Journal of Environment Pollution and Human Health, 2016, Vol. 4, No. 1, 16-23
Available online at http://pubs.sciepub.com/jephh/4/1/3

DOI:10.12691/jephh-4-1-3

Analysis of the Spatial Distribution of Lead Concentration in the Soil of Anka, Zamfara State, Nigeria

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Abstract Over the years Nigeria has experienced outbreaks of lead poisoning alleged to be caused by massive environmental contamination due to local gold ore processing. As recent as late last year (2015), such an outbreak was reported in Niger State while Medecins Sans Frontieres (Doctors without Borders) in March 2010 reported an outbreak that claimed many lives, mostly children, in Zamfara State. Research on lead poisoning in Nigeria has mainly been concerned with the clinical component of the problem, i.e., testing for blood lead levels and treatment. Analysis of the spatial dimension of the problem is not adequately emphasized. However, investigating the spatial dimension (i.e. spatial spread/distribution of lead concentration) is very critical in planning interventions in areas affected by lead poisoning and for a methodical, future-focused planning. This study investigated the concentration of lead, copper, and cadmium in the soil of Anka, and also analyzed the spatial distribution and spread of lead concentration in Anka, one of the areas worst hit by the 2010 lead poisoning outbreak, with a view to giving aid to policy and decision makers in terms of priority areas for intervention and future planning. Soil samples were collected in mining and non-mining areas and analyzed for the concentration of lead, copper, and cadmium. Copper and cadmium were analyzed because they occur in association with lead and are also toxic in certain quantities. Inverse distance weighting (IDW) spatial interpolation technique was employed to determine the spatial distribution of the three heavy metals. The results showed high concentrations of lead in areas where local ore mining and processing are taking place and low concentrations in non-ore processing areas. The results also highlighted areas in urgent need of intervention.

Keywords: *geospatial, heavy metals, ore processing, environmental contamination*

Cite This Article: Felix Ndukson Buba, "Analysis of the Spatial Distribution of Lead Concentration in the Soil of Anka, Zamfara State, Nigeria." *Journal of Environment Pollution and Human Health*, vol. 4, no. 1 (2016): 16-23. doi: 10.12691/jephh-4-1-3.

1. Introduction

1.1. Background

Lead has long been recognized as a harmful environmental pollutant. The Secretary of the Department of Public Health Services of the United States of America in 1991 referred to lead poisoning as the number one environmental threat to the health of children in the United States [16]. Lead is a heavy metal that occurs naturally in the Earth, accounting for 13mg/kg of the Earth's crust, and is dispersed in small amounts into the environment by natural processes [25,30]. It accumulates in the environment, is non-biodegradable, and does not lose its toxicity over time [20,26]. When ingested and inhaled, it circulates in the bloodstream, is reabsorbed in the kidneys and the brain, and is deposited in bones and teeth. Available evidence indicates that lead is neither essential nor beneficial to living organisms, and that all measured effects are adverse – including those on survival, growth, reproduction, development, behavior, learning, and metabolism [12,29,31].

Being the commonest of the heavy metals, lead is used in the production of lead acid batteries, solder, alloys, cable sheathing, pigments, rust inhibitors, ammunition, glazes, and plastic stabilizers [30]. It is a toxic metal whose widespread use has caused extensive environmental contamination and health problems in many parts of the world, with human exposure to lead estimated to account for 143, 000 deaths every year and 0.6% of the global burden of diseases [31]. Lead exists in the Earth's crust, mainly as lead sulphide, and occurs naturally in the environment through a variety of mechanisms including volcanic emissions, geochemical weathering, sea spray emissions, and re-mobilization of historic sources such as lead in soil, sediment, and water from mining areas [5,29]. The majority of lead pollution, however, derives from human activity to extract and exploit the metal [10]. Some of these activities include mining, smelting, refining and informal recycling of lead, production of lead-acid batteries, use of leaded petrol, production of paint, jewelry making, soldering, ceramics and leaded glass manufacture in informal and cottage (home-based) industries, electronic waste, and use in water pipes and solder [5,8,23,22,29,30].

Lead O'Dwyer (1998) defined lead poisoning as a medical condition caused by increased levels of the heavy metal lead in the body, with children and pregnant women being particularly vulnerable, and CDC [4] defined children lead poisoning as a whole-blood lead concentration =>10µg/dl. Exposure to lead affects multiple health outcomes and physiological systems, including hypertension, the gastrointestinal systems, anaemia, nephropathy, vitamin D metabolism, decreased growth, the immune system, the nervous system, behavioural/cognitive/IQ effects and as a result, multiple social effects including increased risk of violence and drug abuse, nerve conductive effects, hearing loss, effects on reproduction and development, and death from encephalopathy [1,3,4,7,10,11,13,16,20,22,23,24,29,30,31].

