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Statistical and Spatial Analysis of Heavy Metals in Soils of Residential Areas Surrounding the Nkana Copper Mine Site in Kitwe District, Zambia

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Abstract

The objective of this study was to assess the heavy metal contamination of soils in three residential areas of Kitwe district namely Nkana East, Nkana West and Wusakile and to determine the spatial distribution of the metals within the soils of the residential areas using geochemical maps. Soil samples were collected in the aforementioned areas and analyzed for Cu, Zn, Pb and Co contents using Atomic Absorption Spectrometry (AAS). The results of the analysis were used to generate geochemical maps using the Inverse Distance Weighting (IDW) interpolation technique in ArcGIS and to calculate the geo-accumulation index (I_{geo}), Enrichment Factor (EF) and Pollution Load Index (PLI). The I_{geo}, EF and PLI were used to assess the soil contamination levels of the four heavy metals. In Nkana West, the I_{geo} for Cu ranged between 1-2 and the EF between 5-20, whereas the I_{geo} and EF values for Co ranged between 0-1 and 2-5 respectively. The I_{geo} values for Cu indicated that the soils were moderately contaminated with Cu while the EF indicated severe enrichment. For Co, the I_{geo} showed moderate contamination while the EF indicated moderate enrichment. In Wusakile, the I_{geo} for Cu was recorded as 0.52 while the EF was recorded as 4.91. These values indicated that the soils in Wusakile were moderately contaminated with Cu. Similar results were recorded for Co although the EF for Co indicated that the soils in Wusakile were severely enriched with the metal. The results for Zn and Pb across all the study areas showed that $I_{geo}<0$ and EF<2, indicating that the soils were uncontaminated with these heavy metals. Both Cu and Co recorded a PLI >1 across all the study areas, indicating that the soils were contaminated with these metals. Statistical analyses across all the study areas showed that Nkana West and Wusakile had the highest mean concentrations of Cu and Co recorded as 1068.96 mg/kg and 343.96 mg/kg respectively, standard deviations recorded as 1666.21 mg/kg and 222.22 mg/kg respectively and Coefficient of Variation (COV) recorded as 1.56 and 1.87 respectively. Spatial analysis revealed that the highest concentration of heavy metals was near active mining areas. Of all the residential areas considered, Nkana West and Wusakile recorded the highest statistical variability and were therefore, the most contaminated areas due to their proximity to Nkana mine site.

Keywords

Heavy Metal, Soil Contamination, Spatial Distribution, Geo-accumulation Index, Enrichment Factor, Pollution Load Index, Kitwe District

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1. Introduction

1.1. Background

Mining of mineral deposits is a very important economic activity as it provides the raw materials required for global industrialization. Due to the increased demand for metals especially by emerging economies such as China and India, there has been an increase in mining activities globally [1]. Developing countries are especially the target destinations for mineral exploitation due to the low cost of mine production, taxation and weak environmental laws and policies. Zambia, a developing country situated in Sub-Saharan Africa is no exception as it is one of the preferred destinations by international mining companies due to its rich mineral wealth, low mining tax and peaceful environment. The country hosts approximately 40 percent and 10 percent of the world's cobalt and copper reserves respectively [2].

Despite the significant benefits of mining to the Zambian economy, some mining practices have had undesirable effects on some areas surrounding major mining activities especially on the Copperbelt where mining dates as far back as 1928 and 1931 for Luanshya and Kitwe districts respectively [3]. These practices have resulted into the gradual release of unwanted toxic substances into the soil and water environment [4-6] as well as ambient air [7]. Among the unwanted substances released into the environment from mining operations are heavy metals such as copper, zinc, lead, arsenic and cadmium [5-6, 8-10]. Heavy metals such as lead, and cadmium impacts negatively on human health and the ecosystem as they are toxic and carcinogenic in nature [11]. It should, however, be noted that the effects and extent of mining pollution on the environment differs from the mining method employed, the minerals being mined, and the type of waste produced [12].

Notwithstanding the history of long-term base metal mining in Zambia, very few studies have been carried out to ascertain the levels and extent of environmental degradation resulting from mining and mineral processing [4, 6, 13]. In addition to this, Zambia and other sub-Saharan countries have inadequate knowledge concerning health hazards posed by heavy metal discharge resulting from mining practices both in peri-urban and urban settlements. In the case of Zambia, particularly in Kitwe district, a study done to assess the levels of knowledge concerning urban health hazards in Kitwe district revealed that 98% of the respondents interviewed in the study had some knowledge of a health hazard unrelated to mining activities [14]. Although this study further revealed that in Nkana West alone, 82.4% of the respondents indicated health risks associated with air pollution due to sulphur dioxide emissions from the processing of copper ore, none of the respondents indicated any health risks posed by heavy metal discharge or hazards associated with the presence of heavy metals in the soils surrounding the study areas as a consequence of mining and mineral processing activities.

A detailed study in Kabwe town in the central province of Zambia revealed high level contamination of soils by heavy metals from past lead and zinc mining [8]. Lead and zinc sulphide deposits with smaller amounts of silver and cadmium were mined and processed in Kabwe town from 1902 to 1994 without adequate pollution control measures [10]. This led to wide-spread lead, zinc, cadmium and copper contamination of the soils at levels much higher than those recommended by World Health Organisation [8]. Consequently, Kabwe town is considered as probably the most contaminated land site in Central Africa [8] and rated among the top 10 worst contaminated sites in the world [15]. In some neighborhoods in Kabwe area, blood lead concentrations of 200µg/dl or more were recorded in children, and records showed the average range of blood lead levels between 50 and 100µg/dl [15]. The record further stated that the blood lead levels in Kabwe were on average 5 to 10 times the maximum permissible value by the Environmental Protection Agency (EPA), which in many cases are considered as potentially fatal. Another study conducted in Namibia showed that soils near mining sites tended to have excessive amounts of heavy metals such as lead and copper and posed a danger to human health and the environment [16]. This study reported values of copper around 150 mg/kg and values of lead more than 164 mg/kg in the soils near the mine. These values are higher than the Canadian guidelines for heavy metals in soil especially in soils intended for agricultural use.

