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Groundwater Assessment and Contaminant Migration in Fractured Shale Aquifers of Abakaliki Mining Areas, Southeast Nigeria

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Abstract
Mineralization and mining activities in the Abakaliki area generate Metallic Trace Elements (MTEs) which disperses and contaminate the environment. This could have serious environmental and health effects both in the vicinity of the mines and offsite. The migration and transport of these MTEs have not been studied and could have an important role in the degradation of groundwater in the area. This study was undertaken to evaluate the levels of hydrogeological parameters, pH, Electrical conductivity, groundwater levels in wells, and geochemical assessment of Mg, Ca, Cl^-, SO_4^{2-}, As, Cr, Mn, Pb, Cd, Fe, Hg, Ag, Ni, Se, Co, and Zn using atomic absorbtion spectrophotometric method. Furthermore, the extent of the influence of fractures on the migration, flow direction and subsequent transport of contaminant in the fractured shales aquifers was done using geohydrological studies and field mapping. Result indicates that MTEs are transported in the saturated zone through fracture network which trends mainly in the NW – SE direction, this controls groundwater occurrence and hydrothermal mineralization in the area. The distribution of geochemical elements indicates higher concentrations in wells within the mining areas and downstream. This is be due to non connectivity of fractures; formations of water divide; and soil/ rock/ water interaction. Levels of Cl^-, SO_4^{2-}, As, Mn, Pb, Cd, Fe, Hg and Se in some wells are above the World Health Organization and Standard Organization of Nigeria guidelines for drinking water. No principal flow direction was indicated, but Northeasterly and Southeasterly groundwater flow vectors were observed. Conceptual models reveal predominance of recharge area in the central parts while the northern and southern parts form the discharge areas. This is useful for proper water resources and waste management planning. The hydrogeological and geochemical investigations show that the contaminants are geogenic rather than anthropogenic.

Keywords: *Groundwater, contamination, Fracture system, Flow direction, Mining and Abakaliki*

Introduction

Groundwater has strategically remained a valuable resource in the Abakaliki area, SE Nigeria, this is due to the lack of surface water reservoirs in the area, and secondary features such as fractures that control groundwater movement and occurrence in the area (Odoh, *et al.,* 2012). The area in the Lower Benue Trough has been renowned for the occurrence of solid minerals including galena, chalcopyrite, sphalerite, quartz, pyrite and siderite (Obage, 2009). The area is underlain by the shales of the Asu River Group (ARG). Deposits of the shales in the area (Lower Benue Trough) (Fig. 1) is characterized by intense uplift, fracturing (Fig. 1 a-c). folding, magmatism and mineralization which have been linked to the Santonian orogeny (Kogbe, 1976; Petters *et al.*, 1987).This, however led to the deposition of these minerals in the area (Obaje, 2009). Since the discovery of lead –zinc and other associated minerals in the Abakaliki area in the early 1925 (Umeji, 2000). industrial and communal mining has been on- going. This has also led to the generation of mine waste and subsequent deterioration of the environment (Obasi *et al.*, 2021, Nnabo *et al.*, 2011; Obasi and Akudinobi, 2019;2020 and Obiora *et al.*, 2016). Apart from potential contamination from the host rock, contaminant migration from the Umuaghara abandoned quarry site (Fig. 1d) (which has been used as the waste receptacle point for dumping waste in the Abakaliki area for about a decade) can affect groundwater quality. These waste decompose and migrate into groundwater sources and are carried along in solution from one point to another (Zhao, 2007). this can pose great danger to groundwater resources. The dissolution of solid minerals due to inherent interaction with groundwater is inevitable. When discharged into the environment, mine effluents can contaminate surface water resources (Rubio *et al.*, 2000; Nieto *et al.*, 2007) and move into the groundwater system as baseflow (Moye *et al.,* 2017). Zhao *et al.* (2004) also opined that they can infiltrate into the underground soils / rocks, which can cause pore- water flow in the pore space in the soil/ rocks. Zhao *et al.* (2007, 2008a) has demonstrated that when the pore-water comes in contact with the soil/rock, it can react chemically with the mine waste, dissolving heavy metals at the mine site. And since the dissolved heavy metals can be transported in the soil/rock through pore-water advection, convection and solute diffusion/dispersion, they can contaminate both the land and the groundwater both at the mine site and offsite. Zhao *et al.* (2008b, 2010a) and Konikow (2011) also noted that minerals in the host rocks can dissolve and migrate into groundwater sources.

Fractures are very important in groundwater studies as they do not only serve as channels and pathways for groundwater but plays an effective role in the control of groundwater quality. Ebong *et al.* (2014) and Arthur, *et al.* (2008) have indicated that shallower aquifers are likely susceptible to contamination, and fractures have protective capacities to prevent such contamination. Myer (2012) has also shown that even deep aquifers can also be affected. While groundwater flow in fractured porous media occurs mainly through fractures, much of the water contained within these aquifers is stored within the matrix. This has important implications for the movement of contaminants or other dissolved substances. Even if the permeability of the matrix is very low, diffusion will cause mixing of solutes in water flowing through the fractures with those in the relatively

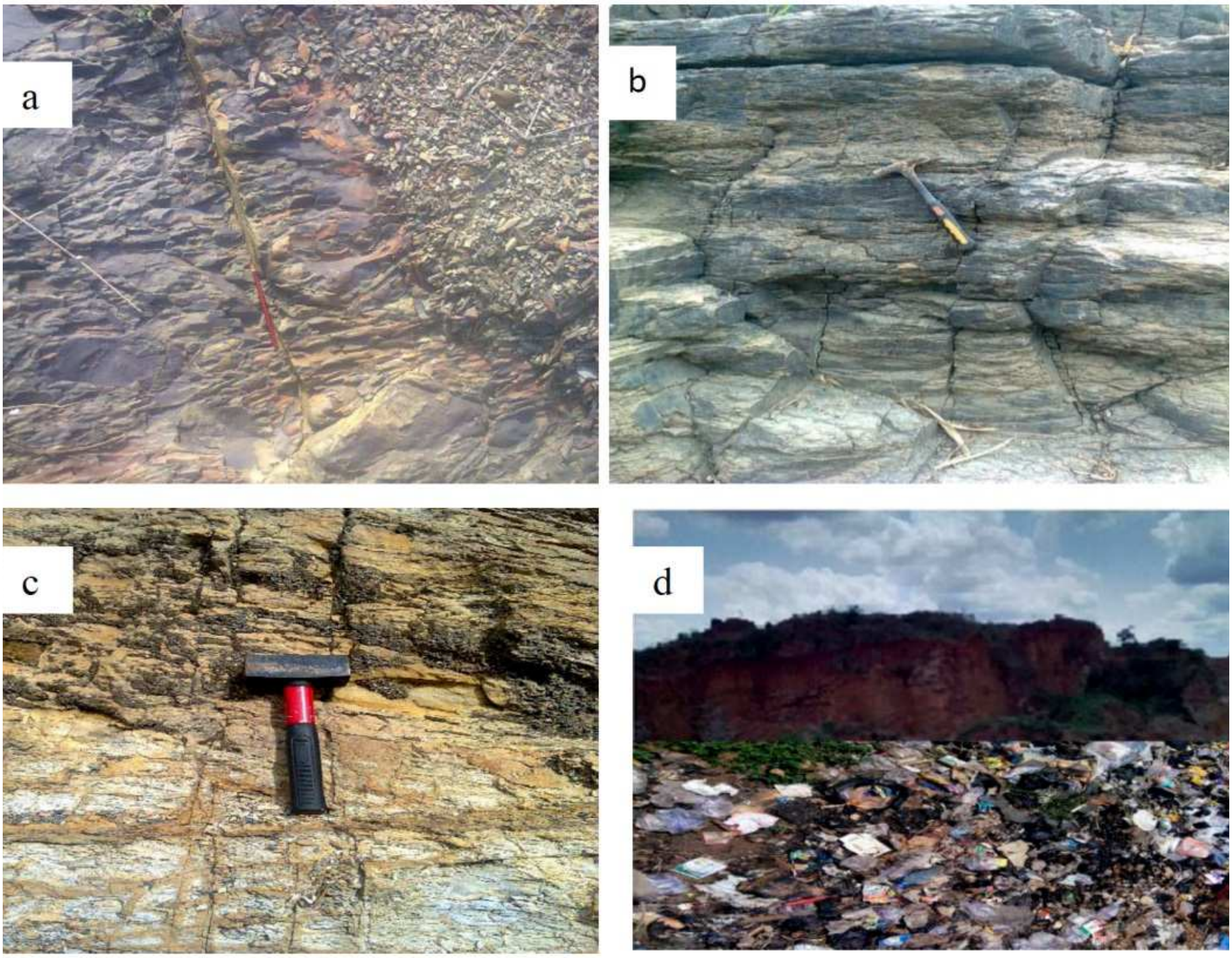

Fig. 1: Field observations of fractures in outcrops (a- c) at (a) Mkpuma Akpatakpa (b) the base of juju hill. (C) Hausa quarters, Abakaliki (d) Part of the Umuaghara abandoned quarry currently in use as the waste dumping site in Abakaliki Metropolis.

