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Environmental risk assessment of lead–zinc mining: a case study of Adudu metallogenic province, middle Benue Trough, Nigeria

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Abstract Assessment of the impacts of lead–zinc mining in Adudu–Imon metallogenic province was carried out. Reconnaissance and detailed field studies were done. Lithologies, stream sediments, farmland soils, mine tailings, artificial pond water, stream water, well water, and borehole water were collected and subjected to atomic absorption spectrometry (AAS) and X-ray fluorescence (XRF) analyses. Geochemical maps were generated using ArcGIS 10.1. Significant contamination with cadmium (Cd), iron (Fe), and lead (Pb) was recorded in the collected water samples. Virtually all collected soil samples were observed to be highly contaminated when compared with the European Union environmental policy standard. The discharge of mining effluents through farmlands to the Bakebu stream, which drains the area, further exposes the dwellers of this environment to the accumulation of potentially harmful metals (PHMs) in their bodies through the consumption of food crops, aquatic animals, and domestic uses of the water collected from the stream channels. The study revealed nonconformity of past mining operations in the Adudu–Imon province to existing mining laws in Nigeria. Inhabitants of this region should stop farming in the vicinity of the mines, fishing from the Bakebu stream channels should be discouraged, and domestic use of the water should be condemned, even as concerned government agencies put necessary mercenaries in place to ensure conformity of miners to standard mining regulations in Nigeria.

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Introduction

The large occurrence of economic minerals in the Benue Trough has attracted several investors in the last five decades. The activities of artisan miners and the nonconformity of some investors to existing mining laws in Nigeria are common occurrences in the country; as such, the environment is left degraded, thereby posing possible threat to the ecosystems. The Adudu metallogenic province, which is located in the middle Benue Trough, is not exempted from these challenges. Although several works have been done to environmentally assess the impact of mining activities in the Benue Trough, the Adudu province has received very insignificant research attention. The facts that the entire mining province is surrounded by farmlands and the deleterious nature of lead and zinc (which are the two minerals mined in the area), coupled with the proximity of settlements to the mining sites, necessitated the need to geochemically assess the impacts of the mining activities in the Adudu province.

Various age groups, regardless of gender discrimination, are involved in artisan mining, and the technology used by these mainly unskilled workers is dominantly primitive. Agricultural implements, such as cutlass, hoe, digger, and shovel, are used by these groups for digging out the overburden to grant them access to the ore body (open cast mining). Underground channeling, lotto, and the use of explosives are also being used. The hoary, open cast mining, which generates large amounts of sulfide-rich tailings (Bhattacharya et al. 2006), has a serious environmental impact on the quality of soils and surface water due to pollution (Igwe et al. 2014; Machender et al. 2014).

According to Nriagu and Pacyna (1988), the metal content in soil is a product of metals originating from natural processes and human activity. It is estimated that the contribution of metals from anthropogenic sources in soil is higher than the contribution from natural ones. Anthropogenic activities such as mining and smelting of metal ores have increased the prevalence and occurrence of heavy/trace metal contaminations and pollutions at the Earth's surface. In general, mined soils are mechanically, physically, chemically, and biologically deficient (Vega et al. 2006), characterized by instability and limited cohesion, with low contents of nutrients and organic matter and high levels of heavy metals (He et al. 2005). Apart from the local disturbance of the physical properties, potential toxic metals (PTMs) can cause a more widespread contamination of soil, sediments, and food crops, leading eventually to loss of biodiversity and a potential health risk to inhabitants in the vicinity of the mining area (Verner and Ramsey 1996; Lee et al. 2001; Zhang et al. 2002; Adepoju and Adekoya 2014).

The lead–zinc mineralization, which occurs in the form of veins and veinlets associated with the host rock, are localized along the northern–southern trending belt of slightly deformed sedimentary Cretaceous sequences (Albian Asu River Group) that measure about 500 m thick (Igwe et al. 2014). This mineralization is structurally controlled and localized in fissures, faults zones, and gently dipping veins. The veins are steeply dipping and have a depth of over 150 m. They vary in width from less than 1 to 20 m and in length from 30 to 120 m. The dominant ores in the areas were observed from the fissures and contain lodes of sphalerite (ZnS) and/or galena (PbS) in association with smaller quantities of copper.

Metallic ores are characterized by occurrence of gangue alongside mineralization of interest. Identified gangues associated with the Pb–Zn deposits in the Benue aulacogen includes siderite ($FeCO_3$), pyrite (FeS_2), marcasite, quartz, and barites, with other secondary minerals such as sulfates, carbonates, and oxides. Marcasite is a ubiquitous gangue mineral, though much less in abundance than siderite and quartz. Chalcopyrite is a minor mineral component, occurring generally in association with siderite and galena. Siderite is found in the main veins, minor fractures, and veinlets. In addition to galena and sphalerite, barite deposits in the trough as well as saline groundwater are of economic importance. Although the environmental impacts of the Pb–Zn mineralization in the lower Benue Trough, which is being mined in the Enyingba district, has received numerous attention from researchers (Ezeh et al. 2007; Ezeh and Anike 2009; Igwe et al. 2014), there is no published work that has examined the effects of mining activities in the Adudu province found by the authors. It is therefore the focus of this research to critically examine the potential risks associated with the mining of these economic minerals on the soils and water (surface and underground).

