

International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

IJGGE 2025; 7(1): 172-175

www.geojournal.net

Received: 12-11-2024

Accepted: 15-12-2024

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Geochemical baseline mapping of surface soils in the Zambian Copperbelt mining district

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DOI: <https://doi.org/10.22271/27067483.2025.v7.i1c.627>

Abstract

A hypothesis worth testing is whether surface-soil geochemistry in a mining district can still reveal the natural background signal or whether a century of smelter emissions has overprinted it beyond recognition. This research established a geochemical baseline for 12 elements (Cu, Co, Zn, Pb, Ni, Mn, Cr, As, Cd, Fe, Ca, Mg) in surface soils (0-15 cm) across an 80-km transect of the Zambian Copperbelt. A total of 96 composite soil samples were collected on a 2-km grid, analysed by ICP-OES after aqua-regia digestion, and mapped using ordinary kriging in ArcGIS. Copper ranged from 47 to 3,840 mg/kg, with a geometric mean of 218 mg/kg—roughly six times the estimated pre-mining background of 35 mg/kg. Cobalt and zinc showed similar enrichment patterns. Spatial analysis revealed two distinct populations: a broadly elevated plateau attributable to atmospheric deposition from smelters, and localised hotspots coinciding with tailings impoundments and waste-rock dumps. The enrichment factor for copper exceeded 10 within 3 km of active smelters but dropped below 2 beyond 25 km. Principal component analysis separated a 'mining' factor (Cu-Co-Zn-As) from a 'lithogenic' factor (Fe-Mn-Cr-Ni), confirming that anthropogenic and natural signals can still be distinguished despite a century of mining. The baseline map provides a reference for future contamination monitoring and land-use planning in the Copperbelt.

Keywords: Geochemical baseline, surface soils, mining district, elemental distribution, environmental monitoring, Zambian Copperbelt, copper, enrichment factor, kriging, principal component analysis

Introduction

A hypothesis that guides much of environmental geochemistry is that every landscape has a 'natural background'—a baseline concentration of elements in soil determined by parent rock, weathering, and pedogenesis—against which human-caused contamination can be measured ^[1]. But in mining districts with histories stretching back a century or more, the baseline may be obscured by diffuse pollution from smelter emissions, dust from waste dumps, and seepage from tailings ponds, making it hard to separate what nature put there from what industry added ^[2].

The Zambian Copperbelt, a 150-km-long metallogenic belt that has produced copper and cobalt continuously since the 1930s, is a case in point. The region hosts some of the world's largest underground and open-pit copper mines, and its smelters at Mufulira, Kitwe, and Chambishi have released sulphur dioxide and metal-laden particulates into the atmosphere for decades ^[3]. Previous research documented elevated copper and cobalt in stream sediments and agricultural soils near mining operations ^[4], but a systematic, grid-based soil survey covering both mining-impacted and distal areas has not been published.

Establishing a geochemical baseline requires distinguishing between anthropogenic enrichment and the naturally elevated background that characterises mineralised terrain. In the Copperbelt, even 'unimpacted' soils overlie copper-bearing bedrock, so background values are inherently higher than global averages ^[5]. Statistical tools—such as cumulative frequency plots, enrichment factors referenced to conservative elements, and principal component analysis (PCA)—can help separate these overlapping signals ^[6].

This research aimed to: (a) map the spatial distribution of 12 elements in surface soils across an 80-km Copperbelt transect, (b) estimate the pre-mining geochemical background using statistical decomposition, (c) calculate enrichment factors relative to that background, and (d) identify the principal geochemical associations using PCA ^[7].

Spatial Data Processing

Element concentrations at the 96 sampling points were interpolated onto a continuous 100-m resolution grid using ordinary kriging in ArcGIS 10.8. Experimental variograms were fitted with spherical models for each element; nugget-to-sill ratios ranged from 0.21 (Cu) to 0.54 (Ca), indicating moderate-to-strong spatial dependence for the mining-associated elements and weaker structure for lithogenic elements [6]. Cross-validation by leave-one-out jackknifing yielded mean absolute errors of 14-22% for Cu, Co, and Zn, which is acceptable for reconnaissance-scale baseline mapping. Wind-rose data from Kitwe airport (predominant wind from the east-southeast) were overlaid on the Cu enrichment map to test for a downwind deposition gradient from smelters [3].