immobile water in the rock matrix. In practice, this means that dissolved substances usually appear to travel more slowly than water. Experimental studies have observed that very large particles (glass beads and bacteriophage) may travel very quickly (because they move through the fractures and do not readily enter the small pores within the matrix). while smaller solutes (including most ions) move more slowly. For example, in fractured shale near Oak Ridge, Tennessee, velocities of small glass beads have been measured to be up to 200 m day-1 (McKay *et al.*, 2000). In southern Ontario, Canada, bacteriophages have been observed to travel at 4 m day-1, while dissolved bromide travels at only 4 cm day-1 (McKay *et al.*, 1993). This movement of solutes between the fractures and the matrix is referred to as matrix diffusion. It causes smaller molecules to appear to move more slowly than larger molecules, depending on their diffusion coefficients. Myer (2012) demonstrated that there is substantial geologic evidence that natural vertical flow drives contaminants, mostly brine, to near the surface from deep evaporite sources. The movement and attributes of groundwater can be studied using groundwater flow maps. This is very useful and can be employed in investigating wide range of hydrologic and hydrogeologic problems such as groundwater flow modeling and prediction, aquifer protection, management, remediation and the study of contaminant transport in hydrogeochemistry (Okiongbo and Akpofure, 2012; Mastrocicco *et al.*, 2010). Groundwater flow maps help for proper management of groundwater resources with respect to waste disposal, plume migration, and effluent/ leachate movement. Myer (2012) also stated that two potential pathways—advective transport through bulk media and preferential flow through fractures could allow the transport of contaminants from the fractured shale to aquifers. Recharge and discharge zones can also be determined using groundwater flow studies (Freeze and Cherry, 1976; Shoemaker, *et al.*, 2008).

Based on the fact that mine operations generate wastes with high concentrations of Metallic Trace Elements (MTEs) and other hydrochemical components (Obasi, 2020; Eyankware *et al.*, 2021; El Amari *et al.*, 2014) and could be transported in solution (Myer, 2012; Moye et al, 2017) as Acid Mine Drainage (AMD). this work is aimed at assessing the impact of the MTDs (Cr, Mn, Fe, Co, Ni, Zn, Cu, As, Se, Cd, and Pb) and major hydrochemical components (Ca, Mg, Na, SO_4^{2-}, Cl) on the groundwater quality of mining areas of Abakaliki. It is necessary to identify the distribution anomalies of the principal contaminants and to indicate the likely impact on the health of the rural dwellers who do not consider these factors since the lack of alternative source of water supply leaves them with no other choice for their domestic uses. In order to understand the AMD in the saturated zone, it is necessary to collect more information about the aquifer fracture system, and the groundwater flow and movement in the area; this is pertinent since groundwater flow and contaminant transport are controlled by fractures and faults. This paper will show the movement and direction in which these contaminants migrate. This study will assist in the establishment of safe and unsafe areas with respect to contaminant transportation and waste management, and will also be used to determine recharge and discharge areas, which constitutes a vital tool in groundwater prospecting and management. This paper is based on field geological, hydrogeological and hydrochemical data.

Site Description, Geology and Physiography

The area is bounded by longitudes 8°00'E and 8°12'E and latitudes 6° 05'N and 6° 34' N covering a total area of about 794.2 km^2. The area is underlain by the ARG (Fig. 2). The occurrence and study of intrusions of pyroclastic rocks in the area is obvious in many places (Olade, 1979). The lithology of the area consists mainly of well-indurated shales, minor argillaceous sandstones, siltstones and mudstones. The well indurated sandstones and siltstones are exposed at the hills and ridges while the shales and mudstones occupy the lowlands. The deposits are the oldest sedimentary rocks in southeastern Nigeria and have undergone tectonism (Kogbe, 1976). It is exposed variously in the Abakaliki area where they are often referred to as the Abakaliki Shales. These shales differ in their physical characteristics. Some are fissile while others are indurated. Hence, the classification into three different units: A, B and C. (Fig. 2). Igneous intrusions were also encountered in the area at Ndiechi, Abakaliki and Ezzagu. Lead- zinc mineralizations (veins and lodes) were observed in some locations, which include Mkpuma Akpatakpa, Ameka, Enyigba, Amorie, Ekweburu Village and Agbaja. Geologically, the Abakaliki area has been renowned for its high tectonic activities which occurred in the Santonian orogenic times (Kogbe, 1976). This orogeny, led to the fracturing of the shales, and hydrothermal inclusion of mineral deposits in the area. These fractures now form the basis for groundwater development and solid mineral exploration in the area (Odoh, *et al.*, 2012).

The geomorphology of the area is controlled by the prevalent structural, lithologic and physico-chemical factors. The topography could be described as comprising irregular ridges and gentle sloping hills. The elevation of the highlands range from 45m to 65m above mean sea level, while the lowlands rise to an average of about 30m (Aghamelu, 2011). The area is characterized by a uniform sloping drainage slightly tilted eastwards.