1.2. Statement of the Problem

Heavy metals found in soils surrounding mines have been known to cause long term effects on the health of humans especially children. This is because they are systematic toxicants that poison the immune system and cause cancer and other clinical effects (Table 1) due to long term exposure [17-19]. Specifically, children are more vulnerable to heavy metal poisoning because they scavenge any objects lying around which may contain heavy metals. Children also have a higher absorption rate and are more sensitive than adults [17]. According to [20], Mopani Copper Mines empty toxic tailings from the Nkana mine sites through pipelines that are left unguarded and have inadequate toxicity warnings. Children are left to play on these pipes, were leakages are frequently reported and in the process, carry the toxic matter with them. Another source of concern is the location of some of the slimes dams and the slag dumps. For the most part, they are located near or are within the residential areas.

Together with leakages from the pipelines, these waste material increases the potential for heavy metal contamination in the soils of the residential areas.

If heavy metals are contained in the soils in areas surrounding Nkana mine site, specifically Wusakile, Nkana West and Nkana East residential areas, the inhabitants of these areas are being exposed to various heavy metals that are negatively affecting the development of genes especially in children as well as polluting the ground and surface water. In some cases, the elevated levels of heavy metals may render the soil to be less fertile, thereby reducing the quality of food grown for subsistence agriculture in these areas. A study to investigate the concentration of heavy metals in the soils of residential areas surrounding Nkana mine site has not been carried out and the spatial distribution of the heavy metals is yet to be addressed.

1.3. Study Objectives

The study had the following objectives:

1. Assess the concentration of heavy metals Cu, Pb, Zn, and Co in soils surrounding Nkana Mine site.
2. To calculate the indices of heavy metal contamination in the superficial soil horizon as basis for comparison.
3. To obtain geochemical maps expressing the levels of contamination of soils by heavy metals and assess the spatial dimension of the problem.

1.4. Study Methodology

1.4.1. Soil Sampling, Laboratory Analysis Quality Control and Spatial Data Analysis

A soil orientation survey for the study area was conducted to determine a suitable sampling medium, sampling logistics and sample spacing. Following the orientation survey, the data collected for the study was divided into primary and secondary data. Primary data involved the collection of soil samples from the residential areas over a regular 500 m x 500 m sampling grid using a hand-held auger drill and a hand-held Global Positioning System (GPS) to locate the sample points. All the sample points were located using the Universal Transverse Mercator coordinates (UTM) and datum WGS 84. The samples were collected over a total area of 4.7 Km^2 comprising of approximately 3.5 Km^2 for Nkana East and Nkana West and 1.2 Km^2 for Wusakile (Figure 1). From the orientation survey, surface soils to a depth of 0.2 m were targeted. About 500-gram samples were obtained at each sample point and packed in sterile, clean sealable polyethylene bags. To monitor laboratory precision, duplicate samples were inserted at a frequency of 1 in 20 samples and the samples taken for laboratory analysis to assess the concentration of heavy metals. Four elements were selected for this study namely: Cu, Zn, Pb and Co. The metals were also chosen based on their common associations with copper in sedimentary stratiform deposits of the Zambian Copperbelt. Atomic Absorption Spectrometry (AAS) was used as a method of analysis, while spatial distribution maps were generated using the Inverse Distance Weighting (IDW) technique for data interpolation in an ArcGIS environment. IDW uses the principle of autocorrelation and is a useful technique because the surfaces created are based on the values obtained from the sample points [21]. Statistical analysis and correlations were done using MS Excel.

Secondary data comprised of a literature search to obtain the maximum allowable concentration limits for the heavy metals selected for the study. This study adopted the soil concentration limits as listed by the World Health Organization [22-23].

Table 1. Clinical aspects of chronic toxicities of heavy metals [18-19].

Metal	Target Organs	Primary Sources	Intake	Clinical Effects
Lead	Nervous system, renal, Hematopoietic system	Industrial dust and fumes, polluted food, Mining waste, Mineral processing, Tailings	Ingestion	Central nervous system disorders, anaemia, and peripheral neuropathy, Brain damage, reduced fertility
Copper	Liver, Kidney, bone marrow, Renal, hepatic and nervous system	Industrial copper products, Mining and mineral processing, tailings	Ingestion	Blood anemia, central nervous system disorders, hepatotoxicity, nephrotoxicity
Zinc	Lungs, Liver, Kidney, Renal, hepatic, reproductive system	Steel processing, Mining and mineral processing	Inhalation	Chills, fever, body weakness, Growth impairment (Children)
Cobalt	Muscles, liver, heart, Skin and respiratory system, thyroid gland	Mining and mineral processing, tailings	Ingestion and inhalation	Skin allergies can affect growth of fetus during pregnancy, Dermatitis, asthma

1.4.2. Laboratory Data Quality Control and Assessment of Soil Contamination

As a form of laboratory quality control, the sample duplicate results were subjected to a Half Absolute Relative Difference (HARD) technique to assess laboratory precision. In this technique, the field duplicates must be within +/- 20% HARD to be 'fit for purpose'. To assess the levels of soil contamination in the study area, several factors (Geo-accumulation index (I_{geo}), Enrichment Factor (EF) and Pollution Load Index or PLI) were used as applied by similar studies [1, 24-26]. Soil contamination can be quantified by using the I_{geo}, which can be determined by using the mathematical expression as given by [1]:

$$I_{geo} = Log_2(C_m/1.5*BV)$$

where C_m is the laboratory analyzed concentration of the metal in the soil sample and BV is the background or average concentration of the metal in the earth's crust, usually taken as the average concentration in shale [25-26]. The number 1.5 is a correction factor that accounts for background data [25]. Table 2 lists the soil quality designation according to I_{geo} values:

Table 2. Soil quality designation according to the I_{geo} ranges [25].

I_{geo} Value	I_{geo} Class	Soil Quality Designation
>5	6	Extremely contaminated
4 - 5	5	Strongly to extremely contaminated
3 - 4	4	Strongly contaminated
2 - 3	3	Moderately to strongly contaminated
1 - 2	2	Moderately contaminated
0 - 1	1	Uncontaminated to moderately contaminated
<0	0	Uncontaminated

Similarly, levels of soil contamination can also be assessed by using the EF as further discussed by [25]:

$$EF = (C_x/C_{ref})_{Sample}$$

where C_x is the concentration of the metal in the environment of concern and C_{ref} is the background concentration of the same metal in a reference environment. Table 3 lists the soil quality designation according to EF value ranges:

Table 3. Soil quality designation according to EF [25].