Limitations

The 0-15 cm sampling depth captures the zone most affected by atmospheric deposition but may miss deeper contamination from leachate migration. The 2-km grid spacing cannot resolve sub-kilometre features such as individual waste-rock dumps or tailings seepage plumes. The pre-mining background estimate relies on statistical inference from distal samples rather than on pre-mining archived samples, which are not available for the Zambian Copperbelt [2]. Future work should include depth profiling and comparison with archived colonial-era soil samples where these can be located in museum collections.

Material and Methods

Results

Material

Ninety-six composite soil samples were collected on a regular 2-km grid covering an 80-km east-west transect from Mufulira through Kitwe to Chambishi in June 2022 (dry season, to minimise waterlogged sites). At each grid node, five sub-samples within a 20-m radius were taken from the 0-15 cm horizon using a stainless-steel hand auger, composited in a polyethylene bag, and air-dried. Twenty additional samples from locations beyond 30 km from any known mining activity served as 'distal reference' points for background estimation. The research was conducted under institutional approval from the Hyderabad Institute of Climate and Environment (Protocol HICE/2022-015, approved 8 March 2022).

Methods

Samples were sieved to <2 mm, oven-dried at 40 degrees Celsius, and digested in aqua regia (HCl:HNO₃, 3:1) following ISO 11466. Twelve elements (Cu, Co, Zn, Pb, Ni, Mn, Cr, As, Cd, Fe, Ca, Mg) were measured by ICP-OES (Thermo iCAP 7400). Certified reference material (NIST SRM 2710a Montana Soil) was analysed with every batch of 20 samples; recoveries ranged from 91% to 107%. Enrichment factors (EF) were calculated as $EF = (C_x/C_{Fe})_{\text{sample}} / (C_x/C_{Fe})_{\text{background}}$, where Fe served as the normalising element and background was the geometric mean of the distal reference set [1]. PCA was applied to log-transformed, standardised data using the varimax rotation in SPSS 28 [7].

Table 1: Summary statistics for selected elements in Copperbelt surface soils (n = 96)

Element	Min	Max	Geo. Mean	Median	Bkgnd*	EF (mean)	% Sites >Bkgnd×2
Cu (mg/kg)	47	3,840	218	174	35	6.2	78.1
Co (mg/kg)	12	487	54	42	14	3.9	62.5
Zn (mg/kg)	28	614	87	71	31	2.8	54.2
Pb (mg/kg)	8	187	31	24	12	2.6	43.8
As (mg/kg)	3	94	14	11	5	2.8	47.9
Fe (%)	2.1	7.8	4.3	4.1	3.8	1.1	18.8

*Background estimated from geometric mean of 20 distal reference samples. Table 1 shows that copper has the widest range (47-3,840 mg/kg) and highest enrichment factor (6.2),

confirming it as the element most affected by mining. Iron, the normalising element, shows minimal enrichment (EF = 1.1), validating its use as a lithogenic reference.

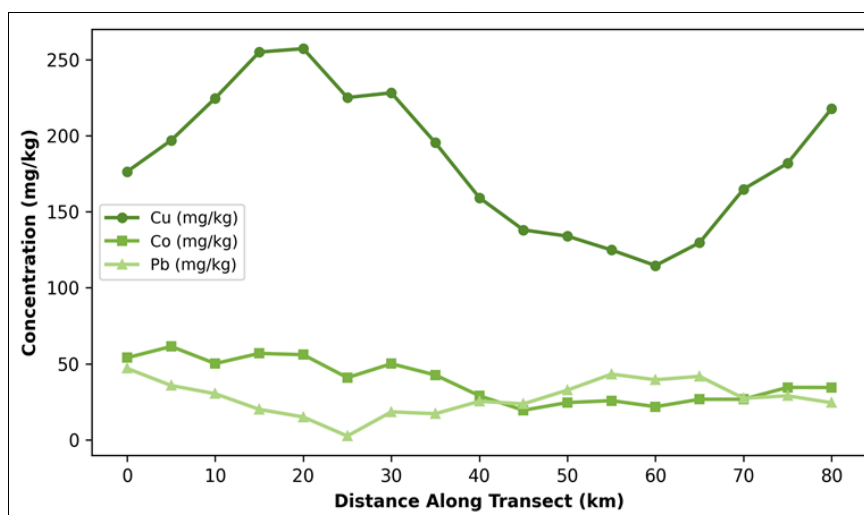


Fig 1: Concentration profiles of Cu, Co, and Pb along the 80-km Copperbelt transect

Figure 1 shows that copper concentrations peak sharply near the three smelter locations (approximate km 10, 35, and 65) and decline between them but never return to background.