Study location

The study area is the Adudu metallogenic province (Fig. 1). It is geographically located in Obi Local Government Area of Nassarawa State. It is located between latitudes 08° 16′ 10.6″ and 08° 13′ 23.7″ N and longitudes 009° 01′ 7.73″ and 009° 01′ 0.35″ E. The area is characterized by gently undulating low lands. Observed ridges in the area are heaps of mine tailings, which are products of past and ongoing mining activities in the area (Fig. 2). The Bakebu stream drains the entire area. It is the major repository of mine effluents that are being discharged from the pits. The geology of the area is typically that of the middle Benue Trough. The local geology of the area as observed from mine pits exposures revealed a basal unit of black shale of about 4 m thick. This is overlain by another distinctive body of weathered shale with thickness estimated at 1.5 m. Sandwiched between this weathered shale and the overlying mottled clay of 0.5 m thick is an intercalated unit of indurated sandstones with regular occurrences of thin (0.3 m) shales in between. The lateritic overburden that caps the sedimentary sequence in the study area was about 1.5 m thick (Fig. 3).

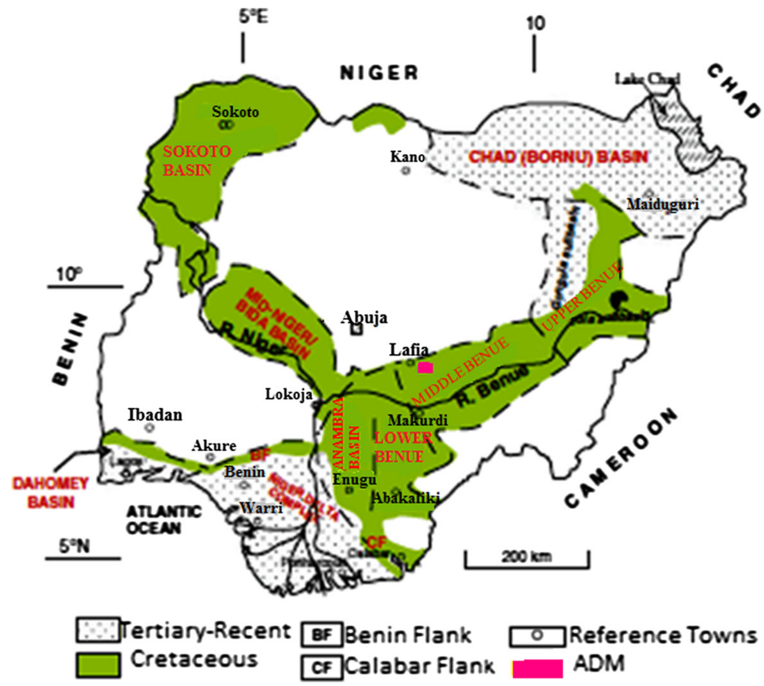


Fig. 1 Map of Nigeria showing sedimentary basins and the study area in pink; ADM Adudu metallogenic province (Modified from Obaje 2009)

Research methodology

Reconnaissance field survey was carried out to have an idea of the routes in the area. Permissions were also sought from small scale companies working in different parts of the Adudu mining province. This was done a week before the field study. Detailed field study was carried out in June–July 2014. Careful observation of the geology was done and recorded. Cereal farms in the neighborhood of the mining province were also observed. Channels used in discharging mine effluents were traced, and pictures were taken.

Fig. 2 A section of the study area

Fifteen soil and ten water samples were collected from the Adudu mining province and the neighboring Imon village. Sample collection sites include abandoned mines, active mines, heaps of tailing, stream, and farm land. Soil samples were collected from mine pits, heap of mine tailings, erosion sites, mine ponds, and the Bakebu stream. These samples were taken at depths of 1 m with hand augers and disposable hand gloves. Stream sediments were taken in an upper-downstream pattern. Samples were carefully bagged and meticulously labeled for onward transmission to laboratories. Water samples were collected from streams, mine ponds, hand-dug wells, and boreholes. Collection of water samples was done using properly sterilized and well-labeled plastic cans. The plastics were filled, tightly corked, and painstakingly labeled to avoid mixing up. Positions of sample collection points were determined using the Global Positioning System (Table 1); the Garmin GPSMAP 78S was utilized for this purpose, and values were recorded in latitude and longitude. Snapshots of relevant exposures and physical effects of mining activities were taken using a digital camera.

Water samples were kept in ice crested coolers to avoid degradation of elements present by possible microorganisms that may be present before transferring them to the laboratory for atomic absorption spectrometry (AAS) test. Collected soil samples were subjected

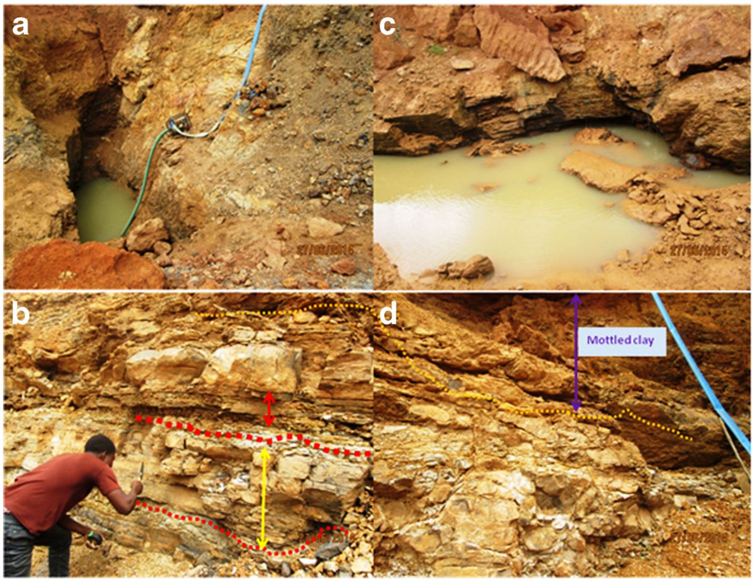


Fig. 3 Photographs showing some rock types as revealed in the mine pits. **a**, **b** The black shale unit. **c** Intercalated indurated sandstone and shale unit. **d** The mottled clay unit