EF	Interpretation
<2	Deficiency to minimal enrichment
2 - 5	Moderate enrichment
5 - 20	Severe Enrichment
20 - 40	Very high enrichment
>40	Extremely high enrichment

Soil contamination can further be assessed by using the PLI as indicated by [26]:

$$PLI = (CF_1 * CF_2 * CF_3 *\ldots CF_n)^{1/n}$$

where CF is the concentration factor calculated in the same way as the EF and n is the number of metals.

1.4.3. Sample Size and Study Limitations

Due to sampling constraints such as restricted access and inaccessibility to some sample points and unsuitable sampling media at some locations, a total of 69 samples were collected across all the study areas. Other sampling constraints were due to the negative perception concerning the outcome of the study by residential and business owners in the study area. Over 20% of the residents approached had a fear of being displaced. Naturally, the residents were not cooperative and restricted access to their properties. Lack of instrumentation at the time of analysis also prevented the concentration of other toxic metals, such as cadmium, arsenic and mercury to be determined although these metals are typically unassociated with stratiform deposits of the Zambian Copperbelt.

2. The Study Area

2.1. Location and Population

Kitwe lies between latitudes 12°49' south and longitude 28°12' east in addition to being bordered by Kalulushi, Luanshya, Lufwanyama and Mufulira districts as well as the city of Ndola. Kitwe district has the highest population density among all the districts of the Copperbelt, with an annual rate of growth of 3.2% and a total population of 517, 543 people making it the second fastest growing district after Mpongwe [14]. Kitwe district sits on a relatively flat land that rises 1,295 m above sea level and covers an area of 777 km^2 with a strip of land about 32 km wide, approximately 64 km long and stretches from Mufulira-Ndola road in the east to Lufwanyama river to the west [27]. The total land area of the district means that the population density equals 666.1/Km^2 which implies that Kitwe is a highly industrious city [14]. In the City of Kitwe, Nkana mine site is surrounded by several populated residential areas (Figure 1), some of which are the focus of this study namely: Wusakile, Nkana East and Nkana West townships. Of the 777 km^2 total land area covered by Kitwe district, the study areas only cover about 4.7 km^2, excluding Mindolo, Cha Cha Cha and Kitwe West townships which are also surrounded by mining activities.

The major mining activities in Kitwe comprise of underground and open pit mining, a concentrator and a cobalt plant at Nkana mine site. These mining activities are run by Mopani Copper Mines [28].

2.2. General Geology of the Study Area

Base metal deposits in the Kitwe area are exclusively argillite hosted (ore shale) and argillite – arenite hosted respectively [30]. The arenite intervals are hosted in a highly permeable and thick conglomeratic layer known as the Mindola clastics formation of the Lower Roan group. The Mindola clastics Formation forms an unconformable contact with the basement, which consists of granites, meta-igneous rocks, meta-pelites and schists [31].

Generally, the soils covering the study area are mostly brown to deep red, indicating that they mostly consist of lateritic residuum, although isolated portions of grey, organic rich clays can be found near dambos. Within the study area, several portions can also be seen to be covered by a mixture of lateritic soils and sediments transported from the old mine tailings.

Elsewhere on the Copperbelt, metals are mined from a regionally extensive north west - south east trending package of sedimentary rock known as the ore shale, which is part of a transgressive sequence of marginal marine meta-sedimentary formations belonging to the Neo-Proterozoic Katangan Supergroup. Deposits also occur at various stratigraphic horizons that straddle the ore shale in arenaceous, argillaceous and carbonate packages of the Lower and Upper Roan, the Mwashia and Kundelungu groups [32]. These deposits are mined at several localities in basins located along the south-western limb of a regional fold whose core forms part of the Paleoproterozoic basement [31] complex or the Kafue Anticline. These localities are in Luanshya, Chambishi, Chingola and Chililabombwe towns. In general, the average concentration of base metals in these localities (and Kitwe), particularly copper, are expected to be higher than the average crustal abundances because these localities form part of the metallogenic province of copper.

