Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-671

Multivariate statistical approaches for source identification of heavy metal pollutants around copper mine tailings pond at Malanjkhand, India

Akshay Kumar Singh, Anumita Mishra
Department of Civil Engineering, Indian Institute of Technology Roorkee, India, mishra.anumita@gmail.com

ABSTRACT: Heavy metal contamination around mining sites poses serious environmental and human health risks, especially in regions where mining activities are prevalent. This study investigates the application of multivariate statistical approach (Principal component analysis and Pearson's correlation) for origin identification of heavy metal pollutants in the vicinity of copper mine tailings ponds in Malanjkhand District, Madhya Pradesh, India. The total concentrations of key heavy metals (Zn, Cu, Fe, Pb, Ni, Mn and Cd) in the water sample were taken from the available literature on the Malanjkhand copper mine to determine pollution levels and sources of production. Pearson's correlation results showed that Cu exhibited a positive correlation with Fe, Zn, Ni, and Cd at the 0.01 significance level, suggesting a common origin. Additionally, negative correlations were observed between pH and Cu, Zn, Ni, Fe, Mn, and Cd, which indicates an inverse relation. Principal component analysis (PCA) with varimax normalised rotation was implemented to identify the potential source of heavy metals in water samples in the vicinity of the mine. PCA results indicated that the heavy metals Zn, Ni, Fe, Mn, Cd, and Cu in the water sample surrounding the mining area were strongly influenced by mining activities. The effect of low pH and mobility of heavy metals on the hydraulic conductivity and soil strength has been discussed. The results emphasise the necessity of enhanced pollution control measures and long-term monitoring to reduce the environmental hazards associated with mining activities in the region.

KEYWORDS: Copper mine tailings, Heavy metals, Multivariate statistical method, Principal component analysis.

1 INTRODUCTION

The modernisation and advancement of countries have led to a significant increase in copper utilisation across various developmental sectors. This growing demand has placed immense pressure on the mining industry to enhance copper production. However, large-scale copper extraction generates substantial amounts of copper tailings as a byproduct of ore processing. 1 ton of copper ore yields approximately 0.96 tons of tailings (Singh & Mishra 2023). These tailings contain sulphur minerals such as pyrite, marcasite, and chalcopyrite, which oxidise when exposed to water and air, forming sulphuric acid. This acidification lowers the environmental pH, creating conditions that favour the leaching of heavy metals into the water system, a process known as acid mine drainage (AMD) (Akcil & Koldas 2006). AMD contaminates both underground and surface water, posing long-term ecological and health risks (Kefeni et al. 2017). Critically for geotechnical engineering, these chemical changes can fundamentally alter the physicochemical and mechanical properties of the soil, affecting its strength, compressibility, and permeability (Zhang et al. 2024). Malanjkhand copper deposit holds nearly 221 million tons in total reserves, with an annual production of nearly 2.1 million tons at an average copper grade of 1.31%. Annually, Malanjkhand produces nearly 2 million tons of tailings (Indian Minerals Yearbook-2022, 2024).

Most of the research on the Malanjkhand copper mine for its geological and mineralogical characteristics, including ore genesis, minerals in granite rock, and hydrothermal processes (Stein et al. 2004; Panigrahi et al. 2008). However, only a few studies have reported toxic mine drainage containing elevated levels of Cu, Zn, and Cd that severely impact soil and sediments (Pandey et al. 2007; Ma et al. 2022). Minerals such as alpersite and epsomite occur as efflorescent salts in hot environments and accumulate high concentrations of heavy metals, but dissolve during rain, releasing stored heavy metals and increasing contamination levels (Equeenuddin et al. 2017). River water quality is affected by anthropogenic activities like mining and discharge of wastewater, as well as natural factors including geology and climate (Kazi et al. 2009). Groundwater and soil near mining sites must be evaluated to determine impacts from extraction and geological interactions (Singh et al. 2008). Recent studies have increasingly employed multivariate statistical techniques to identify contamination sources in surface and underground water systems (Barakat et al. 2016; Wu & Wang 2007). Multivariate statistical methods have been widely applied in underground water quality assessments from different origin points (Prasad et al. 2019; Kumarasamy et al. 2014). These statistical approaches are equally powerful for geotechnical analysis, as they can help correlate specific contaminant sources and concentrations with changes in soil engineering behavior (Kossoff et al. 2014). Multivariate statistical approaches, including factor analysis, principal component analysis, and cluster analysis, were used to study surface water quality variations across 38 monitoring sites in Can Tho City, Vietnam, from 2008 to 2012. Similar approaches were used to examine pollution sources in Indian rivers like the Yamuna and Ganga (Sharma et al. 2015) and to determine factors that control hydrochemical variation in the Tamiraparani river basin (Kumarasamy et al. 2014). Numerous studies have demonstrated the effectiveness of principal components analysis and cluster analysis for surface water quality evaluation (Hai et al. 2009; Razmkhah et al. 2010).