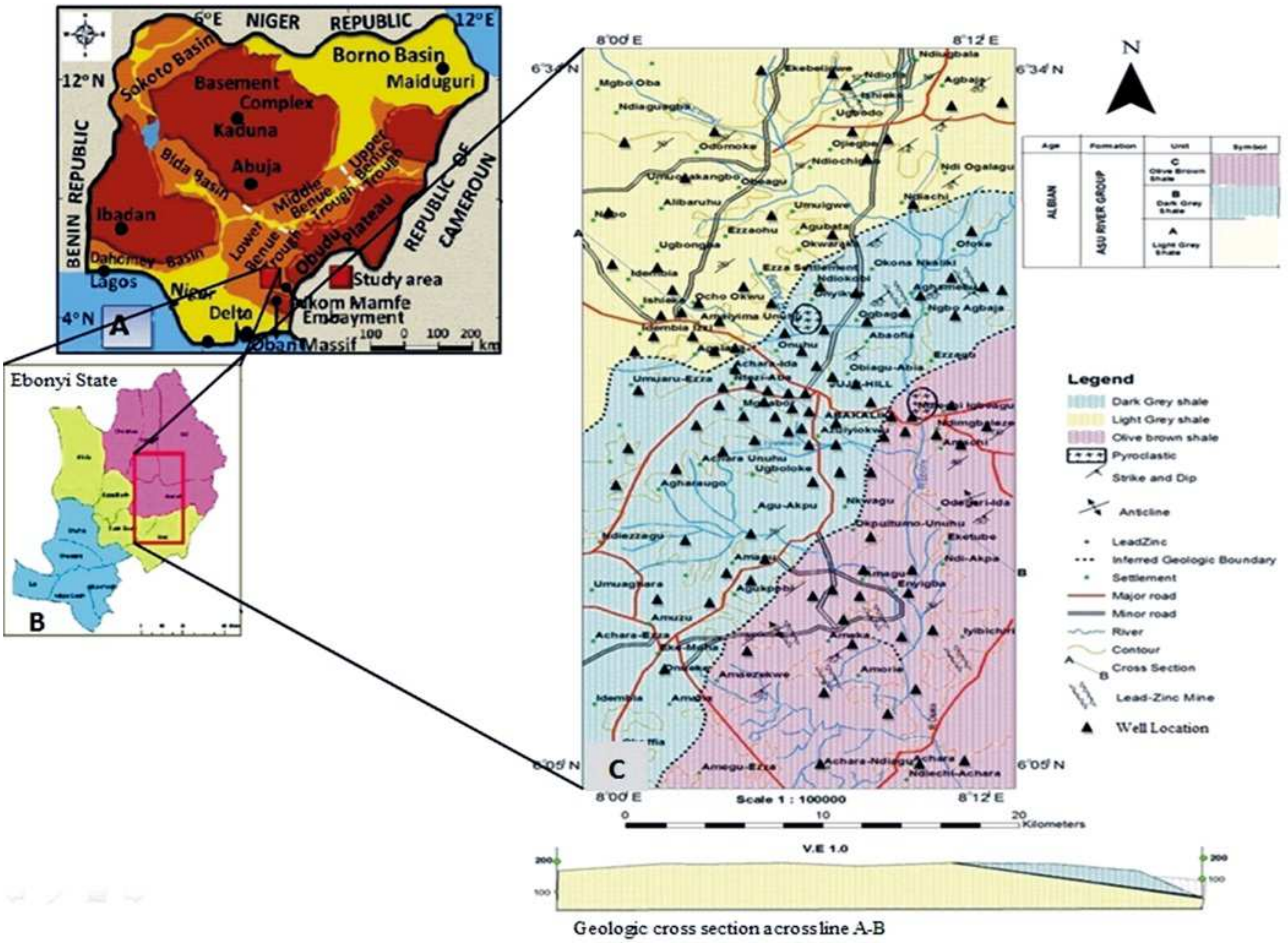

Fig. 2: (A) Geologic map of the Nigerian sedimentary Basins showing the Lower Benue Trough LBT). Middle Benue Trough (MBT) and the Upper Benue Trough (UBT) (NGSA, 2006) (B) Map of Ebonyi State showing the Study area (C) Geologic map of the study area showing the main rock type and location of hand dug wells in the area.

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Materials and Methods

This research involved three major stages: data collection in the field for fracture mapping and hydrological studies, processing and interpretation.

Geologic Field Mapping

Geologic field mapping was carried out to determine the basic rock types and map surface fractures in the area. Fifty – eight azimuths of joints and fractures were measured at various outcrops in the area. They include Onu- Ebonyi, Azoto – Amachi, Enyigba, River Ewe, Ebonyi River and Juju hill. These azimuths were used to plot rose diagrams for analysis of the major fracturation of the area. Locations of the fractures (Fig. 3) were georeferenced using Garmin GPS map78s. Lineament map of the area was extracted from Digital Evolution Model using Quantum- Geographical Information system (Q-GIS) and used to compare field measurements.

Hydrologeological Studies

According to Buddermeier and Schlooss (2000). the most direct and accurate method of determining the direction of groundwater movement is by measuring the elevation of groundwater at multiple locations over the aerial extent of an aquifer. With the aid of a Water Level Meter (Heron Dipper T). one hundred and ten (110) hand dug wells were observed for measurement of water level and depth of wells (Fig. 2; Table 1). Global Positioning System (GPS Garmin GPS map 78s) was used to georeference each point. The surface elevations at different points were recorded. The uniform water level coincided with static water level in the case of an unconfined aquifer while it was the piezometric surface if the aquifer was confined (Buddermier and Schlooss, 2000). Hydraulic heads were subsequently converted to meters to enable for groundwater contouring and visualization. Aquifer conceptual model was used to deduce velocities of the groundwater at various points in the area and the particle path lines were obtained according to Todd (1980) and Fetters (1981).

Mathematically,
Let DHDW = the depth from the surface of the earth to the water level in the hand-dug well (Direct Bore hole logging)
E = the surface elevation with respect to the mean sea level
Swl = The true or uniform water level otherwise known as the static water level in the case of an unconfined aquifer then

Swl = E - DHDW..(1)

The values of the static water levels were contoured on the map of the study area using Suffer 11 software. These lines represented the water table contours. Bradbury and Muldoon (1992) describe fractures that are visible in alfalfa fields using lineament map and aerial photographs, and use these photographs to determine fracture orientation and density. Three dimensional (3D) elevation map and conceptual groundwater flow model for the aquifer was generated using SUFFER 11. Using Buddermeier and Schlooss (2000) deductions, groundwater would flow from the highest values of contour lines to the lowest values in a direction perpendicular to the contour lines.

Water Sample Collection and Analytical Procedures

Twenty - four (24) groundwater samples were collected systematically from different locations in the area. The water samples from all observation wells were stored in a plastic1-liter container for detailed chemical analysis. These containers were washed thoroughly with distilled water and dried before being filled with the water samples. To obtain a composite sample, they were collected after the well was subjected to pumping for 5–10 mins (for pump wells) while hand dug wells were cleared of visible wastes before sample collection. Filtration of water samples was done in the in the field using 0.45µm diameter disposable filters to ensure the removal of suspended solids before storage in prepared bottles. Acidification of samples was done with 1.0 mL of conc. HNO_3 using new syringes. This is necessary to prevent sorption. The samples were stored in ice packed containers to maintain the transportation temperature. Accordingly, before the sampling, sample bottles and beakers were washed thoroughly and soaked in distilled water acidified with 1.0mL of HNO_3 for three days. They were also rinsed with dilute HNO_3 and vigorously rinsed at least three times with the water sources at the point of water collection.

Laboratory analysis for the concentration of As, Cr, Zn, Ni, Mn, Pb, Cu, Hg, Cr, Ni, Cd, Ag and Se were analysed using Fast Sequential (FS) (Varian 240 AA) Atomic Absorbtion Spectrophotometer. Physical parameters including electrical conductivity and pH were measured in-situ at the points of collection, electrical conductivity meter (DDS 307 model). and pH meter (Hanna model H1991300) were used respectively. All sampling steps and data analysis was performed according to standard methods for water and wastewater (APHA, 1995).

Result

Hydrochemical Distribution

The result of groundwater analysis has been presented in table 1 below. The highest concentrations of hydrochemical elements including Cl, As, Fe, Cd, Cr, Mn, Pb, Se, Hg and Zn were observed in the mineralized region, while SO_4^{2-} and Cl^- indicated significant concentration even away from the mineralized region. Highest concentration of sulphate was recorded in wells OP7 (452.7mg/L). OP11 (510.3mg/L) and OP19 (930mg/L). Chloride concentration ranges 3.6mg/L to 2360mg/L. Highest concentrations were recorded in wells OP3, OP11, and OP18 (Fig. 3b). These wells are located in Enyigba and Ameka areas where salt lakes have been observed (Obasi, 2017). The high values can be linked to the movement of rich salt waters from the salt lakes to other areas. Only few MTEs will be detailed in this paper. Arsenic is found in a concentration range of 4.01mg/L. Highest values were recorded in wells OP1, OP12, OP13, OP18 and OP22. These wells are located in the mining areas of Ameka and Amanchara. Wells OP18 and OP22 are however, located in the drainage tributary system of the Abakaliki area (Fig. 3a) indicates dispersion of groundwater through groundwater flow systems. The Cadmium concentrations has a range of 0.509mg/L with no detectable concentrations in wells OP1, OP3, OP4 and OP24, highest concentrations were recorded in wells in the mining areas (Fig. 3a). This concentrations can be linked to the weathering and subsequent dissolution of the chalchopyrite and pyrite ores in the area. Cadmium's mobility in water depends on several factors including the pH and the availability of organic matter. Generally, cadmium will bind strongly to organic matter and this will, for the most part, immobilize cadmium (Autier and White, 2004). Cadmium in water tends to be more available when the pH is low (acidic) (Elinder, 1992). Manganese concentrations in the area was intermediate and well distributed except for wells OP1 (2.9mg/L). OP3 (4.576mg/L). OP2 (9.914mg/L) and OP4 (12.10mg/L). Well OP2 and OP4 are anomaly high and are located in the mining areas of Enyigba and Mkuma Akpatakpa respectively (Fig. 3a). High concentrations of Mn are attributed to the dissolution of chalcopyrite and siderite ores in the Enyigba and Mkpuma Akptakpa area. Mn concentration is controlled by the solubility, pH, Eh (oxidation-reduction potential). and the characteristics of the available anions in water (Clewell *et al.*, 2003). Mercury has a similar distribution with manganese (Fig.3a). However, the measured concentrations are significantly lower. Indeed, high concentrations are around the mineralized areas. Gilmour and Henry (1991) noted that the most common organic form of mercury, methylmercury, is soluble, mobile, and quickly enters water by dissolution. Hydrochemical distribution for lead shows unequal distributions with a range of 4.29mg/L. Wells OP2, OP14 and OP15 (around Enyigba) and wells OP3, OP4, OP5 and OP24 (Mkpuma Akpatakpa) recorded higher concentrations. This result clearly indicates that the lead ores (galena) significantly affect the quality of groundwater of the area. Apart from the composition of the ores, the low pH (Table 1). the salinity and presence of CO_2 in the water sources causes faster dissolution of lead in water (ATSDR, 2007). Cobalt, nickel, zinc and copper has similar hydrochemical distribution phenomenon, their concentrations is not centered in the mineralized areas alone. However, they tend to decrease significantly away from the mines (see Fig. 3a and b). Concentration of Mg, Ca are higher in the non-mineralized areas of Abakaliki urban with ranges of 25.62mg/L and 51.99mg/L respectively. These high concentrations of Mg and Ca in the Abakaliki area are

