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Socio-economic influence of hydrogeology in regions adjoining coal bearing formation: Water policy in Anambra Basin

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Abstract

The Coal Province lies within the central portion of Anambra Basin and along the axis of regional water resources catchment of Southeastern Nigeria. Although this area includes a prolific aquifer, the high cost of development and treatment of the groundwater degraded by AMD has created water scarcity problems against water policy initiatives. Social and economic impacts were investigated, even as policy measures for rehabilitation purposes through water resource management were highlighted. Several geoscientific methods were integrated for the investigations. Mean resistivity up to 30 Ω-m relatively at shallow depths indicated aquitards of Enugu/Mamu Formations, whereas the aquifer reflected resistivity $\leq$1,000 Ω-m at depths of $\geq$180 m across Ajali Sandstone. Alkaline-rich seepage flushed Fe-rich AMD at aquifer-aquitard interfaces adjoining the river catchment area. The AMD-induced oxidation process produced noxious Ca-Mg-Na-HCO_3-SO_4-Cl facie. These results were correlated with policy related questionnaires. Plans for water security were proposed, mainly to channel groundwater directly from the regional aquifer, or the chemically degraded seeped water from the fluvial system, into constructed water reservoir (treatment) columns prior to distribution to the town-water supply. Such water resource development is cost effective; and with management policies regulated by relevant decision-making agencies, sustainable supply is assured.

Keywords: Acid mine drainage (AMD); Economy; Policy makers; Regional aquifer; River catchment; Water supply

Highlights

- Poor operation, development and maintenance of water resources scheme in Nigeria, particularly around Enugu region prompted this study.

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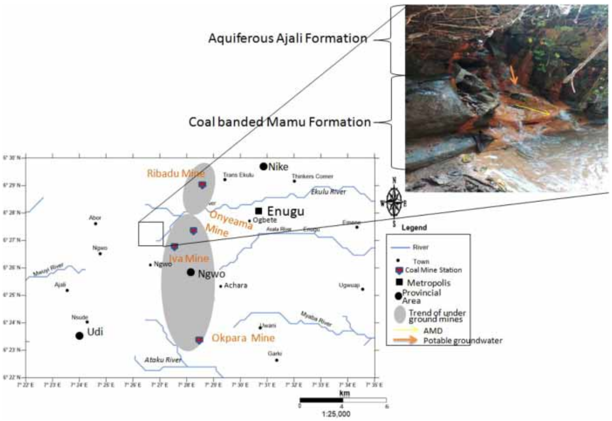
- Economic losses are surpassing gains earlier accrued from coal exploitation in the studied region.
- This impasse is felt via water resources against water policy standpoint.
- The hazards and causative processes were identified.
- The information can guide in decision making intervention.

Graphical Abstract



Introduction

Background

Enugu coal province is an ancient city in Southeastern Nigeria. The region is located at the center where industrialized potable water is produced and distributed in hygienically sealed packs (60 cL watertight sachets and various sizes of bottles) to different parts of Nigeria. The water is supplied from an adjoining, prolific, potable inland and regional freshwater aquifer of Ajali Sandstones, and does not undergo rigorous chemical treatment prior to the industrial packaging. The product is generally supplied across Nigerian states, even as the demand increases. However, people across the region live in poverty relating to water supply problems. A previous literature review noted the problematic water supply in Enugu State (Nganje *et al.*, 2011; Utom *et al.*, 2012). Hitherto, residents around Enugu province, populated mainly by low income earners (Onugbo *et al.*, 2010), obtain water for domestic and other purposes from independent water vending systems operated by private sectors (Onyenechere *et al.*, 2012). It is bothersome that the amount of money spent on the insufficient water supplied (per day) from the private vendors can be ten times larger than the cost of ample water that would be supplied via pipes or taps for one month (World Bank and Federal Republic of Nigeria Water Supply and Sanitation, 2000). Except for a few affluent individuals, the water vending service is unaffordable, especially as the failure of the water pipe project has not been overcome in Enugu region. These challenges were connected with quality induced scarcity and high cost of water resource development due to drainage of coal mine effluents into the fluvial setting emanating from the groundwater system.

Remarkably, the coal field province lies north of the Enugu-Udi ranges of Escarpments, along the regional water divide. The divide separates two major hydrological zones in the Anambra Basin.

Intensive mining of the coal deposits had earlier crisscrossed the coal fields (Abiodun, 2015). The Water Project (2019) noted that such activity has aggravated poverty in Africa due to the induced lack of water supply. Enugu Metropolis is a typical case because few out of the population have access to water supply (Ojibo, 2009) and has caused lowly wellbeing of people (Khatri & Vairavamoorthy, 2007). This can be attributed to the reason why the average residents of the coal province and adjacent regions live below the poverty line, and the situation can be even worse in rural settlements (Bassi & Kumar, 2012) around the downstream communities. Thus, identifying and understanding the complex upstream-downstream linkage in the Basin is important (Pandeya *et al.*, 2020) in order to examine the cultural, social and economic significances of water resources.

Lack of expertise and costs of investment impede the utilization of water resources (Rambabu *et al.*, 2020), just as lack of vision sometimes aggravates the problem (Christian-Smith *et al.*, 2011). On this note, agencies, stakeholders and policy makers concerned for public water supply seem to lack strategies for potable water supply development in the region (Eneh & Nnaji, 2017), particularly the 21st century policy ideas. Limitations in previous studies prompted the present research in order to determine some innovative remedy. The resulting data can be annexed into the data bank of the national water policy in order to boost the efficiency of manpower in the ministry of water resources and other related sectors. The study linked activation of inert chemicals via coal mining to the deterioration of water resources around Enugu and the adjoining regions. It was found that ecological menaces from the existing mining operations and the hydrogeologic/geologic conditions of the region created a wide economic gap between income per average resident and the huge incomes belonging to a few businessmen who own large-scale water bottling factories. Closing the gap entails scientific policy initiatives, as well as cooperation among stakeholders of the water sector as proposed in this study. The proposed plan will improve the water infrastructure which has been marred by poor operation and maintenance (National Water Policy, 2004).

In general, previous studies related the high poverty level to low income earning among the population of the region, yet the cause of the low incomes remained unknown. The main novel finding in this study was tracing the major reason for the economic challenge for the lack of, or inadequate, water policy initiatives. Then, it closes the gap by proposing job opportunities through development of the water resource infrastructure in Anambra Basin.

Geologic history and geomorphologic setting

The Santonian tectonic episode deformed the entire Benue Trough into a variety of landforms and geologic features, such as folds, faults, fractures, synclines and axial ridge belts (Obaje, 2009), and above all, formed the Abakaliki anticlinorium that detached the western extreme of the trough as an isolated depression. Sedimentation filled the depression with post Santonian sediments and thus formed a platform referred to as Anambra Basin. According to Odunze *et al.* (2013), the Basin fill commenced in the late Campanian with deposition of the Nkporo Group (mainly Enugu shale and Owelli sandstones) and spanned to early Maastrichtian. In the middle Maastrichtian, the coal bearing Mamu formation was deposited, followed by Ajali sandstones, as well as the onset of Nsukka formation in the mid-late Maastrichtian (Obi & Okogbue, 2004). The general geology of Anambra Basin and other adjoining regions is summarized in Figure 1.

Locally, the coal bearing flank which adjoins Ajali formation is drained by various rivers eastwards, following downgrading altitudes (Figure 2). The average altitude of the coal province region is about 100 m with a mean monthly temperature ranging from 24 to 28 °C; mean annual rainfall is between 1,200 and

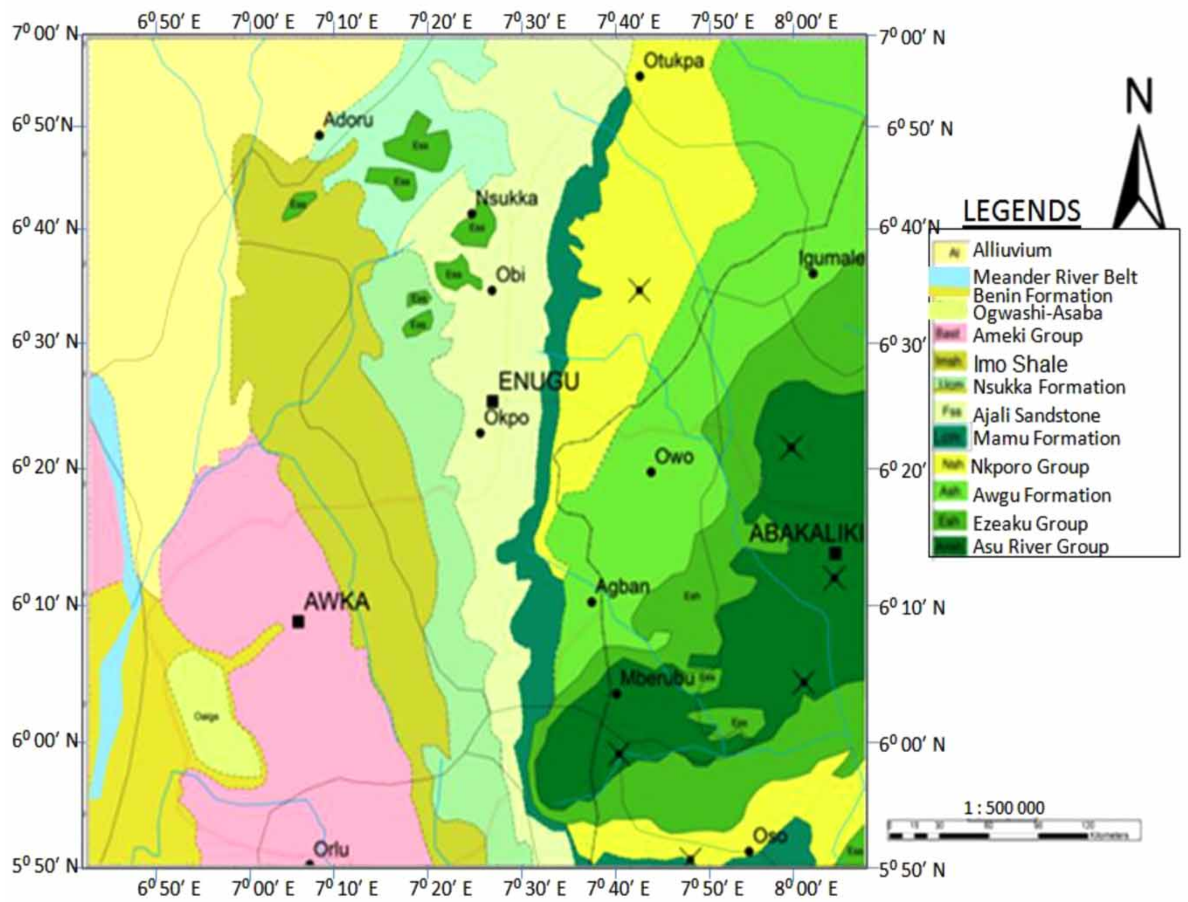


Fig. 1. Regional geological map of Abakaliki, Anambra and Afikpo depocentres.

2,000 mm. Okpara *et al*. (2013) described similar weather conditions as climatic components that support vegetation such as the Guinea forest (see Supplementary Material, ESM.No.1[i]A) being characterized by bimodal rainfall distribution. However, the climate has gradually been lost to tropical/derived Savanna ecology (see ESM No.1 [i] B) due to climate change. An elongated valley dots the boundary between the coal rich formation and Ajali sandstones. The valley is characteristically marked by evergreen vegetation (see ESM No.1 [i] A, B) because of perennial seepages from the sandstone aquifer.