Sources of lead leading to poisoning include lead in air which occurs primarily due to gasoline additives and industrial emissions; lead in dust derived from soil and airborne pollutants or from parents who bring it into the home after having been exposed at the workplace; lead in foods which results from food and drink cans and certain vegetables; lead in paints, ceramic glazes and cosmetics; and lead from lead smelters, incinerators, battery recycling plants and other industrial activities [5,7,23,29]. Recent reductions in the use of lead in petrol (gasoline), paint, plumbing, and solder have resulted in substantial reductions in lead levels in the blood. However, significant sources of exposure to lead still remain, particularly in developing countries [3,30].

In March 2010, Medecins Sans Frontieres (Doctors without Borders) was alerted to a high number of child fatalities in some locations in Zamfara State, Nigeria, where an estimated four hundred children were reported to have died [19]. Laboratory testing later confirmed high levels of lead in the blood of the surviving children. These deaths were alleged to have been caused by acute lead poisoning as a result of massive environmental contamination from small-scale artisanal mining (ASM) and ore-processing of gold in lead-rich ore [7]. This assertion was corroborated by WHO [32] when it observed that a high incidence of convulsions and death in young children in some villages in Zamfara State has been noted, with a strong likelihood that this is due to lead poisoning, and that the full scale of the problem is still not fully determined.

Many surveys examining the prevalence of elevated paediatric blood lead levels give insufficient attention to the geography of the major known risk factors [20]. A Geographic Information System (GIS) addresses the spatial variation inherent in the distribution of these risk factors, and can identify areas, streets, and even individual dwellings with a high probability of environmental lead, and predictions can then be validated and confirmed with analysis of blood or dust/water samples [20]. In 2004, CDC employed GIS technology to develop and improve preventive interventions, using Jefferson County, Kentucky, as the study area. The aim of the study was to identify children at risk to lead exposure, 'at risk children' defined as those children living in housing built before 1950 or in an area with a high proportion of older housing. The data sets used for the study included child blood lead screening data, US census data, and tax assessor (property) data. The results of this study showed that more children living in older housing had elevated blood lead levels than those living in newer housing. A major downside to this study is that ZIP codes (used for geo-coding) are unreliable for GIS mapping because they cross state, county and municipal boundaries, and their boundaries change while new ZIP codes are added periodically. Also, the approach adopted in this study may be difficult to replicate in developing countries like Nigeria because of a lack of data on blood lead levels, unreliable census data, and lack of property formalization.

Perham [21] also conducted a study to determine the highest risk areas for lead poisoning in Hartford. Data such as age of housing, location of children with elevated blood lead levels, census data, building type, and buildings with soil samples with lead levels >400ppm were collected and used. The weighted overlay analysis method was used by assigning weight to each data source, assigning risk values, running layers through weighted overlay tool, and mapping the results. 28% of residential buildings were shown to have a very high risk for lead poisoning and the highest risk areas were determined to be Barry Square, Frog Hollow, and Northeast. The same deficiencies noted in the CDC [3] study also applied in this study, the approach being difficult to replicate in developing countries.

Mapping was also utilized by van Geen *et al.* [28] to estimate the population of Peru living in the vicinity of active or former mining operations who could be exposed to lead from contaminated soil. In this study, geographic coordinates were compiled for 113 active mines, 138 ore processing plants, and 3 smelters, as well as 7,743 former mining sites. The population living within 5km of these sites was calculated from census data, and the lead content of soil in the mining towns, and mines and ore processing plants was mapped. The study concluded that soil contamination with lead is likely to be extensive in Peruvian mining towns. Although this study did not take into consideration the implications of other heavy metals that usually occur in association with lead in ores (copper, cadmium) which are also toxic at elevated levels, the approach may be replicated in Nigeria and other areas with a history of mining.

In developing countries, awareness of the public health impacts of exposure to lead is growing. However, relatively few of these countries have introduced policies and regulations for significantly combating the problem [23]. Both occupational and environmental exposures have remained a serious problem in many developing and industrializing countries. Lead is a global public health issue but it is only just being recognized as a potential problem in many developing countries, with studies only now being reported from Africa, Asia, and South America [23]. Riederer *et al*. (2011) described Zamfara State as a hotspot of lead exposure and environmental pollution, and drew attention to the continued existence of lead hotspots in the developing world, undermining the need for investigation in these regions where data is of poor quality or non-existent.