Table 1: Result of Groundwater analysis in the mining areas of Abakaliki

Sample No	pH	ElC µs/cm	TDS mg/l	Cl mg/l	SO4-2 mg/l	Fe mg/l	Mg mg/l	Na mg/l	Ca mg/l	Pb mg/l	Cu mg/l	Cr mg/l	Ni mg/l	Mn mg/l	Cd mg/l	Ag mg/l	Co mg/l	Hg mg/l	As mg/l	Se mg/l	Zn
OP1	6.25	152	71.58	30	54	0	0	5.3264	4.92	0.04	0	0	0	2.901	0	0.354	0.01	2.3	0	0	0
OP 2	6.47	327	53	1204	45	0.37	25.619	1.4442	5.1	0	0	0	0	9.914	0.061	0.243	0.01	1.9	1.88	0.0005	0
OP 3	7.12	345	43	2250	84	2.78	0	6.3872	4.2	4.29	0	0	0	4.576	0	0.253	0	0.7	0	0	0
OP 4	6.99	79	67.2	37	22	0	18.168	4.8955	0	0	0	0	0	12.1	0	0.191	0	0	0	0	0.157
OP 5	6.03	376	1.3	36	259.2	0	19.172	0	51.99	3.2	0	0	0	1.134	0.238	0.04	0.01	0.15	4.01	1.2505	1.72
OP 6	7.17	257	0.8	55	205.8	0	19.619	0	45.22	2	0.002	0	0	0	0.305	0	0.17	0.071	3.739	1.2314	0.086
OP 7	8.72	103	4	53	452.7	0.08	10.658	82.317	12.79	4.19	0.158	0	0.17	2.149	0.115	0	0.21	0.175	3	1.0429	0.774
OP 8	6.61	98.5	28.4	52	329.1	0	19.604	110.62	32.95	2.73	0.028	0	0	0	0.374	0	0.17	0.372	1.61	2	0
OP 9	6.68	88.3	34.2	37	292.2	0	19.563	114.91	45.03	2.77	0	0	0	0	0.264	0	0	0.223	3.48	2.1391	0.036
OP 10	8.78	79.8	21.6	39	333.3	0	19.527	111.93	37.24	2.26	0	0	0.09	0	0.278	0	0.21	0.372	2.73	2.6608	0
OP 11	5.75	850	50	2360	510.3	0	19.338	103.38	24.38	2.43	0.008	0	0.08	0	0.433	0	0.24	0.363	2.86	2.6782	0
OP 12	8.87	78.2	17.4	47	238.7	0	20.449	101.74	8.579	2.76	0.022	0	0.06	0	0.447	0	0.06	0.249	2.94	2.4869	0
OP 13	7.09	648	4.2	55	222.2	2.1	17.521	82.444	9.884	1.88	0.051	0	0	0	0.382	0	0.22	0.445	1.79	0.8232	0
OP 14	7.07	543	4	54	201.6	0	17.815	73.825	19.61	1.66	0.032	0.09	0	0	0.509	0	0.18	0.384	2.36	0.8258	0
OP 15	7.03	418	3.8	92	185.2	0	19.853	100.1	26.83	1.87	0.054	0	0.05	0	0.164	0	0	0.395	2.02	1.3095	0.038
OP 16	6.99	420	3	897	164.6	0	20.073	109.71	26.33	2.76	0.002	0	0.07	0	0.318	0	0.05	0.334	1.11	0.9729	0.107
OP 17	7.05	521	3.4	40	205.8	0.02	14.151	83.117	20.59	2.63	0.018	0	0	0.002	0.343	0	0.08	0.383	2.26	1.2503	0.021
OP 18	6.99	587	16	2050	337.4	0	15.167	81.673	32.71	2.76	0	0	0.26	0.093	0.353	0	0	0.294	1.94	0.7091	0
OP 19	6.71	357	4	4.7	930	2.09	3.124	10.682	26.58	1.95	0	0	0.04	0.066	0.144	0	0	0.48	0.43	0.795	0.002
OP 20	6.97	325	18	3.7	703.7	2.8	19.404	115.85	191	2.33	0	0	0	0.135	0.088	0	0.14	0.396	2.93	0.2999	0
OP 21	6.95	419	8	3.6	662.5	0	19.571	102.76	43.94	1.93	0	0	0	0	0.378	0	0.13	0.448	2.9	0.4166	0
OP 22	7.05	605	10	3.7	78.19	1.5	9.69	84.953	15.63	2.08	0.067	0	0	0	0.245	0	0.05	0.437	2.53	0.5103	0
OP23	6.44	85.4	16	32	267.5	1.23	6.116	54.187	9.017	1.97	0	0	0.04	0.591	0.272	0	0.07	0.392	1.97	0.5437	0.18
OP 24	7.39	457	1	38	242.8	0	20.582	50.791	191	3.8	242.8	10.1	12.62	0.6	0	2.058	0.58	0.791	1.91	0	0

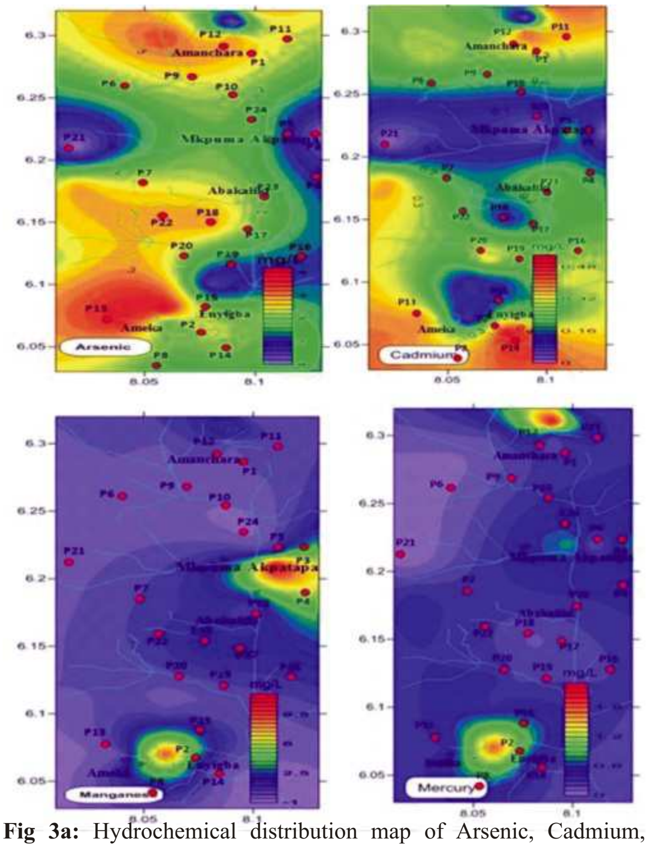

Fig 3a: Hydrochemical distribution map of Arsenic, Cadmium, Manganese and Mercury in groundwater in the mining areas of Abakaliki

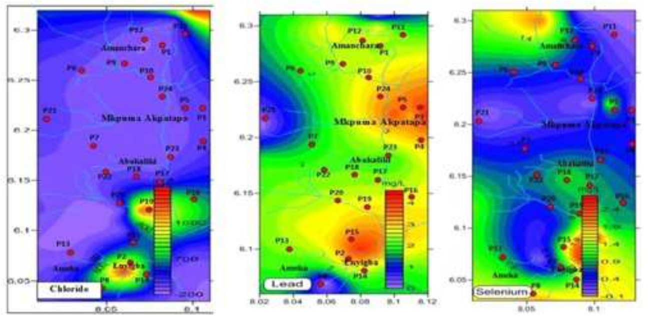

Fig 3b: Hydrochemical distribution maps of Chloride, Lead and Selenium in groundwater of the mining areas of Abakaliki

the main reason for groundwater hardness in the area. This is linked to the highly indurated and carbonaceous shales of the ARG which underlie the area. Mg and Ca groundwater in the area evolve hydrochemically into the $CaCO_3$ and $MgCO_3$ salts which causes water hardness. In addition, the effects of the high carbonate pyroclastics in the area cannot be over emphasized.