Materials and methods

The impact of anthropogenic interference on the fluvial regime was investigated by adopting a combined methodological framework, comprising field survey (Mitra *et al.*, 2020), laboratory and statistical analyses. The field survey was mainly composed of geological, geophysical and hydrogeological/hydromorphological analyses. These techniques were used to study the outcrops, subsurface units, and to verify the general status of water resources in the area. For ground probing, vertical electrical sounding (VES) was carried out in 30 locations (Figure 3) using an ABEM instrument (Signal Averaging System [SAS]

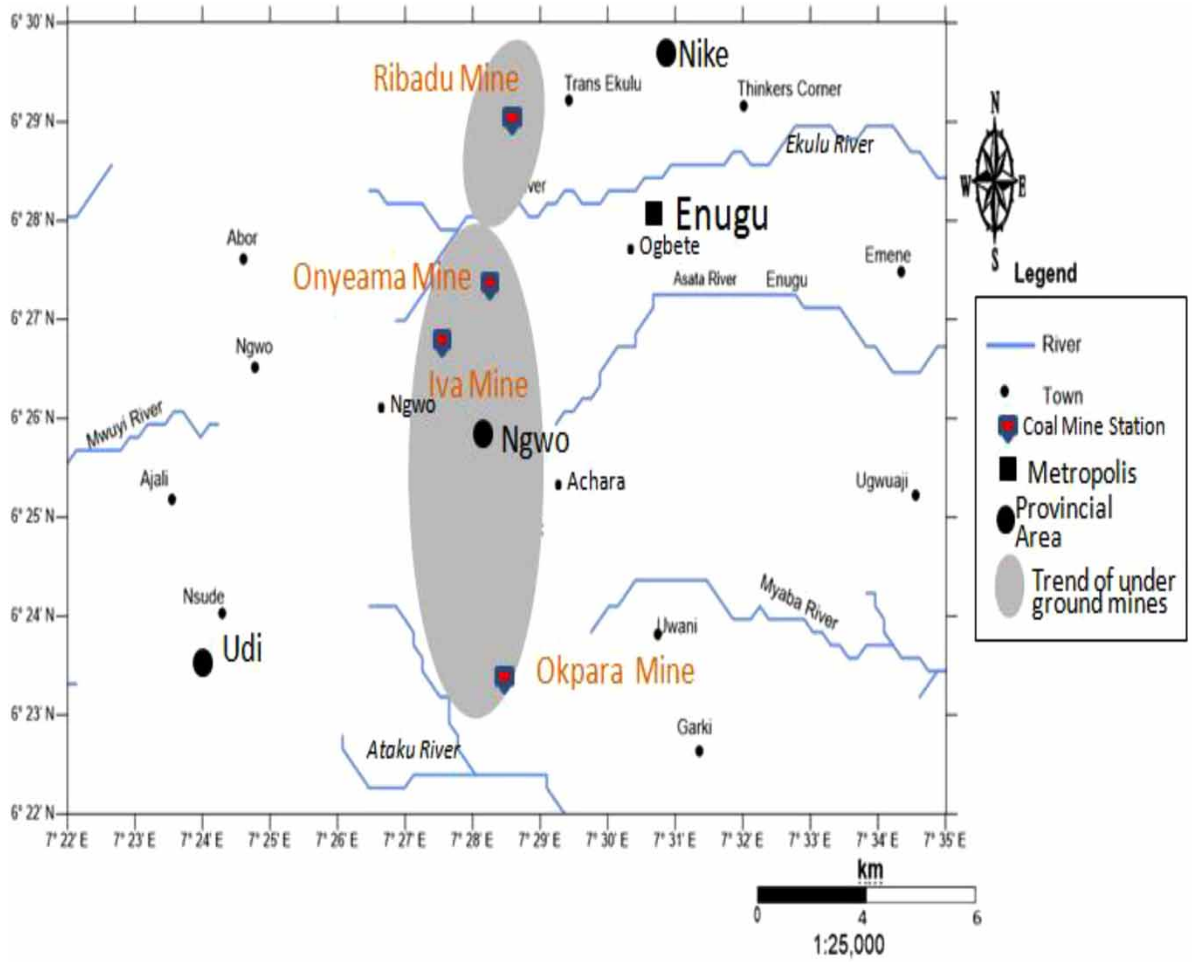


Fig. 2. Map of the river source protection zone (RSPZ) around the coal province showing trends of interconnected underground mines intersecting major river catchment basins.

1000) via Schlumberger configuration. The acquired field data were manipulated through the software program (INTERPEX) to produce graphical geomodels. As shown in Figure 3, the VES locations were grouped into five lines of cross sections for interpretation purposes.

Hydrogeochemical analysis commenced with water sampling (see ESM No.1[ii] A, B, C, D) in 26 locations (Figure 4). The samples were transported under cooled/refrigerated conditions within 24 hours to the Analytical Laboratory, Federal Secretariat, Ibadan, Nigeria. A statistical product for service solutions, SPSS (version 13), was used for statistical analysis (Ukpai & Okogbue, 2017) of the geochemical data, while graphical interpretations were aided using aquachem software (version 15). Static water levels were measured using a dip meter (Heron model), following guidelines for the instrument in Ukpai *et al*. (2016) for determination of the pressure heads.

The textural properties of the overburden sandstones were evaluated via grain-size examination by performing sieve analysis on each 50 g sandstone sample collected at surface horizons in 10 locations across the Mamu and Ajali formations. This analysis serves as a potential alternative for estimation of hydraulic

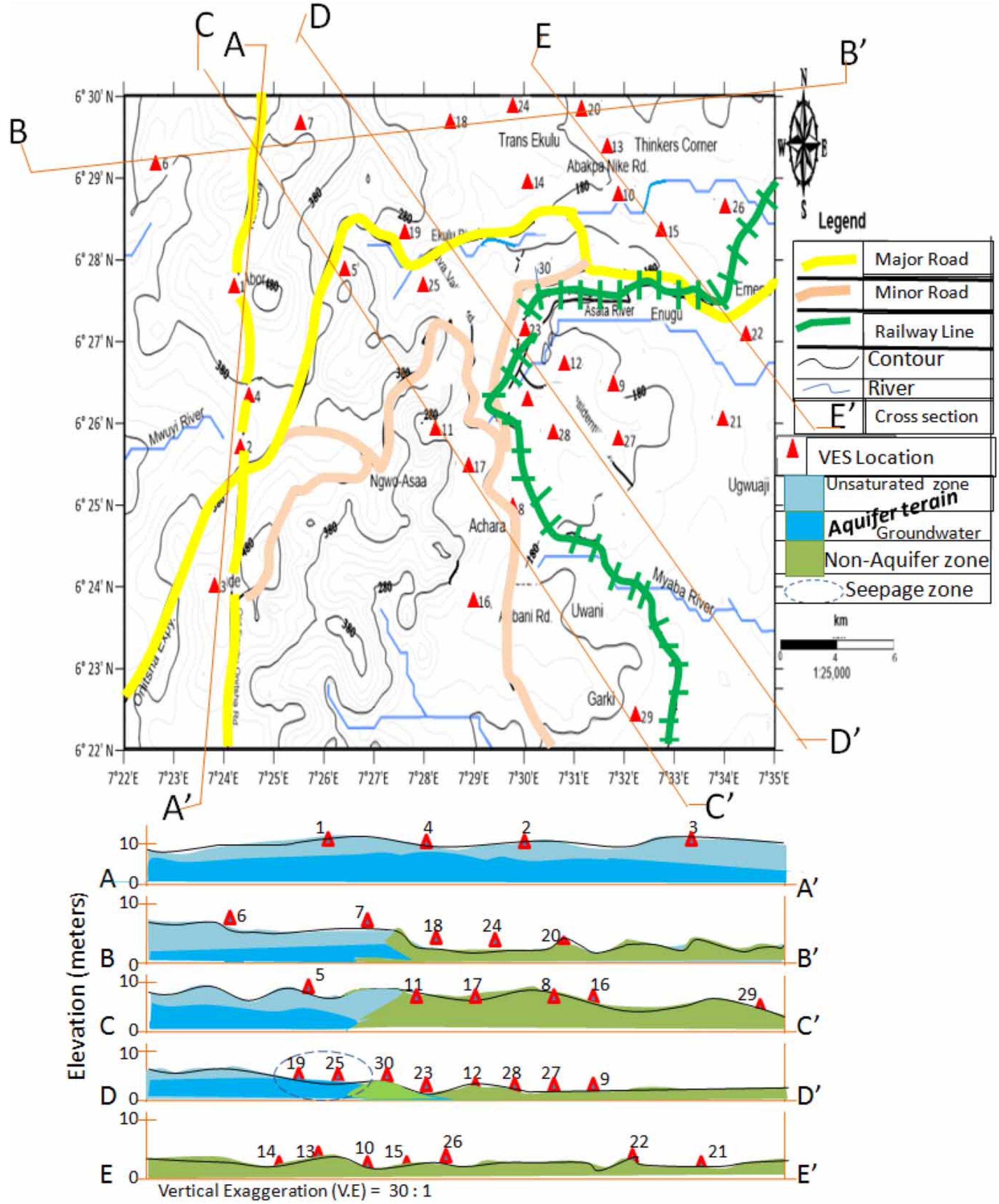


Fig. 3. Map showing VES locations with traverse cross sections.

