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In Search of Portable Water Supplies within a Brine and Mine Water-Invaded Region for Serving Some Communities around Ishiagu, Afikpo and Environs in Abakaliki Basin, Southeast Nigeria

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Abstract

The study investigates the hydrogeochemical characteristics of some towns in the Abakaliki Basin, comprising, Ishiagu, Aka Eze, Amaseri, Afikpo and Okposi communities, with the aim of sourcing for portable water in the area. The basin is underlain by Albian sediments, essentially shales, in the lowlands, which were affected by low-grade metamorphism that had produced slates. The highlands comprise basic intrusives from episodes of magmatism and metallic ore mineralisation. Injection of brines into the aquifer system and low, seasonal aquifer recharge from rainfall results in poor water quality in the area. The study analyzes the geochemical distribution in water sources in the area and identifies sources of pollutants to guide the better choice of portable water. Results of hydrogeochemical analysis of both surface and groundwater from the communities were compared with World Health Organization to identify portable water locations in the area. While the salt lake at Okposi is the main source of brine intrusion in the study area, the Pb/Zn mine at Ishiagu is the main source of mine-water pollution in the study area. Most chemical parameters, (especially Cl^-, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^-) maintain high concentrations within the salt lake area, with the values declining away from the salt lake. The main anthropogenic source of pollution in the area, especially at Ishiagu, is the indiscriminate surface mining of lead-zinc without proposer waste management practices. Possible sourcing for portable water in the study area includes a deep borehole at Ishiagu, away from lead-zinc intrusives. At the Okposi axis, searching for portable water in boreholes should target shallower aquifers that do not communicate with the deeper-seated brine zones, likewise targeting zones farther away from these brine-invaded areas. A controlled pumping rate could potentially ensure that the cone of depression was not low enough to reach the brine zone at depth. In addition, desalination could also potentially render the salt water drinkable if properly handled to eliminate the high concentration of salts in the water to the level of acceptable limit by the WHO. Based on the study, the best area to target for portable water in the study area is Afikpo, with most geochemical elements naturally occurring within WHO's standard concentration while portable water could be harnessed in areas further away from mining sites, especially at deep groundwater.

Keywords

Abakaliki Basin, Portable Water, Brine Aquifer, Salt Lake, Pollution, Desaline Water

1. Introduction

The study area covers Amaseri, Afikpo, Ishiagu, Okposi and Aka Eze towns, all within the Abakaliki Basin (**Figure 1**). The area is underlain by shales of the Asu River group. These areas are highly mineralized. The aquifer is an unconfined type, with low permeability. The area is bounded by latitudes 5˚50'00"N and 6˚04'00"N and longitudes 7˚30'00"E and 8˚0'00"E. It covers about 1437 sqkm. The area is part of the Ebonyi River basin, which is a subset of the Cross River plains. The formations in the Abakaliki Basin mostly lack good aquifers because it is underlain by shales instead of aquiferous rocks such as sandstones or gravel. The shales provide quasi-aquiferous conditions due to their highly weathered and jointed nature, but the quantity of water provided is insufficient to meet the growing demands for potable water in the area. When an adjourning main city, Abakaliki was elevated to the status of the state capital, the water demand rose sharply in such a way that every possible source of water now has to be considered as important. It has, therefore, become necessary to constantly evaluate both the quantity and quality of water available from the Abakaliki Shales. In addition, shales of the Asu River Group are known to generate high runoff conditions because of their low permeability. The flat-lying topography, high runoff and heavy tropical rainfall in the area have resulted in the existence of several surface water bodies such as ponds and ephemeral streams. These ephemeral water bodies are not viable options as potable water sources because often, they neither survive the long spells of the dry season nor carry sufficient water even in the rainy season. **Figure 1** is a map showing the topography and drainage systems of the study area inset map of Nigeria, Ebonyi state. **Figure 2** is contaminated mine water in an abandoned mine quarry pit in the Ishiagu area.

Figure 2 shows an abandoned mine pit in the Ishiagu area. The mine pit was previously an active mine quarry for dolerite sill. After the mine has been abandoned,

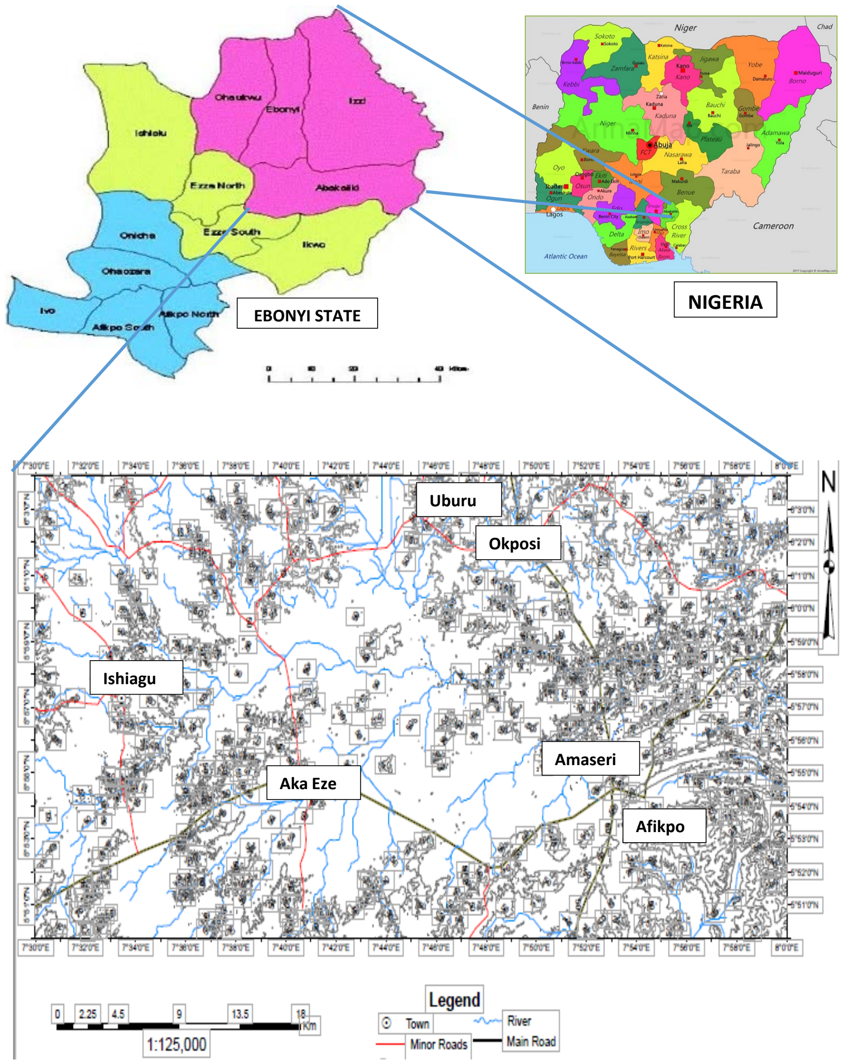


Figure 1. Location map showing the topographic and drainage pattern of the map area around the study area: Ishagu, and Afikpo areas and the environs, in Ebonyi state, south east Nigeria and inset map of Ebonyi state and Nigeria.