Hydrogeological Studies

Table 2 shows the location, water table and elevation of 110 hand dug wells sampled for this study. Hydraulic heads were subsequently converted to meters to enable for groundwater contouring and visualization. Aquifer conceptual model was used to deduce velocities of the

Table 2: Water Table Levels of Wells in the Study Area.

S/N	GPS LOCATION (CO-ORDINATE)		LOCATION OF WELL	WATER TABLE (m)	ELEVATION (m)	CORRECTED DATUM (m)
1	06^{0}19’41.3”	08^{0}07’12.4”	43, Igweorie str; Abakaliki.	36.08	56	19.92
2	06^{0}19’42.5”	08^{0}07’12.8”	31, Igweorie Str; Abakaliki.	22.96	59	36.04
3	06^{0}19’43.1”	08^{0}07’12.8”	30, Igweorie Str; Abakaliki.	16.4	57	40.6
4	06^{0}19’38.2”	08^{0}07’12.2”	37, Igweorie Str; Abakaliki.	29.52	52	22.48
5	06^{0}19’37.4”	08^{0}07’11.8”	25, Igweorie Str; Abakaliki.	32.8	60	27.2
6	06^{0}19’37.1”	08^{0}07’10.3”	16, Igweorie Str; Abakaliki.	29.52	61	31.48
7	06^{0}19’36.2”	08^{0}07’10.3”	13, Igweorie Str; Abakaliki.	24.928	56	31.072
8	06^{0}19’37.0”	08^{0}07’09.0”	8, Igweorie Str; Abakaliki.	32.8	54	21.2
9	06^{0}19’34.8”	08^{0}07’08.5”	7, Igweorie Str; Abakaliki.	28.536	56	27.464
10	06^{0}19’36.1”	08^{0}07’08.56”	4, Igweorie Str; Abakaliki.	31.16	57	25.84
11	06^{0}19’34.7”	08^{0}07’7.8”	5, Igweorie Str; Abakaliki.	20.664	53	32.336
12	06^{0}19’40.3”	08^{0}07’10.6”	4, Igweorie Str; Abakaliki.	36.08	54	17.92
13	06^{0}19’40.3”	08^{0}07’09.6”	6, Elias Odili Str;Abakaliki.	35.096	62	26.904
14	06^{0}19’49.6”	08^{0}07’09.0”	8, Elias Odili Str; Abakaliki.	38.048	56	17.952
15	06^{0}19’39.5”	$O8^{0}$07’12.8”	39, Igweorie Str; Abakaliki.	41.984	58	16.016
16	06^{0}19’46.3”	08^{0}07’14.3”	50, Igweorie Str; Abakaliki	20.336	64	43.664
17	06^{0}19’45.3”	08^{0}07’14.4”	57, Igweorie Str; Abakaliki	11.48	61	49.52
18	06^{0}19’41.8”	08^{0}05’45.6”	12^{B} Sakamori Qtrs, Amagu Str	17.384	73	55.616
19	06^{0}19’42.1”	$08^{05’}$45.1”	10^{A} Sakamori Qtrs, Amagu Str	16.4	72	55.6
20	06^{0}19’42.2”	08^{0}05’46.6”	11A Sakamori Qtrs, Amagu Str	14.104	72	57.896
21	06^{0}19’41.7”	08^{0}05’44.2”	9^{B} Sakamori Qtrs, Amagu Str	16.4	70	53.6

22	06^{0}19’42.7”	08^{0}05’46.7”	13A Sakamori Qtrs, Amagu Str	18.69	72	53.31
23	06^{0}19’37.8”	08^{0}05’47.9”	18B Sakamori Qtrs Amagu str	24.928	75	50.072
24	06^{0}19’36.6”	08^{0}05’47.3”	19A Sakamori Qtrs Amagu str	19.68	75	55.32
25	06^{0}19’37.2”	08^{0}05’43.5”	1B, Sakamori Qtrs Amagu str	19.68	69	49.32
26	06^{0}19’38.9”	08^{0}05’44.1”	3B, Sakamori Qtrs Amagu str	22.96	70	47.04
27	06^{0}19’41.0”	08^{0}05’43.8”	5B, Sakamori Qtrs Amagu str	19.68	72	52.32
28	06^{0}19’45.4”	08^{0}05’31.1”	9, Nnoroom Str; Abakaliki.	11.48	74	62.52
29	06^{0}19’47.8”	08^{0}05’50.3”	24, Aloh Str, Abakaliki.	7.216	64	56.784
30	06^{0}19’48.6”	08^{0}05’52.2”	17, Aloh Str, Abakaliki	9.84	72	62.16
31	06^{0}19’48.0”	08^{0}05’51.5”	21, Aloh Str; Abakaliki	16.4	75	58.6
32	06^{0}19’58.2”	08^{0}06’07.7”	14, Ngbowo Street Kpirikpiri .	16.4	74	57.6
33	06^{0}20’02.5”	08^{0}06’08.0”	29, Ngbowo Street Kpirikpiri.	24.272	73	48.728
34	06^{0}20’05.3”	08^{0}06’09.4”	19, Ngbowo Street Kpirikpiri.	26.24	74	47.76
35	06^{0}19’00.4”	08^{0}05’25.3”	3B, Odinukwe Street.	39.36	71	31.64
36	06^{0}19’00.2”	08^{0}05’23.9”	9, Odinukwe Street.	39.36	72	32.64
37	06^{0}21’19.6”	08^{0}04’48.1”	Ugwuachara Area.	19.68	80	60.32
38	06^{0}21’18.5”	08^{0}04’48.8”	Ugwuachara Area.	16.73	71	54.3
39	06^{0}21’12.9”	08^{0}04’47.8”	Ugwuachara Area.	18.04	63	44.96
40	06^{0}21’21.9”	08^{0}04’48.5”	Ugwuachara Area.	29.52	75	45.48
41	06^{0}21’25.1”	08^{0}04’40.2”	Ugwuachara ASrea.	30.83	70	39.17
42	06^{0}22’38.4”	08^{0}02’41.0”	Ishieke Ikelegu Area.	22.63	75	52.37
43	06^{0}221’40.0”	08^{0}02’40.6”	Ishieke Ikelegu Area.	19.02	68	48.98
44	06^{0}22’40.8”	08^{0}02’40.3”	Ishieke Ikelegu	16.07	72	55.93
45	06^{0}22’57.9”	08^{0}02’35.8”	Ishieke Ikelegu Area.	33.78	72	38.22
46	06^{0}22’56.3”	08^{0}02’39.1”	Ishieke Ikelegu Area.	14.76	69	54.24
47	06^{0}22’56.0”	08^{0}02’40.6”	Ishieke Ikelegu Area.	13.12	68	54.88
48	06^{0}22’54.5”	08^{0}02’41.1”	Ishieke Ikelegu Area.	16.73	72	55.27
49	06^{0}22’56.0”	08^{0}02’43.1”	Ishieke Ikelegu Area.	15.09	78	62.91
50	06^{0}22’54.6”	08^{0}01’59.4”	Ishieke Ikelegu Area.	23.29	80	56.71
51	06^{0}22’53.7”	08^{0}02’00.9”	Ishieke Ikelegu Area.	19.68	77	57.32
52	06^{0}22’56.0”	08^{0}02’02.1”	Ishieke Ikelegu Area.	23.62	85	61.38
53	06^{0}22’50.9”	08^{0}02’04.1”	Ishieke Ikelegu Area.	22.30	82	59.7
54	06^{0}22’53.7”	08^{0}02’05.4”	Ishieke Ikelegu Area.	35.42	82	46.58
55	06^{0}22’52.5”	08^{0}02’07.8”	Ishieke Ikelegu Area.	30.18	77	46.82
56	06^{0F}22’52.1”	08^{0}02’08.0”	Ishieke Ikelegu Area.	29.52	76	46.48
57	06^{0}19’44.6”	08^{0}05’20.5”	Kpirikpiri Abakaliki	11.48	77	65.52
58	06^{0}19’44.4”	08^{0}05’21.0”	Kpirikpiri Abakaliki	13.12	77	63.88
59	06^{0}19’51.7”	08^{0}06’00.2”	Kpirikpiri Abakaliki	22.30	88	65.7
60	06^{0}19’51.1”	08^{0}05’59.2”	Kpirikpiri Abakaliki	24.6	79	54.4
61	06^{0}19’51.1”	08^{0}05’59.2”	Kpirikpiri Abakaliki	20.99	84	63.01
62	06^{0}19’50.8”	08^{0}05’58.4”	Kpirikpiri Abakaliki	23.29	78	54.71
63	06^{0}19’50.3”	08^{0}05’57.0”	Kpirikpiri Abakaliki	22.96	82	59.04
64	06^{0}19’51.4”	08^{0}05’55.9”	Kpirikpiri Abakaliki	16.07	78	61.93
65	06^{0}19’50.3”	08^{0}05’55.9”	Kpirikpiri Abakaliki	21.32	85	63.68
66	06^{0}19’49.1”	08^{0}05’52.9”	Kpirikpiri Abakaliki	14.76	81	66.24
67	06^{0}19’48.4”	08^{0}05’52.2”	Kpirikpiri Abakaliki	14.10	81	66.9
68	06^{0}19’47.9”	08^{0}05’51.6”	Kpirikpiri Abakaliki	13.45	80	66.55
69	06^{0}19’48.0”	08^{0}05’51.1”	Kpirikpiri Abakaliki	11.48	78	66.52
70	06^{0}19’47.8”	08^{0}05’50.4”	Kpirikpiri Abakaliki	8.53	81	72.47
71	06^{0}20’37.1”	08^{0}05’55.5”	Kpirikpiri Abakaliki	13.78	72	58.22
72	06^{0}20’37.7”	08^{0}05’53.2”	Kpirikpiri	20	74	54
73	06^{0}20’36.8”	08^{0}05’56.5”	Kpirikpiri Abakaliki	13.45	73	59.55
74	06^{0}20’36.7”	08^{0}05’58.9”	Kpirikpiri Abakaliki	17.06	70	52.92
75	06^{0}20’43.1”	08^{0}05’44.2”	Kpirikpiri Abakaliki	6.23	82	75.77