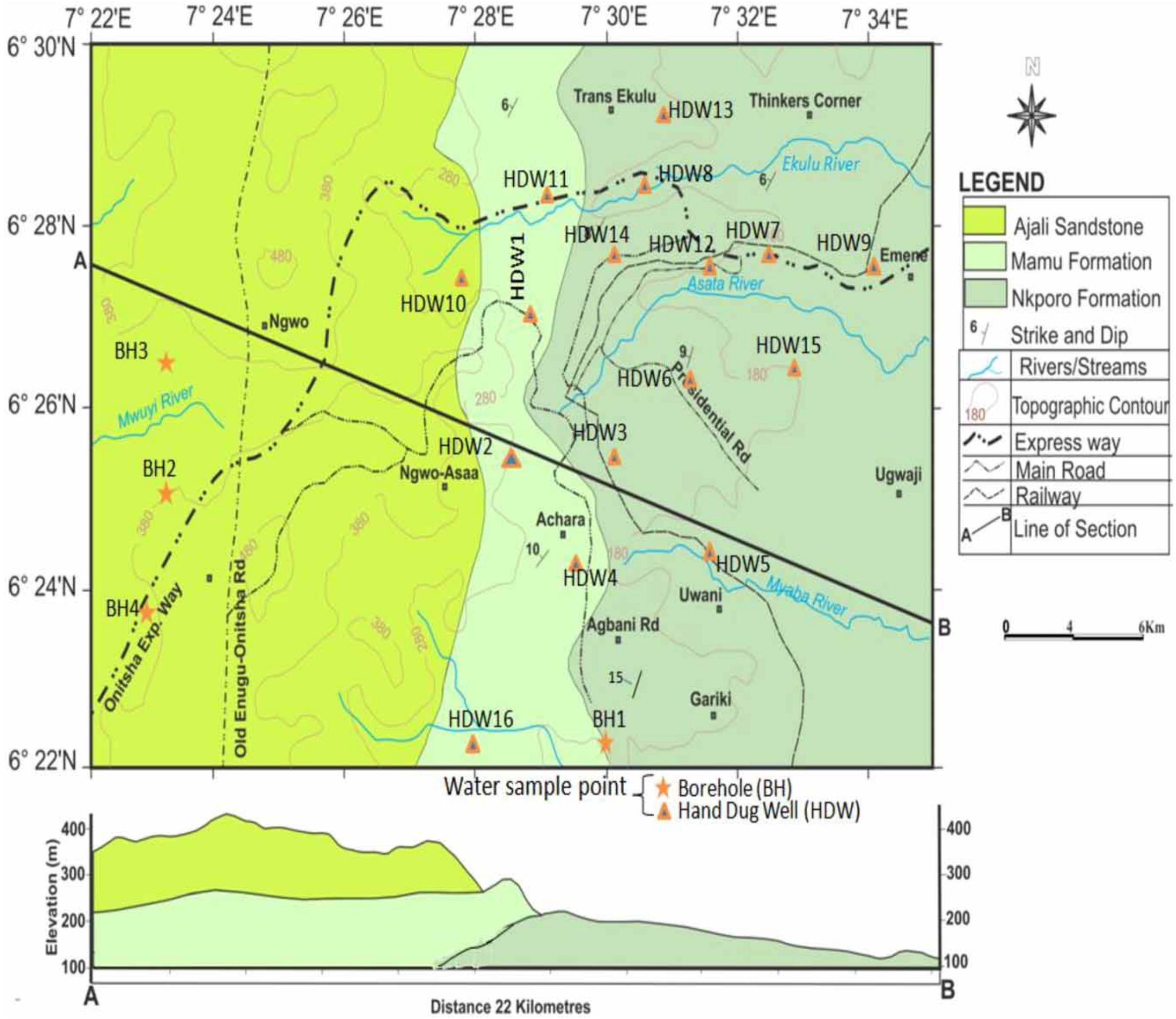


Fig. 4. Local hydrogeological map of the coal province with superimposed water sample locations.

conductivity (Jayakumar *et al.*, 2012) in order to determine the extent of porosity available for infiltration. Accurate results were guaranteed by brushing the screen openings to remove waste particles prior to the analysis. The entire set up was vibrated for about 10 minutes using a mechanical shaker. Thereafter, the material retained on the bottom pan was weighed and average values were recorded. Graphs of weight (in %) were plotted against particle sizes (in Φ and mm). Relevant percentile values were derived from the graphs and are shown in Equations (1) and (2) for analysis of statistical parameters:

$$\text{Mean}(M_e) = \left(\frac{\emptyset 16 + \emptyset 50 + \emptyset 84}{3}\right) \tag{1}$$

$$\text{Standard deviation (SD)} = \left(\frac{\emptyset 84 + \emptyset 16}{4}\right) + \left(\frac{\emptyset 95 + \emptyset 5}{6.6}\right) \tag{2}$$

The porosity (n) of the overburden sand was evaluated from the empirical relationship with coefficient of uniformity (CU) shown in Equation (3) (Ukpai *et al.*, 2017) as:

$$n = 0.255(1 + 0.83^{\mathrm{CU}}) \tag{3}$$

where:

$$\mathrm{CU} = \frac{D60}{D10}\ (\mathrm{Fetter}, 2007) \tag{4}$$

D_{10} (mm) and D_{60} (mm) represent the 10th and 60th percentiles respectively in the graphs of cumulative weight (%) against particle size in mm.

A systematic review of past research studies relating to the study theme was undertaken following Bassi *et al.* (2020) in order to highlight policies that link cultural significance of the research with livelihoods and society.

Results and interpretation

Water resource prospect

From the interpreted geomodel data (ESM No.2C), the aquifer zone was inferred at an average depth of $\geq$200 m and mean resistivity $\leq$1,000 Ohm-m, stretching across the 4th, 5th and 6th geoelectrical layers (see Supplementary Material, Appendix: from ESM 2b to 2f). The relative thicknesses are summarized in Table 1. The surveyed locations are superimposed on a local map of the area, and interpreted relative to the respective group of the VES traverses in each cross section (see Figure 3). Comparison of Figures 3 and 4 showed that all traverse cross sections were traced from Ajali formation except line E-E′. Comparing the grouped VES locations in the cross sections with Table 1, the VES points in each group depicted aquifer zones only at the axis of Ajali sandstone. As observed, line A-A′ showed an aquifer zone with the comprised VES 1, 2, 3 and 4, all in Ajali sandstone formation. The VES 6 and 7 indicated an aquifer zone in a portion of the sandstone formation of line B-B′. Furthermore, only VES 5, which falls within the sandstone formation, indicated the presence of an aquifer zone in line C-C′. More so, in line D-D′, VES 19 and 25 were deduced as aquifer zone at the edge of the sandstone terrain. None of the VES locations, namely VES 10, 13, 14, 21, 22 and 26, in line E-E′ signified aquifer. Thus, the Ajali formation produced a groundwater resource from the western side of the coal province (see Figure 4). This fact was further proven from the water table model (Figure 5) which showed eastward slanting of hydraulic gradients, indicating groundwater occurrence and flow from the western corner of the studied region.

Although the porosity is effective, generally at 50% (Table 2), the sandstone aquifer is mainly formed in the 5th geoelectric unit. Relatively, Offodile (2002) reported that efficient hydraulic conductivity and transmissivity characterized the porous media of the aquifer zone at the 5th layer. Such an aquifer zone is absent around Enugu metropolis and adjacent downstream areas due to argillaceous sediments that formed the underlying Mamu and Enugu formations. In these formations, composite sandy shale layers which could reflect low resistivity (Ukpai *et al.*, 2020) were inferred as aquitards at shallow depths. Comparison of Table 1 and Figure 4 shows that most of all VES locations characterizing low

Table 1. Summary of geophysical data for vertical electrical sounding.

VES	ρ_1 Ωm	ρ_2 Ωm	ρ_3 Ωm	ρ_4 Ωm	ρ_5 Ωm	ρ_6 Ωm	ρ_7 Ωm	Th_1 (m)	Th_2 (m)	Th_3 (m)	Th_4 (m)	Th_5 (m)	Th_6 (m)	d_1 (m)	d_2 (m)	d_3 (m)	d_4 (m)	d_5 (m)	d_6 (m)
1	171	451	2,155	710	1,824	86	–	1.5	19.2	23	58.9	115.4	–	1.5	20.7	43.7	102.6	218	–
2	158	187.8	369.2	3,550.0	1,077.0	147.9	–	1.0	1.5	2.2	29.4	201.8	–	1.0	2.5	4.7	34.1	236	–
3	1,891	1,466	5,002	9,166.0	925.1	–	–	1.3	13	5.5	155.7	–	–	1.3	14.3	19.8	175.5	–	–
4	200	11,986	5,101	622.1	331.7	–	–	2.1	7.2	124.1	124.1–	–	–	2.1	9.3	133	257.5	–	–
5	299	1,242	2,961	9,318	165.8	–	–	0.8	1.1	8.4	167.8	–	–	0.8	1.9	10.3	177.9	–	–
6	1,348	21,967	2,795	10,696	406.4	–	–	1.3	0.8	16.4	120	–	–	1.3	2.1	18.5	139.1	–	–
7	518	1,482	3,195	5,533	584.8	–	–	2.5	25.4	55.2	88.9	–	–	2.5	25.9	81.1	170	–	–
8	399	33.2	17.1	63.8	–	–	–	5.5	17.0	104	–	–	–	5.5	22.5	127	–	–	–
9	399	58.5	4.8	4.0	75.1	32.8	–	1.8	2.9	4.7	9.6	60.5	–	1.8	4.7	9.4	19.0	79.5	–
10	202	12.3	18.2	2.5	–	–	–	3.7	21.8	97.1	–	–	–	3.7	25.5	123	–	–	–
11	58.2	49.8	23.9	6.8	30.3	–	–	0.7	7.1	29.1	60.0	–	–	0.7	7.8	36.9	96.9	–	–
12	2,415	130	19.7	116	–	–	–	1.0	18.4	98.9	–	–	–	1.0	19.4	119	–	–	–
13	254	924	254	24.2	253.6	400	1,510	0.7	1.4	3.6	5.8	26.3	71	0.7	2.1	5.7	11.5	37.8	109
14	204	646	23.3	13.1	20.0	–	–	1.0	2.1	5.9	8.0	66.6	–	1.1	3.2	9.1	17.1	85.7	–
15	80.6	45.3	6.3	33.3	6.3	–	–	1.5	6.4	22.5	98.8	–	–	1.5	7.9	10.4	129.2	–	–
16	2,648	176.5	14.0	22.6	38.3	–	–	1.9	6.9	51.2	97.9	–	–	1.9	8.8	60.0	157.9	–	–
17	7,769	156	72	45	260	–	–	0.9	1.5	25.7	102.5	–	–	0.9	2.4	26.1	128.6	–	–
18	199	225.5	11.2	20.8	26.3	–	–	0.1	7.6	70.0	90.3	–	–	0.1	7.7	77.8	168	–	–
19	943	1,313	169.6	57.6	10.6	25.5	–	1.0	4.7	7.7	21.8	147.8	–	1.0	5.7	13.3	35.1	183	–
20	627	149.1	63.4	11.9	–	–	–	5.9	5.7	14.6	97.7	–	–	5.9	11.6	26.1	125.9	–	–
21	455	104.4	33.2	23.5	–	–	–	4.3	26.8	119.2	–	–	–	4.3	31.1	150	–	–	–
22	90.3	433.1	275.1	26.9	52.4	71.0	–	1.0	0.8	10.8	67.0	47.2	–	1,0	1.8	12.6	79.6	127	–
23	139	29.7	14.3	29.7	7,3			2.9	25.1	53.9	105.1	–	–	2.9	28.0	82.0	187.1	–	–
24	114	54.7	24.0	12.6	–	–	–	2.1	20.9	8.3	93.0	–	–	2.1	25.0	31.3	125.1	–	–
25	144	1,069	42.5	21.5	161.3	–	–	1.0	3.0	11.1	113.6	–	–	1.0	4.0	15.1	128.7	–	–
26	92.4	330.9	106.9	44.8	130.2	12.5	10.2	1.4	4.5	5.6	23.3	49.8	95	1.4	5.9	11.5	34.8	84.6	180
27	211	272.8	61.4	18.2	26.4	–	–	2.1	6.8	14.0	122.1	–	–	2.3	9.1	23.0	145.1	–	–
28	1,024	2,559	28.9	15.2	23.5	–	–	3.8	11.0	40.6	69.8	–	–	3.8	14.8	55.4	125.2	–	–
29	60.1	4.5	40.7	16.0	10.5			1.1	4.1	39.9	152.7	–	–	1.1	5.2	45.1	178	–	–
30	46.6	174	25.7	16.3	29.2	–	–	1.7	6.3	11	97	–	–	1.7	8.0	19.0	115.7	–	–

Note: Yellow is the aquifer representative unit and depth; Dark ash is inferred typical recharge zone.