Figure 2. Abandoned dolerite mine quarry at Ishiagu area, showing polluted shallow mine-water pond which is a major source of surface water pollution.

during rains, the pit becomes a collection center for a large volume of water that exists as ponds. As the underlying formation is essentially impermeable shale, the water in the pit runs off as surface water to join the larger drainage system in the area. Since the dolerite sill was associated with galena, (PbS), water leaving the pit carries along with it, the mine tailings which constitutes heavy metal like lead and zinc ions into the surrounding environment as the major source of pollutants.

[1] had discussed the process of groundwater occurrence and management. [2] had undertaken a geochemical interpretation of the groundwater flow system. [3] had studied the salt water zones in eastern Nigeria. [4] published a discussion on Groundwater hydrology. [5] in his book, described the nature of water based on geochemistry. [6] had studied the contaminant transport mechanism of salt lakes via hydrogeochemical analysis and also the hydrogeological princes in Nigeria. [7] discussed the variables involved in the selection of water quality assessment. [8] had performed a characterization of natural water through chemical characterization. [9] had also studied the drinking water standards in Geology and Environmental Science. [10] had studied the impact of metal mining on domestic water quality and drew a conclusion on the possible source of pollutants in the area. [11] in his discussion of water quality standards in relation to the chemical characteristics of groundwater as it moved through different media. Likewise, [12] had developed standard methods for water quality assessment. Rajesh *et al*. [13] studied the groundwater quality and its hydro-chemical characteristics in shallow aquifers. [14] had discussed the physiochemical properties of water during water quality assessment. The World Health [15] had released a standard chemical concentration for different elements in water that would serve as a standard reference in determining the quality of portable water that is safe for human consumption.

[16] carried out a geochemical characterization of groundwater for quality assessment. [17] studied the geochemical characteristics of geothermal spring water in a geothermal province in India. [18] and [19] had independently performed a water quality assessment using hydrogeochemical analysis of geothermal water in India.

Given the preponderance of brine water invasion and indiscriminate mining activities, compounding the water quality of most locations, this study adopts an empirical approach. It is intended to identify portable water in the area by analyzing the geochemical composition of water samples taken from both surface and boreholes from different communities in the study area. The results are then compared with world portable water standards like those of the World Health Organization. The objectives of this study are to identify brine and mine-water-invaded zones in the study area, determine the areas where portable water could be obtained based on the distribution of ionic composition, and how to source portable water from brine and mine-water-invaded zones. Such investigation has not received much attention in previous hydrogeological research in the area, and we thus use the results of the present study to complement existing studies in the area.

2. Research Methods and Materials

2.1. Field Techniques

The study adopted an experimentation approach. The sampling technique comprised the collection of 20 surface and groundwater (boreholes and hand-dug well) samples in the study area, namely: Ishiagu, Aka Eze and Amanze. Okposi and Afikpo areas, out of which 15 samples were selected for detailed hydrochemical analysis, essentially to determine the chemical composition and concentration. Values of other physico-chemical parameters such as Electrical Conductivity (EC), Total Dissolved Solids and suspended matter have not considered vital for realizing the aim and objectives of the current study. The sampling points were chosen within and outside the areas where anthropogenic activities are most likely to affect the groundwater and surface water so as to possibly determine the concentration of the target pollutants in the area. This is to isolate areas with less effect, which is potentially containing portable water. Surface water samples were collected at the center of the water bodies found at the mining sites, while groundwater samples were taken from boreholes from running water in the water taps at variable depths depending on the water table in the sampling area. Water samples were taken using clean, dry plastic bottles. Samples bottles were first rinsed with the water sample it is to contain before taking the sample. The nozzle of borehole pumps was similarly cleaned to avoid contamination. Samples were transported to the laboratory each day where the analyses are done. Long storage was avoided as analysis was conducted daily to ensure that samples used were unaltered.

2.2. Field Data Sampling, Quality Assurance and Instrumentation

To ensure quality, 50 cl by volume of water was collected and labelled. The sampling bottles were previously rinsed with distilled water. At the sampling location, the water to be collected is used to further rinse the bottle before collection. Samples were gathered in boxes and transported to the laboratory before the close of work each day and stored in refrigerator for use the same day or the following day. Samples were filtered with 0.45 μm filter size and about 5 ml by volume is taken for each run of the analysis. Care was taken to avoid contamination of samples with the environment and samples from different sample points by careful labelling.

The analytical equipment used for the laboratory analysis adopted the standard [12] ionic composition determination for both cations and anions. Flame photometric and [11]'s EDTA method were adapted to evaluate the potassium and sodium composition of all the water samples taken from the study area. Both the Stiff and Pipper trilinear diagrams were employed to characterize the ionic composition of the water samples by exploiting the percentage value of the chemical ions present. The percentatage composition of each ionic composition was derived from the following relations (1) - (4):

$$\text{Cation Concentration }(\text{meq}) = \frac{\text{Cation concentration }(\text{meq/L}) \times \text{valence}}{\text{Atomic weight}} \tag{1}$$

$$\%\text{ Cation} = \frac{\text{Cation Concentration }(\text{meq}) \times 100\%}{\text{Sum of all Cation concentration }(\text{meq})} \tag{2}$$

$$\text{Anion Concentration }(\text{meq}) = \frac{\text{Anion concentration }(\text{meq/L}) \times \text{valence}}{\text{Atomic weight}} \tag{3}$$

$$\%\text{ Anion} = \frac{\text{Anion Concentration }(\text{meq}) \times 100\%}{\text{Sum of all Anion concentration }(\text{meq})} \tag{4}$$