Despite the acknowledgement that lead is an environmental and public health hazard of global proportions, yet the spatial dimensions of lead poisoning in the developing world remain poorly understood due to the persisting lack of data. This is in contrast to developed countries where studies have been carried out (e.g. [8,10,11,12,15,21,28]. The few studies carried out in Nigeria have been mostly limited to the clinical component of the problem. The spatial dimension has not been emphasized. To elucidate the spatial dimension of lead poisoning, this study sought to analyze the concentration of lead, copper, and cadmium (Cu and Cd were also analyzed because they occur in association with lead and are also toxic in certain quantities) in the soil of the study area and to determine their spatial pattern of spread and spatial variation in concentration. This is important for policy and decision makers to make informed decisions in combating the menace of lead poisoning in terms of intervention and methodical, future-focused planning.

1.2. Study Area

Anka is one of the 14 Local Governments of Zamfara State. It is located between latitudes $11^0$39'N and $12^0$18'N, and longitudes $5^0$54'E and $6^0$19'E. With an area of $2{,}940km^2$, Anka has a population of 263,400 (National Population Commission, 2006, cited in Blacksmith Institute, 2011). Ten villages were selected as sampling locations (Figure 1).

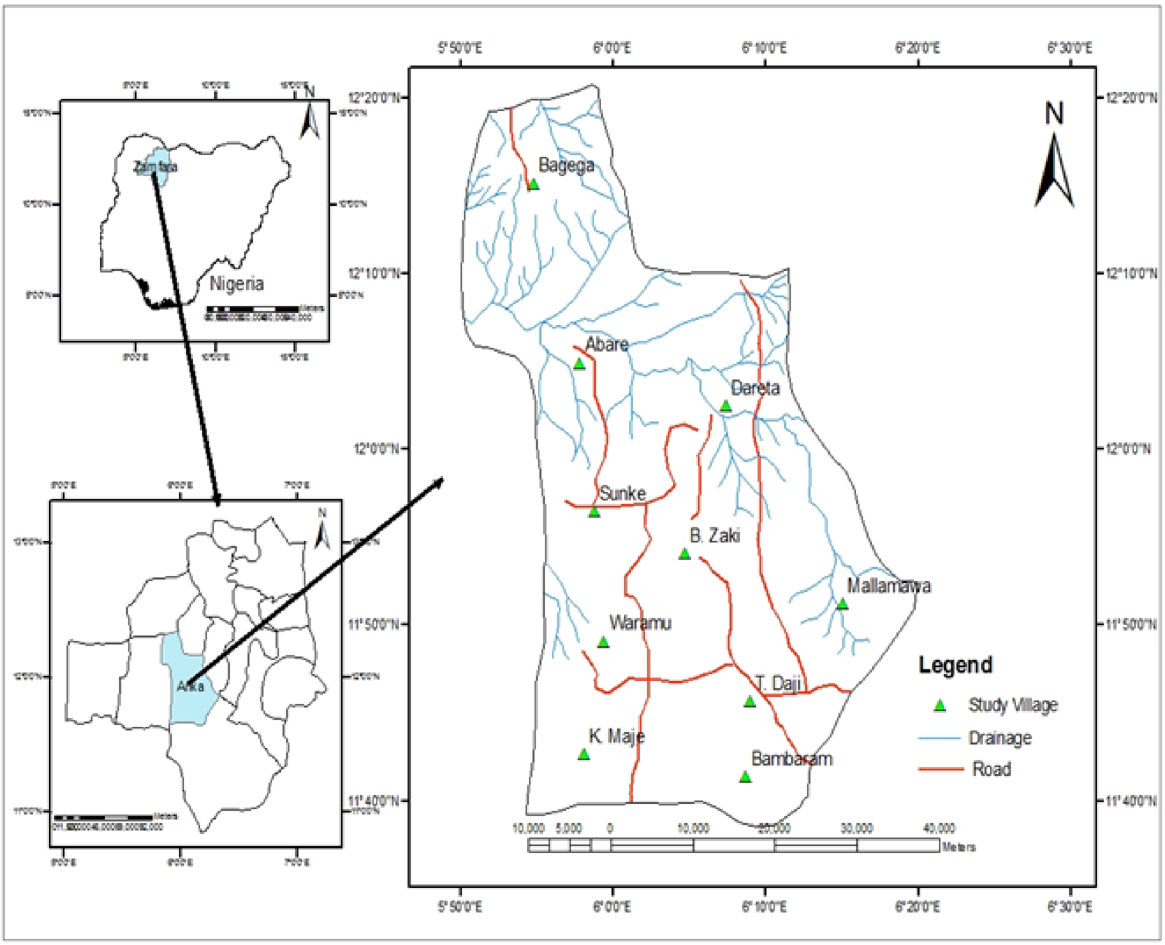

Figure 1. Study Area

Lead-zinc occurrence/mineralization in Nigeria is often associated with minor to significant amounts of copper and gold [18]. The geology of Anka is characterized by the Anka schist belt that hosts the lead mineralization, and the lead-copper-silver-gold (Pb-Cu-Ag-Au) poly-metallic association [17]. Lead (Pb) mineralization in Zamfara State occurs in veins and as stringers in wall rocks in a variety of rocks like quartz-schists, and quartzitic-phyllitic schists within the N-S trending Anka schist belt.

The climate of Anka is warm tropical with temperatures rising up to 38^0C between March and May. Rainy season starts in late May to September while the dry season known as harmattan lasts from December to February. Two major soil types, ferruginous tropical soils and lithosols, dominate the local government [24]. The vegetation of the area consists of northern Guinea Savannah, characterized by short and stringy shrubs.