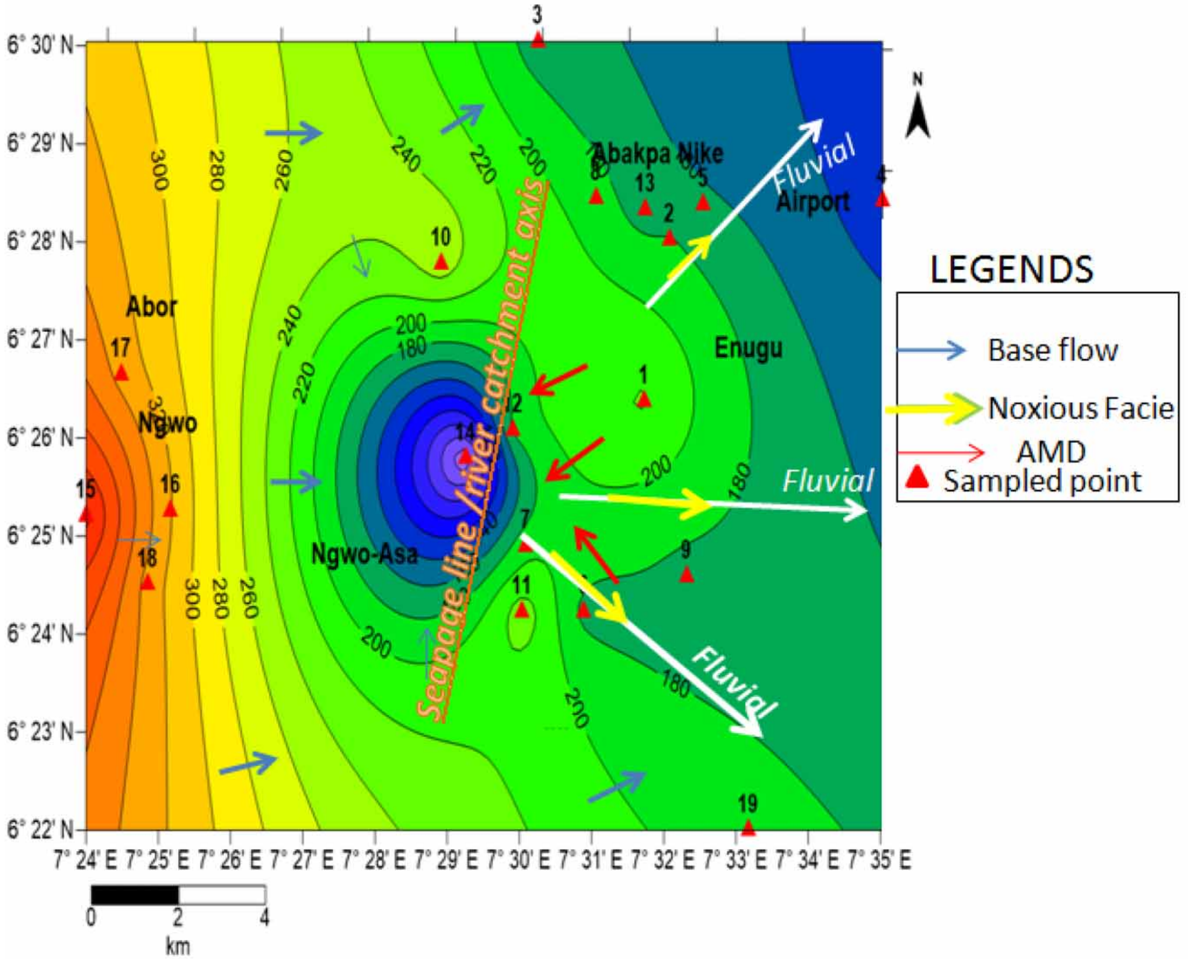


Fig. 5. Water table map showing hydraulic heads. Base flow, seepage line, AMD and directions of the produced fluvial setting.

resistive units with narrow thickness at the shallow depths fall within the Mamu and Enugu formations. This is why occurrence of groundwater is difficult around the coal city, an issue of concern that needs an intervention scheme by the policy making section of the water sector.

Lithofacie description/hydrologic significance

Figure 4 shows the local geologic setting; by which the Enugu Shale member of Nkporo Group underlies the eastern part while the western portions of the area are underlain by the Ajali sandstones. As seen in Figure 4, the Mamu formation (or lower coal measure) underlies the central part. The shale unit of the Enugu formation is characteristically bluish-grey (see ESM No.1 [ii] E), highly fissile and dipped into the coal bearing Mamu formation. The coal bearing formation consists of coal seams sandwiched beneath laminated shale (Figure 6(a) and 6(g); ESM No.1 [ii] G), and generally covered mostly by either mudstones, sandy clay (Figure 6 {E1, E2}) which is whitish in places, or ferruginized clastics

Table 2. Results of statistical parameters and graphical analysis of grain size distribution.

S/No	Location	Sample source	Mean	SD	Sorting	D_{10} (Φ)	D_{10} (mm)	D_{60} (Φ)	D_{60} (mm)	CU	Porosity (n) in %
1	9th mile 1	Ajali Sandstones	1.677 (M. grained)	0.775	MS	0.70	3.85	1.50	3.22	0.84	50
2	9th mile 1		2.807 (Fine grained)	1.871	PS	−0.70	4.75	3.50	3.38	0.71	50
3	9th mile 1		1.183 (M. grained)	0.940	MS	−0.79	4.90	1.29	3.40	0.69	50
4	Abor 1		1.243 (M. grained)	1.176	PS	−0.22	5.38	1.40	3.24	0.60	50
5	Abor 2		0.867 (C. grained)	0.801	MS	−2.80	5.25	1.22	3.35	0.64	50
6	Abor 3		1.767 (M. grained)	1.484	PS	0.82	3.80	1.63	3.00	0.79	50
7	Abor 4		1.197 (M. grained)	0.985	MS	−0.60	5.13	1.28	3.35	0.65	50
8	Nsude 1		1.527 (M. grained)	1.252	PS	0.79	4.00	1.41	3.25	0.81	50
9	Nsude 2		1.347 (M. grained)	1.077	PS	2.62	5.50	3.45	3.78	0.69	50
10	Nsude 3		3.305 (V.F.grained)	2.569	PS	0.68	2.07	1.40	1.25	0.60	50
Minimum			0.87 (Coarse grained)	0.775	–	−0.22	2.07	1.22	1.25	0.60	50
Maximum			3.305 (V.F.grained)	2.569	–	2.62	5.50	3.50	3.78	0.84	50

Note: MS = moderately sorted, PS = poorly sorted, WS = Well sorted, M = Medium, C = Coarse, V.F = Very fine.

that occur mostly as ironstone plates (see Figure 6(d)). These subordinate sediments are mostly damped in-between the Mamu shales.

Mudstone/sandy clay dominates the feet of the adjoining range of hills as typically identified around Iva and Onyeama mines (see ESM No. 1[ii] F) by the valley flank. These hills demarcated Enugu shale from the coal bearing formation, whereas the valley separated the coal mines from the aquifer of Ajali sandstone. The sandstone formation is whitish where fresh (see ESM No. 1[iii]), cross-bedded and with thick lateritic cover. Tijani & Nton (2009) typified these characteristics as representative of Ajali sandstones. It is iron stained where weathered, poorly sorted and coarsely grained at contact with the Mamu formation. Seemingly, the coarse nature enhanced baseflow to the boundary with the less permeable lower coal measure. The baseflow produced river tributaries at the axial valley adjoining the coal mines where the aquifer outcropped to produce the fluvial process. This fluvial setting initiated surface water resources, particularly to the eastern downstream of the region where the underlying geology (mainly shales) supports hydrologic flow at the surface. Targeting the water resources at the catchment area for management purposes would be a robust decision in the water resources development across Anambra Basin and the adjoining regions. Water policy of this kind would ensure safe water delivery, even to other areas that have been challenged by little or no water supply.

Specific textural analysis

Phi values were derived from graphical resolutions of the sandstone analysis (see ESM No. 3x[i]; x = a, b, c, … j}) and shown in Equations (1) and (2), thus the results for mean and standard deviation (SD), respectively, were obtained (see Table 2). Table 2 shows that the SD ranged from poorly to moderately sorted sandstones, while the mean is generally dominated by medium grain size. Tijani *et al.* (2010) reported a

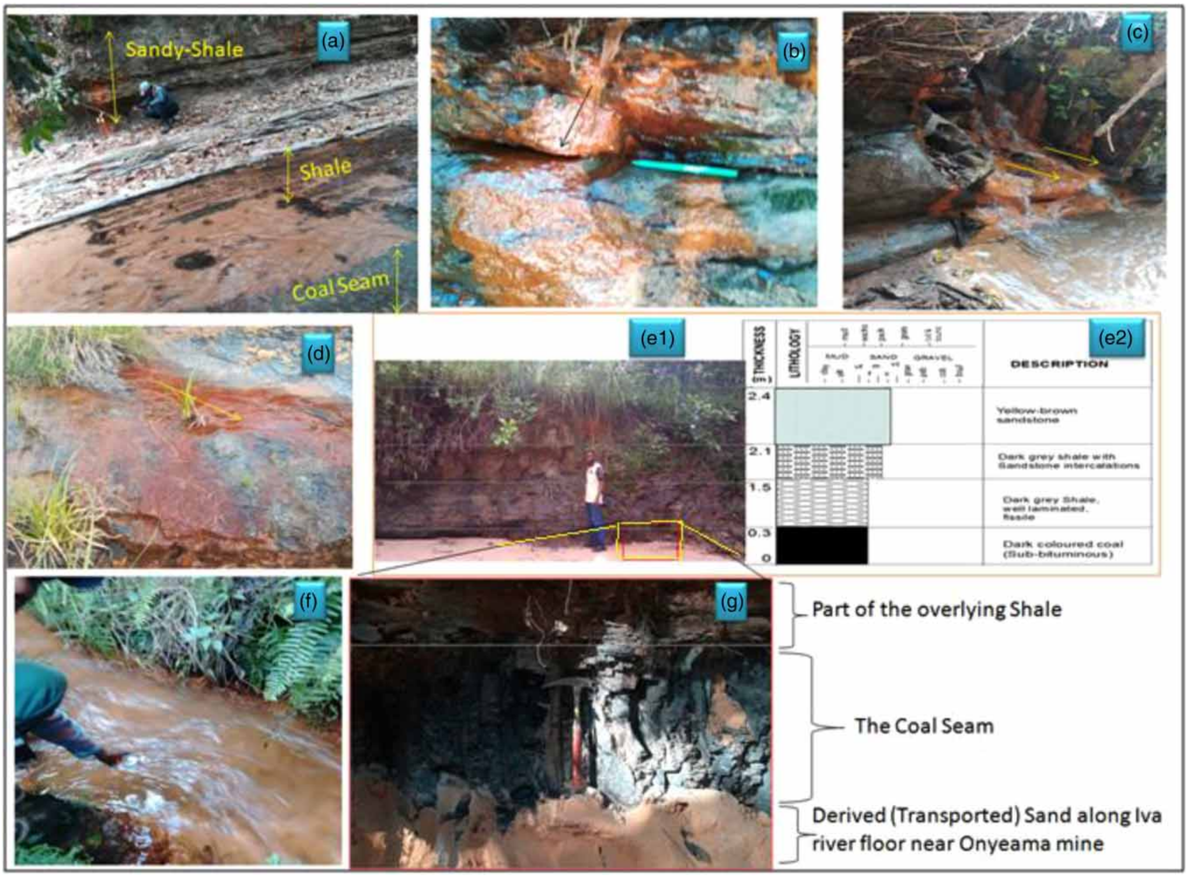


Fig. 6. (a) Surface profile of lithologic units of Mamu Formation by Okpara mine; (b) Slimy coating of Fe (being a typical trace of AMD) on shale bed near Okpara mine; (c) Groundwater seeping and flushing AMD (indicated with yellow arrow) at a seepage face around the Okpara mine; (d) AMD flow between shale-ironstone contact near Okpara mine; (e1) Lithological section (by Iva river bank) representing geological sequence of most of the coal mine environment; (e2) Modeled section correlating the measured lithological sequence; (f) High turbidity due to mixed acid and alkaline hydrogeochemical facie (i.e. Ca-Mg-Na-HCO_3-SO_4-Cl water type) by downstream axis of Ekulu River; (g) Enlarged portion of the coal seam and part of the overlying shale. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wp.2021.275.

downward coarsening sequence, while Ukpai *et al*. (2017) identified the aquifer zone in the coarsely grained sandstone facie. The coarse nature is characterized by porosity of about 50% (see Table 2).