Despite growing concerns about heavy metal contamination, significant knowledge gaps persist regarding the limited systematic investigation of heavy metal source identification, and the absence of advanced multivariate statistical approaches for discriminating between anthropogenic (Mining) and geogenic heavy metal sources. Therefore, the present study aims to identify and differentiate the sources of heavy metal pollution by employing advanced multivariate statistical approaches, including principal component analysis (PCA) and Pearson correlation analysis (PA), to provide a basis for predicting their potential impact on key soil engineering properties.

2 MATERIAL AND METHODS

2.1 *Study area*

The research was conducted at the Malanjkhand copper mining operation, situated in Madhya Pradesh's Balaghat district at coordinates 22°02'N, 80°43'E. This facility represents the country's most significant copper extraction site under the management of Hindustan Copper Limited (HCL). The mining area is positioned within the watershed region where the Banjar and Son river systems converge, approximately 575 meters above sea level.

Mining operations utilise a pipeline system that employs pressurised water to transport processed sand and waste materials to containment facilities. The site features a processing facility with an annual capacity of 2 million tons, employing heap leaching methodology for copper extraction. The local hydrogeological conditions consist of an unconfined aquifer system with depths varying between 11 and 42 meters, encompassing both shallow and deep zones. The presence of consolidated rock formations and heterogeneous subsurface conditions results in inconsistent and generally reduced groundwater movement throughout the region. Figure 1 shows the satellite image of the Malanjkhand Copper Mine and tailings pond.

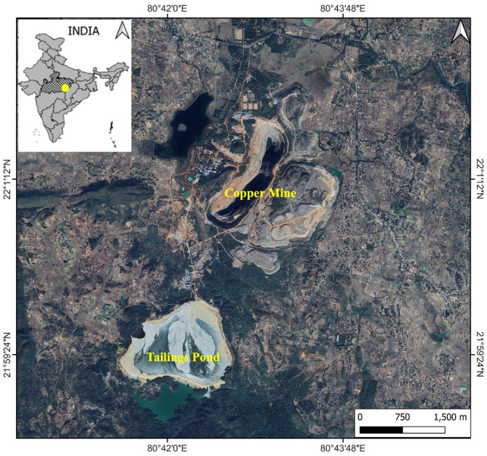

Figure 1. Satellite image of the study area

2.2 *Geological formation*

The regional stratigraphy encompasses two primary geological units: an ancient crystalline foundation and overlying metasedimentary sequences belonging to the Chilpi Ghat Formation. This formation comprises coarse-grained sedimentary rocks, including conglomerates, arkosic sandstones, and quartzites, which rest upon the underlying basement rocks. The foundation complex is characterised by granitic intrusions, quartzites, aplitic bodies, and mafic rock units. The contact between these geological units creates an unconformable relationship that is prominently exposed along the southern and western margins of the copper mineralisation zone.

2.3 *Statistical evaluation*

This study defines the values for the pH and heavy metal concentration (Zn, Ni, Cu, Cd, Pb, Fe, and Mn) in the water were obtained from the detailed hydrogeochemical study on Malanjkhand copper mine, conducted by Equeenuddin et al. (2017) the as shown in Table 1. Multivariate techniques, including PCA and PA, were applied to examine the relationships between heavy metals and their potential sources.

Principal Component Analysis (PCA) is a statistical approach that reduces the dimensionality of the variables by transforming the associated variables into a lower set of unrelated components, known as principal components (PCs). These components capture the maximum variance in the data, allowing for the identification of underlying patterns and dominant pollution sources. In this study, PCA was applied to reduce the dimensionality of the heavy metal dataset while retaining most of the original variability. The extracted components were interpreted on the basis of their loading factor with values >0.7, 0.30–0.75, and <0.30 indicating strong, moderate, and meaningless associations, respectively.

Pearson's correlation analysis was employed to evaluate the linear relationships between pairs of heavy metals. The value of the correlation coefficient (r) is between −1 to +1. Values near 0 mean that the variables have no significant correlation. The strength of the linear relationship is given by the coefficient's absolute value, and its direction (positive or negative association) is shown by the sign. This analysis helped in identifying metals that may share common sources or exhibit similar geochemical behaviour in the aquatic environment. Statistical data analysis was performed using IBM SPSS Statistics.

Table 1. Heavy metal concentrations reported by Equeenuddin et al. (2012).

Location	pH	EC	Cu	Pb	Zn
W1	3.8	1565	9.2	0	0.15
W2	3.4	1827	14.7	0	0.24
W3	4.7	1404	11.2	0	0.16
W4	5.33	2209	49.6	0.04	0.42
W5	6.1	1693	20.1	0	0.26
W6	4.35	2075	60.8	0	0.46
W7	6.75	937	0.12	0	0
W8	7.06	152	0.18	0	0
W9	7.53	167	0.03	0	0
W10	7.24	254	0.09	0	0
W11	6.99	622	0.04	0	0
W12	6.82	754	2.48	0	0.01
W13	7.56	334	0.05	0	0
W14	2.39	2873	65.2	0	1.45
W15	2.48	2230	15.6	0	0.37
W16	7.7	279	0.08	0	0
W17	7.1	302	0.06	0	0
W18	6.34	281.4	0.04	0.01	0.003
Average	5.758	1108.800	13.865	0.003	0.196
IS:10500 (2012)	6.5-6.8	300	1.5	0.01	15

Table 1 *(contd.)* Heavy metal concentrations reported by Equeenuddin et al. (2012).