3. Results of Analyses

Results of the average concentration (mg/l) of the metallic elements, Ca, Fe, Pb, Zn, Cu, Cd, Cr, Mg and K in surface water for the Ishiagu area are: 140.4, 0.48, 0.06, 9.80, 0.06, 0.15, 0.03, 140.22 and 0.04 (mg/l), respectively. For Aka Eze and for the same elements, the result is as follows: 124.2, 0.04, 0.04, 7.90, 0.04, 0.10, 0.03, 118.4 and 1.03 (mg/l), respectively. For Amaseri also, the results are 109.7, 0.30, 0.03, 6.40, 0.04, 0.08, 0.02, 89.6 and 0.97 (mg/l), respectively, and Afikpo: 100.6, 0.24, 0.02, 5.90, 0.03, 0.06, 0.01, 62.7 and 0.38 (mg/l), respectively. The average concentrations (mg/l) for the metallic elements for the groundwater in Ishiagu are: 158.3, 0.03, 0.04, 8.2, 0.04, 0.12, 0.03, 88.2 and 0.01 (mg/l), respectively; for Aka Eze: 101.2, 0.02, 0.03, 6.9, 0.03, 0.08, 0.02, 60.3 and 0.41 (mg/l), respectively; for Amaseri: 86.31, 0.01, 0.02, 5.30, 0.02, 0.06, 0.02, 44.2 and 0.30 (mg/l), respectively; and for Afikpo: 43.2, 0.02, 0.01, 4.80, 0.01, 0.03, 0.01, 27.3 and 0.20 (mg/l), respectively, as shown in Table 1 gives the WHO maximum allowable concentration (MAC) limits for drinking water for the metallic elements, Ca, Fe, Pb, Zn, Cu, Cd, Cr, Mg and K as 200, 0.03, 0.01, 5.0, 1.0, 0.02, 0.01, 150 and 0.16 (mg/l), respectively. Table 2 shows that the constituent of brine and its concentration at various locations such as Cl, Na, SO_4^{2-}, Mg, Ca,

Table 1. Table showing the percentage concentrations of metallic elements in (A) Surface water, (B) WHO and (C) Borehole water samples analyzed (mg/l) and their locations.

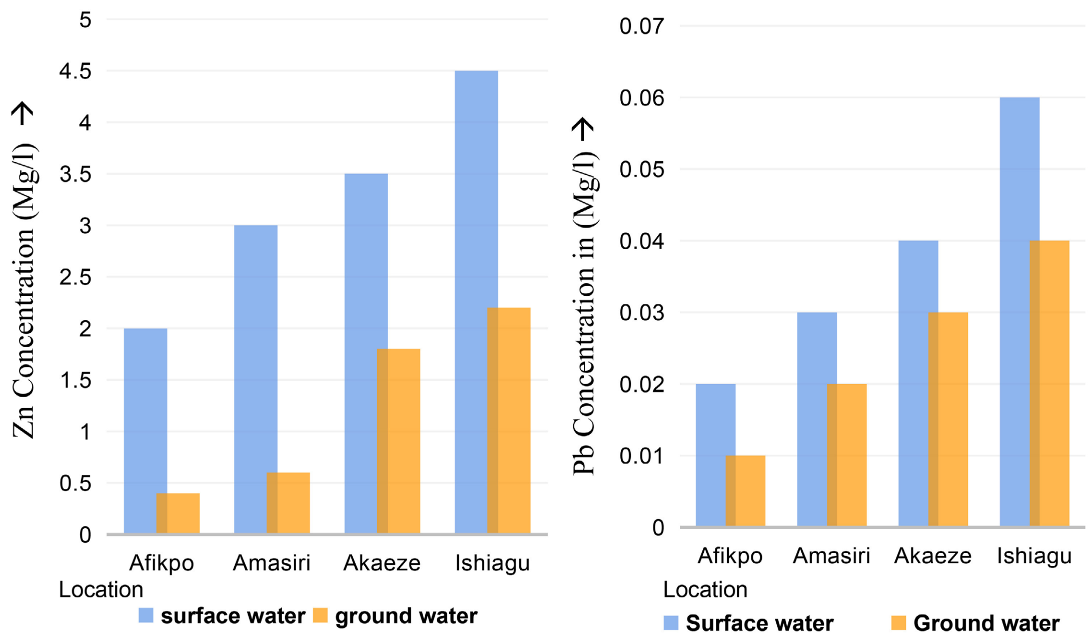
Element	A. SURFACE WATER				B	C. BOREHOLE WATER			
	Ishiagu	Aka Eze	Amaseri	Afikpo	WHO	Ishiagu	Aka Eze	Amaseri	Afikpo
Ca	140.4	124.2	109.7	100.6	200	158.3	101.2	86.31	43.2
Fe	0.48	0.4	0.3	0.24	0.03	0.03	0.02	0.01	0.02
Pb	0.06	0.04	0.03	0.02	0.01	0.04	0.03	0.02	0.01
Zn	9.8	7.9	6.4	5.9	5	8.2	6.9	5.3	4.8
Cu	0.06	0.04	0.04	0.03	1	0.04	3	0.02	0.01
Cd	0.15	0.1	0.08	0.06	0.02	0.12	0.08	0.06	0.03
Cr	0.03	0.03	0.02	0.01	0.01	0.03	0.02	0.02	0.01
Mg	140.22	18.4	89.6	62.7	150	88.2	60.3	44.2	27.3
K	0.04	1.03	0.97	0.38	0.16	0.01	0.41	0.3	0.02

Table 2. Brine concentration at Okposi and Afikpo boreholes and the WHO standard and desaline water.

ELEMENT	OKPOSI BH (Mg/l)	AFIKPO BH (Mg/l)	Desaline Water	WHO (Mg/l)
Chloride	980	280		250
Sodium	396	219	235	200
Sulphate	700	420	198	400
Magnesium	350	190	394	150
Calcium	342	225	0.1	200
Potassium	117	39		35
Bicarbonate	98	14		11
Bromide	23	6		4.5
Strontium	19	8		7.1
Silica	6.4	6.4		6
Boron	4.5	4.5		4
Fluoride	27	2	1.3	1.5

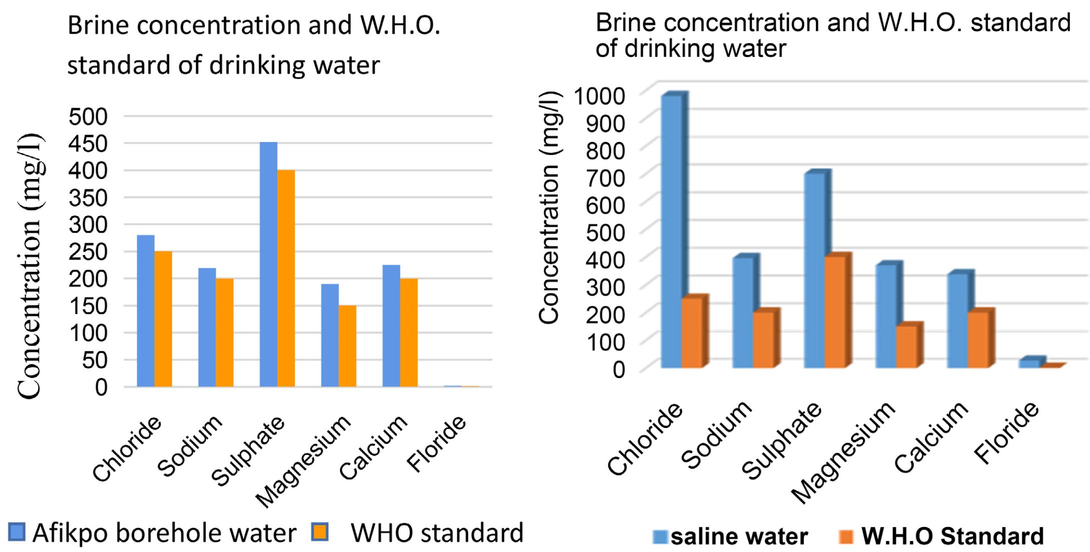
K, HCO_3^-, Br, Sr, SiO_2, B and F^-, for Okposi borehole, are: 980, 396, 700, 350, 342, 117, 98, 23, 19, 6.4, 4.5 and 27 (mg/l), respectively; for Afikpo borehole,: 280, 219, 420, 190, 225, 39, 14, 6, 8, 6.4, 4.5 and 2 (mg/l), respectively; that of the desalinated water,: 235, 198, 394, 0.1, 197, 79, 142, 67, 8, 6.4, 4.5 and 1.3 (mg/l), respectively. Table 2 shows that the following constituents of brine: Cl, Na, SO_4^{2-}, Mg, Ca, K, HCO_3^-, Br, Sr, SiO_2, B and F^- for WHO drinking water standard are: 250, 200, 400, 150, 200, 35, 11, 4.5, 7.1, 6.0, 4.0 and 1.5 (mg/l), respectively. These serve as quality control. Figure 3(A) and Figure 3(B) show Histogram of different concentrations of lead and zinc of the fresh and salt lake in the area, from ground and surface water samples. Also, Figure 4(A) and Figure 4(B) show the histogram plots for element concentration for Okposi and Afikpo respectively, and which data are presented in Table 2.