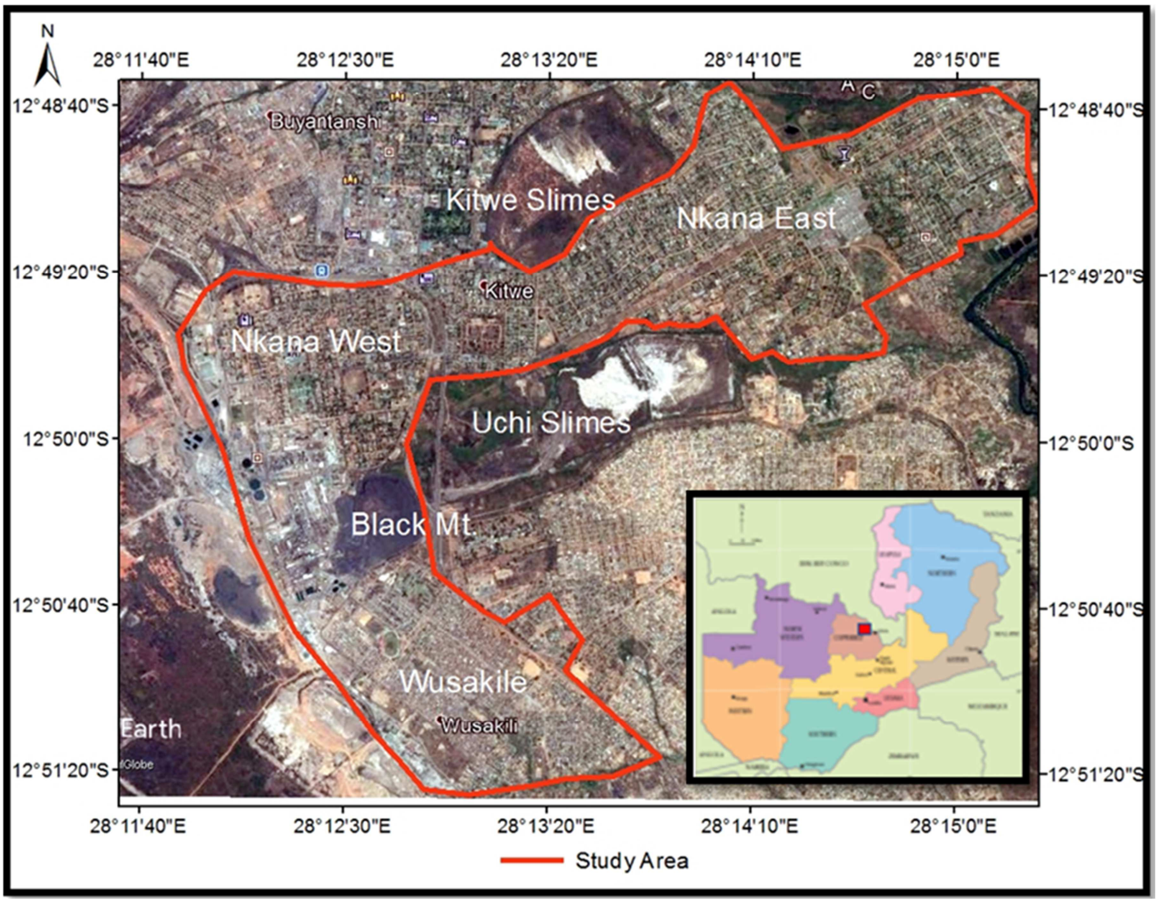

Figure 1. Study area comprising Nkana West, Nkana East and Wusakile residential areas (red boundary). Image courtesy of [29].

3. Results and Discussion

3.1. Descriptive Statistics

Table 4-6 and Figure 2 summarize the descriptive statistics for all the residential areas under this study. For all the study areas, copper showed the highest range, mean, sample variance and standard deviation (SD) followed by cobalt. For Nkana West and Wusakile, copper and cobalt showed the highest means (1068.96 mg/kg and 48.46 mg/kg and 343.96 mg/kg and 118.88 mg/kg, respectively) whereas the highest range and SD for copper (6821.20 mg/kg and 1666.21 mg/kg) were found in Nkana West alone. In Nkana East, the COV varied in the order Cu>Co>Zn>Pb while that of Wusakile varied according to the order Co>Cu>Zn>Pb. The Coefficient of Variation (COV) for copper reported similar behavior across all the study areas. In summary, all the statistical parameters indicated that compared to zinc and lead, copper and cobalt where widely spread in Nkana West and Wusakile residential areas. The higher variability observed in the copper and cobalt data in Nkana West and Wusakile areas can be attributed to the proximity of these two residential areas to Nkana mine site and related mining activities (Figure 1) as well as other anthropogenic activities such slag litter from the transportation of slag material from the slag dumps to local smelters (small scale ore processing operations) within Kitwe.

Table 4. Summary descriptive statistics for Nkana West residential area.

Metal	No. of Samples	Minimum	Maximum	Range	Mean	Sample Variance	SD	COV
Copper	25	26.80	6848.00	6821.20	1068.96	2776239.43	1666.21	1.56
Zinc	25	10.80	140.80	130.00	47.65	1162.11	34.09	0.72
Lead	25	0.40	48.80	48.40	18.55	173.23	13.16	0.71
Cobalt	25	0.12	286.80	286.68	48.46	4283.89	65.45	1.35

Table 5. Summary descriptive statistics for Nkana East residential area.

Metal	No. of Samples	Minimum	Maximum	Range	Mean	Sample Variance	SD	COV
Copper	23	32.00	1136.80	1104.80	379.01	144473.23	380.10	1.00
Zinc	23	2.00	100.80	98.80	33.41	802.12	28.32	0.85

Table 6. Summary descriptive statistics for Wusakile residential area.

Metal	No. of Samples	Minimum	Maximum	Range	Mean	Sample Variance	SD	COV
Copper	18	27.00	1640.00	1613.00	343.96	147617.49	384.21	1.12
Zinc	18	4.00	160.00	156.00	35.77	2215.38	47.07	1.32
Lead	18	1.00	60.00	59.00	20.01	174.95	13.23	0.66
Cobalt	18	6.00	698.00	692.00	118.88	49382.41	222.22	1.87

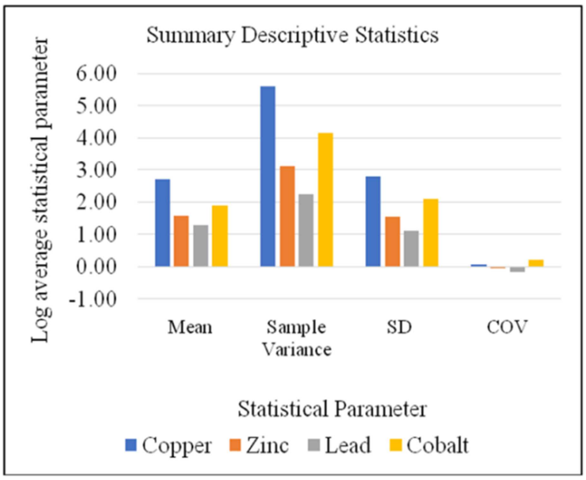

Figure 2. Log transformed summary descriptive statistics across all the study areas. The COV expresses the relative variability in the dataset. In this figure, copper and cobalt have the highest variability while lead has the least variability.

3.2. Concentration of the Heavy Metals

Table 7 shows the total number of samples greater than the maximum allowable limits for heavy metal contamination in soils expressed as a percentage of the total number of samples collected for each area. This study used comparative values (maximum allowable limits or Permissible Values (PV) for soils) as adopted by the World Health Organization [22-23]. Other comparative standards were obtained from literature [21, 33-34]. Table 7 indicates that of the total number of samples collected in Nkana West residential areas, none indicated any contamination with respect to Pb whereas for Zn and Co 32% and 24% of the samples reported above the PV. For Wusakile residential area, Zn and Co had 22% and 27.8% of samples respectively above the PV. For Cu, >90% of the samples reported values above the PV with Nkana West contributing the highest percentage of samples. All the samples across the study areas indicated the level of heavy metal contamination to be in the order of Cu>Co>Zn>Pb. The heavy metal concentration across all three study areas is summarized in Figure 3 which shows that only Cu and Co where above the recommended thresholds for heavy metal contamination in soils.

