern part of Abakaliki town.

Type E (Na–K–Cl–SO_4) constitutes 10 % of the total water types and involves water samples 3 and 18. It can be found in deep subsurface zone where halite or normal salt (NaCl) is harbored. The water type is dominant near the pyroclastic massif which is the site for town water supply reservoir, off Water Works Road in Abakaliki town (sample 18), and at the Ameri village (sample 3) in the located south of Abakaliki town, where salt was mined before the 1967 civil war. Sample 3 which is from hand-dug well (about 250 meters deep) is the particular salt well where the salt was mined. It is therefore observed that the pipe-borne water (sample 18) has the characteristics of deep water type even though its source is apparently from the surface; this could be as a result of reagents applied for treatment before distribution.

Figure 7 depicts the areal distribution of the water types. Type C (recharge zone) is surrounded by type B (intermediate zone) in the northwest and aligns southeastward with type A (mixing groundwater zone). The type A confines type E (deep groundwater zone) at northcentral while type B extends to the center of Abakaliki town where it is overlain by a central refuse dump located beside Iyokwu River, near Tycoon Filling station which is 1/2 km away from Federal Teaching Hospital, Abakaliki, along Enugu–Abakaliki express road. From there, the water type moves to join type A at location 10 (Nkwagu). Toward the south, the dominant type B sandwiches water type C and joins type D; the water type D is inferred as water after a short distance of travel from recharge zone, advancing to the depth regime. It dominates only in location 4.

The sandwiched recharge zone of type C within the serially isolated and wide spread intermediary type B (see Fig. 7) is correlated with the series of isolated recharge points marked by cone-like uplifts as shown in Fig. 5 indicated same trending sources of groundwater recharge. Thus, the recharge areas in hydrogeological studies are obviously signified by levels of higher groundwater heads. A comparison of the facie flow in Fig. 7 with the groundwater flow directions obtained from the water table map (Fig. 4) clearly proved variability of the flow system. The idea of groundwater evolution from recharge zone to the intermediate zone and down to the deep zone according