2. Materials and Methods

GIS has been employed in this study as a decision support system. Based on GIS technology, spatial decision support systems tools are designed to collect, integrate, and model spatial data. An effective spatial decision support system tool would provide decision makers with a means of accessing relevant data from existing datasets and model prospective service configurations within and across their regions. Densham [6] stated that spatial decision support systems are explicitly designed to provide the user with a decision-making environment that enables the analysis of geographical information to be carried out in a flexible manner while Malczewski [14] defined a spatial decision support system as an interactive computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision making while solving a semi-structural spatial decision problem.

A soil augur was used to collect soil samples in the study area at depths between 0 – 10cm. A hand-held Global Positioning System (GPS) receiver unit was used to fix the locations of sampling points in Universal Transverse Mercator coordinates (WGS – 84 datum). Labeled polythene bags were utilized as sample collection bags.

Soil samples were collected using soil augur at depths of 0-10cm. Stratified random sampling technique was used in selecting the sampling location. The population was stratified or separated into mining and non-mining, using the chain-referral method. The chain-referral method involves an iterative, cyclical process to identify villages of interest through interviews with State and local officials, traditional rulers, and other stakeholders [13]. Five mining and five non-mining villages were selected out of the several villages identified based on their locations to ensure uniform spread. Soil samples were collected from the identified villages at ore processing points, three (3) samples collected from each of the five villages identified as being at most risk from lead poisoning as a result of ore processing activities and three samples each from the five non-mining villages. A total of thirty (30) surface soil samples were collected for laboratory analysis. Locations of sampling points (Figure 2) were fixed using a Global Positioning System (GPS) receiver unit.