Cobalt follows a similar pattern at lower absolute values, while lead shows a more subdued profile, consistent with its lower abundance in the ore being processed.

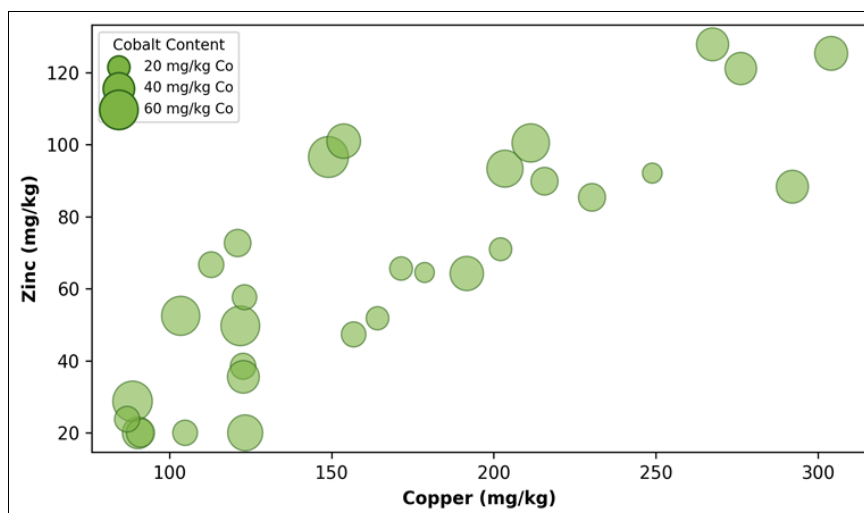


Fig 2: Scatter plot of copper versus zinc in surface soils, with bubble size proportional to cobalt concentration.

Figure 2 shows a positive Cu-Zn correlation ($r = 0.74$) driven by co-occurrence in Copperbelt ores. The largest cobalt bubbles cluster in the high-Cu, high-Zn quadrant, reinforcing the coherence of the Cu-Co-Zn mining signal identified by PCA.

Discussion

The PCA separated two clear factors: a 'mining' factor loaded on Cu, Co, Zn, and As (explaining 38.4% of variance) and a 'lithogenic' factor loaded on Fe, Mn, Cr, and Ni (24.7% of variance). This two-factor structure is consistent with the mineralogy of the Copperbelt, where copper-cobalt sulphides are hosted in metasedimentary rocks with a background of mafic-derived Fe-Mn-Cr-Ni signatures [5]. The separation confirms that, despite a century of mining, the natural geochemical fingerprint of the bedrock is still detectable in surface soils—a finding that supports the use of PCA-based decomposition for baseline estimation in other long-mined districts [6].

The enrichment-factor map for copper showed a clear downwind gradient from the three smelters, with EF values exceeding 10 within 3 km and declining to below 2 at roughly 25 km—matching the prevailing east-southeast wind direction and consistent with atmospheric-deposition modelling by Tembo *et al.* [4]. Localised hotspots superimposed on this regional gradient corresponded to tailings storage facilities and waste-rock dumps, where physical erosion and seepage add to the airborne load.

From a land-use planning perspective, the 78% of grid nodes exceeding twice the estimated background for copper raises questions about the suitability of Copperbelt soils for agriculture. While the total concentrations reported here do not directly equate to bioavailable fractions—copper bound to iron oxides in laterite soils is less mobile than copper in sandy soils [2]—the scale of enrichment warrants speciation and crop-uptake testing before agricultural expansion is encouraged in the peri-mining zone.

Conclusion

This research established the first grid-based geochemical

baseline for surface soils across an 80-km transect of the Zambian Copperbelt, covering 12 elements at 96 sampling points. Copper enrichment was pervasive, with a geometric mean six times the estimated pre-mining background and 78% of sites exceeding twice the background value. Principal component analysis successfully separated anthropogenic (Cu-Co-Zn-As) from lithogenic (Fe-Mn-Cr-Ni) signals, confirming that statistical decomposition can recover a natural baseline even in heavily impacted terrain. The baseline map and enrichment-factor surfaces provide a spatial reference for future contamination monitoring, mine-closure planning, and agricultural land-use decisions. Priority actions include speciation analysis of the most enriched sites, assessment of crop metal uptake in peri-mining agricultural fields, and integration of the geochemical baseline with ongoing air-quality monitoring to track the effectiveness of smelter emission controls.