to X-ray fluorescence (XRF) to unveil possible mineralogical contaminants or pollutants that may be present. Knowing fully well that various analytical methods have their individual strengths and weaknesses, AAS was used to also analyze all collected soil samples. The essence of this is to validate the result obtained from XRF. The elemental analysis of all the collected soil, rock, tailing, and stream sediment samples was carried

Table 1 Summary of sampling locations and sample description

Location	Latitude	Longitude	Altitude (m)	Sample description	Sample code
1	08° 13.820′	009° 01.043′	143	Black shale; mine pond	LCS01; LCW01
2	08° 13.830′	009° 01.038′	159	Spring water	LCW02
3	08° 13.809′	009° 01.018′	171	Mine tailings	LCS03
4	08° 13.774′	009° 01.023′	162	Farmland soil	LCS04
5	08° 13.456′	009° 00.150′	162	Farmland soil	LCS05
6	08° 13.774′	009° 00.936′	164	Artificial pond	LCW03
7	08° 13.736′	009° 00.831′	161	Farmland soil	LCS07
8	08° 13.266′	009° 01.309′	157	Stream sediments; stream water	LCS08; LCW04
9	08° 13.758′	009° 00.765′	152	Stream sediments; stream water	LCS09; LCW05
10	08° 13.679′	009° 00.770′	160	Black shale; stream water	LCS10; LCW06
11	08° 13.635′	009° 00.773′	161	Sandstone	LCS11
12	08° 13.643′	009° 00.991′	171	Grayish shale	LCS12
13	08° 13.604′	009° 01.037′	174	Mine tailings	LCS13
14	08° 13.396′	009° 00.992′	166	Weathered clay; mine pond	LCS14; LCW07
15	08° 13.361′	009° 00.992′	173	Mine tailings	LCS15
16	08° 13.237′	009° 00.937′	166	Mine tailings	LCS16
17	08° 13.228′	009° 01.800′	172	Control sample	LCS17
18	08° 13.958′	009° 01.075′	168	Bore hole	LCW08
19	08° 16.057′	009° 01.402′	174	Bore hole	LCW09
20	08° 16.106′	009° 01.274′	178	Well water	LCW10

out using the energy-dispersive X-ray fluorescence (EDXRF) spectrometry. Collected samples were carefully divided into three parts and labeled: one part was kept as backup while the other two were forwarded to the laboratories for analyses.

A total of 15 soil samples (including rocks, stream sediments, and tailings) and ten water samples collected from different sources (Fig. 4) were analyzed with PG990 AAS. The concentrations of cadmium (Cd), cobalt (Co), iron (Fe) (Fig. 5), manganese (Mn), lead (Pb), zinc (Zn) (Fig. 6), sodium (Na), potassium (K), copper (Cu), and calcium (Ca) in the 25 samples were determined by flame atomization, using air-acetylene flame and single element hollow cathode lamp and following the equipment procedures (Weltz 1985; Beaty 1988). Calibration curve for these metals was obtained by preparing different concentrations of each metal from the stock solution (1000 ppm) for each cation. These were used in preparing a linear curve, passing through zero, for each of the metals.

Results and discussion

The metals potassium (K), calcium (Ca), titanium (Ti), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), germanium (Ge), strontium (Sr), zirconium (Zr), lead (Pb), bismuth (Bi), barium (Ba), and arsenic (As) were recorded as being present in all analyzed samples that were subjected to XRF