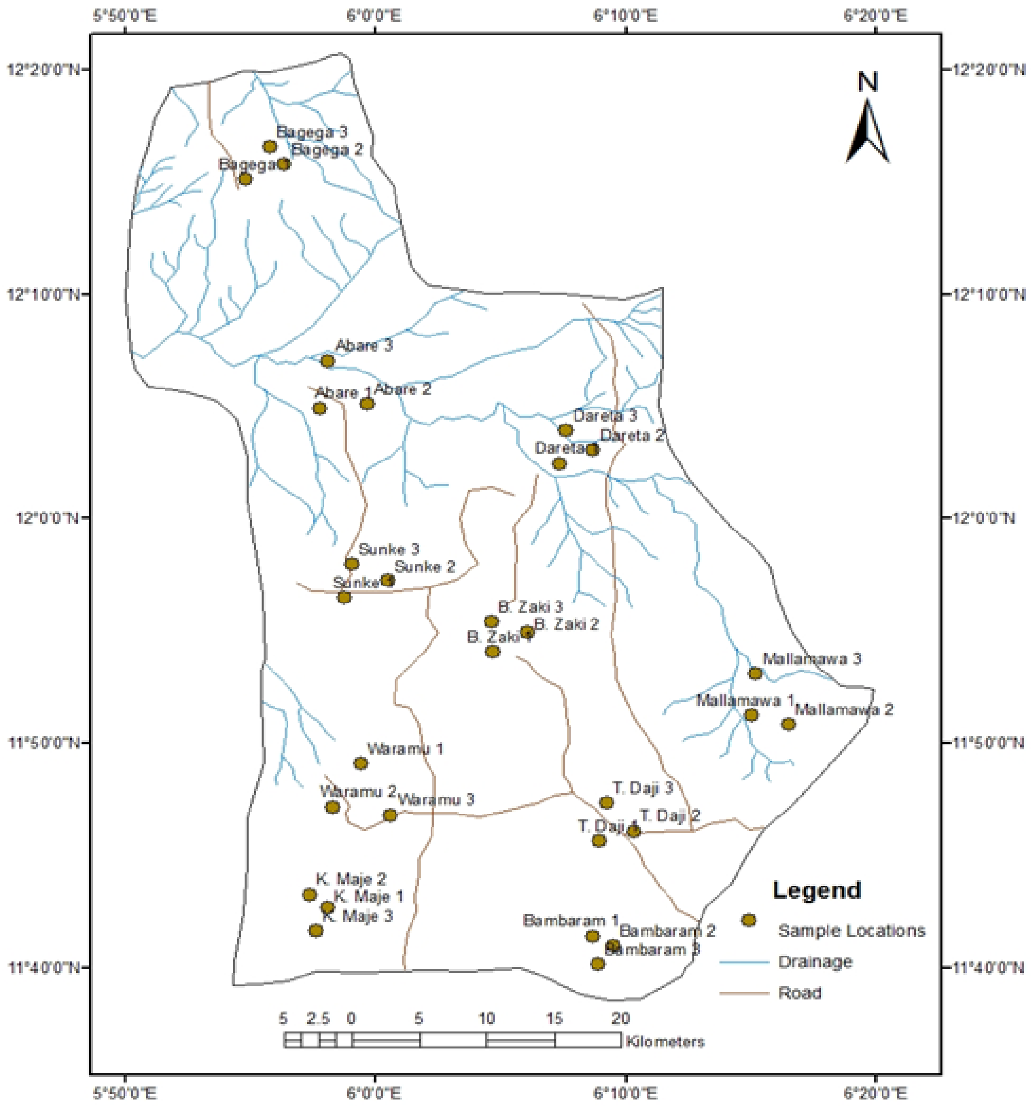

Figure 2. Soil sampling locations

The soil samples were analyzed for the concentrations of lead, copper, and cadmium employing the Atomic Absorption Spectrophotometry method. This is a technique used to identify substances, especially metals, and their concentrations. Copper was chosen for analysis along with lead because lead-zinc occurrence/mineralization in Nigeria is often associated with minor to significant amounts of copper and gold, with copper known to be toxic at elevated levels [18]. Cadmium was equally analyzed because cadmium and solutions of its compounds are known to be toxic, and it is a bye-product of the mining and smelting of lead and zinc [24].

For depicting the spatial distribution of lead, copper, and cadmium concentrations in the study area, the Inverse Distance Weighting (IDW) interpolation method was employed. Interpolation is based on the principle of autocorrelation. While there are many spatial interpolation algorithms for spatial datasets such as kriging, IDW was chosen because it creates surfaces based on the measured points or sample points.

3. Results and Discussion

3.1. Results

3.1.1. Concentration of Lead, Copper, and Cadmium

The descriptive statistics for the concentrations of lead, copper, and cadmium is summarized in Table 1. The mean value for the concentration of lead in mining villages was 36,450.67mg/kg and in non-mining villages was 467.33mg/kg. The mean value for the concentration of copper in mining villages was 24.87mg/kg and in non-mining villages was 17.65mg/kg. The mean for cadmium was 0.18mg/kg for mining villages and 0.14mg/kg for non-mining villages. The permissible limits for lead, copper, and cadmium in soils are 400mg/kg, 50mg/kg, and 3 – 10mg/kg respectively.