According to Burden & Sims (1999), particle density (P_d) of soil depends mainly on the mineral grains. On this note, Tijani *et al.* (2010) reported that Ajali sandstone formation is dominated by quartz minerals. Meanwhile, Blake (2008) typified quartz minerals with $P_d = 2.65$ g/cm^3. Therefore, it is safe to fix the standard value of P_d into Equation (5) for empirical verifications of the porosity (Hao *et al*., 2019), thus:

$$n = 1 - \frac{Bulk\ density\ (Bd)}{Particle\ density\ (Pd)} \tag{5}$$

The standard particle density (P_d) for all sandy soil is 2.66 g/cm^3 (Revil *et al.*, 2002) while the (dry) bulk density (B_d) of such soil is normally smaller than the P_d (Vitz *et al.*, 2019) and is classified within the range of 1.2–1.8 g/cm^3 for fine soil with little or no organic content (Brady & Well, 1999), such as Ajali formation (see ESM No.1 [iii]). Similarly, half of P_d (i.e. 1.33 g/cm^3) is generalized as B_d (Burden & Sims, 1999) in situations where the B_d value is unknown locally. Thus, the porosity (**n**) of each representative sandstone sample was estimated at 0.5 by fixing the standard values of P_d and B_d in Equation (5). The porosity can be confirmed as 0.5, being the value obtained from the empirical analysis and equivalent to the 50% obtained earlier from sieve analysis. As seen in Table 2, the porosity is uniform and within the range of 35–50% established for typical sand (Hao *et al.*, 2019). The value is at the upper limit of 50%, possibly due to the clay-like granular nature of the finely grained sandstones at the surface (see ESM No.1 [iii] A, B, C). This corresponded with typical 50% value for the pore space of surface soil (USDA–NRCS, 2019). The enormous porosity and low-moderate bulk density signifies little or zero compaction of the overburden sandstones and implies high infiltration potential. These characteristics expose the aquifer to recharge from rainfalls, especially during extreme events. In such conditions, Kadhem & Zubari (2020) affirmed that large amounts of water become available in a relatively short time. Thus, effective hydrologic interplay between meteorological and hydrogeological regimes has been suspected across the Ajali sandstone setting, mainly due to uniform porosity from the surface to the deep saturated subsurface.

For instance, the exponential decaying form of Equation (6a) was used to estimate the level of decrease in porosity with depth (Medina *et al.*, 2011), thus:

$$\mathbf{n}_{(z)} = \mathbf{n}_0 e^{-kz} \tag{6a}$$

where $\mathbf{n}_{(z)}$ = porosity at depth; $\mathbf{n}_0$ = porosity at ground level; k = compaction coefficient (m^{-1}) and z = depth (m).

In a sand and clay mixture, Revil *et al.* (2002) used the standard value of **k** as 6×10^{-8} Pa^{-1}, but for average sand in Nigeria, **k** ranged from 4.0×10^{-4} to 6.0×10^{-4} m^{-1} (Nwachukwu & Odjegba, 2001; Benjamin & Nwachukwu, 2011). Therefore, if 0.5 and 200 m represent $\mathbf{n}_0$ and mean aquifer depth (**z**) respectively as deduced earlier, then estimation in Equation (6b)–(6d) using the **k** values showed negligible porosity decay of about 0.1%. The 0.1% is the difference between $\mathbf{n}(z) \approx 48.9\%$ (deduced in Equation 6(d)) and $\mathbf{n}_0 \approx 50\%$ (deduced in Equations (3) and (5)). This arithmetical analysis followed the fact that small e^{-kz} in Equation (6a) is approximated as shown in Equation (6b), in relation to a typical expansion of radioactive decay equation when the exponents are negligible (Miyaoka, 2011), therefore:

$$e^{-\mathrm{kz}} \approx 1 - \mathrm{k}z \tag{6b}$$

Then, Equation (6a) is transformed to:

$$\mathbf{n}(z) = \mathbf{n}_0(1 - kz) \tag{6c}$$

hence:

$$\mathbf{n}(z) = 0.5(1 - [6.1 \times 10^{-12}\mathrm{m}^{-1} \times 200\mathrm{m}]) \tag{6d}$$

where: 6×10^{-8} Pa^{-1} = 6.1×10^{-12} m^{-1}.

Chemistry of the water resources

Ionic concentration

Seeing the summary of hydrogeochemical status in Table 3, the maximum pH in all surface water (SW) sampled around the coal mines is about 6.00 ± 1, but is within the neutral range in samples from shallow groundwater representative hand-dug wells (HDW) and in those from boreholes (BH) or deep groundwater regimes. Seemingly, the pH is less mild at the fluvial processes than in the groundwater system, and appears to reflect configurations of total dissolved solutes (TDS), electrical conductivity (EC) and total hardness (TH). Contents of acid salt ions like SO_4^{2-} and Cl^-, as well as dissolved alkaline metal such as Na^+ have considerable contributions to the trends of EC and TDS. The concentrations of alkalinity (HCO_3^-) and Ca appeared to be more significant in the compositions of TDS and TH than the influences of other ions. The minimum values of these parameters were observed in the upstream environment as typically represented in BH 3, whereas the maximum was relatively observed in the downstream area. However, concentrations of NO_3 are very low, and could be adjudged to be negligible if compared with the 50 mg/L permissible limit stipulated by the World Health Organization (WHO, 2011). Following previous studies which attributed pollution of water supply by NO_3 to agricultural effluents (Elhatip *et al.*, 2003; Hooker *et al.*, 2008; Nemčić-Jurec & Jazbec, 2017); the slight concentrations of NO_3 signifies the absence of any surface-based effluent, especially from domestic and agricultural activities in areas adjoining the coal province. It means that drainage relating to coal mining has formed the effluents exclusively. This is because dissolved iron (Fe) is locally high in fluvial representative samples around the coal mines and may be linked to acid mine drainage (AMD). According to Hanraham (2012), AMD can be produced when strata containing pyrite (FeS_2) is exposed to oxidation in acidic water dominated by iron and sulfate. The process is expressed in chemical reaction (1) (Fitch, 2015; Liang *et al.*, 2015) thus:

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) \underset{\text{(First Phase Acidity)}}{\rightarrow} 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \quad (1)$$

The resulting pH exhibited by the AMD is characteristically low due to the steady release of H^+ and SO_4^{2-} via continuous (non-pulse) loading from abandoned underground mines (see ESM No.1-iv {C and D}). Supposedly, the enrichment of atmospheric oxygen raised the oxidation potential along the AMD path; for which the Fe^{2+} oxidized to Fe^{3+}, as shown in reaction (2) below:

$$2Fe^{2+}(aq) + O_2(g) + 4H^+(aq) \rightarrow 2Fe^{3+}(aq) + 4H_2O(l) \quad (2)$$

Typical process in reaction (2) is possible at pH >3.0, as seen in Table 3a, and would still produce supplementary acidification (Luptakova & Andras, 2019). The resulting Fe^{3+} has continuously induced prevalence of a brownish and reddish or even yellowish slimy coating of iron film on affected rocks and stream banks across the coal bearing region (Figure 6(b)–6(d); ESM No.1 {[iv]A}) in line with the history of ferric iron. This fact showed that AMD is perennial at the upstream river catchment, hence a matter of serious concern.

Locally, as the AMD is flushed by highly alkaline (HCO_3) freshwater streams at the point of seepage from groundwater to the fluvial process (ESM No.1{i}D), acidity was injected into the tributaries up to

Table 3. Results of hydrogeochemical analysis.

S/No	Sample Code	Location Names	pH	Turbidity (NTU)	TDS (mg/L)	EC (µS/m)	TH (mg/L}	NO_3 (mg/L)	SO_4 (mg/L)	HCO_3 (mg/L)	Cl (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	Fe (mg/L)
1.	HDW1	Ugwu Aron	7.03	1	183	274	180	0.66	40	184	40.26	52	19.53	2	37.63	0.00
2	HDW 2	Agbani Rd, Enugu	7.06	0	198	297	202	0.82	36	200	42.15	61	12.21	4	12.00	0.00
3	HDW3	Kennyatta, Mkt.	7.00	1	59	89	80	0.33	26	84	7.18	29	1.95	2	10.00	0.00
4	HDW4	Achara Layout	6.95	0	843	1,265	420	1.16	78	428	95.96	136.	19.53	12	36.79	0.13
5.	HDW5	Ugwuaji	6.78	6	697	1,046	400	1.34	80	396	89.11	126	20.76	10	77.78	0.54
6	HDW 6	Independ Layout 1	6.97	2	790	1,186	440	0.82	86	436	93.45	132	26.86	8	87.92	0.02
7	HDW 7	New Haven	7.03	0	132	198	122	0.25	22	98	8.96	40	5.37	4	12.00	0.00
8.	HDW8	Abakpa 1	7.05	0	241	362	200	0.32	36	192	41.22	67	7.81	3	16.00	0.00
9	HDW 9	Emene/ Emenite	7.05	10	289	434	180	0.38	38	264	44.56	80	14.16	7	38.77	0.32
10.	HDW10	Thinker's Corner	7.04	1	139	209	210	0.21	34	204	28.98	58	15.87	5	29.16	0.00
11.	HDW11	Ugbene II Abakpa	7.00	0	85	127	170	0.25	26	168	17.79	54	8.3	3	16.19	0.00
12.	HDW12	Ogui Rd by GTB	7.01	0	143	215	232	0.32	30	230	21.68	73	12.03	6	15.11	0.00
13	HDW13	Abakpa 2	7.00	1	49	74	136	0.38	16	128	16.78	40	8.79	6	10.00	0.02
14.	HDW14	OtukwuEmene	7.02	1	185	278	192	0.21	20	180	32.15	59	12.87	5	17.15	0.00
15.	HDW15	Independ Layout 2	7.03	5	193	289	192	0.20	22	188	34.25	60	12.01	5	21.82	0.00
16.	HDW16	Awkunanaw	7.03	0	159	239	182	0.34	18	180	31.19	58	13.44	7	14.84	0.00
17.	BH1	Garki	7.05	0	154	231	140	0.76	38	136	33.79	40	9.77	5	54.94	0.01
18.	BH2	Okwe Rd, 9th Mile	7.00	1	19	28	82	0.16	3	80	9.96	22	6.35	3	5.23	0.00
19.	BH3	Umuavulu Abor	7.01	0	11	16	64	0.10	2	66	4.98	16	5.86	1	10.46	0.00
20.	BH4	Nsude	7.01	0	19	28	80	0.14	3	78	9.94	22	5.86	4	4.3	0.00
21	SW1	Iva Seepage	6.09	0.38	80	120	264	0.26	16	256	33.07	69.6	25.74	6	16	0.23
22	SW2	Iva mine	5.79	7.22	135	200	298	0.51	34	292	49.96	80.0	28.03	7	21	7.46
23	SW3	Onyeama mine 1	5.45	12.48	60	90	208	0.57	28	200	51.27	54.4	20.59	4	10	10.67
24	SW4	Onyeama mine 2	4.94	15.12	60	90	216	0.55	26	210	50.19	54.0	22.88	6	12	10.08
25	SW5	Okpara mine	5.85	22.44	35	50	180	0.50	30	180	53.76	48.79	16.59	5	14	12.30
26	SW6	Okpara Seepage	5.97	0.06	35	50	190	0.42	20	190	39.17	51.21	17.73	5	12	0.11
Minimum			4.94	0.38	11	16	64	0.10	2	66	4.98	16	1.95	1	4.32	0.02
Maximum			7.06	22.44	843	1,265	440	1.34	86	436	95.96	136	26.86	12	87.9	12.30
WHO (2011)			6.5–8.5	1.0	500	–	100	50	250	–	250	75*	50*	–	75	0.30
NSDWQ (2015)			6.5–8.5	5.0	500	1,000	150	50	100	–	250	–	–	–	200	0.30