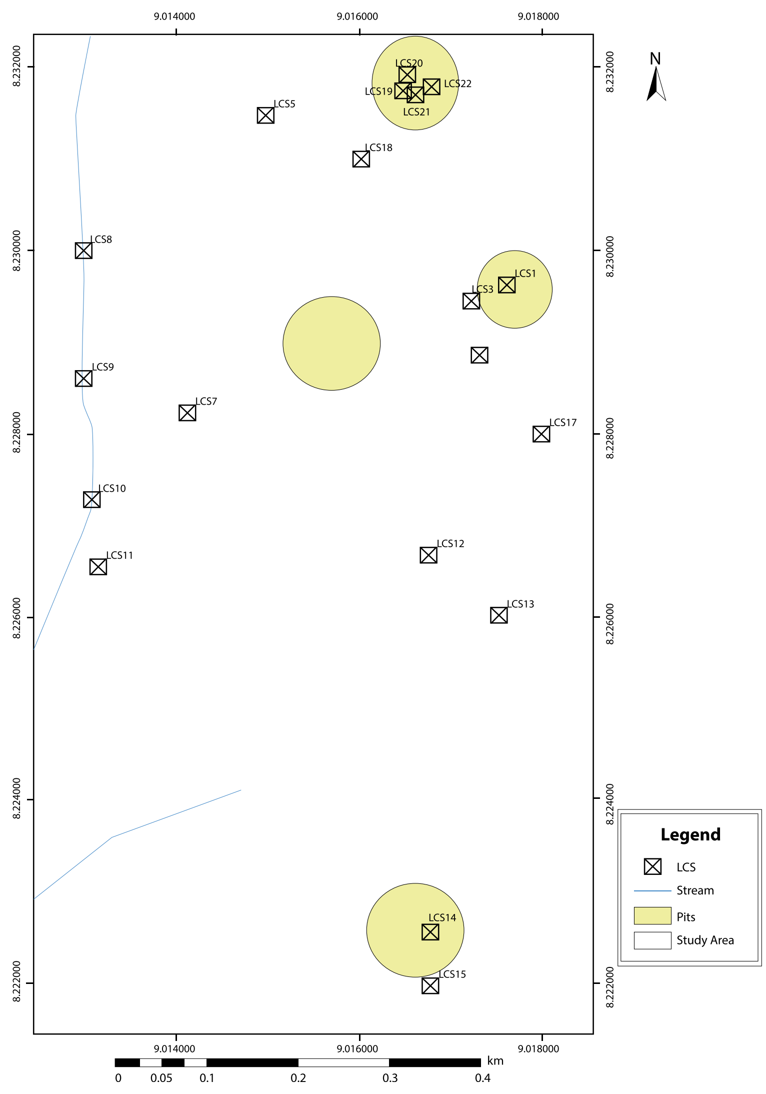
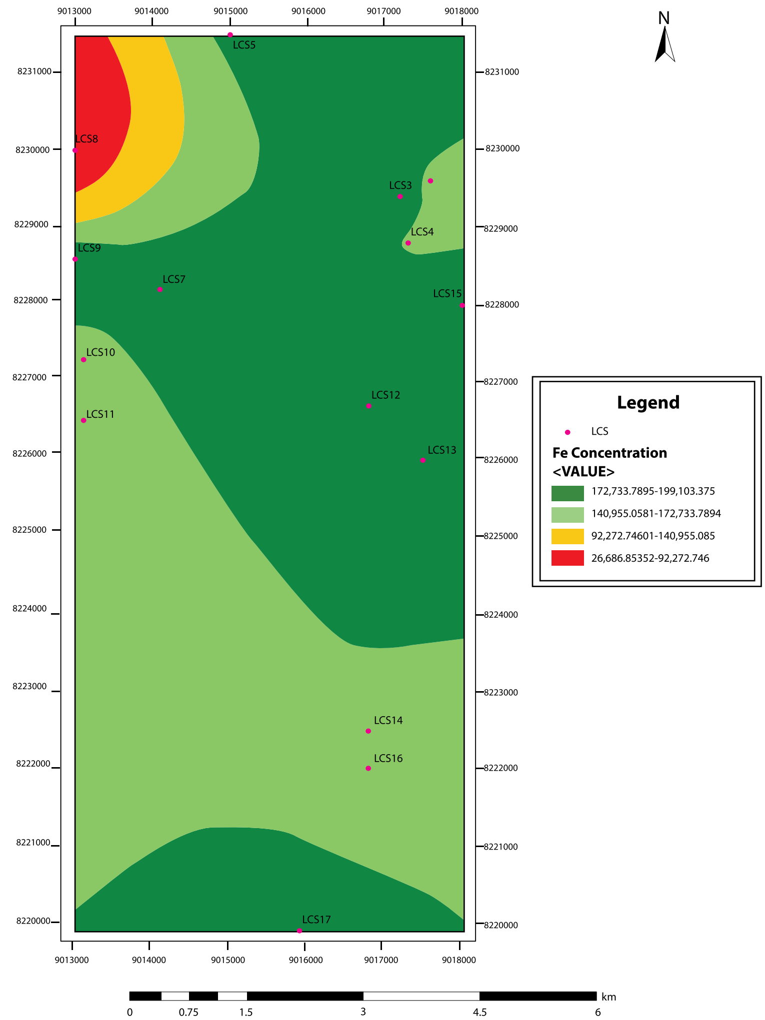


Fig. 4 Map of the study area showing sample collection points

Fig. 5 Concentration map of iron in the study area



analysis. To avoid ambiguity of data interpretation and discussion, samples will be grouped based on their sources in this segment.