Figures 5-7 are charts that show the analysis of the results obtained from (A) Stiff and (B) Piper diagrams which expresses the characterization of water type at Okposi, Afikpo boreholes and that of the desalinated water and applying the WHO. drinking water standard as quality control, and also to determine the TDS (mg/l) in the water. Figure 5(A) shows a stiff diagram comparing the water type at Okposi and Figure 5(B) shows WHO drinking water standard based on the cation and anion concentration. Figure 5(C) also shows a piper diagram showing a Trilinear relationship of the geochemical assemblage from Okposi and in comparison with the WHO standard for drinking water. Figure 6(A) shows stiff diagram characterizing the water type at Afikpo BH-2 and Figure 6(B) shows WHO drinking water standard based on the cation and anion concentration. Figure 7(A) shows the result of the plot of the geochemical constituents of Desaline and Figure 7(B) shows WHO water type showing the locations of portable water zone at Afikpo. Figure 8 is Stiff diagrams showing element concentrations in the



(A) (B)

Figure 3. (A) Histogram of Zn concentration from surface and groundwater in the study area; (B) Histogram of Pb and Zn concentration (Mg/l) from surface and groundwater in the study area.



(A) (B)

Figure 4. (A) Histogram of Brine conc. at Okposi and WHO; (B) Histogram of Brine concentration at Afikpo and WHO.

water samples taken from both Borehole and surface water at the indicated localities in the study area. The stiff diagram from equivalent concentration from WHO standard is included for comparison.

Figure 8 shows the Stiff diagrams for individual borehole and surface water samples taken from the 4 surrounding towns: (A) Amasiri, (B) Afikpo, (C) Aka Eze and (D) Ishiagu areas.

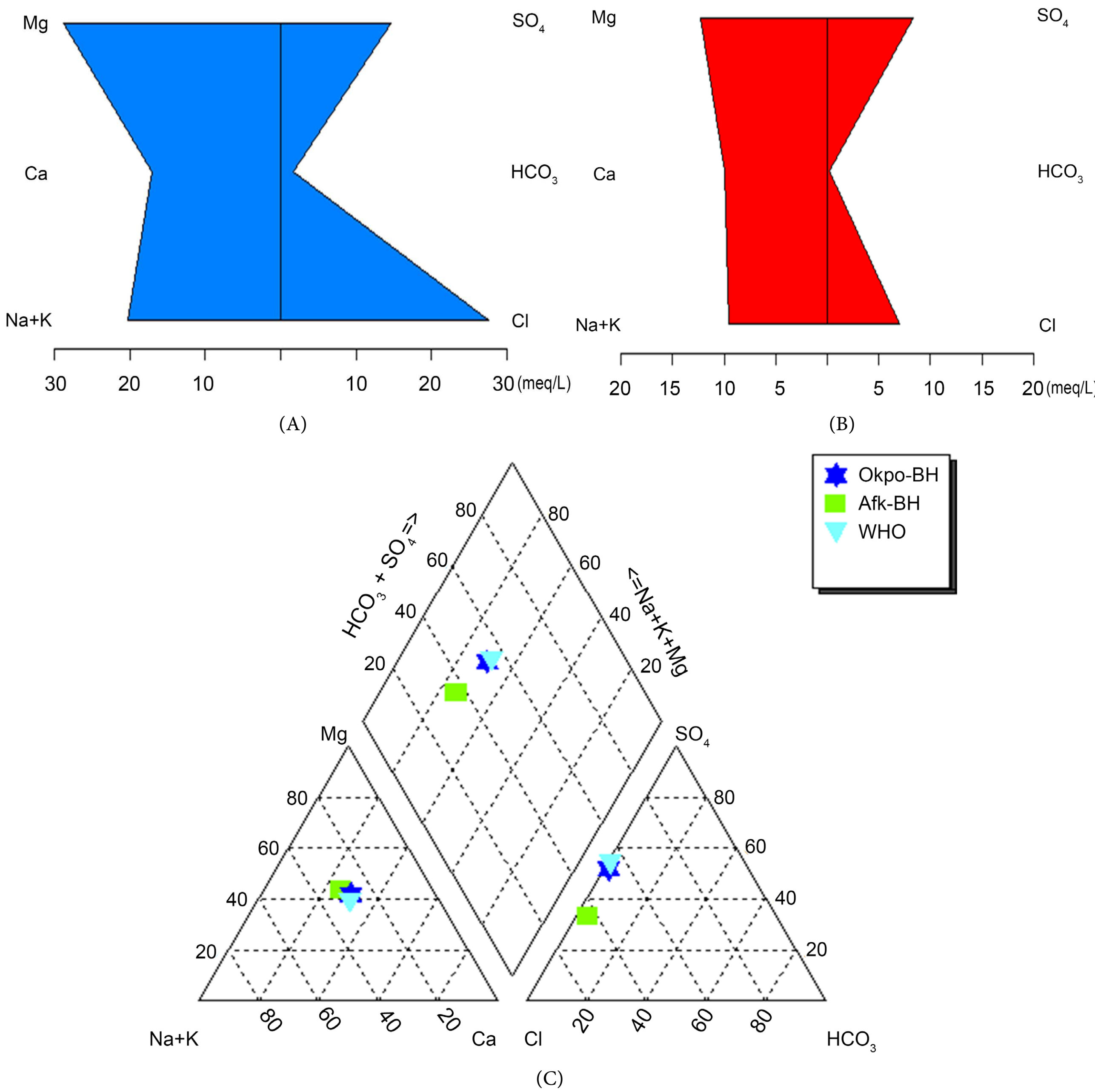
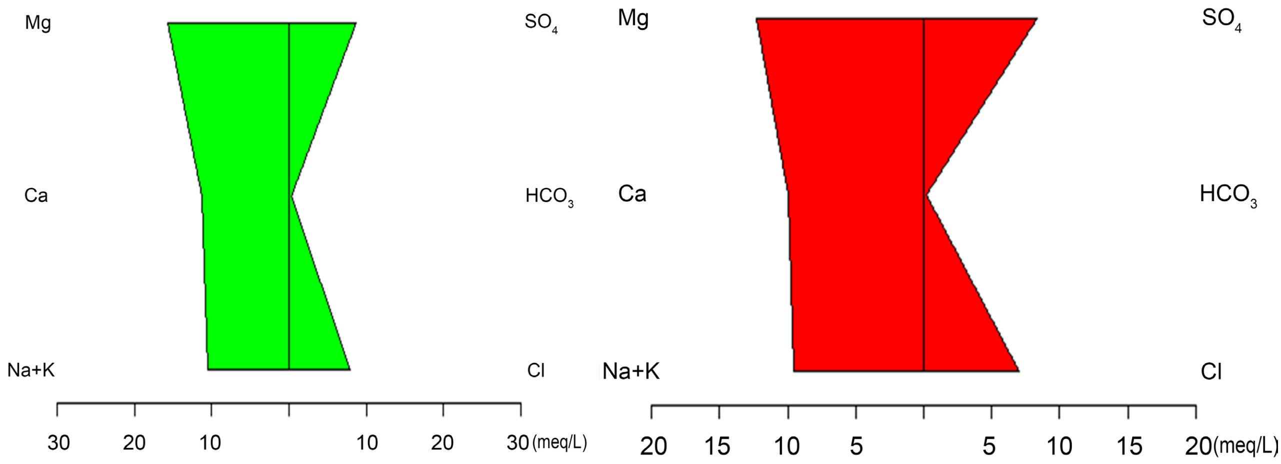