Table 7. Summary statistics for heavy metal concentration in the study areas. The permissible values for soils are according to the World Health Organization [22-23] and other literature [21, 33-34].

Study / Residential Area	Metal	No. of Samples	Mean (mg/kg)	WHO Standards (mg/kg)	No. of samples > permissible value	% of samples > permissible value
Nkana West	Copper	25	1068.96	30	24	96.0
	Zinc	25	47.65	50	8	32.0
	Lead	25	18.55	85	0	0.0
	Cobalt	25	48.46	50	6	24.0
Nkana East	Copper	23	379.01	30	23	100.0
	Zinc	23	33.41	50	6	26.1
Wusakile	Copper	18	343.96	30	17	94.4
	Zinc	18	35.77	50	4	22.2
	Lead	18	20.01	85	0	0.0
	Cobalt	18	118.88	50	5	27.8

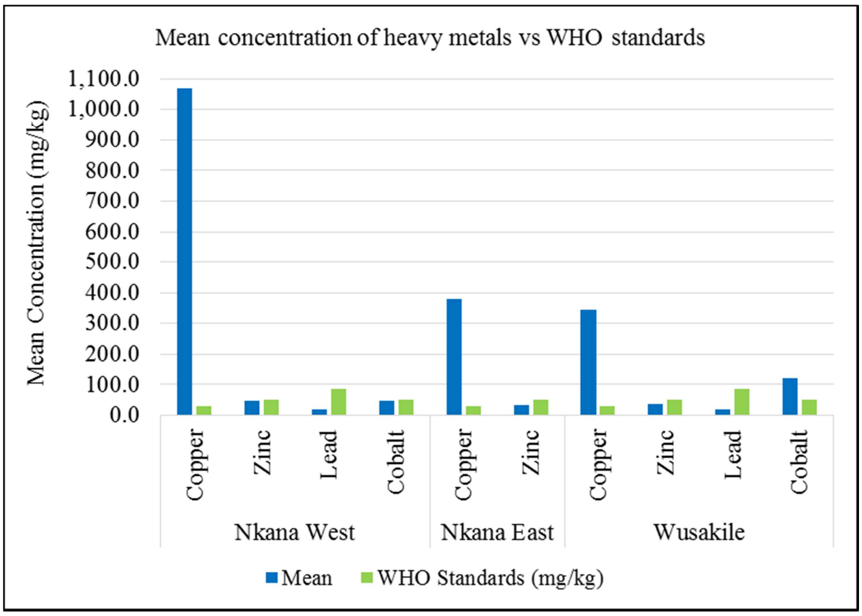

Figure 3. Mean concentration of heavy metals compared with WHO permissible values (PV) for soils. Of all the areas sampled, Nkana West and Wusakile showed the highest levels of copper and cobalt concentrations. Nkana West alone had the highest concentration of copper.

3.2.1. Geo-accumulation Index (I_{geo}), Enrichment Factor (EF) and Pollution Load Index (PLI)

Table 8-11 shows the I_{geo}, EF and the PLI calculated from the mean concentration of heavy metals across all the study areas. For the average crustal values or background concentrations, this study adopted 'average shale' values as applied by researchers in similar studies [25-26, 35]. For Nkana West (Table 8), the I_{geo} for Cu falls in the range of 1-2 whereas the EF is between 5-20. For these range of values, the soil is designated as moderately contaminated but severely enriched with the heavy metal of concern [24-26]. Consequently, the soils in Nkana West are moderately contaminated but severely enriched with Cu and show moderate enrichment and contamination with respect to Co. The I_{geo} and EF values for Co fall within the range of 0-1 and 2-5 respectively. This implies that the soils in Nkana West are moderately contaminated and moderately enriched with Co. On the other hand, the results show that I_{geo}<0 and EF are <2 for both Zn and Pb, indicating that the soils are uncontaminated with these heavy metals.

For Nkana East (Table 9), the results show that I_{geo} for Cu is within the range of 0-1 whereas the EF falls between 5-20. This indicates that the soils in Nkana East residential area are marginally contaminated with Cu although the EF shows severe enrichment in the metal. The results for Zn in Nkana East show a similar trend with those of Nkana West. The results for Pb and Co were not included in the data analysis for Nkana East because the precision analysis of the field duplicates exceeded +20% HARD.

For Wusakile area (Table 10), I_{geo} and EF values for Cu were calculated as 0.52 and 4.91 respectively. These values indicate moderate contamination and moderate enrichment of soils with Cu respectively. The I_{geo} and EF for Co recorded 0.62 and 6.26 respectively. This implies moderate contamination but with severe enrichment of the soils with Co. The values for Zn and Pb indicated minimal enrichment and therefore, zero contamination.

Table 8. Index of geo-accumulation, enrichment factor, and soil quality designation for Nkana West.

Metal	Average Shale (mg/kg)	Mean Concentration (mg/kg)	I_{geo}	Enrichment Factor	I_{geo} Class	Soil Quality Designation
Copper	70	1068.96	1.01	15.27	2	Severe enrichment, Moderately contaminated
Zinc	95	47.65	<0	0.50	0	Deficiency to minimal enrichment, uncontaminated
Lead	20	18.55	<0	0.93	0	Deficiency to minimal enrichment, uncontaminated
Cobalt	19	48.46	0.23	2.55	1	Moderate enrichment, moderately contaminated

Table 9. Index of geo-accumulation, enrichment factor, and soil quality designation for Nkana East.

Metal	Average Shale (mg/kg)	Mean Concentration (mg/kg)	I_{geo}	Enrichment Factor	I_{geo} Class	Soil Quality Designation
Copper	70	379.01	0.56	5.41	1	Severe enrichment, moderately contaminated
Zinc	95	33.41	<0	0.35	0	Deficiency to minimal enrichment, uncontaminated

Table 10. Index of geo-accumulation, enrichment factor, and soil quality designation for Wusakile.