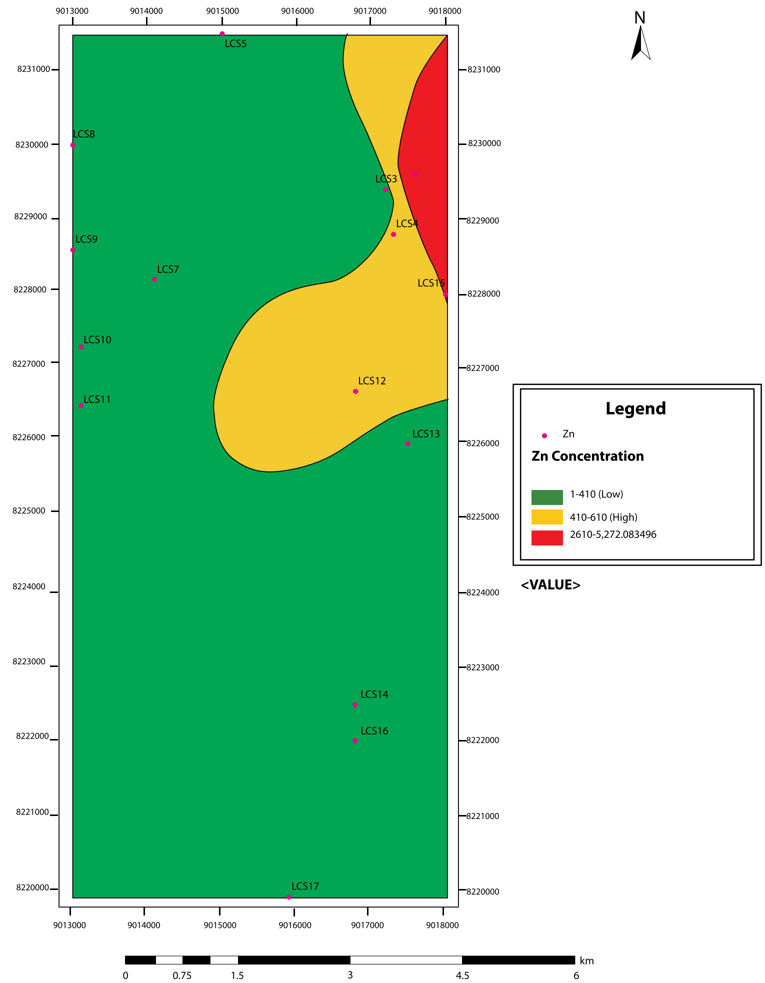
Rock contamination

LCS01 (black shale), LCS10 (indurated shale), LCS11 (sandstone), LCS12 (grayish shale), and LCS14 (weathered clay) were recorded of some metals. Highest concentration of potassium was reported in the black shale, with concentration as high as 28,328 mg l^{-1}, conversely; LCS12 recorded the lowest potassium concentration at 4133 mg l^{-1}. Lead and zinc were richly detected in these lithologies with concentrations ≥ 81.90 and 302 mg l^{-1}, respectively. Careful observations revealed that the iron is the most dominant metal in all analyzed rock samples. The presence of germanium at concentrations not less than 40 mg l^{-1} (LCS01) was documented in the five rock samples analyzed. Mean concentrations (in mg l^{-1}) of nickel, zirconium, strontium, copper, and calcium in the rock types evaluated are 304.25, 997.46, 510.81, 62.93, and 7666.24, respectively. Bismuth occurs in the range of 39.95–8.99 in the samples (though it was not detected in the LCS01). The metals gallium and germanium were reported at 207.56 and 273.35 mg l^{-1}, respectively.

Stream contamination

Critical examination of XRF result for LCS08, LCS09, and LCS10 generally revealed higher concentration of base metals downstream. Although there are some anomalies in this trend, the metals K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Ga, Ge, Sr, and Pb all honored this pattern. The high concentrations observed in the aforementioned

Fig. 6 Concentration map of zinc in the study area



samples is connected with the fact that mine effluents are channeled into the Bakebu stream, as well as the movement of surface run-off from the mine province into the stream, owing to the relatively lowland nature of the stream environ. The pollution of stream bed sediments has several consequences for stream ecosystem and human health (Gerhat and Blomquist 1992). This is particularly of concern in the study area owing to the fact that farmers, mine workers, and children all drink from and bathe in the stream (Fig. 7). In addition, field evidences and oral interviews of some inhabitants revealed that the stream is a source for aquatic food in the Adudu area, as fishing traps were conspicuous in various tributaries of the stream.

Ingesting this water or aquatic animals sourced from it will undoubtedly transfer some doses of these detected potentially harmful metals (PHMs) into the human system. Gale et al. (2004) had reported that microorganisms and certain aquatic plants and animals often concentrate toxic metals from dilute aqueous environments, although these PHMs are generally known to tenaciously bind to the organic matter contained within soil, sediments, and suspended particulates within the water column.

Fig. 7 Inhabitants bathing in the contaminated Bakebu stream

Organically bound metals may dissociate as free ions and participate in cation exchange reactions with various minerals and living organisms, depending on ambient pH, ionic strength, temperature, and in some cases, specifically interacting cations or anions (Gale et al. 2004).

Though, without specific trend, the presence of toxicant metals such as Cd, Co, Fe, Mn, Pb, Zn, Na, K, Cu, and Ca was detected from the water samples collected from the channels of the Bakebu stream. Careful comparison of the recorded geochemical parameters in the stream water (Table 2) with the 2011 drinking water standard of the World Health Organization (WHO) revealed that the Bakebu stream is polluted at least with lead (Pb) and cadmium (Cd). Lead affects the development of the brain and nervous system in children and increases the risk of high blood pressure and kidney damage in adults, while cadmium causes sensory disturbances, liver injury, convulsions, shock, and renal failure (WHO), although lead in the stream samples falls considerably below the set (WHO) standard. The contamination/pollution of stream water by deleterious metals, such as cadmium, was confirmed, with concentrations in the range of 0.011–0.016 mg l^{-1}, against the 0.003 mg l^{-1} permissible limit set for drinking water. FEPA (1991) had reported that Cd is listed in the environmental quality standard for soil and water pollution in Nigeria. A critical examination of the cadmium and zinc concentrations in the analyzed samples revealed that the quantity of the latter doubles the former in all samples. This is in agreement with the findings of Eggenberger and Waber (1998) who stated that cadmium is usually present in the environment as minute impurities of Zn.