Table 1. Descriptive Statistics

Metals (Mining and non-mining locations)	No. of Samples	Minimum	Maximum	Mean	Std. Deviation	Coefficient of Variance
Lead – Mining	15	700	62000	36450.67	20819.46	0.57
Lead – Non-mining	15	320	670	467.33	91.53	0.20
Copper – Mining	15	10.15	49.19	24.87	12.28	0.49
Copper–Non-mining	15	9.10	25.18	17.65	4.95	0.28
Cadmium – Mining	15	0.01	0.35	0.18	0.095	0.53
Cad. – Non-mining	15	0.05	0.31	0.14	0.07	0.50

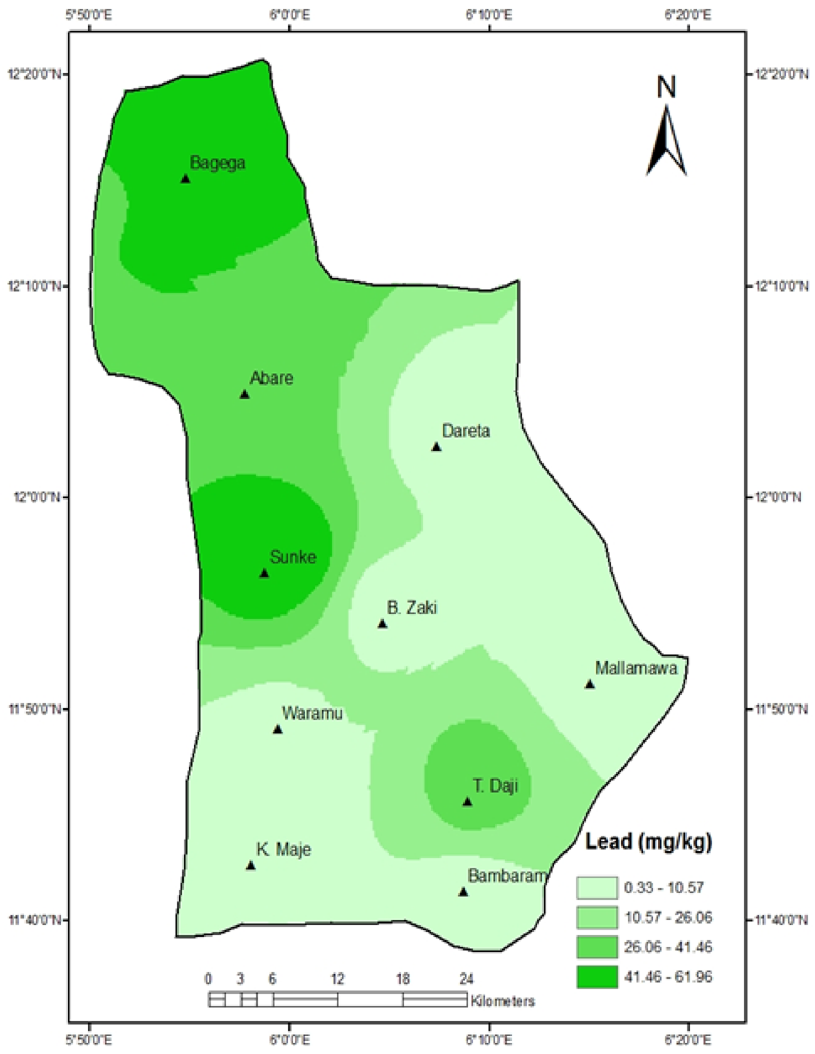

Figure 3. Spatial distribution of lead concentration in the study area

3.1.2. Spatial Distribution of Lead, Copper, and Cadmium

Presence of lead was recorded in all the sampled locations of the study area. However, there was a significant difference in the concentration of lead in mining and non-mining villages. Spatial variation in concentration (Figure 3) showed that mining villages recorded high concentration of lead (with the exception of Dareta village) while non-mining villages recorded low lead concentration. On the other hand, Figure 4 and Figure 5 show that the spatial variation of copper and cadmium in the study area is not influenced by ore processing activities.