Metal	Average Shale (mg/kg)	Mean Concentration (mg/kg)	I_{geo}	Enrichment Factor	I_{geo} Class	Soil Quality Designation
Copper	70	343.96	0.52	4.91	1	Severe enrichment, moderately contaminated
Zinc	95	35.77	<0	0.38	0	Deficiency to minimal enrichment, uncontaminated
Lead	20	20.01	<0	1.00	0	Deficiency to minimal enrichment, uncontaminated
Cobalt	19	118.88	0.62	6.26	1	Severe enrichment, moderately contaminated

Table 11 below summarizes the PLI for the heavy metals across all the three study areas. The data shows that the PLI for Cu was in the order Nkana West > Nkana East >Wusakile while that of cobalt was in the order Wusakile > Nkana West. In the case of Zn and Pb, PLI<1 for Nkana West and Wusakile residential areas. Both Cu and Co have PLI >1 in both residential areas in which Cu has the highest PLI.

Table 11. PLI values for all three study areas.

	Copper	Zinc	Lead	Cobalt
Nkana West	6.56	0.40	0.45	1.21
Nkana East	3.12	0.22	N/A	N/A
Wusakile	2.93	0.19	0.79	2.01

3.2.2. Correlation Analysis

Generally, correlation analysis (Table 12) did not indicate any relationships between the data sets across all the three study areas. Although Cu and Co showed elevated levels of contamination as seen from the I_{geo}, EF and PLI, these metals did not show any correlations suggesting an unrelated source as shown in Figure 4 and Figure 5.

Table 12. Correlation matrix for the heavy metals across all three study areas.

	Copper	Zinc	Lead
Zinc	0.24		
Lead	0.38	0.16	
Cobalt	0.00	0.30	0.08

3.3. Spatial Analysis

Spatial distribution (geochemical maps) maps were generated for all the four heavy metals across all the three study areas. These maps are shown in Figure 4-7. The higher concentrations of Cu (Figure 4) are generally centered around currently active mining sites and old slimes dams such as the slag dump locally known as the 'black mountain' and the Kitwe and Uchi Slimes dams respectively (Figure 1). The 'black mountain' is part of the Nkana mine site and periodically receives waste products of ore processing from Nkana mining operations and is exploited for its unprocessed ore by small scale miners. In contrast, the higher concentrations of Co.

(Figure 5) are not centered around any mining activity or slimes dams. However, the concentrations above the PV were observed around the Wusakile gas pump station. This observation suggests that the distribution of Co in the Wusakile area is unrelated to mining activities but may be a factor of Co compound-fuel-gaseous-emission associated catalytic conversion mechanisms in automobile engine which reduces nitrogen monoxide (NO) emissions from vehicle exhaust fumes as discussed by several researchers [36-39].

The spatial distribution map for Zn and Pb (Figure 6 and Figure 7) indicated isolated but widely spread elevated concentrations across the study areas. Such a pattern can be attributed to the relative mobility of the heavy metals in the dominant soil types (lateritic residuum and clayey soils) of the study areas and acid mine drainage which reduces soil pH and consequently increases heavy metal mobility and concentrations in the surficial environment [1]. [40] have indicated the relative order of mobility and adsorption of elements in various soil types: in clayey soils, the order is Zn>Pb>Cu and in iron rich soils (goethite), the order is Cu>Pb>Zn>Co. Although the dominant soils across the study areas are lateritic, the distribution pattern with respect to Zn (Figure 6) may be a function of its higher relative mobility compared to Pb, Cu and Co. Consequently, Zn was not seen to be proximal to mining related activity or the slimes dams. Although Pb shows a similar spatial spread, higher concentrations (Figure 1) are located between the old Kitwe and Uchi slimes dam in Nkana East residential area (Figure 1). The area between the two slimes dams (and all study areas) has a high density of population and is therefore associated with a high level of anthropogenic activities that contribute to the spread of Pb and other metals. Frequently, children from Nkana East, Wusakile and Ndeke residential areas use the Old Uchi slimes dam as a playground and adults also use this dam as a pathway across the residential areas daily.