TH: Total Hardness.

the range of $4.98 \leq pH \leq 6.1$ (see Table 3) as reflected by all surface water representative samples (SW1–SW6) near the coal mines. This is in agreement with Vallero (2006) who noted that streams affected by coal mine drainage exhibit acidity with a pH range of 2.5–6.0. Similarly, water resources adjoining any AMD are usually polluted (Lachmar *et al.*, 2006). Yellow or orange coating which characterized the acidic pollutants indicates suspended iron materials. This is because dissolved iron, particularly Fe^{3+}, precipitates to ferric hydroxide [$Fe(OH)_3$] at pH>4.5 (Scholz, 2006) as shown in reaction (3) below:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+ \qquad \text{(3) (second phase acidity)}$$

(Ferric Iron) (ferric (second phase acidity) hydroxide))

Reaction (3) shows that precipitation to iron (III) hydroxide [$Fe(OH)_3$] depletes oxygen content, resulting in a gradual or slow shift towards alkalinity and low redox. Although the pH could have increased, the inherent acidity charges the fluid with H^+. In this study, this stage has been termed second phase of acidity caused by the steady release of H^+. According to Weiner (2000), hydrolysis of ferric ion (Fe^{3+}) releases more acid to the water and forms insoluble ($Fe(OH)_3$ which coats the stream bed with yellow or orange colored deposits (see ESM No.1{ii} i). In these conditions, the ferric compound could remain stable in chemical suspension. From the analogy, it appears that the turbidity observed in streams around the coal bearing formation was created by suspension of the precipitated $Fe(OH)_3$. These findings can guide policy initiative for chemical cleansing across the water resource provenance.

Provenance identification

In Figure 7(a), the representative samples clustered and overlapped at the hydrogeochemical facie zone that depicts alkaline agitated water type. Utom *et al.* (2013) and Ukpai *et al.* (2016) interpreted such facie trends as representative of water recharged from meteoric origin. Orientation or distribution patterns of components in zone A (meteoric facie) towards intermediate facies zone B signified influences of the AMD. Generally, HCO_3 is the prevailing anion with subordinate SO_4-Cl, whereas Ca dominated in the cation series. Meanwhile, Mg and Na are subsidiary cations. These compounds combined as Ca-Mg-Na-HCO_3-SO_4-Cl facies being defined as meteorically recharged water type that has been influenced by intermediate facies. The dominant (zone A) facies revealed water recharged from precipitation (rich in HCO_3^-), but flushes subsidiary/subordinate effluents that may have evolved from connate source (rich in Cl^-); both ends meet at zone AB (see Figure 7). Typically, SO_4^{2-} is dominant at the intermediate facie zone, which in this study was predicted from AMD as probable or apparent facies of zone B (see Figure 7(b)). This notion is based on the tendency of some components representing samples around the coal mines; comprising SW2, SW5, HDW 2 and mainly HDW 3; to encroach 50% edge of zone B from zone A domain (see Figure 7(a)).

According to Fawang *et al.* (2012), Ca-Mg-HCO_3 is a potable groundwater representative principal facies which can be degraded during evolution as Ca-Mg-Na-HCO_3-SO_4 due to interaction with mineralized water. In the present study, the principal facies [Ca-Mg-HCO_3] was degraded beyond the [Ca-Mg-Na-HCO_3-SO_4] to [Ca-Mg-Na-HCO_3-SO_4-Cl]. The principal hydrogeochemical facies are potable, though they bear traits of weak carbonic acid that depict a water supply of meteoric origin, such as the

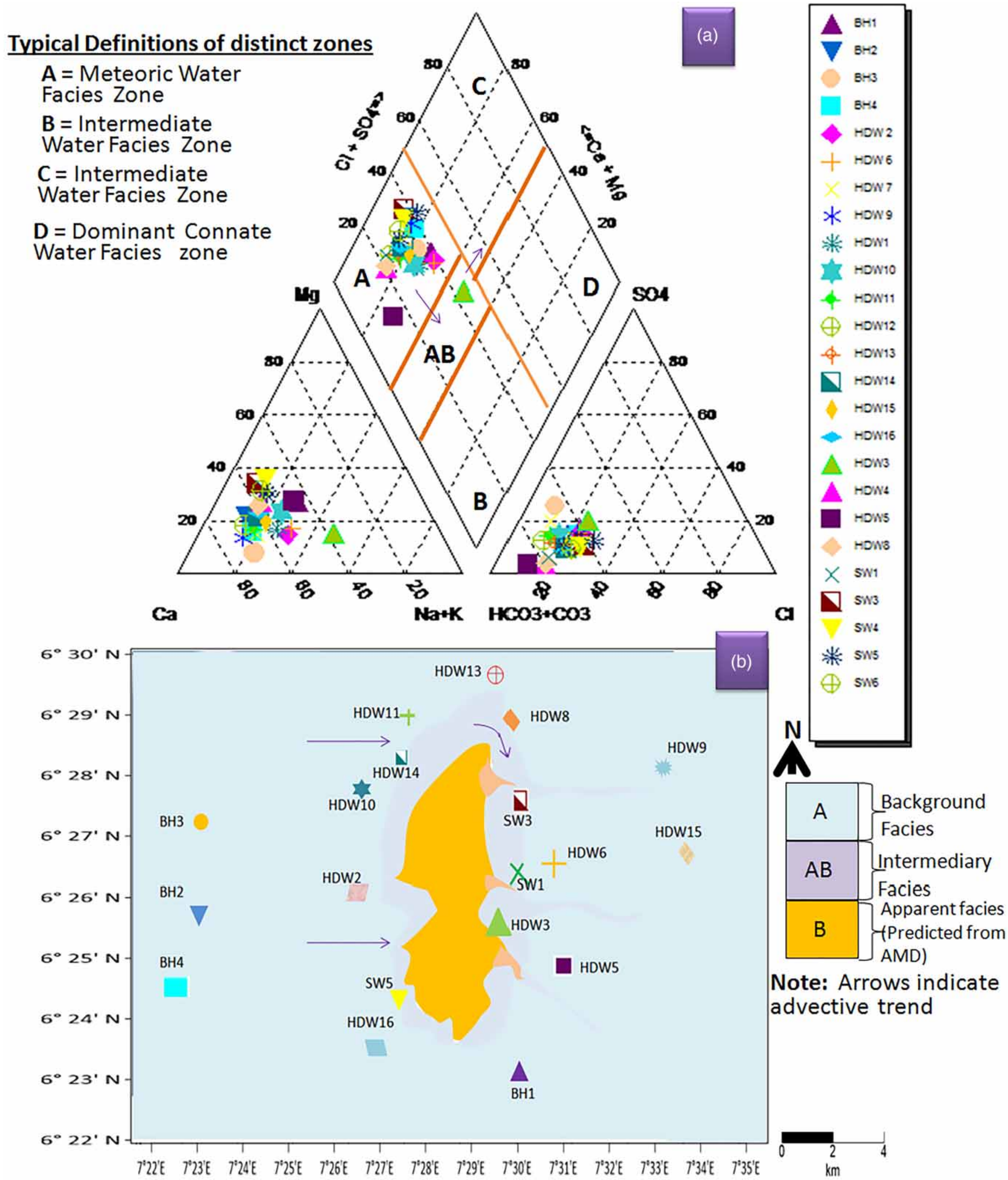


Fig. 7. (a) Piper graph showing the resultant hydrogeochemical facies; (b) Corresponding map view of the sample locations.

facie representing a water resource from Ajali sandstone. It has been noted that facies characterized with $SO_4^-Cl^-$ are being swayed by AMD. Therefore, channeling groundwater from the sandstone aquifer with a decision to bypass the AMD environment is an exclusive panacea which relevant policy makers, federal or state agencies can consider in the plans to subside or curb any chemical processes that can induce acid-water facie(s) to water resources environment.

Chemical processes

Based on correlative analysis (CA) of the ions to verify the ecological relationship, the coefficients (x) in Table 4 were interpreted as: non-correlation at probability of error [P_e]>5% (i.e. level of confidence [L_c]< 95%); minor correlation at $P_e \leq 5\%$ (or $L_c \geq 95\%$) and strong correlation at $P_e \leq 1\%$ error (or $L_c \geq 99\%$). In the matrix table, non-correlation, minor correlation and strong correlation were within such ranges as: $x<0.4$; $0.4 \geq x \leq 0.5$ and $0.5 \geq x \leq 1.0$ respectively. The level of confidence up to 95 and 99% reflect 0.05 and 0.01 respectively (Ukpai & Okogbue, 2017; Ukpai *et al.*, 2020). As seen in Table 4, TDS, EC, total hardness (TH) and all ions of alkaline salt correlated with each other without correlating with pH and Fe, while Mg correlated across all parameters. It appears therefore, that configuration of the pH is chemically influenced by processes associated with Fe rich AMD while the group of ions relating to alkalinity influenced configurations of other physical parameters. The pH only correlated with Fe at $x = -0.837$ and with Mg at $x = -0.553$, whereas Fe correlated only with Mg at 0.430. This could be attributed to the strong impact of pH on the oxidation of Fe, just as Mg is chemically compatible in the process. According to Lamaka *et al.* (2016), magnesium (Mg) is a negative electrochemical potential element, hence prone to corrosion due to its susceptibility to noble impurity elements like Fe. For the fact that iron (Fe) can enlarge cathodically active sites at the surface of corroding magnesium (Mg), and because Fe accelerates corrosion in impurity containing Mg (Hoche *et al.*, 2016), chemical affinity between Fe and Mg exists. So, it is safe to presume inexhaustible oxidation of Fe in the water resource even across long fluvial distances, especially as the Mg is continuously loaded from carbonate minerals sandwiched in shales that underlie areas around the downstream region.

Surprisingly, there is no correlation of SO_4^{2-} with pH, possibly indicating a drastic reduction of sulfate ion in the AMD by sulfate reducing bacteria (SRB). Such a biochemical reaction is expressed in reaction (4):

$$SO_4^{2-} + 2H_2 + H^+ \rightarrow HS^- + 4H_2O \tag{4}$$

Although the SO_4 and Fe were produced from the same source (see reaction (1)), the resulting acidity is a function of oxidation of iron (Utom *et al.*, 2013). The independent influence of Fe on the acidity was confirmed in reaction (3) rather than in reaction (1) where both ions (i.e. SO_4 and Fe) predisposed acidity. It is suspected that the processes in reactions (2) and (4) were simultaneous as redox in the AMD domain, for which Fe^{2+} dissolved to Fe^{3+} (see reaction (2)) via oxidation while SO_4^{2-} dissolved to HS^- (see reaction (4)) via reduction. The acidic trait of SO_4 may be negligible to affect the pH in the second acidic phase produced in reaction (3). Therefore, the first and second phases of acidity exist but the pH may be lower in the first phase (reaction (1)). This explains why non-correlation existed between SO_4 and pH at 0.123, and with Fe at -0.014. Meanwhile, SO_4 reduced as Fe increased, hence the negative sign ($-$) as seen in Table 4. It had been noted that alkalinity is the eventual product of biotic reduction of SO_4 (Rambabu *et al.*, 2020), hence

Table 4. Correlations analysis (CA) of hydrogeochemical data.