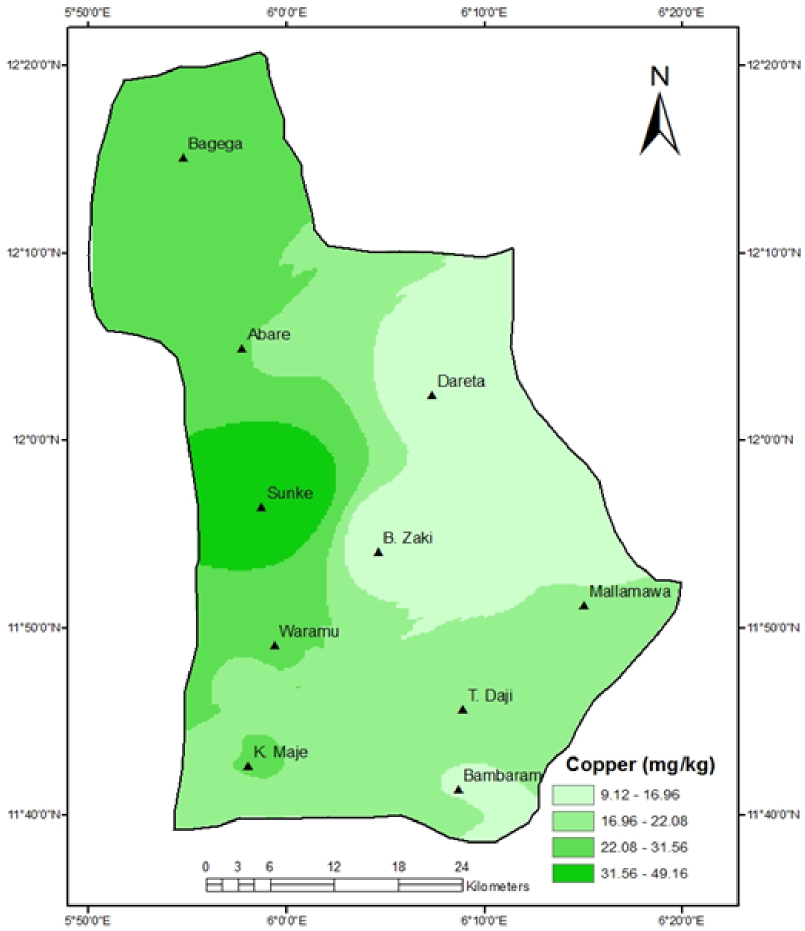

Figure 4. Spatial distribution of concentration of copper in the study area

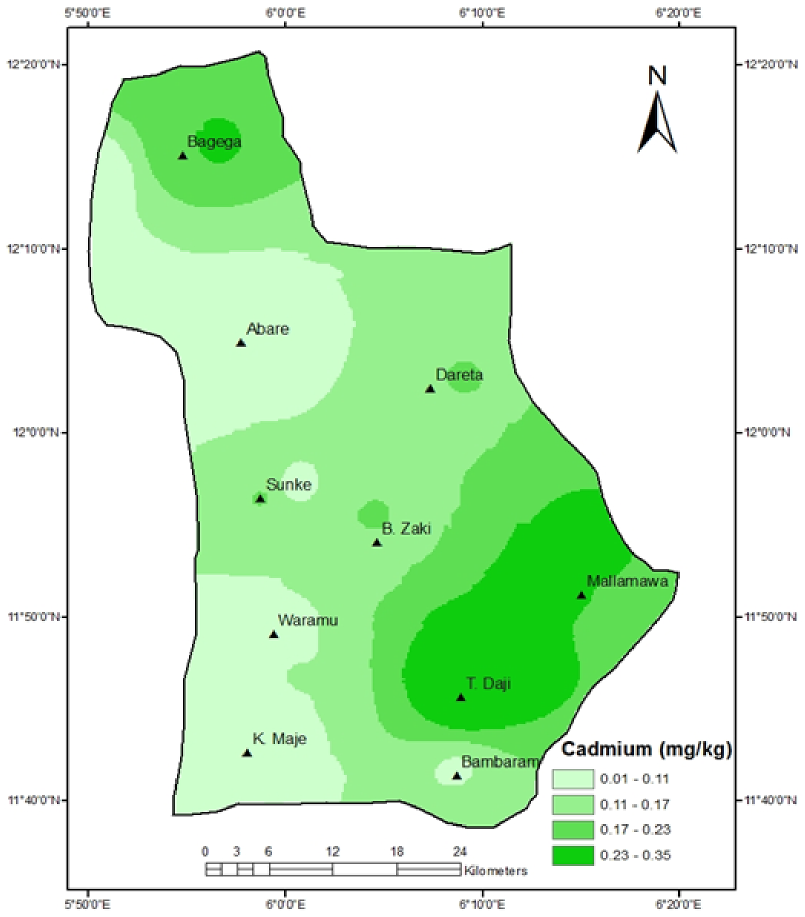

Figure 5. Spatial distribution of the concentration of cadmium in the study area

3.2. Discussion

3.2.1. Concentration of Lead, Copper, and Cadmium

The mean value of lead concentration recorded for the mining villages was 36,450.67mg/kg from a range of 700-62,000mg/kg, with a coefficient of variation of 0.57. The coefficient of variation suggests that there is some variation in the data. This may be as a result of the data obtained at Dareta village. This village has undergone remediation, and therefore recorded low values of lead concentration. The permissible limit for lead in soils is 400mg/kg while the average for the study area is 36,450.67. Table 2 and Table 3 show the US-EPA and Canadian standards for lead in soil, while Table 4 shows the NESREA standard for lead in soil. The concentration of lead in the study area is abnormally high, far above the accepted limits (400mg/kg), and must be attributed to the local processing of gold ore in the study area since concentration of lead in non-ore processing locations were within acceptable limits.