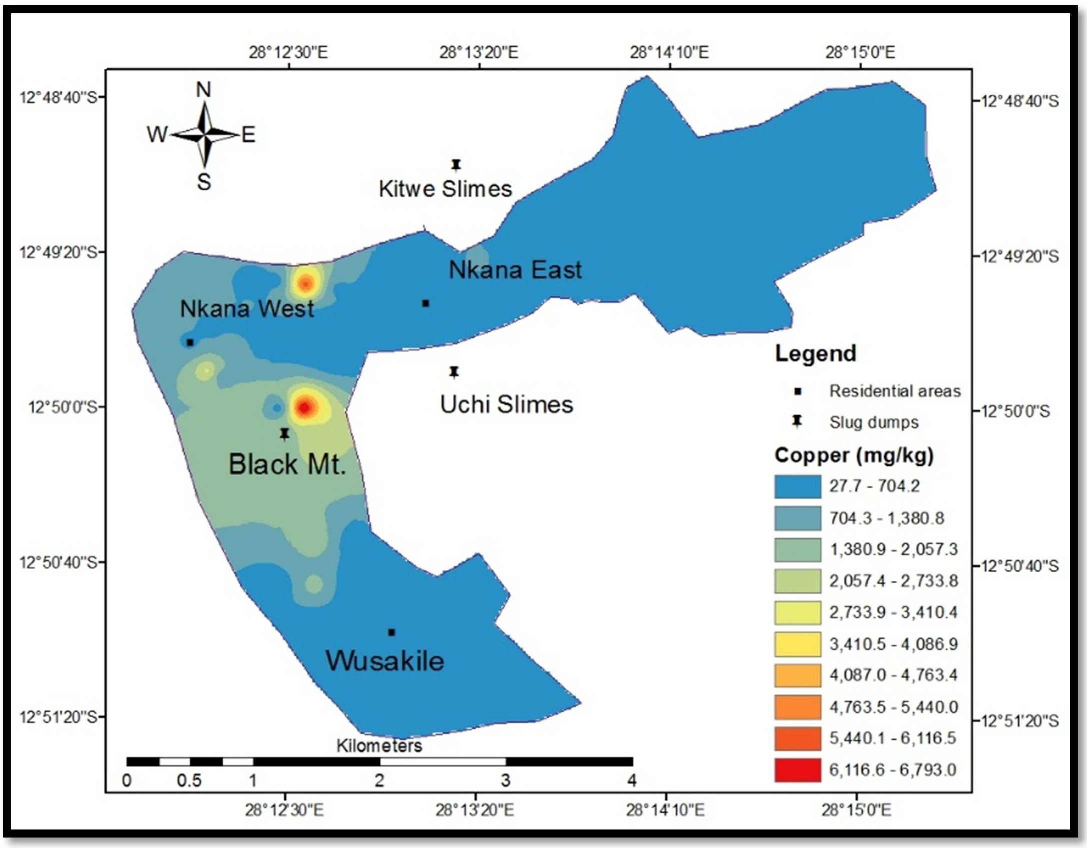

Figure 4. Spatial distribution of copper across the three study areas.

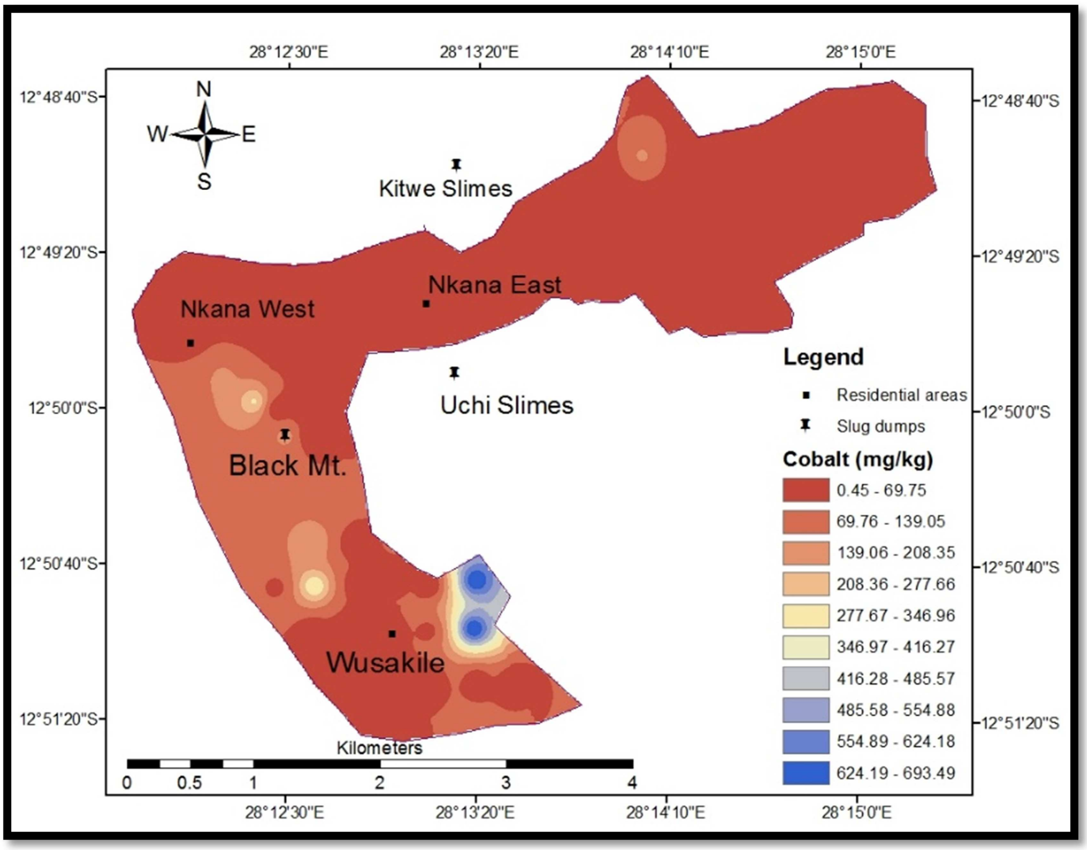

Figure 5. Spatial distribution of cobalt across the three study areas.

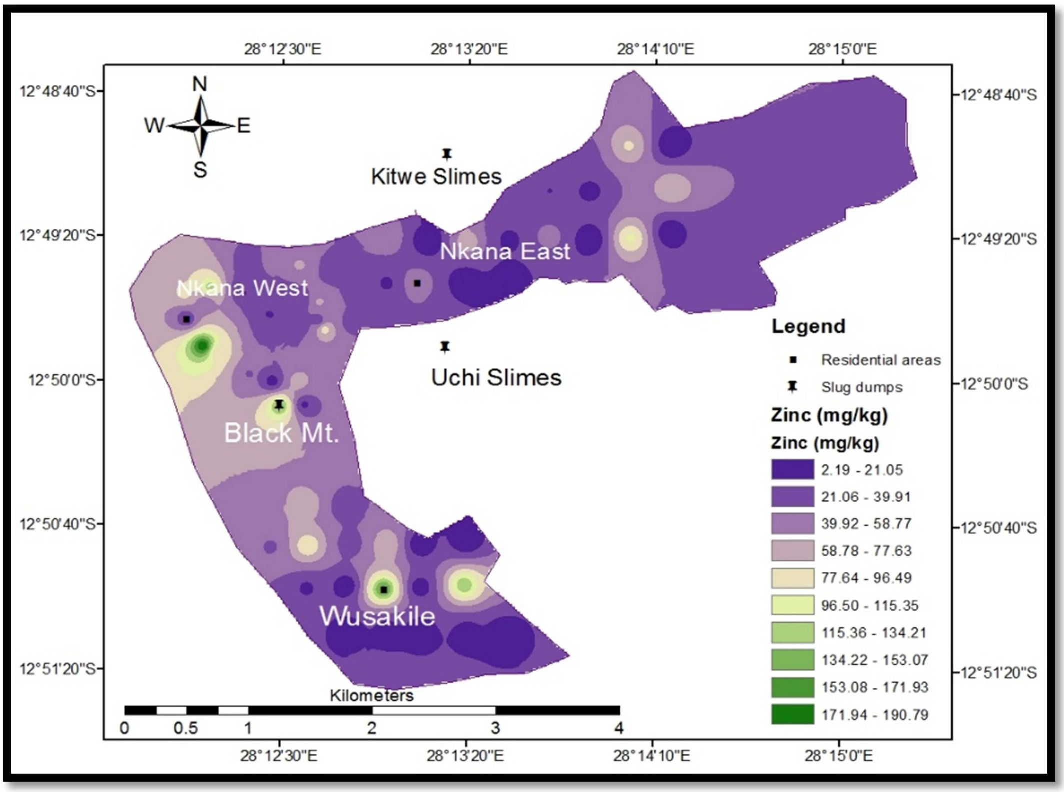

Figure 6. Spatial distribution of zinc across the three study areas.