Allert et al. (2013) had reported concentrations (mg l^{-1}) as high as 122 (lead), 308 (zinc), and 18.8 (cadmium) in fishes harvested from the Big River, southeastern MO, USA. Although the scope of this current study does not involve the examination of aquatic

Table 2 Contamination levels of different water sources in the Adudu area as obtained from AAS (measured mg l^{-1})

WHO (2011)		0.003		+		0.01
Code	Source	Cd	Co	Fe	Mn	Pb
LCW1	Mine pit	0.012 ± 0.0003	0.008 ± 0.0003	0.104 ± 0.0008	0.036 ± 0.0014	0.008 ± 0.0006
LCW2	Spring	0.006 ± 0.0002	0.007 ± 0.0004	0.097 ± 0.0001	0.040 ± 0.0009	0.007 ± 0.0006
LCW3	Mine pit	0.005 ± 0.0001	0.009 ± 0.0003	0.088 ± 0.0003	0.043 ± 0.0004	0.005 ± 0.0004
LCW4	Stream	0.011 ± 0.0005	0.013 ± 0.0017	0.099 ± 0.0006	0.038 ± 0.0005	0.007 ± 0.0002
LCW5	Stream	0.016 ± 0.0001	0.011 ± 0.0002	0.060 ± 0.0003	0.035 ± 0.0006	0.010 ± 0.0002
LCW6	Stream	0.011 ± 0.0001	0.012 ± 0.0005	0.045 ± 0.0002	0.043 ± 0.0006	0.008 ± 0.0006
LCW7	Mine pit	0.001 ± 0.0004	0.012 ± 0.0006	0.172 ± 0.0004	0.038 ± 0.0005	0.013 ± 0.0005
LCW8	Borehole	0.012 ± 0.0002	0.008 ± 0.0004	0.093 ± 0.0003	0.042 ± 0.0008	0.006 ± 0.0004
LCW9	Borehole	0.004 ± 0.0003	0.006 ± 0.0003	0.114 ± 0.0011	0.038 ± 0.0005	0.009 ± 0.0008
LCW10	Well	0.007 ± 0.0003	0.011 ± 0.0004	0.100 ± 0.0004	0.041 ± 0.0008	0.011 ± 0.0004

WHO (2011)	+	*	+	2.00	
Code	Zn	Na	K	Cu	Ca
LCW1	0.111 ± 0.0017	0.097 ± 0.0008	0.192 ± 0.0014	0.088 ± 0.0008	0.078 ± 0.0004
LCW2	0.121 ± 0.0009	0.099 ± 0.0011	0.584 ± 0.0015	0.127 ± 0.0008	0.077 ± 0.0007
LCW3	0.099 ± 0.0042	0.111 ± 0.0003	0.755 ± 0.0014	0.144 ± 0.0007	0.081 ± 0.0003
LCW4	0.093 ± 0.0021	0.101 ± 0.0003	0.600 ± 0.0019	0.091 ± 0.0001	0.070 ± 0.0002
LCW5	0.079 ± 0.0014	0.106 ± 0.0005	0.093 ± 0.0036	0.091 ± 0.0004	0.098 ± 0.0002
LCW6	0.092 ± 0.0028	0.134 ± 0.0008	0.566 ± 0.0028	0.117 ± 0.0010	0.066 ± 0.0008
LCW7	0.160 ± 0.0041	0.151 ± 0.0021	0.885 ± 0.0037	0.172 ± 0.0008	0.110 ± 0.0007
LCW8	0.109 ± 0.0018	0.092 ± 0.0008	0.280 ± 0.0023	0.100 ± 0.0003	0.096 ± 0.0005
LCW9	0.120 ± 0.0019	0.102 ± 0.0002	0.771 ± 0.0022	0.129 ± 0.0005	0.080 ± 0.0003
LCW10	0.117 ± 0.0011	0.099 ± 0.0004	0.129 ± 0.0022	0.095 ± 0.0003	0.090 ± 0.0005

Fig. 8 **a** Heaps of tailings. **b** Abandoned mine pit. **c** Mine pond. **d** Gully development

animals in the Bakebu stream, strong inference can however be drawn, bearing in mind that the Big River, Missouri was a repository of mine effluents from its surrounding mines for many decades, just like the Bakebu stream of the Adudu mining province. Field studies conducted in other mining districts of the world have documented reduced population densities of riffle-dwelling crayfish downstream from Pb to Zn mines (Allert et al. 2008, 2012), and the sensitivity of crayfish to mining-related metals has been documented through both laboratory and in situ toxicity tests (Allert et al. 2009; Knowlton et al. 1983; Wigginton and Birge 2007). Crayfish are also vectors for the transfer of metals to higher trophic levels (Schmitt et al. 2011). Additionally, Besser and Rabeni (1987) had reported that the riffle-dwelling fish community of Ozark streams is also sensitive to metals from Pb to Zn mining. The reasonably high level of PHMs in the stream sediments and water of the Bakebu stream could pose prolonged danger to the ecosystem and humans long after the cessation of mining activity in the district. Resongles et al. (2014) had demonstrated the persistence of metals (Pb, Zn, Cd, Tl, Hg) and metalloids (As, Sb) in the enrichment of the Gardon River, Southern France, even after a long period of being