76	06^{0}20’44.5”	08^{0}05’46.6”	Kpirikpiri Abakaliki	9.51	81	71.49
77	06^{0}20’49.0”	08^{0}05’49.8”	Kpirikpiri Abakaliki	23.94	84	60.06
78	06^{0}20’47.5”	08^{0}05’49.1”	Kpirikpiri Abakaliki	22.63	78	55.37
79	06^{0}20’47.2”	08^{0}05’48.1”	Kpirikpiri Abakaliki	17.38	83	65.62
80	06^{0}20’44.8”	08^{0}05’46.6”	Kpirikpiri Abakaliki	12.79	84	71.21
81	06^{0}20‘42.5”	08^{0}05’47.4”	Kpirikpiri Abakaliki	16.4	78	61.6
82	06^{0}19’56.2”	008^{0}04’30.6”	Anti-Bomb Squatters	31.49	82	50.51
83	06^{0}19,56.8”	008^{0}04’26.4”	Anti-Bomb Squatters	27.22	80	52.78
84	06^{0}19’52.8”	008^{0}04’25.8”	Anti-Bomb Squatters	29.52	80	50.48
85	06^{0}19’52.3”	008^{0}04’25.3”	Anti-Bomb Squatters	27.55	80	52.45
86	06^{0}19’53.0”	008^{0}04’26.4”	Anti-Bomb Squatters	30.18	86	55.82
87	06^{0}19’54”	008^{0}04’30.2”	Anti-Bomb Squatters	22.96	92	69.04
88	06^{0}19’50.7”	008^{0}04’29.6”	Anti-Bomb Squatters	26.24	81	54.76
89	06^{0}19’52.2”	008^{0}04’31.1”	Anti-Bomb Squatters	27.22	89	61.78
90	06^{0}19’53.1”	008^{0}04’31.4”	Anti-Bomb Squatters	24.6	77	52.4
91	06^{0}19’52.6”	008^{0}04’32.5”	Anti-Bomb Squatters	27.22	80	52.78
92	06^{0} 23 44.7’’	008^{0} 11 55.6’’	Mkpuma Akpatakpa	22.40	71	48.6
93	06^{0} 33 09’’	008^{0} 05 8.43’’	Mkpuma Akpatakpa	23.41	59	35.59
94	06^{0} 30’08”	008^{0}05’7.43”	Ekbiligwe	18.20	62	43.8
95	06^{0}12’23.7”	08^{0}06’49.3”	Amagkpau Village Enyigba	22.96	48	25.04
96	06^{0}12’28.3”	08^{0}07’05.4”	Amagu Village Enyigba	36.08	52	15.92
97	06^{0}12’14.9”	08^{0}07’22.5”	Amagu Village Enyigba	36.08	72	35.92
98	06^{0}12’10.2”	08^{0}07’28.6”	Amagu Village Enyigba	26.24	69	42.76
99	06^{0}10’20.3”	08^{0}07’29.1”	Ogidiga Ndufu Alike	52.48	55	2.52
100	06^{0}10’42.8”	08^{0}08’19.0”	Enyigba mile site	11.48	56	44.52
101	06^{0}12’28.5”	08^{0}08’25.3”	Enyigba Village	32.8	49	16.2
102	06^{0}10’31.2”	08^{0}09’20.0”	Enyigba Village	32.8	51	18.2
103	06^{0}12’17.9”	08^{0}07’23.3”	Ndufu Alike	29.52	48	18.48
104	06^{0}13’12.1”	08^{0}08’15.0”	Ndufu Alike	39.36	62	22.64
105	06^{0}30’10.0”	08^{0}08’14.0”	Amanchara	35.81	71	35.18
106	06^{0}24’29.1”	08^{0}10’13.12”	Mkpuma Akpatakpa	30.2	64	33.17
107	06^{0}24’20.3”	08^{0}08’55.6”	Mkpuma Akpatakpa	29.68	74	44.32
108	06^{0}33’ 8.22”	08^{0}06’28.32”	Ugbodo	22.41	53	30.58
109	06^{0}24’31.4”	08^{0}10’47.72”	Ngbo Agbaja	39.48	62	22.52
110	06^{02}’’29.25”	08^{0}07’16.43”	Ngbo Agbaja	34.12	60	25.88

Fig 4: Relationship between fractures and groundwater in the mining area of Abakaliki: (a) fractures map, R1 to R6: rosette diagrams of fracturation of Onu Ebonyi, Juju hill, Azuoto Amachi, Enyigba, Mkpuma Akpatakpa and Ezzagu respectively. (b) field observation with mineralized zone (c) description of the aquifer of the study area.

groundwater at various points in the area and the particle path lines were obtained. Fig. 4 shows the relationship between fractures and groundwater.

Fracturation

The mining areas of Abakaliki are underlain by the ARG shales. The sediments are deeply fractured and altered; this implies relative permeability of the rocks. Rose plots show a major direction of NW – SE and a minor direction of NE - SW for the fractures of the area (Fig. 4a). this is in line with structural trends described by Obarezi and Nwosu (2013) and Kogbe (1976). Table 3 shows azimuths of fractures in the study area from field mapping. In some places, the low grade metamorphism with hydrothermal veins of quartz, galena, chalcopyrite, siderite and sphalerite shales were observed (Fig. 4b) as stated by Umeji (2000) and Olade (1979). This result is a vital link with the tectonic activities in the area (Olade, 1979; Kogbe, 1976).