Variables	pH	TDS	EC	TH	NO_3	SO_4	HCO_3	Cl	Ca	Mg	K	Na	Fe
Ph	1	0.287	0.288	–0.107	–0.298	0.123	–0.080	–0.198	0.044	–0.553**	–0.039	0.249	–0.837**
TDS	0.287	1	10.000**	0.851**	0.503**	0.923**	0.865**	0.840**	0.915**	0.418*	0.751**	0.802**	–0.213
EC	0.288	10.000**	1	0.851**	0.502**	0.923**	0.864**	0.839**	0.914**	0.417*	0.751**	0.802**	–0.214
TH	–0.107	0.851**	0.851**	1	0.577**	0.870**	0.983**	0.915**	0.970**	0.775**	0.818**	0.697**	0.087
NO_3	–0.298	0.503**	0.502**	0.577**	1	0.642**	0.553**	0.679**	0.500**	0.598**	0.382	0.540**	0.326
SO_4	0.123	0.923**	0.923**	0.870**	0.642**	1	0.880**	0.890**	0.904**	0.527**	0.686**	0.853**	–0.014
HCO_3	–0.080	0.865**	0.864**	0.983**	0.553**	0.880**	1	0.924**	0.985**	0.765**	0.836**	0.719**	0.067
Cl	–0.198	0.840**	0.839**	0.915**	0.679**	0.890**	0.924**	1	0.900**	0.745**	0.771**	0.717**	0.257
Ca	0.044	0.915**	0.914**	0.970**	0.500**	0.904**	0.985**	0.900**	1	0.656**	0.840**	0.729**	–0.031
Mg	–0.553**	0.418*	0.417*	0.775**	0.598**	0.527**	0.765**	0.745**	0.656**	1	0.578**	0.458*	0.430*
K	–0.039	0.751**	0.751**	0.818**	0.382	0.686**	0.836**	0.771**	0.840**	0.578**	1	0.545**	0.044
Na	0.249	0.802**	0.802**	0.697**	0.540**	0.853**	0.719**	0.717**	0.729**	0.458*	0.545**	1	–0.173
Fe	–0.837**	–0.213	–0.214	0.087	0.326	–0.014	0.067	0.257	–0.031	0.430*	0.044	–0.173	1

**Correlation is significant at the 0.01 level.

*Correlation is significant at the 0.05 level.

the strong correlation of SO_4 with ions, even those of alkaline species. According to Yesilnacar & Kadiragagil (2013), alkaline species, mainly carbonate minerals, buffer acidic water.

In principal component analysis (PCA), two out of five derived components loaded up to 85.6%, comprising 66.2% for C1 and 19.6% for C2 in the total of 96.6% incorporated variables (Table 3c). Negligible eigen-values were observed in C3, C4 and C5, for which information relating to any geological process was hidden (Ukpai & Okogbue, 2017). A factor is significant if the eigen-value is greater than/or equal to 0.5 (Okogbue & Ukpai, 2013). All except pH and Fe are eigen-values in C1; while in C2, all except Fe, pH and Mg are not eigen-values, whereas NO_3 is the only significant variable in C3. Obviously, the coefficients that correlated earlier in the CA as neutralizing agents of the alkaline family (Table 4) are the group of significant variables in C1, whereas the opposing corrosion agents were grouped in C2 (see Table 5). Thus, while neutralization and oxidation reactions have been deciphered in C1 and C2 respectively, there is no interpreted geological process in C4 and C5, even as loading of a single variable (example, NO_3) is not sufficient to derive any process in C3. Identification of these chemical processes is requisite information for decision makers in designing policies that can abate water resource deterioration.

Findings from these results and interpretations were tied into discussions of this work. The discussion was encased in the critical areas of water policy within organizational responsibility for the water resources management as proposed by the Food and Agriculture Organization (FAO, 1995), namely, operations management, planning/coordination, design/construction, regulation, and social/environmental action.

Discussion

Policy operations: identification of risks

Minor levels of compaction (i.e. little or no reduction in pore spaces with depth), as predicted in Ajali formation (Figure 8), signifies uniform porosity and shows an homogeneous and isotropic stance of

Table 5. Principal component analysis (PCA).

	Component (C)				
Parameter	C1	C2	C3	C4	C5
pH	–0.018	–0.967	0.073	0.022	–0.001
TDS	0.924	–0.325	0.026	0.137	–0.018
EC	0.924	–0.326	0.026	0.137	–0.018
TH	0.965	0.084	–0.154	–0.084	–0.016
NO_3	0.653	0.348	0.583	–0.021	–0.331
SO_4	0.944	–0.134	0.189	0.105	0.103
HCO_3	0.973	0.055	–0.171	–0.076	0.014
Cl	0.954	0.190	0.026	0.107	0.055
Ca	0.970	–0.076	–0.180	0.001	0.009
Mg	0.708	0.564	–0.110	–0.389	0.016
K	0.828	0.008	–0.393	0.137	–0.188
Na	0.811	–0.261	0.319	–0.174	0.281
Fe	0.051	0.911	0.067	0.325	0.190
% of extraction	66.2	19.6	5.7	3.0	2.1

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

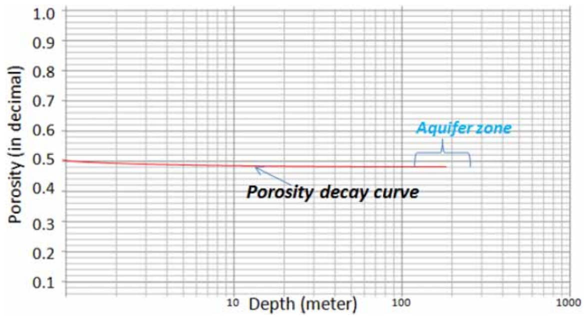
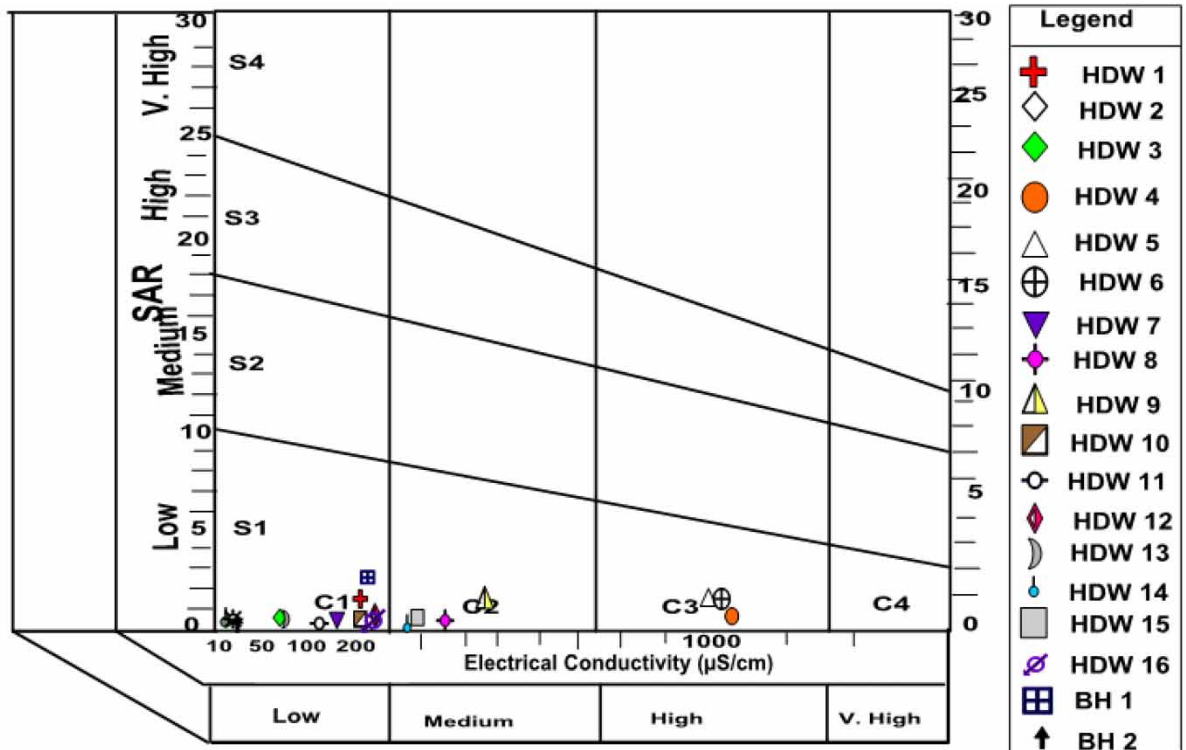


Fig. 8. Graph showing slight decay of porosity to about ≤0.1% at a depth of ≥200 m: indicates minor level of compaction.

permeability. Though the textural character enhanced baseflow from the regional aquifer to the seepage axis, the resulting river regime was greatly hampered by the AMD dispersed from coal mines. As seen in Table 3, the pH for the representative samples around the coal mines is lower than the background at the outskirts, possibly due to the contamination of AMD at the catchment river source. The pH increased from first to second acidic phases due to the neutralizing effect of the freshwater, but the later phase is more persistent due to the recurring oxidation process caused by the ion charged water along the fluvial courses. Such chemical conditions have been very dangerous to aquatic life due to the lethal impact of concentrated H^+, dissolved Fe and [$Fe(OH)_3$] on fishes in the affected rivers and this is linked to the failing of fish farming among riparian communities in the downstream areas. According to Jennings *et al.* (2008), $Fe(OH)_3$ diffuses thousands of miles along streams affected by AMD, resulting in the coating of slimy materials on the surface of stream sediments and streambeds. These slimy coats destroy the availability of clean gravel used for spawning, as well as reduce fish food items such as benthic micro invertebrates. Furthermore, fine-flocs produced by the $Fe(OH)_3$ not only coats the stream bottom but harms aquatic life (Vallero, 2006), especially fish, and crop production which can be farmed for economic purposes at riparian communities.

Advection of the polluting chemicals from the upstream river catchment adjoining the coal province was indicated by concentrations of electrical conductivity greater than the 1,000 μS/m limit specified by NSDWQ (2015) in drinking water and greater than the 750 μS/m limit (see Table 3) specified in irrigation water against salt sensitive crops (Hiscock, 2005). Such were observed in hand dug wells (HDW) that depict shallow groundwater; comprising HDW 4, HDW 5 and HDW 6. Representative samples from these wells clustered at class 3 (Figure 9), being the domain of high salinity (Singh *et al.*, 2010). Anomalous salinity impairs plant growth (Hernández & Almansa, 2002; Munns, 2005) and consequently reduces crop productivity. These conditions have affected agri-business through losses of income. The aquatic deterioration hampers the objectives of the National Water Policy (2004) with respect to protecting riparian rights in terms of farming. These circumstances prompt the migration of people to urban areas (Shahid *et al.*, 2018).