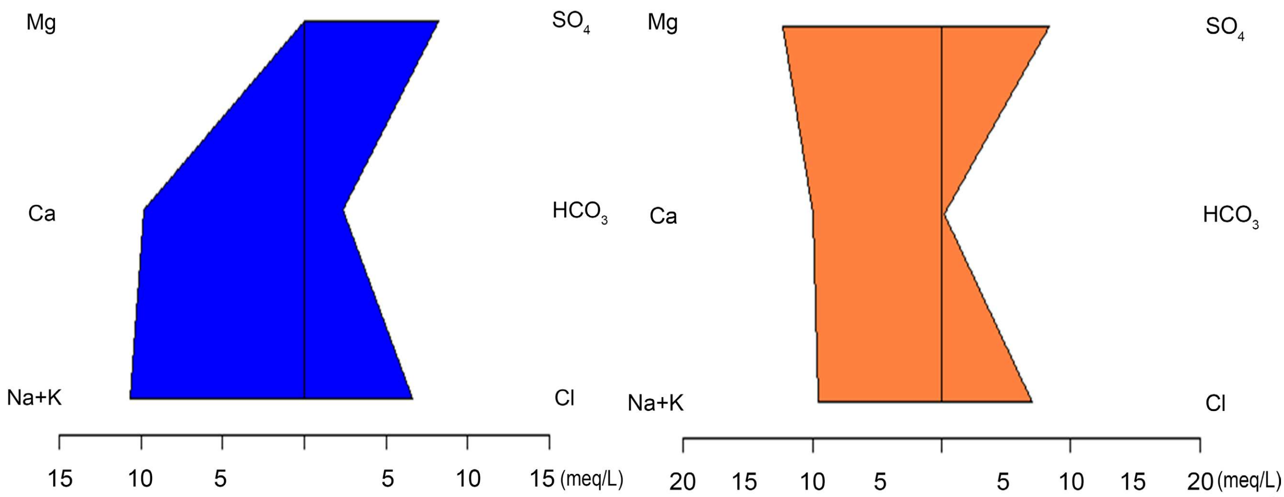
Figure 5. (A) Stiff diagram comparing the water type at Okposi and (B) WHO drinking water standard based on the cation and anion concentration; (A) Okposi Water Type: Mg-Cl; Dissolved Solids 3054.5 mg/l; (B) WHO Drinking Water Type Mg-SO_4; Dissolved Solids 1260.5 mg/1. (C) Piper diagram comparing the water type at (A) Okposi and (B) WHO drinking water standard based on the cation and anion concentration.

Figure 9 is a Piper diagram showing the comparison of the different chemical element concentration in the water samples in the study area and the WHO standard. It is a trilinear double plot of the cations Ca-K-Mg, and Pb-Zn-Fe for the water samples from the study area: Okposi, Aka Eze, Amasiri, Ishiagu, and also WHO standard. Aka Eze surface water and Amasiri borehole water show the similar portable water standard with WHO in the dominance proportion of the Ca-Mg^+ but differs with the low values of K^+ and Ca^{2+} in this same samples.



(A) (B)

Figure 6. (A) Stiff diagram characterizing the water type at Afikpo BH-2 and (B) WHO drinking water standard based on the cation and anion concentration. (A) Afikpo Borehole-2: Water Type Mg-SO_4; Dissolved Solids 1260.5 mg/l; (B) WHO Drinking Water Type Mg-SO_4; Dissolved Solids 1260.5 mg/l.



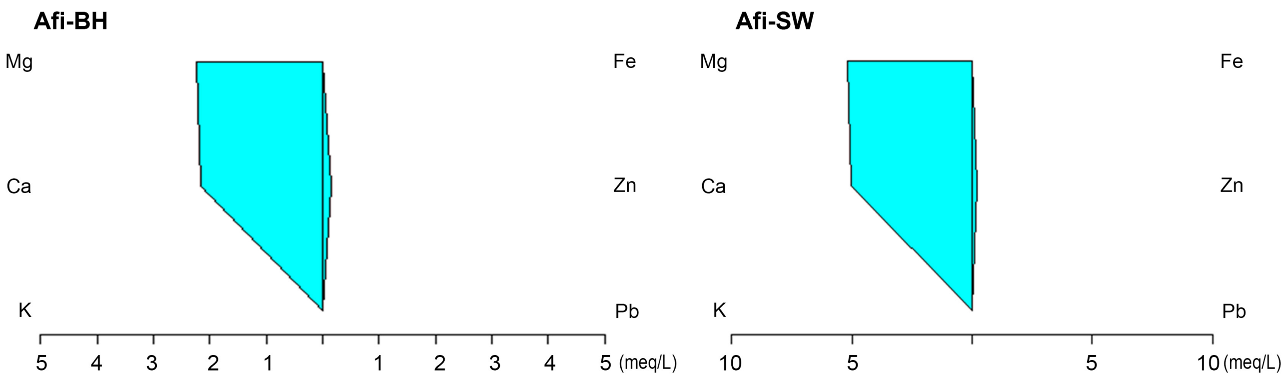
(A) (B)

Figure 7. (A) Desaline and (B) WHO water type showing the locations of portable water zone at Afikpo. (A) Desaline Water Type Mg-SO_4; Dissolved Solids 1204.7 mg/l; (B) WHO Drinking Water Type $MgSO_4$; Dissolved Solids: 120.5 mg/l.