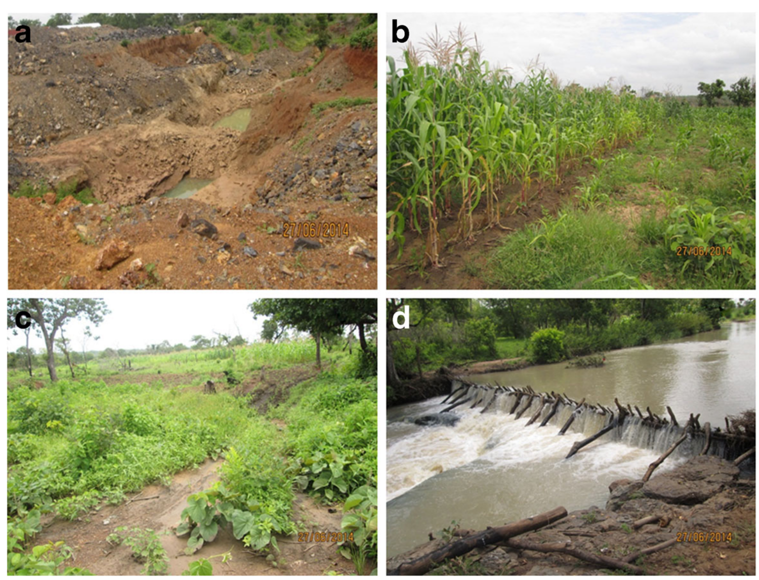


Fig. 9 **a** Degraded topography. **b**, **c** Channels of mine effluents in farmland. **d** The channel of the Bakebu stream

free of mining activity. Olade (1987) had reported poor but persistence dispersion of lead, cadmium, and Sb in streams of the Benue Trough, thereby confirming this assertion.

Farmland (soil) contamination

The XRF and AAS analyses expressly confirm the field observations made during this research. Crop plants that are contiguous to the channels of mine effluents in the area were observed to display yellow coloration. This physically observed anomaly decreases as one moves away from the mine effluents' channels (Figs. 8 and 9). The X-ray fluorescence analysis revealed very high concentrations of PHM in the samples in the farmland soil. The metals K, Ca, Ti, Mn, Ni, Cu, and Zn were detected in the ranges of 6235–17,416, 1631.14–4299, 11,111–15,573, 3055.51–7645.26, 3055.51–7645.26, 107.88–246.72, 23.97–59.93, and 2.68 × 10^{-6}–1099 mg l^{-1}, respectively, in the farmland soils. Similarly, concentration (mg l^{-1}) ranges of 17.98–105.88 (Ga), 83.904–235.73 (Ge), 145.83–262.69 (Sr), 145.83–262.69 (Sr), 320.63–1101.74 (Zr), 62.93–473.46 (Pb), and 8.99–12.99 (Bi) were also observed in the analyzed farmland soils (Table 3).

Table 3 Mean elemental concentrations (measured in mg l^{-1}) in soils, rocks, stream sediments, and tailings as obtained from AAS

Code	Description	Cd	Co	Fe	Mn	Pb
LCS1	Black shale	0.008 ± 0.0002	0.008 ± 0.0004	0.073 ± 0.0008	0.043 ± 0.0006	0.012 ± 0.0008
LCS3	Mine tailings	0.003 ± 0.0002	0.005 ± 0.0008	0.074 ± 0.0002	0.047 ± 0.0007	0.010 ± 0.0001
LCS4	Farmland soil	0.001 ± 0.0006	0.009 ± 0.0003	0.085 ± 0.0035	0.047 ± 0.0004	0.009 ± 0.0003
LCS5	Farmland soil	0.003 ± 0.0004	0.013 ± 0.0001	0.046 ± 0.0008	0.048 ± 0.0001	0.006 ± 0.0004
LCS7	Farmland soil	0.010 ± 0.0003	0.017 ± 0.0006	0.114 ± 0.0006	0.049 ± 0.0001	0.008 ± 0.0003
LCS8	Stream sediments	0.019 ± 0.0004	0.021 ± 0.0005	0.219 ± 0.0002	0.092 ± 0.0003	0.017 ± 0.0005
LCS9	Stream sediments	0.020 ± 0.0002	0.016 ± 0.0004	0.150 ± 0.0003	0.086 ± 0.0005	0.015 ± 0.0004
LCS10	Indurated shale	0.026 ± 0.0002	0.021 ± 0.0004	0.152 ± 0.0005	0.101 ± 0.0005	0.016 ± 0.0004
LCS11	Sandstone	0.018 ± 0.0002	0.042 ± 0.0007	0.187 ± 0.0009	0.091 ± 0.0002	0.012 ± 0.0003
LCS12	Grayish shale	0.033 ± 0.0004	0.020 ± 0.0002	0.172 ± 0.0011	0.100 ± 0.0005	0.019 ± 0.0008
LCS13	Mine tailings	0.026 ± 0.0001	0.034 ± 0.0002	0.202 ± 0.0004	0.068 ± 0.0003	0.021 ± 0.0005
LCS14	Weathered clay	0.028 ± 0.0002	0.016 ± 0.0003	0.261 ± 0.0007	0.069 ± 0.0009	0.016 ± 0.0007
LCS15	Mine tailings	0.018 ± 0.0003	0.029 ± 0.0001	0.196 ± 0.0002	0.077 ± 0.0003	0.014 ± 0.0000
LCS16	Shale	0.020 ± 0.0002	0.018 ± 0.0002	0.144 ± 0.0004	0.110 ± 0.0002	0.022 ± 0.0002
LCS17	Control sample	0.028 ± 0.0004	0.013 ± 0.0001	0.182 ± 0.0007	0.109 ± 0.0005	0.02 ± 0.0007