Groundwater Flow Direction in the Fractured Media

To avoid contamination and the transfer of contaminants in the groundwater of the mining areas of Abakaliki, it is necessary to identify the direction of groundwater flow in the shale formation. Piezometric, electrical conductivity maps (Fig. 5) and 3D elevation map (Fig. 6) generated from SUFFER 11 have been used to deduce conceptual groundwater flow model and direction. The hydraulic head in each well was calculated (see Table 1 above). The piezometric map shows isopiezes ranging from 70 m (the highest level of the aquifer) to 10 m. These estimates indicate a major flow direction towards the North-East and South-East. The groundwater is on an average of 30 - 40 m deep into the Albian ARG shales. The shales are well exposed at the outcrop (Fig. 1a- c and 4b). they occur as impermeable geological layer between the topographic surface and the roof of the groundwater table (Fig. 4c). They form a system of semi – confined and unconfined aquifers in the area. Due to the fracturation of the shales, groundwater is directly recharged through processes of infiltration during precipitation (Fig. 4b and 4c).

The physico-chemical characteristic of the groundwater is the heterogeneous distribution of the electrical conductivity (Fig. 5b). The conductivity varies from 600µS/cm to the SW, with a minimum of 250 µS/cm at wells P4, P7, P18, P20, P23 and P24, around the Abakaliki urban areas. The maximum variations are in the vicinity of the wells P11 and P12 (Amanchara). and P8, P13 and P14 (Ameka – Enyigba) with conductivities about 500 µS/cm. These values indicate a high rate of mineralization in the groundwater of the mining fields.

Groundwater Flow Direction and Hydrochemical Distribution

Contaminant transport and fate is fundamentally different in fractured rocks than in unconsolidated (sand and gravel) aquifers. Significantly more uncertainty exists as to the direction and rate of contaminant migration, as well as the processes and factors that control chemical and microbial transformations (USGS 2010). Raju and Reddy (1998) showed that flow vectors in shales are controlled by the fracture system of the shales. However, conceptual groundwater flow map of the study area shows two major vector directions of groundwater. These are the southeast and northeast flow vectors (Fig. 5). Fracture map (Fig. 4a above). and rosette plots of fracture shows a major NW- SE and minor NE – SW system (Fig. 4 R1 to R6). Odoh (2010) also studied the surface outcrop of fractures in the Abakaliki urban area and observed a dominant NW- SE direction for the outcrop. It can be deduced that the fractures are not connected in all places; therefore, regional connectivity of groundwater flow cannot be established. This is pertinent, and explains the hydrochemical distribution pattern of contaminants following isolated trends (Fig. 3a and b). However, dominant fractures occur in the Enyigba areas (Fig. 4). this can be linked to the high concentrations of major MTEs like Cd, Se, Pb, Cl, Mn and Hg in well OP2 which penetrated the area. Apart from the fact that hydrochemical attributes may be higher in the mining sites, the non – connectivity of the fractures has reduced or limited the migration of the chemical elements to other areas. Doe (2010a) emphasized that secondary porosity, which result from chemical leaching of minerals or the generation of a fracture system, is the primary source of fluid movement in rocks. The network of interconnected fractures allows fluid movement through rock formations with very low primary porosity. The groundwater analysis was used to identify and quantify the elements with high concentration which may pollute groundwater. Result indicates that over 70% of all water samples are above the World Health Organizations (WHO, 2011) and Standard Organization of Nigeria (SON) threshold for

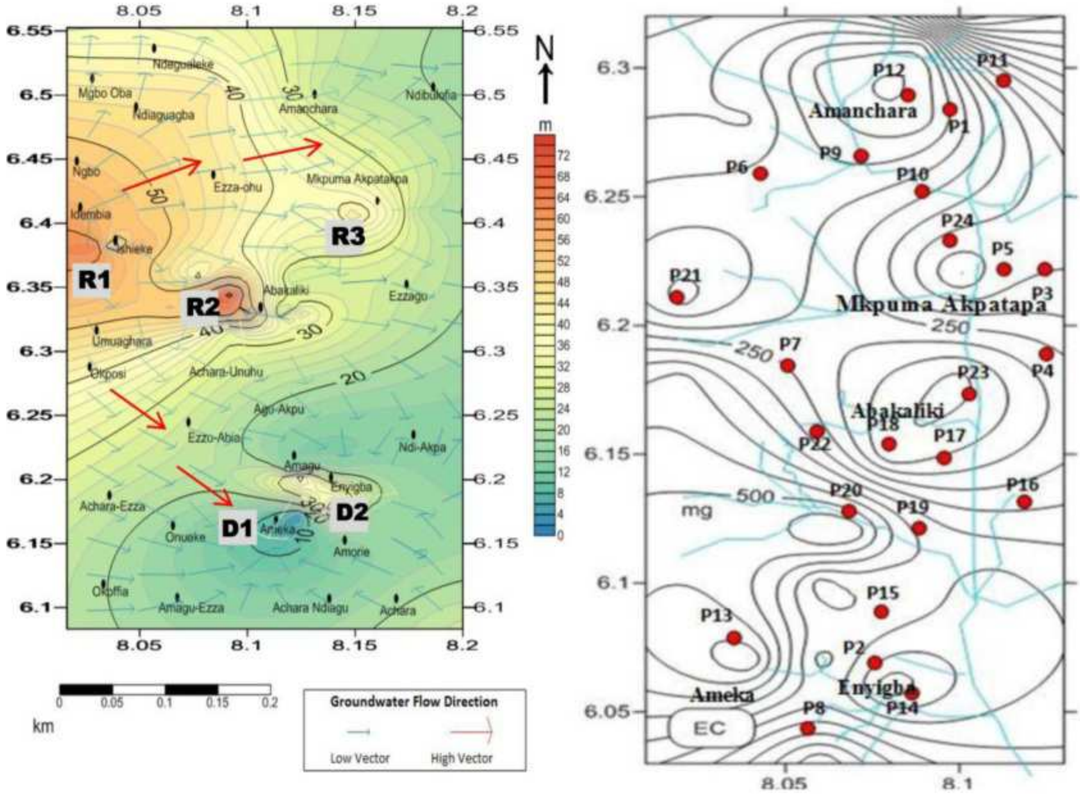

Fig 5a: Groundwater Flow Map of the Abakaliki area. R1, R2 indicate recharge zones; D1, D2, D3 indicate discharge zones while the red arrow show flow directions of groundwater. 5b: Electrical conductivity distribution map of the mining areas of Abakaliki.

drinking water. Wells mostly affected are those located within the mining areas of Enyigba, Ameka, Amanchara and Mkpuma Akpatakpa. Dissolved contaminants and fluids will generally spread through fracture networks. High concentrations of As, Pb, Cd, Cr and Mn have been associated with the hydrochemical dissolution of mineralized veins, while high concentrations of Ca and Mg are due to very high carbonate and organic content of the ARG shales. Consequently, high concentrations of chloride are linked to the existence of salt lakes in the Enyigba areas, isolated fractures can serve as conduits to wells. High values of sulphates are as a result of dissolution of high iron components of iron forming AMDs in the groundwater.