Ishiagu and Amasiri Boreholes share moderate values of Zn^{2+} and Pb^{2+} content, with very little Fe. A combined plot of the double trilinear plots show a dominance of high Zn^{2+} Fe^{2+} for the Afikpo and surface water and Amaseri borehole and dominance of Ca^{2+} Mg^{2+} for the other samples. Ishiagu and Amasiri Boreholes share moderate values of Zn^{2+} and Pb^{2+} content, with very little Fe. A combined plot of the double trilinear plots show a dominance of high Zn^{2+} Fe^{2+} for the Afikpo and surface water and Amaseri borehole and dominance of Ca^{2+} Mg^{2+} for the other samples.

4. Discussion

Results of laboratory analyses in Table 1 show that the mine water Pb/Zn ratios


Afi-BH
Mg
Ca
K
Fe
Zn
Pb
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Afi-SW
Mg
Ca
K
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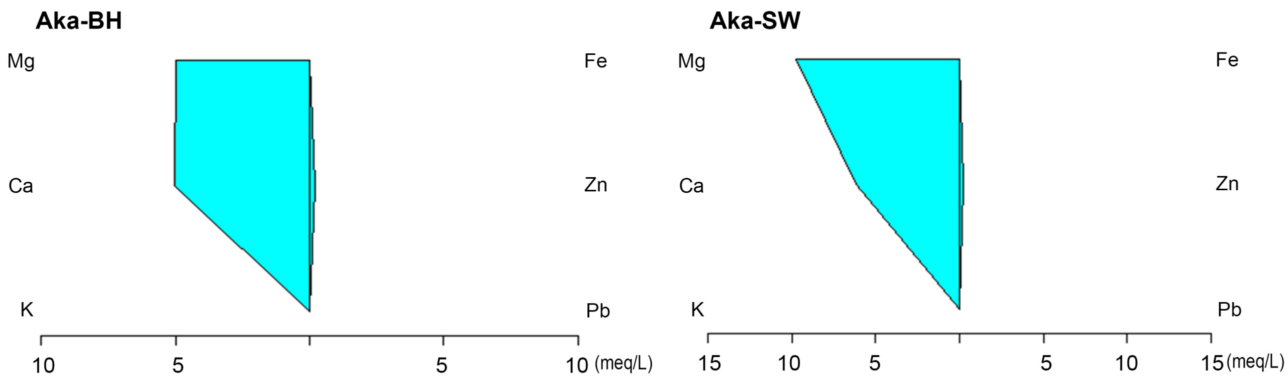
Zn
Pb
10 5 5 10 (meq/L)

(A)


Aka-BH
Mg
Ca
K
Fe
Zn
Pb
10 5 5 10 (meq/L)
Aka-SW
Mg
Ca
K
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Zn
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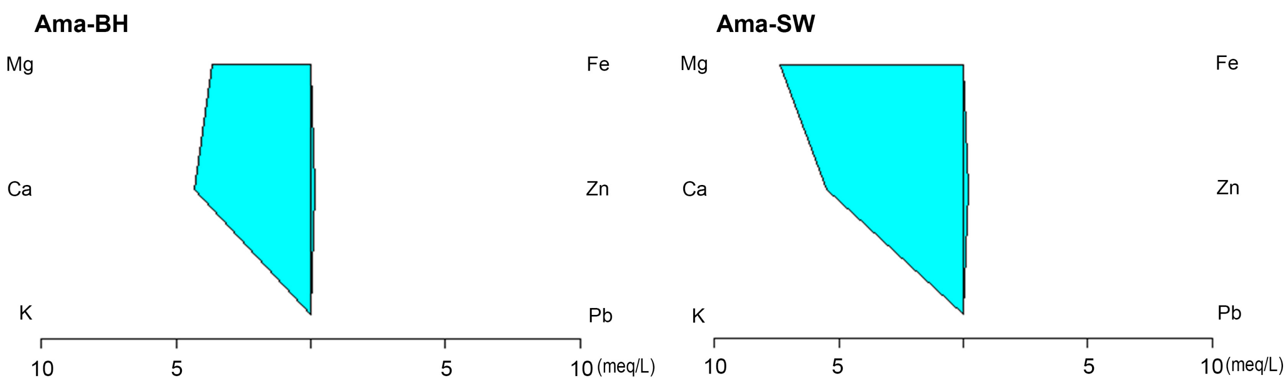
15 10 5 5 10 15 (meq/L)

(B)


Ama-BH
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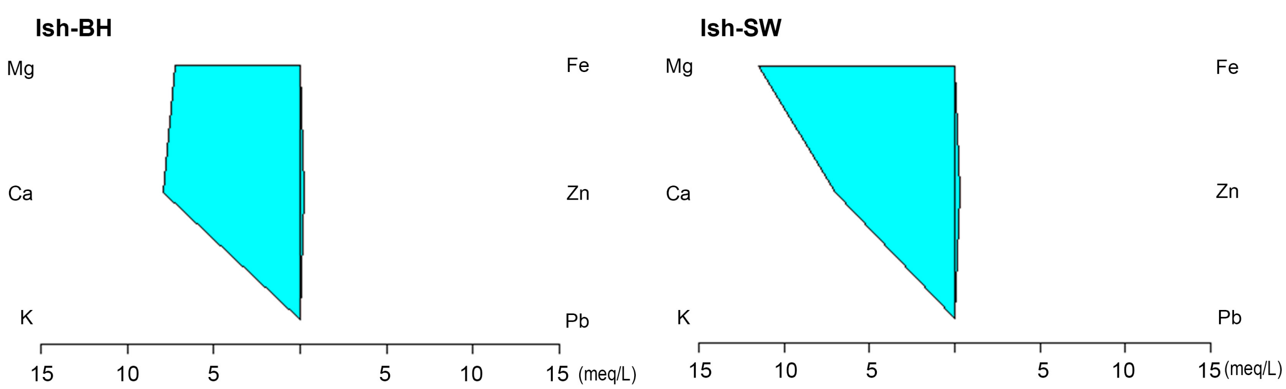
(C)