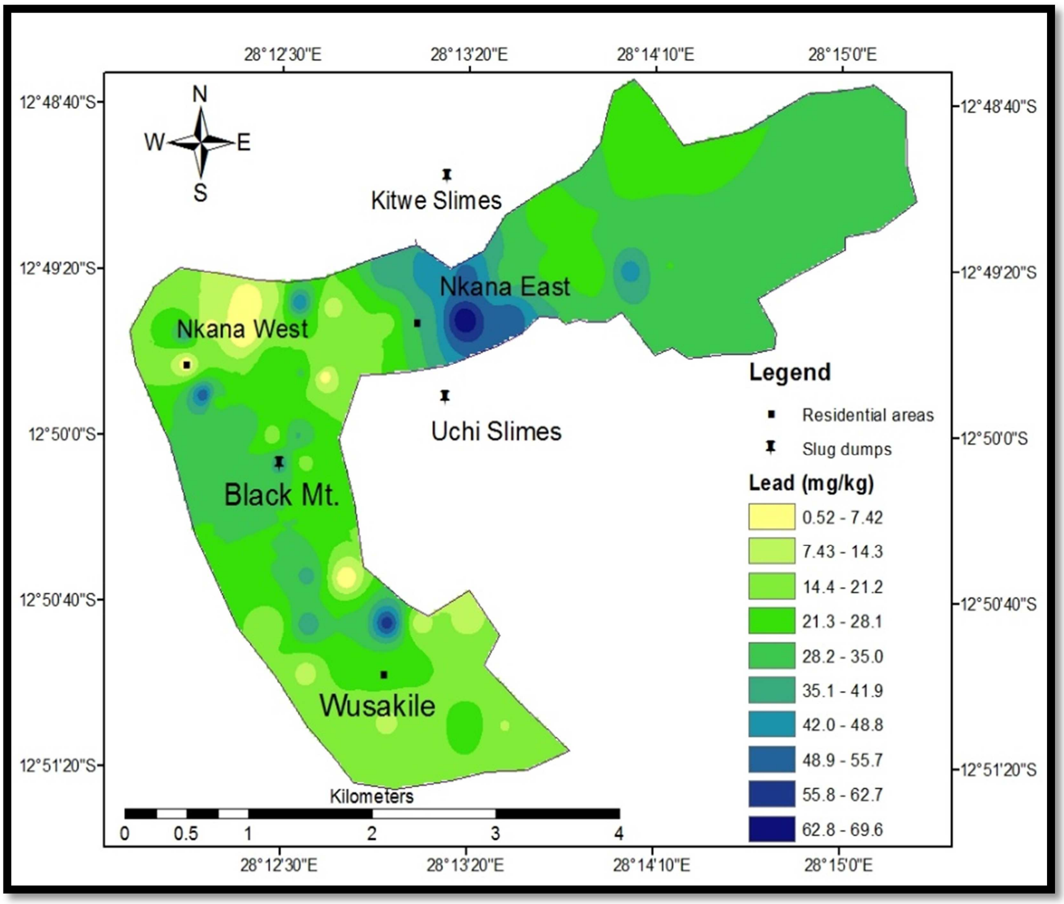

Figure 7. Spatial distribution of lead across the three study areas.

4. Conclusions

The statistical parameters used in this study indicated that according to the WHO standards, all the three study areas showed that the average concentration of Cu and Co exceeded the maximum allowable limits for heavy metal concentration in the soils of the study areas whereas Zn and Pb did not. Cu and Co had the highest mean concentration (1068.96 mg/kg and 118mg/kg respectively) recorded in Nkana West and Wusakile residential areas. Both Cu and Co had the highest average standard deviation, sample variance and coefficient of variation across all the three study areas. The concentration of all the heavy metals in the soils of the study areas were according to the order Cu>Co>Zn>Pb. The I_{geo} and the EF indicate that the soils in Nkana East, Nkana West and Wusakile are severely enriched but moderately contaminated with Cu. This was expected because the study areas are part of a metallogenic province of Cu in which the metal concentrations are expected to be greater than the average crustal abundances. The same classification can be applied to Nkana West and Wusakile in the case of Co. Both classifications agree with the PLI which is >1 for Cu and Co across all the three study areas. The I_{geo} indices and EF for all areas with respect to Zn and Pb indicate that the soils have a PLI <1 and are therefore, uncontaminated with these metals. The spatial distribution map for Cu shows that elevated concentrations are primarily associated with mining activities whereas the spatial distribution maps for Pb and Co are consistent with other anthropogenic activities. The distribution patterns for all the four heavy metals can also be attributed to their relative mobility in the dominant soils of the study area. The spatial distribution and elevated levels of metals in the soils can also be attributed to variably wind-blown dust particulates, high population density and acid-mine drainage which reduces soil pH and increases metal mobility in the surficial environment especially during peak rainy seasons and subsequent elevated water tables in the regolith profile. Kitwe town is also littered with small scale mining and ore processing operations. Slag dump material is regularly transported from the slag dumps to the processing centers using routes that mainly pass through residential areas. These transportation activities also contribute to the contamination of residential soils with heavy metals. Although the Pearson correlation coefficient did not indicate a common source for the heavy metals in the study, both the statistical analysis and the spatial distribution maps showed a close relationship between elevated concentrations of heavy metals and the location of current mining activities and old slimes dams.

Conflict of Interest

The authors declare that they have no competing interest.

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