Result of the analysis of the concentration of copper in the study area showed that the mean was 24.87mg/kg of a range 10.15-49.19mg/kg and 0.49 coefficient of variation for the mining villages and 17.65mg/kg of a range of 9.10-25.18mg/kg and 0.28 coefficient of variation for the non-mining villages. The coefficient of variation suggests that there is little variation in the data obtained in the study area. The maximum permissible limit for copper in soil is 50mg/kg [24]. This implies that copper is well within the acceptable standards. Although copper is toxic at elevated levels, and occurs in association with gold and lead, the result shows that copper is not implicated in the environmental contamination of the study area.

Table 4 shows the World Health Organization (WHO), Denmark, and Canadian standards for cadmium in soils. The average concentration of cadmium in the study area from result of the analysis was 0.18mg/kg in ore-processing areas and 0.14mg/kg in non-ore processing areas with coefficient of variation at 0.53 and 0.50 respectively. This shows that cadmium is well within the acceptable standards for soil cadmium concentration, and therefore, cadmium is not implicated in the environmental contamination of the study area.

Table 2. United States Standard for Lead in Soils

Bare soil location	Standards (mg/kg)
Play areas (yards)	>= 400mg/kg
All other locations	>= 1200mg/kg

Source: US-EPA (2001).

Table 3. Canadian Standards for Lead in Soils

Bare soil location	Standards (mg/kg)
Industrial	600mg/kg
Agriculture	70mg/kg
Residential	140mg/kg
Commercial	260mg/kg

Source: Canadian Council of Ministers of the Environment [2].

Table 4. Some standards for heavy metals in soils (in mg/kg)

S/N	Parameters	Denmark standards	WHO standards	NESREA standards
1	Cadmium	5	10	3 – 6
2	Chromium	Not fixed	Not fixed	Not fixed
3	Lead	40	70	250 – 500
4	Iron	Not fixed	Not fixed	Not fixed
5	Zinc	500	200	300 – 600

Source: Ezigbo [9].

3.2.2. Spatial Pattern of Spread of Concentration of Lead

High lead concentration was observed in all the mining villages except Dareta while low concentration was recorded in the non-mining locations. The technique of inverse distance weighting interpolation employed also showed the spatial spread of very high values, high values, and medium values of lead concentration in the mining villages. This is an indication that mining processes may be responsible for lead contamination of the study area. The significance of this is that an area of very high lead concentration is indicative of areas that are in most need of intervention, and vice-versa. This can be a very powerful and useful tool for policy and decision makers when planning remediation. Also, mapping of lead in soils can be useful in educating the populace, especially children to avoid contaminated areas that have been identified and mapped. This may help to reduce the incidence of lead poisoning.

4. Conclusion

Presence of lead was shown and spatially depicted in all the villages studied, with only the level of concentration differing between mining and non-mining villages of the study area. Mining areas recorded very high lead concentration while non-mining areas recorded low lead concentration. Policy and decision makers may find such data useful for determining areas in urgent need of intervention. Concentrations of copper and cadmium were determined to be within the internationally acceptable threshold. We can conclude that copper and cadmium are not implicated in the environmental contamination of the study area.

Study of food pathways (livestock, crops) should be undertaken as livestock was seen to be drinking from ponds that may be contaminated, and crops may grow on contaminated soil. Mercury is known to be used as a coagulant in the local processing of gold ore as witnessed in the study area. There is a need to study mercury pollution before it becomes a crisis as is the case with lead. As mercury is very toxic, this could easily damage the health of exposed persons especially children who tend to play on the ground where mercury may have been spilled. There is also need for the study of the mobility of these toxic heavy metals. Further study of the whole state is clearly needful as the geographic extent and, number of people potentially affected is still not known. Any villages in Zamfara state not yet assessed where suspected and/or confirmed mining and ore processing activities have taken/are taking place should be assessed immediately for possible lead pollution and poisoning.

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