The major groundwater vectors indicate two watershed flow patterns in the area; these are the Isieke – Abakaliki- Amanchara and the Ezza-obia – Amagu – Ameka – Enyigba watershed pattern. Analysis of the flow direction shows that waters from the northwestern area flows radially away from the Isieke and Idembia areas (which makes up the highlands) to Ndiagu, Amanchara, Mpkuma Akpatakpa, Ezzagu, Umuaghara, and Achara – Unuhu areas (which makes up the the lowland areas) (Fig. 5). The other watershed flow pattern shows that the water flows radially from the Achara- Ezza, Ezza- obia, Onueke, Amagu, Achara and Ndiakpa into the Ameka areas. However, because of the high elevation of Abakaliki, Idembia, Isieke and Enyibga areas, a regional radial flow pattern can be ascribed for the entire area. This implies that groundwater flows away from Isieke, Idembia, Enyigba and Abakaliki to other lowland areas (Fig. 6). These flow regimes controls contaminant transport. Myer (2012) and Schubert (1980) demonstrated that advective transport through bulk media and preferential flow through fractures could allow the transport of contaminants from the fractured shale to aquifers. The implication of this to contaminant transport in the Abakaliki area is that the rich carbonate composition of the Abakaliki Shale (which forms the semi- confined aquifer in the area) can flow in groundwater to other areas but the hydrochemical constituents of the Ameka, Enyigba, Amorie and Enyigba (which constitutes the major mining areas) do not flow towards the Abakaliki (which is the urban) area. Miller (1999) noted that when saturated, carbonate-rock aquifers with well-connected networks of solution openings yield large volumes of water to wells that penetrate the solution cavities, even though the undissolved rock between the large openings may be almost impermeable. Because water enters the carbonate-rock aquifers rapidly through large openings, any contaminants in the water can rapidly enter and spread through the aquifers. This is also true for the Mkpuma Akpatakpa and Amanchara mining areas. The flow direction indicates a westerly movement of groundwater from the Mkpuma Akpatakpa and Amanchara areas to the Ndiobulofia and Ezzagu areas. Vitolins et al; (2010) stated that shales, for example, whose matrix comprises primarily clay and silt particles, are moderately impermeable to water flow through the matrix but still have sufficient porosity to allow for the diffusion of contaminants into the matrix. This is supported by Doe (2010a) which emphasized that diffusion is an important consideration in the construction of a conceptual site model and selection of a site remedy because the contaminants in the rock matrix could become a contaminant source zone if the concentration in the fractures falls below the concentration of contaminants in the rock matrix. These contaminants can migrate, especially from the Umuaghara abandoned quarry waste dump site to the urban areas of Abakaliki. Doe (2010a). also opined that in some cases contaminants can be introduced to the fractured rock system as a non-aqueous phase liquid. These liquids are hydrophobic and can be lighter or heavier than water. In this situation, multi-phase flow will occur. Doe (2010a) describes the flow as follows: In multiphase flow, density-based gravitational forces come into play along with capillary forces that act along the interfaces between the fluids (or gasses) and the solid surfaces of the pores or fractures. The significance of these forces — gravity, viscosity, and capillarity — vary with the pore size or fracture aperture, where capillarity dominates in smaller pores or fractures and gravity dominates in larger ones. In a multiphase flow system, capillary pressures can immobilize wetting phase fluid in the smallest aperture fractures. In larger fractures, flow occurs according to Darcy's law but with different permeabilities for each phase that depend on their saturations. In the largest fractures, gravity dominates flow, producing a variety of non-Darcian flow processes that may be very rapid and are still poorly understood. Cook (2003). also noted that diffusion will cause mixing of solutes in water flowing through the fractures with those in the relatively immobile water in the rock matrix. This research also shows that the recharge zones are along the fractured shales and sandstone ridges/ hills of the Idembia, Isieke Enyigba, and Abakaliki areas, while the discharge zones are along the bases of the slopes forming the lowlands. Evidences for the discharge zones are the existence of seepages at the valley slopes (Odoh *et al.*, 2012; Aghamelu, *et al.*, 2011). The continuity patterns of the flow system are demonstrated by the distribution of groundwater heads in the area. The implication of this is very important in waste disposal and management. Groundwater recharge areas are not adequate sites for waste disposal, this is because they can easily pollute and contaminate groundwater sources. In Abakaliki metropolis, the waste management agency is currently using the abandoned quarry pits at Umuaghara as the central waste dumping sites. This is grossly inappropriate as this area is part of the recharge areas. Konikow (2011) noted that any waste input in groundwater will flow to pollute or contaminate other areas. Moreover, the shales and pyroclastics which these quarry pits are composed of, have high frequency of joints and fractures due to inherent tectonism and blasting. This provides secondary porosity structures where these groundwater pollutants and contaminants can migrate and be transported from one point to another.

Hydraulic Head Distribution

The hydrogeologic complexity of fractured formations makes their characterization very difficult. The distribution of hydraulic head in fractured-rock aquifers can be difficult to measure because these aquifers commonly exhibit significant spatial and temporal variations in head as well as complex responses to recharge events (Muldoon and Bradbury, 2005). Aquifer conceptual model (Fig. 5) shows the various directions of groundwater flow in the area. Velocities of the groundwater at various points in the area and the particle path lines as obtained following Todd (1980) and Fetter (1981) shows higher heads in the Northeastern and southeastern parts of the area. The hydraulic gradient and anisotropy of the transmitting medium control the specific flow paths between recharge and discharge areas. In homogeneous, isotropic media groundwater flow perpendicular to equipotential lines. Anisotropy can result in flow which is oblique with respect to equipotential lines (Fetter, 1981).

Conclusion

Sedimentary rock aquitards are important controls in regional groundwater flow systems. The impact of mineralization in groundwater and the link between secondary induced porosity (fractures) and the movement of groundwater in the mining areas of

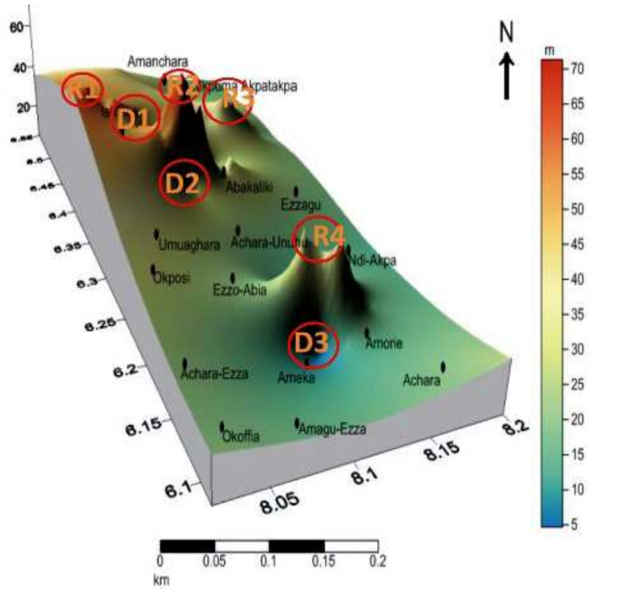

Fig 6: 3D Elevation map of the study area with recharge and discharge areas. R indicate recharge areas, while D indicate the discharge areas.

Abakaliki have been studied in this work. The relationship between the hydrodynamic parameters (porosity, permeability) and the degree of fracturation network of the shale aquifer could have an influence on the circulation of the groundwater and of the MTE dispersion. Absolutely, the lithologic (carbonaceous and mineralized ARG shales) factor is crucial to explain the groundwater contamination. High concentrations of MTEs and major hydrochemical constituents above the drinking water threshold were recorded in groundwater sources in the mineralized areas. Two principal groundwater flow vectors in the southeasterly and northeasterly directions were observed. Rose plots and fracture map show that tectonism has serious effects on groundwater flow in the area, with major trend in the NW – SE direction. The fracture pattern controls the groundwater movement and hydrothermal enrichment of minerals. 3D conceptual model for groundwater flow reveals predominance of recharge area in the axis of Abakaliki metropolis while the Enyigba, Ameka, Amorie, Alibaruhu axis are the discharge areas. Waste dumps in the Abakaliki metropolis (espacially Umuaghara) should be relocated to the discharge areas as the former forms the recharge areas. This poses great danger to water resources management and supply in the area. Recharge areas are not proper areas for waste dumps. Groundwater contaminants can migrate and be transported in solution from the Abakaliki area to other areas but contaminants from the mining areas do not migrate towards the metropolis where there is high urban population.

In this paper, hydrogeologic data have been used to deduce groundwater flow direction, also hydrochemical analysis were conducted for a season to show a significant occurrence and distribution of the MTEs in the area. In the future, pumping test and Visual Modflow and contamiantion models will be used to understand the dispersion of MTEs, and hydrochemical analysis will be carried out in wet and dry seasons to ascertain the consistency of the concentrations in the mining areas of Abakaliki. Wells in the mining communities are the main sources of drinking water as well as in the agriculture and livestock. Therefore, in order to protect the Abakaliki environment and the public health, the health effect and contamination control policies must be the subject of an environmental valuation with the update of Nigerian standards. Indeed, the control policies will be adopted to reduce the exposure of MTE (As, Pb, Cd, Cr, Hg and Mn) through water resources and agricultural products along scientific vulgarization and education to the inhabitants of the mining areas.

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