Ish-BH
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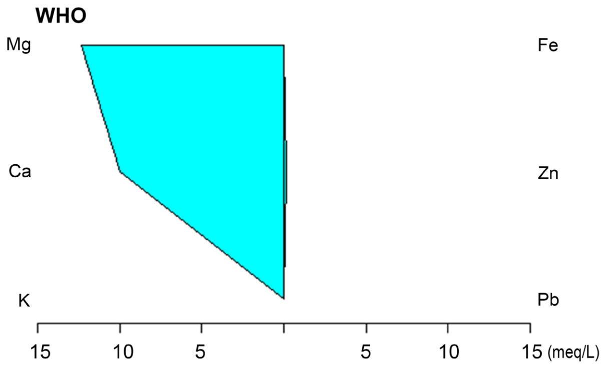
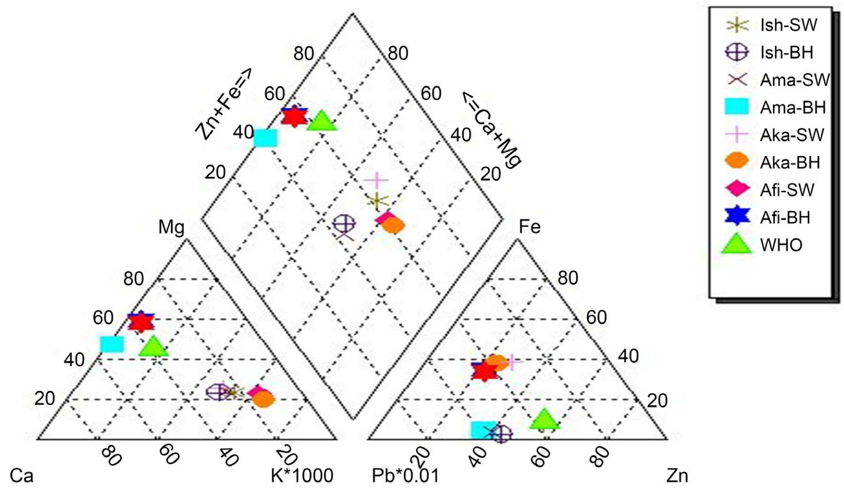
(D)

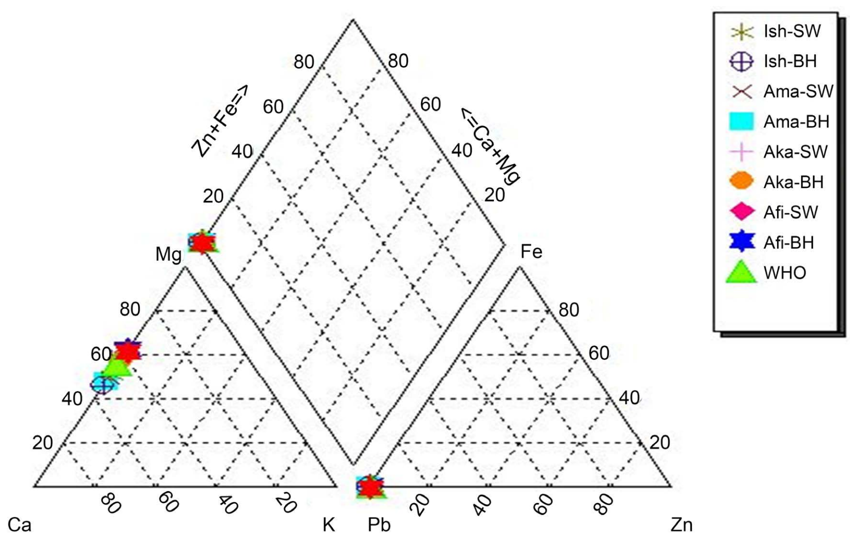


(E)

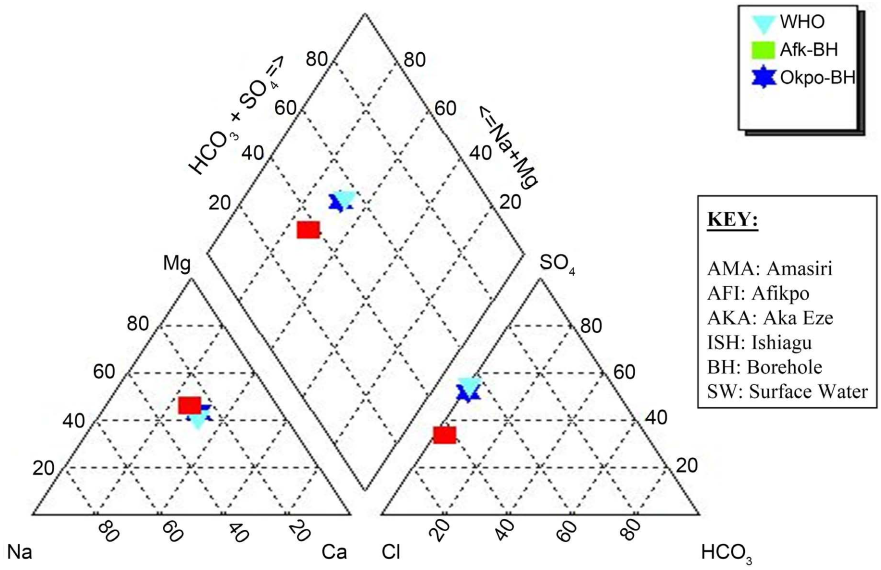
Figure 8. Stiff diagram showing element concentrations in the water samples taken from both Borehole and surface water at (A) Afikpo, (B) Aka Eze, (C), Amasiri (D) Ishiagu areas in the study area. The stiff diagram from equivalent concentration from (E) WHO standard is included for comparison. (A) Afikpo Borehole Water, Afikpo Surface Water; (B)Aka Eze Borehole Water, Aka Eze Surface Water; (C) Amasiri Borehole Water, Amasiri Surface Water; (D) Ishiagu Borehole Water, Ishiagu Surface Water; (E) Who Water Standard.



(A)



(B)



(C)

Figure 9. Piper diagram showing the comparison of the different chemical element concentration in the water samples in the study area and the WHO standard.

are higher in surface water than in groundwater; and the concentrations decrease as we move away from the location of mining activity at Ishiagu to where there is no mining activity at Afikpo. For surface water, Pb/Zn ratios are 0.06/9.8 (mg/l) at Ishiagu, and 0.02/5.9 (mg/l) at Afikpo; for groundwater the Pb/Zn ratios are 0.04/8.2 (mg/l) at Ishiagu and 0.01/4.8 (mg/l) at Afikpo. The WHO drinking water standards show that the Pb/Zn ratios should not exceed 0.01/4.8 (mg/l). Integration of these results with the Afikpo borehole water Pb/Zn ratios of 0.01/4.8 (mg/l) shows that the water is virtually free from mine pollution. Table 2 shows the metal concentrations in brines in the various borehole locations at Okposi and Afikpo. The concentration of Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, Ca^{2+} and Fe^{2+} at Okposi borehole are 980, 396, 700, 350, 342 and 27 (mg/l), while at Afikpo borehole, the concentrations are: 280, 219, 420, 190, 225 and 2 (mg/l), respectively. The WHO drinking water standards show that the concentration of Cl^-, Na^+, SO_4^{2-}, Mg^{2+}, Ca^{2+} and Fe^{2+} are 250, 200, 400, 150, 200, and 1.5 (mg/l), respectively. The brine metal concentrations at Okposi are far greater than at Afikpo, because of the high recharge potential of the Okposi salt-water lake aquifer. The brine metal concentrations at the Afikpo borehole show comparable values with the WHO maximum acceptable concentration (MAC) for drinking water, which indicates relative freshness of the Afikpo borehole water.