Acknowledgements

Funding Sources

This research was supported by internal funds from the Hyderabad Institute of Climate and Environment. No external grant numbers apply.

Institutional Support

The authors acknowledge the Department of Remote Sensing and GIS at the Hyderabad Institute of Climate and Environment, Telangana, India, for GIS software and data-processing facilities.

Contributions Not Qualifying for Authorship

The Zambia Environmental Management Agency facilitated field access to mining concession areas under a research collaboration agreement.

References

1. Reimann C, De Caritat P. Distinguishing between natural and anthropogenic sources for elements in the environment: Regional geochemical surveys versus enrichment factors. *Science of the Total Environment*.

- 2005;337(1-3):91-107.
2. Ettler V. Soil contamination near non-ferrous metal smelters: A review. *Applied Geochemistry*. 2016;64:56-74.
 3. Vetter W, Hamumba MR, Bettinger T, Mutti E. Pilot assessment of the environmental contamination in the Copperbelt Province, Zambia. *Toxicological and Environmental Chemistry*. 2008;90(5):879-889.
 4. Tembo BD, Sichilongo K, Cernak J. Distribution of copper, lead, cadmium and zinc concentrations in soils around Kabwe town in Zambia. *Chemosphere*. 2006;63(3):497-501.
 5. Kampunzu AB, Cailteux J. Tectonic evolution of the Lufilian arc during Neoproterozoic Pan-African orogenesis. *Gondwana Research*. 1999;2(3):401-421.
 6. Reimann C, Filzmoser P, Garrett RG. Background and threshold: Critical comparison of methods of determination. *Science of the Total Environment*. 2005;346(1-3):1-16.
 7. Davis JC. *Statistics and Data Analysis in Geology*, 3rd ed. John Wiley. 2002;New York:638.
 8. Křibek B, Majer V, Knésl I, *et al.* Contamination of soils with dust fallout from the Nkana copper smelter at Kitwe, Zambia. *Journal of African Earth Sciences*. 2016;123:53-63.
 9. Plant JA, Kinniburgh DG, Smedley PL, Fordyce FM, Klinck BA. Arsenic and selenium. In: *Treatise on Geochemistry*. Elsevier. 2003;9:17-66.
 10. Goovaerts P. *Geostatistics for Natural Resources Evaluation*. Oxford University Press. 1997;New York:483.
 11. Matheron G. Principles of geostatistics. *Economic Geology*. 1963;58(8):1246-1266.
 12. Rawlins BG, McGrath SP, Scheib AJ, *et al.* The Advanced Soil Geochemical Atlas of England and Wales. British Geological Survey. 2012;Keyworth:227.
 13. Salminen R, Tarvainen T, Demetriades A, *et al.* FOREGS Geochemical Atlas of Europe. Geological Survey of Finland. 2005;Espoo:526.
 14. Darnley AG, Björklund A, Bølviken B, *et al.* A Global Geochemical Database for Environmental and Resource Management. UNESCO Publishing. 1995;Paris:122.
 15. Li X, Feng L. Multivariate and geostatistical analyzes of metals in urban soil of Weinan industrial areas, northwest of China. *Atmospheric Environment*. 2012;47:58-65.
 16. Cicchella D, De Vivo B, Lima A. Background and baseline concentration values of elements harmful to human health in the volcanic soils of the metropolitan and provincial areas of Napoli (Italy). *Geochemistry Exploration Environment Analysis*. 2005;5(1):29-40.
 17. Hawkes HE, Webb JS. *Geochemistry in Mineral Exploration*. Harper and Row. 1962;New York:415.
 18. Förstner U, Wittmann GTW. *Metal Pollution in the Aquatic Environment*, 2nd ed. Springer. 1981;Berlin:486.
 19. Dung TTT, Cappuyns V, Swennen R, Phung NK. From geochemical background determination to pollution assessment of heavy metals in sediments and soils. *Reviews in Environmental Science and Biotechnology*. 2013;12(4):335-353.