Similarly, in the downstream regions of the ancestral city, young (riparian) village dwellers who would have engaged in a farming occupation have migrated to the nearby (coal) city in search of alternative means of livelihood. The migration is related to the increasing population density characterizing the metropolitan. For instance, Enugu town is currently grouped among the densely populated World Urban Areas with a density estimate of about 5,500/km^2 (Demographia, 2020). Such a dense population is suspected to contribute to the high unemployment rate in Enugu metropolis. The situation synchronized



SAR		Electrical Conductivity (µS/cm)			General Remark	Sampling Locations
Class	State	Class	Range	State		
S1	Low (Less than 10)	C1	<250	Low	Excellent	HDW 3, 7, 10, 11, 12, 13, 16; BH 1, 2, 3, 4
S2		C2	250 -750	Medium	Good	HDW1, 2, 8, 9, 14, 15
S3		C3	750 -2250	High	Doubtful	HDW 4, 5, 6
S4		C4	>2,250	Very High	Unsuitable	Nil

Fig. 9. Classification of the groundwater based on US salinity diagram.

with the earlier prediction of the United Nations World Water Assessment Programme (WWAP, 2016) that water shortage, as well as problems of access to water and sanitation limits economic growth and job creation. It was also noted in Nwankwo *et al.* (2020) that inadequate water supply, poor sanitation and depleting water quality all negatively impact educational opportunities, livelihood choices and the food security of low-income families across the world.

Scientific intervention and policy designs

In view of the occupational and economic crises, it falls on the governments to retract decisions of mining activities at water resource catchments or initiate policies that can lessen the troubles associated with the digging of coal in areas around water supply provenances. In Nigeria, this task is achievable if strong co-operation exists between the federal government and the Council of Nigerian Mining Engineers and Geoscientists (COMEG). The council regulates and controls the practice of mining engineers and geoscientists in all its aspects and ramifications in accordance with its ACT. Such ACT was ratified in 1990 to drive the government's policy on mineral exploitation. Furthermore, if water-use permit ACT, as established in the Nigerian Minerals and Mining Regulations (NMMR, 2011), is enforced on mining operators in the upstream river catchment, further ecological consequences would drastically be reduced to a minimum; even at the downstream axis of the watershed. Based on this analogy, every catchment area across the globe should be mapped as a river source protection zone (RSPZ) for the purpose of resolute attention. Such attention demands for shared responsibility of stakeholders in the sector, particularly in the execution of water policies.

Based on the findings in this study, a policy was scientifically outlined, thus: Magnesium ion (Mg^{2+}) was earlier identified as an admixture in the major active chemical processes (oxidation and neutralization) prevalent in the water resources, and suggested the use of its synthetic oxide like MgO as a suitable treatment reagent. Injection of this oxide can bind up or mop dissolved elements into heavier and less mobile complex forms that may easily be removed by industrial filtration. The filtration can be achieved by constructing water reservoirs through dams fitted with industrial filter columns across the rivers adjoining the axis of seepage-AMD intersections. Safety planning of water reservoirs is outlined in Ukpai (2020). The dammed water reservoir can expose the charged water resource to steady aeration before releasing to downstream fluvial flow. By this mechanism, the dissolved ions are subjected to redox and hydrolysis. Typically, the chemical processes lead to forming heavier (denser) oxides or hydroxides as seen in the chemical transformation of $Fe^{2+ \text{ or } 3+}$ to the denser $Fe(OH)_3$ or $Fe(OH)_3$. Having deciphered that this hydrolyzed product is lethal but less mobile, it is safe to affirm that this transformation impedes the mobility of the toxic solid Fe for easy filtration. Thus, designing a proper treatment strategy and management system (as earlier proposed) is required to mitigate some of these challenges. Such a policy may provide a return of incomes (Rambabu *et al.*, 2020) in order to alleviate low economy and restore the associated emotional and social impacts associated with ecological devastation induced by the water scarcity.

Therefore, collaboration among policy makers in the water sector is vital (Christian-Smith *et al.*, 2011) for the implementation of this newly initiated recuperative idea of revamping the RSPZ. From this standpoint, emphasis is laid on the policy collaboration in the form of a joint partnership on service delivery in water supply to bridge the gap between the society and the water resources. The partnership may comprise: national decision makers on water sector like the River Basin Development Authority (RBDA) and Nigeria Hydrological Service Agency (NIHSA); technical partners like hydro-chemists and biochemical scientists; as well as financial partners like global development agencies, such as the United Nations Development Programme (UNDP) and the United State Agency for International Development (USAID). According to the FAO (1995), integrated water planning; especially with international agencies, resolves possible conflicts.

Economic design

Drilling to the deep regional aquifer is costly and may have contributed to the scenarios asserted by Onyenechere *et al.* (2012); that residents of the region rely on a daily water supply delivery via lorry tankers by commercial borehole owners amidst a lack of public water facilities. This is because the AMD agitated water supply deteriorates materials used for construction and development of a water pipe scheme. Failures of the scheme for a town water supply may be related to plights which Obeta (2016) emphasized to have disconnected the rural communities adjoining Enugu region from free share of a water supply scheme. Therefore, if reforms should be aimed to restore balance between the available water resources and people's needs (Laurenceau *et al.*, 2020), then relief from the water supply plight is possible as the policy makers invest in building water projects, such as the surface water reservoirs as proposed earlier. The water reservoir could capture the out-seeping perennial base-flow from the groundwater regime of the regional aquifer along the seepage face into a treatment column facility before distribution. By this scheme, a sustainable potable water supply would be guaranteed to the growing population at affordable subsidized annual or monthly rates from the managing agency. The project marks 'a paradigm' from non-revenue condition to capacity building tariff revenue investment. Job opportunities could be available to the surging population, and there will be an economic surge via value added tax (VAT) to the state or federal Government from water sales. Hutton & Haller (2004) confirmed similar interventions as cost-beneficial, especially in developing countries where the return on every US$1.0 investment for water and sanitation improvements ranged from US $5 to US$28. The potential economic benefits outweigh the investment cost; even in pessimistic scenarios. According to the WHO (2007), investing in water alone without sanitation amounts to a global average return of four times the original cost.

In Enugu region, low income earners customize water usage based on their budgets, hence drink little or no certified quality water. According to Tarrass & Benjelloun (2012), the global health burden caused by inadequate access to water is staggering, with more than a million deaths yearly. The mortality impact due to lack of water and sanitation in Africa has caused economic losses up to $28.4 billion, and has affected about 5% of the GDP (UNESCO, 2009). As it stands, income per person determines the amount of water consumed. However, there should be a right of access to a potable water supply as every person has the right to life. Intervention investment in a water scheme can grant the assurance of public access to sustainable potable water. The best proposal is to initiate a public-private partnership in the scheme intervention program to supplement government and community joint participation proposed by the National Water Supply & Sanitation Policy (2000) for management purposes. Involving stakeholder agencies in setting and collection of water-use charges, as well as issuing operating licenses (Schreiner & Van Koppen, 2002) is an effective strategy in water resource management.

Environmental exposure and the social effect

The major mode of bioaccumulation of noxious chemicals relating to the AMD is by the oral route via ingestion of affected water supply and herbs (vegetables). The toxic effect of the AMD on fish has been confirmed in Jennings *et al.* (2008), who indicated that humans who consumed affected fish are vulnerable to the related toxicity. Therefore, food-borne is a major means of human exposure to hazardous ions instilled from the AMD. Exposure to excess contents of Fe in water (see Table 3) is highly risky; Oguntoke *et al.* (2009) listed some associated diseases like diarrhea, abdominal pain, seizures, shock, low blood glucose, liver damage, convulsions, coma and possible human death. It means that people around the downstream region, particularly those that make up the huge population of riparian communities, are mostly vulnerable to these diseases. This deduction is based on the previous report by Ukpai *et al.* (2019) who traced provenances of major rivers across parts of lower Benue Trough to the studied catchment area. They detailed how the rivers recharge local aquifers at the downstream via a fracture-riverbed interconnection. Seeing that the northern portion of the catchment of Anambra

Basin overlapped with the coal mines (see Figures 1 and 2), the dependability of local aquifers at the downstream regions has become questionable. Relatively, it is safe to state that the ecosystem service values (ESV) from upstream to downstream zones have drastically depreciated due to land use, particularly on agro-ecology, aquatic biodiversity and in the overall terrestrial food chain. Meanwhile, the ecosystems in general provide services of fundamental importance to human well-being and livelihood (Costanza *et al.*, 1997), thus they require proper land-use planning to enhance the ESV (Negash *et al.*, 2020).

According to the United Nations (UN-Water, 2007), water quality degradation has become a major cause of water scarcity. The National Water Supply & Sanitation policy (2000) recommended 120 liters per capita per day. However, previous works identified a lesser supply of about 95 liters per capita per day around Enugu and its environs (Onyenechere *et al.*, 2012). On this note, it appears that deficient water utility maximization in the region is a major cause of social anxiety among the people. Therefore, an alternative means of alleviation is to develop a water supply facility which will not be based on 'out of pocket payment', rather by an organizationally sponsored prepayment system. Okoli *et al.* (2019) emphasized that 'out of pocket payment' for water supplies impoverish households.

Impoverishment of this type arises because people forego other necessities for water with the little available income. If nothing causes social anxiety as much as poverty, then poverty is the major drive of anger and conflicts. Prevention of conflict is better than resolution of the consequence. Therefore, the preventive measure entails curbing the ecological pathways of human exposure to the ill-fates relating to poor water supply. To check this menace in Anambra Basin, environmental objectives must be set up by any agency that oversees ecological affairs. Part of the objectives should include the assessment of Land Use and Land Cover (LULC) change. According to Chamling & Bera (2020), monitoring and assessment of LULC change is fundamental in environmental health evaluation and imperative in ecosystem managements.

Conclusions

The following conclusions were derived:

- The water supply problem is endemic in Enugu region because groundwater occurrence is greatly hampered by underlying geology which allows seepage at formation contacts, mainly between aquitards of the coal bearing Mamu formation and the regional aquifer belonging to Ajali sandstones. Meanwhile, great depths to the aquifer have caused high costs in the development of groundwater in the basin.
- Empirical investigation demonstrates that porosity of the sandstone is the same across the length and breadth, for which the homogeneous and isotropic nature of permeability was suspected. Thus, the aquifer has the baseflow potential to recharge the fluvial system.
- The regional aquifer is not only potable, it yields efficiently to wells and feeds adjoining fluvial systems that traverse beyond Anambra Basin; thereby producing a water supply for the entire region and across states in Nigeria.
- Alkaline drainage from the aquifer flushes some of the unsafe Acid Mine Drainage (AMD) from abandoned coal mines, hence the degraded quality of the water supply at the river catchment axis.

- Groundwater from Ajali formation is directly exported to adjoining areas by portable means via the uneconomic mode of pump and load into tanker lorries for water delivery.
- The water resource economy has been jeopardized, particularly in supply services to households, agriculture, and other riparian related businesses.
- Given the site conditions, limited water supply businesses grew among private organizations who could afford groundwater development from the deep regional aquifer; to sell at a profit.
- The average population spent much out of their incomes purchasing small quantities of potable water for family use. Many cannot afford the price.
- This water scarce situation has further impoverished the average resident of the region, especially as agribusiness has deteriorated at riparian downstream.
- The panacea relies on policy making and strong decision making to either channel groundwater from the aquifer and bypass the inherent AMD environment to a constructed central reservoir system or streamline the chemically influenced seepage to the reservoir for treatment purposes. In any case, a sustainable water supply can be distributed from the reservoir to adjoining towns via a pipe line or aqueduct.
- Such a scheme could revitalize the water management boards and ensure a steady supply to citizenry for adequate cleansing and wellbeing.
- Though investment into water infrastructure requires large expenditures, it sustains quality of life, attracts employment opportunities, rehabilitates farms, and levels supply shortages for the private water bottling companies.

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Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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