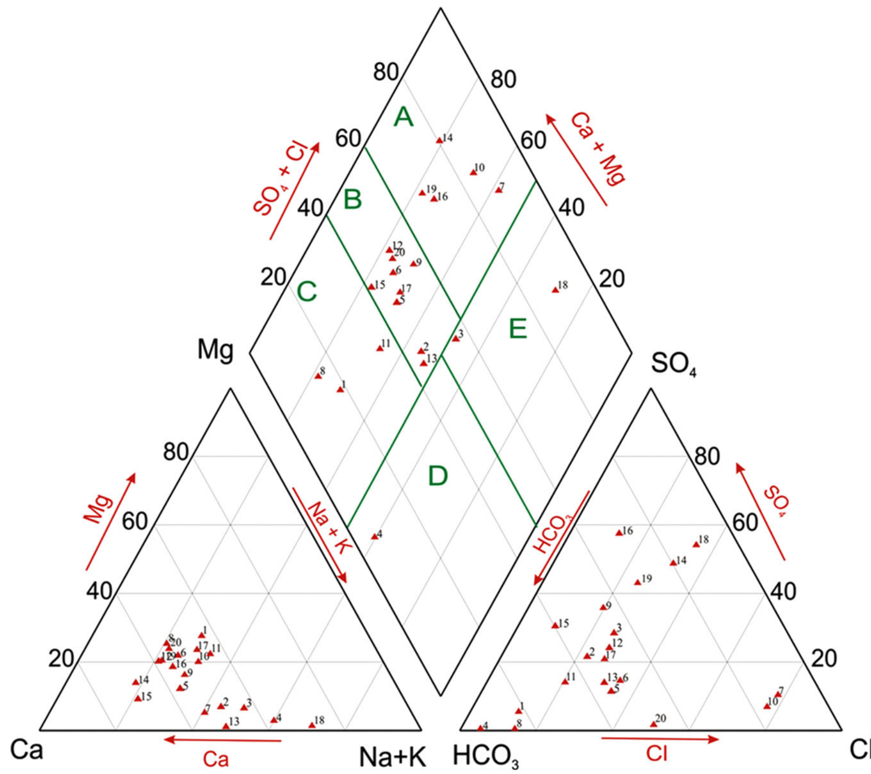

Fig. 6 Piper trillinear diagram

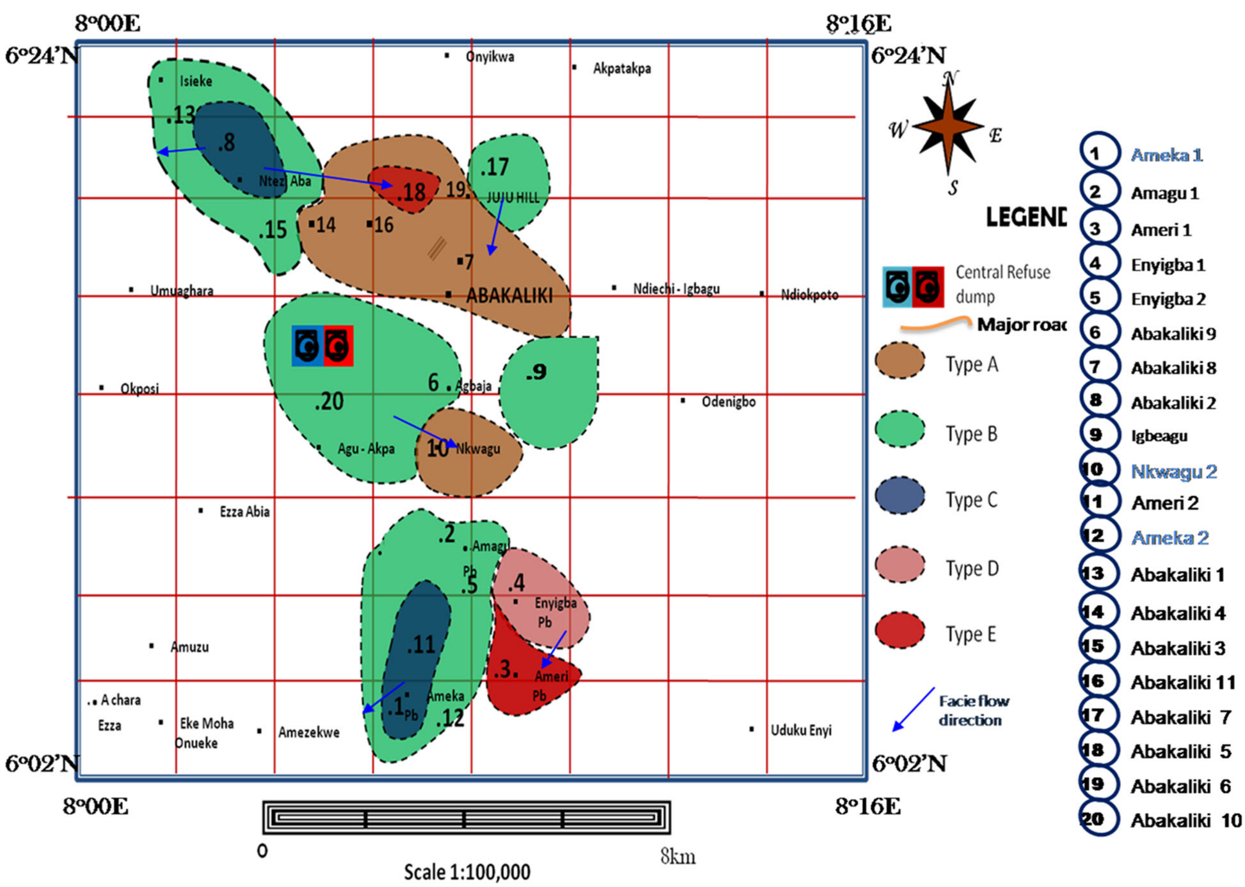

Fig. 7 Isopleth map showing distribution of the hydrochemical facies

Table 7 Summary characteristics of the water types for the aquifers of the studied area

Facie group	General characteristics	Occurrence	Interpretation
A	High SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} Low Na^+, K^+, HCO_3^- pH 6.68–7.91	Predominantly at Abakaliki municipal	Mix groundwater zone. Falls within very weak alkalinity range (Nton et al. 2007)
B	High HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} Low Na^+, K^+ pH 7.09–8.10	Abakaliki metropolis by a central refuse dump and around the derelict mine sites	Intermediate zone. It is alkaline water type
C	High HCO_3^-, Ca^{2+}, Mg^{2+} Low Na^+, $K^{+.}$ pH 6.54–8.10	Adjacent of the abandoned mine sites	Hard water due to high bicarbonate content. Have influence of weak acid, signifies recharge of meteoric water
D	High HCO_3^-,Na^+, K^+ Low SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} pH 6.00	Observed at the old mine province; Enyigba	Evolves from slight acidic to alkaline water depict water from short distant transit
E	High SO_4^-, Cl^-, Na^+ and K^+ Low Mg^{2+} while HCO_3^- and Ca^{2+}. Range from low to moderate pH 5.28–7.37	Town water supply reservoir and from abandoned Ameri mine site	Connate water characteristic, high content of halite (NaCl). Acidic due to treatment reagent for the pipe-borne water

to Chebotarev (1955) was delineated in the facie map which explains flow from water type C, passes through type B to type A and flows downstream to type E, whereas type D may be flowing from type C via cation exchange medium and discharges to the surface, thereby forming a spring or even continues to join the deep water (type E) via anion exchange process. The modeled directions of the facie flow are indicated by the arrows as shown in Fig. 7, which depicts local variable flow system vis-a-vis the groundwater flow pattern exhibited in the water table map (see Fig. 4). The summary characteristics of the water types in the study area are outlined in Table 7.

Conclusions

Five hydrochemical facies, namely Ca–Mg–Cl–SO_4 as type A, Ca–Mg–HCO_3–Cl–SO_4 as type B, Ca–Mg–HCO_3 as type C, Na–K–HCO_3 as type D and Na–K–Cl–SO_4 as type E, are prevalent in the groundwater of the area, each producing a water type that is dominantly alkaline. The water types are interpreted as groundwater from mixing groundwater environment, intermediate groundwater zone, recharge zone, discharge/transit zone and deep groundwater zone, respectively. Their relative abundances as delineated on the hydrofacie map show that Ca–Mg–HCO_3–Cl–SO_4 which is within an intermediate groundwater zone is the most abundant.

The facie flow was correlated with the groundwater flow, and both confirm the variability of flow system whose pattern is not uniform, rather to various directions indicating non-regional groundwater flow. From the studies of environmental impact of the formation lithology on the groundwater, the major groundwater sources that feed the Cross River basin from the area are mineralized connate water and water from precipitation.

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