Code	Zn	Na	K	Cu	Ca
LCS1	0.110 ± 0.0016	0.108 ± 0.0010	0.535 ± 0.0023	0.130 ± 0.0014	0.045 ± 0.0010
LCS3	0.104 ± 0.0011	0.123 ± 0.0009	0.539 ± 0.0098	0.139 ± 0.001	0.039 ± 0.0002
LCS4	0.085 ± 0.0038	0.111 ± 0.0009	0.320 ± 0.0023	0.091 ± 0.0006	0.049 ± 0.0006
LCS5	0.080 ± 0.0002	0.093 ± 0.0005	0.254 ± 0.0030	0.105 ± 0.0013	0.091 ± 0.0001
LCS7	0.105 ± 0.0012	0.123 ± 0.0007	0.520 ± 0.0067	0.122 ± 0.0014	0.085 ± 0.0002
LCS8	0.139 ± 0.0004	0.179 ± 0.0009	1.221 ± 0.0025	0.111 ± 0.0043	0.153 ± 0.0002
LCS9	0.147 ± 0.0003	0.198 ± 0.0004	2.490 ± 0.0022	0.248 ± 0.0017	0.184 ± 0.0006
LCS10	0.182 ± 0.0012	0.174 ± 0.0007	3.052 ± 0.0027	0.257 ± 0.0008	0.132 ± 0.0003
LCS11	0.208 ± 0.0015	0.162 ± 0.0009	1.199 ± 0.0033	0.185 ± 0.0009	0.156 ± 0.0004
LCS12	0.193 ± 0.0021	0.208 ± 0.0005	2.723 ± 0.0032	0.203 ± 0.0005	0.153 ± 0.0003
LCS13	0.215 ± 0.0008	0.212 ± 0.0010	1.311 ± 0.0004	0.103 ± 0.0008	0.160 ± 0.0008
LCS14	0.220 ± 0.0012	0.191 ± 0.0006	2.150 ± 0.0005	0.231 ± 0.0008	0.147 ± 0.0004
LCS15	0.184 ± 0.0031	0.189 ± 0.0009	1.676 ± 0.0008	0.244 ± 0.0006	0.145 ± 0.0002
LCS16	0.192 ± 0.0084	0.163 ± 0.0009	0.823 ± 0.0006	0.299 ± 0.0006	0.122 ± 0.0003
LCS17	0.177 ± 0.0035	0.178 ± 0.0005	1.891 ± 0.0005	0.271 ± 0.0008	0.171 ± 0.0003

These values are similar to that published by Olade (1987), who reported concentrations of 12–30, 2200–7500, and 500–1800 ppm for cadmium, lead, and zinc, respectively, in the soils of the Cretaceous Benue Trough. According to Ekeleme et al. (2013), the distributions and concentrations of arsenic, cadmium, and lead in the soil samples acknowledged potential risks associated with lead–zinc mineralization and mining due to enrichment of these elements in the surface soils and continuous exposures of human beings and animals to these risks. The quantities of arsenic and lead in the Arufu mining district, which is a neighboring mining province to the one under study, have been reported to be higher than permissible levels (Ekeleme et al. 2013), thereby posing potential threat to the health of dwellers of the communities where mining activities are ongoing or were carried out. A common, prolific source of base metals in agricultural soils and food crops is mining (Nganje et al. 2010).

Plants grown on farmlands enriched with PHMs have been established to take up some of these deleterious metals/metalloids into their system; although this is dependent on the interplay of several other factors, such as the bioavailability of the metals, the type of plants, the age of the plants, and the parts of plant (Xian 1989; Alloway 1990; Jung et al. 2002), the high concentrations of trace metals recorded in the farmland soils and the potential health hazards associated with these harmful metals/metalloids call for concern. McCluggage (1991) had reported that excess accumulation of potential toxic metals (PTM) such as Pb, Ni, Cu, and Zn is toxic to humans and other animals.

Igwe et al. (2014) had reported that dwellers of uncivilized environment with minimal level of education and awareness are more risk-prone when compared, knowing fully well that lead (Pb) taken internally in any of its forms is highly toxic and that the effects are usually felt after it has accumulated in the body over a period of time (Duruibe et al. 2007). The symptoms of lead poisoning are anemia, weakness, constipation, colic, palsy, and often paralysis of the wrists and ankles. Children are especially endangered from lead, even at levels once thought safe. Lead can reduce intelligence, impair memory, and cause hearing problems. In adults, lead hazard at levels once thought safe is that of increased blood pressure (Microsoft Encarta 2009). Though cadmium (Cd) is of various uses in day to day life, excessive intake of Cd and solutions to the body could be toxic with cumulative effects similar to those of mercury poisoning. The use of cadmium-rich effluents obtained from a zinc mine to irrigate rice paddies have been documented to result in adverse health effects on local farmers who fed on the rice cultivated in the contaminated farmland (Kobayashi 1978).

Conclusion

Risk assessment of the Pb–Zn mining in the Adudu province, middle Benue Trough was carried out. Significant level of contamination/pollution was recorded in the analyzed samples. Generated geochemical maps alongside field observation revealed notable pollution of the farmlands and stream channels. This contamination could in turn impact the food crops grown on these farmlands and aquatic foods sourced from the stream channels. This study revealed gross unconformity of past mining activities in the region to the existing mining laws/acts in Nigeria.

Recommendations

Taking clues from the findings of this study, it is recommended that concerned agencies should ensure the ongoing mining operations in the region conform to set standards and mining laws. Inhabitants of this region should be discouraged from farming in the region and alternative plots of land should be made available to them for farming by the government to avoid more exposure to these toxic metals. Provisions of portable borehole water should be made available to the inhabitants of the area, as streams and wells in the area are contaminated already. Integrated study using holistic approach is recommended in the area to examine the level of PHMs in aquatic animals in the Bakebu channels as well as plant parts.

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