The charts in Figure 5 and Figure 6 are Stiff and piper diagrams respectively used to visualize and characterize the water type of Okposi, Afikpo borehole water and that of WHO drinking water type in terms of their cation and anion concentration. The Stiff trilinear diagram shows that the water type of Okposi borehole is an Mg-Cl type with a TDS value of 3054.5 mg/l; while that of Afikpo is an Mg-SO_4 type with a TDS value of 1404.8 mg/l. When these values are compared with corresponding WHO MAC values for TDS (Mg-SO_4: 1260.5 mg/l), it is clear to see that the Afikpo borehole water is portable. The results in Table 2 shows that the concentration of brine in desaline water, with the concentration of Na^+, SO_4^{2-}, Mg^+, Ca^{2+} and F^{2+} are 235, 198, 394, 0.1, and 1.3 (mg/l), respectively, which are below those of the WHO's MACs in drinking water , indicating freshness and portability. The chart in Figure 7 shows a Stiff diagram of desaline water with water of the $MgSO_4$ type, and TDS of 1204.7 mg/l, which almost coincides with the WHO's MAC for drinking water of the $MgSO_4$ type, and TDS of 1260.5 mg/l. These magnitudes of these values underline the fact that, moving away from the mining sites and salt-water lake increases the chances of intersecting portable water sources. The desalination of brine also enhances the chance of sourcing portable water supplies in the study area. Figure 8 is a map showing borehole locations and portable water zones demarcated in this study. From Figure 9(A) which shows the Trilinear (Piper) diagram comparing the different chemical element concentration in the water samples in the study area and the WHO standard indicate a dominantly Ca^{2+} + Mg^{2+}. Rich concentration with low Fe^{2+} + Zn^{2+} concentration in most samples. Figure 9(B) shows a trilinear plot of cation-cation double plot, showing geochemical characteristics of water samples from (surface): Ishiagu, Amasiri, Aka Eze, and Afikpo. The borehole water includes Ishiagu, Amasiri and Aka Eze Ishaigu. This showed on the left trilinear plot a dominance of $Ca^{2+}Mg^{2+}$ for boreholes from Ishiagu and Aka Eze similar to the WHO standard for portable water. A combined cation concentration classification from the diamond plot shows dominance of high $Ca^{2+}Mg^{2+}$ and very low $Zn^{2+}Fe^{2+}Pb^{2+}$.

Figure 9(C) also shows 2 trilinear plots, the left representing the cations (Na^+, Ca^{2+}, Mg^{2+}) and the right representing the anions (Cl^-, HCO_3^-, SO_4^{2-}) for Afikpo surface and borehole data. A combined class of the samples showed the dominance of Na^+ + Mg^{2+} cations and HCO_3^- + SO_4^{2+} anion.

5. Conclusion

Searching for portable water in the study area involved the use of hydrogeochemical characterization to identify varying degrees of high chemical constituents in both surface and groundwater. Groundwater and surface water in the study area contain chemical constituents, which are high and indicate high levels of salinity that are traceable to the naturally occurring salt lakes in the area. Hydrochemical dynamics at the Okposi salt lake, involving temporal changes in metal fluxes, is the main cause of brine intrusion. The Pb/Zn mine at Ishiagu releases contaminated mine water that invades the study area. The hydrogeochemical investigation carried out at Okposi has led to the following realizations: The concentration of the major cations such as Ca^{2+}, Mg^{2+}, Fe^{2+}, K^+, Na^+, and anions, such as S-O_4^{2-}, HCO_3^-, Cl^-, and NO_3^- fall above the WHO recommended MACs for drinking water. These observations are linked to the high salinity of the various water resources in the area. There is a high concentration of Ca^{2+} and HCO_3^-, low concentrations of TDS, Mg^{2+} and SO_4^{2-} in the recharge areas, while high concentrations of Na^{+}, Cl^{-}, K^{+} and HCO_3^{-} predominate in the discharge areas. Trace amounts of Al^{3+}, Br^{-}, HCO_3^{-}, Cu^{2+}, F^{-}, I^{-}, Zn^{2+}, As^{3+}, Pb^{2+}, Ag^{+}, Mo^{2+} and Ni^{2+} are observed, but high concentrations of Pb^{2+} and Zn^{2+} in both surface water and groundwater also exist. Most chemical parameters (especially Cl^{-}, Na^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^{-}) maintain relatively high concentrations within the salt lake area, with the values declining away from the salt lake. Overall, 3 viable solutions for maximizing the sourcing of portable water in the area are maintaining low pumping rates in areas close to the salt such as the Okposi, desalination of brine water and location of water boreholes away from the sources of pollution, like the salt zone or mine quarries. The Afikpo area shows a lower concentration of elements and is the best location for sourcing portable water.

Recommendation

Managing the surface and groundwater resources for harnessing portable water would entail a proper selection of areas away from brine lakes as well as containing anthropogenic activities that would redirect the recharge or flow pattern of the brine-invaded groundwater in the uninvaded areas. The result from the study shows that portable water can be sourced distances away from the salt lakes in Okposi where the concentration of the high chemical constituents will be within WHO's permissible standards. Geochemical and geophysical investigations should be conducted before sitting boreholes in these areas to identify brine-invaded areas, thereby isolating the salt lakes. One way of achieving portable water in this area is to limit the groundwater to a shallow enough depth to avoid tapping from the mine-invaded zone. In the Ishiagu area, the incident of the high value of pollutants is linked to anthropogenic activity, like the mining of lead-zinc in the area. Here, surface water suffers higher pollution. Sourcing of portable water at the Ishiagu area shall target the groundwater in deep boreholes away from the led zinc mines areas as the geochemical results from deep boreholes show the concentration of elements within the WHO's permissible limits. Sourcing portable water in the area could be achieved in areas of high anthropogenic activity by proper management of waste from mines which introduce the highest concentration of lead and zinc as major water pollutants for both the surface and groundwater in the area. Afikpo areas, with the minimum permissible concentration of most elements, by WHO standards, remain the most viable location for sourcing portable water in the study area.

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Originality of Research

The authors hereby declare that the work presented in this paper is original and has not been presented for publication, either in part or whole by the authors to any other journal.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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