Location	Ni	Fe	Mn	Cd
W1	0.06	0.039	0.005	0.004
W2	0.1	0.026	0.007	0.005
W3	0.06	0.08	0.02	0.006
W4	0.11	0.14	0.015	0.02
W5	0.08	0.062	0.008	0.015
W6	0.12	0.19	0.036	0.006
W7	0.01	0.007	0.002	0
W8	0	0.005	0	0
W9	0	0.003	0	0
W10	0	0.008	0.001	0
W11	0	0.012	0.002	0
W12	0.02	0.03	0.009	0
W13	0	0.014	0.006	0
W14	0.42	68	2.65	0.028
W15	0.13	6.2	1.06	0.02
W16	0	0.03	0	0
W17	0	0.006	0.003	0

W18	0.007	0.008	0	0
Average	0.062	4.159	0.212	0.006
IS:10500 (2012)	0.02	0.3	0.3	0.003

3 RESULTS AND DISCUSSION

This section presents an analysis of the pollution level of heavy metals in water near the copper mine and compares the value with IS:10500 (2012). Multivariate analysis was conducted to assess the correlation between the pH and heavy metals and source identification.

3.1 *pH, electrical conductivity and concentration of heavy metals*

Equeenuddin et al. (2017) collected water samples from 18 locations surrounding the copper mine and analysed heavy metal concentrations using atomic absorption spectrophotometry (AAS). In the present study, these reported concentrations were compared with the permissible limits set by IS:10500 (2017).The pH of the water samples, as measured by Equeenuddin et al. (2017), ranged from 2.39 to 7.70, with an average of 5.75 (Table 1), indicating acidic conditions in the study area. This acidity is attributed to acid mine drainage (AMD), resulting from the interaction of rainwater with sulphide-rich minerals and mine waste, such as copper tailings (Bempah et al. 2013). The recorded pH values fall below the acceptable range for drinking water as per IS:10500 (2012). Low pH from acid mine drainage mobilises heavy metals, chemically degrading clay liners to increase permeability and promote subsurface erosion (Amiri & Ghasemi 2025). Figure 2 shows the flow chart of soil erosion.

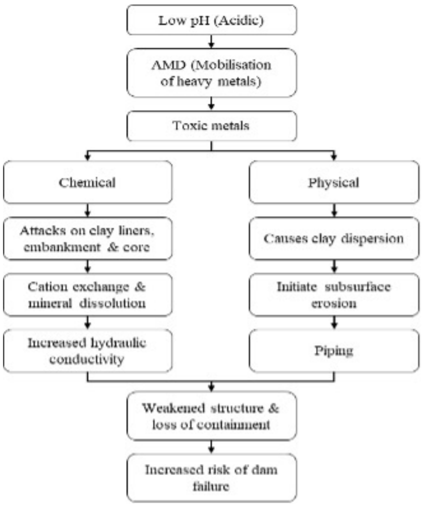

Figure 2. Flow chart of soil erosion

Additionally, the electrical conductivity (EC) of the water samples averaged 1108.8 μS/cm, exceeding the IS:10500 (2012) permissible limit, suggesting that a high concentration of dissolved minerals alters the soil plasticity and compaction characteristics.

The study by Equeenuddin et al. (2017) reported average heavy metal concentrations of 13.865, 0.003, 0.196, 0.062, 4.159, 0.212 and 0.006 (ppm) for Cu, Pb, Zn, Ni, Fe, Mn and Cd, respectively. Among these, Cu, Ni, and Fe levels surpassed the IS:10500 (2012) guidelines. High concentration of metal cations compresses the clay double layer. This forces the particles closer together, which changes soil plasticity, making it less flexible and more brittle. Consequently, the soil strength is reduced, and its permeability is increased (Ma et al. 2022). Table 1 summarises the heavy metal concentrations in water samples from the Malanjkhand copper mine area, as documented in the original study.

3.2 *Pearson's correlation between pH and heavy metals*

Pearson's correlation analysis of the water samples is presented in Table 2. The analysis revealed strong positive correlations of Cu with Zn, Ni, Fe, and Cd at the 0.01 significance level, and a moderate positive correlation between Cu and Mn at the 0.05 level. pH showed negative correlations with Cu, Zn, Ni, Fe, Mn, and Cd, indicating inverse relationships that confirm the active leaching of these elements due to acid generation, a critical geochemical process that can undermine the long-term stability of tailings dams by promoting internal weathering and weakening of soil fabric. At the 0.01 significance level, the correlation coefficients between Cu and Zn, Ni, and Cd were 0.86, 0.82, and 0.77, respectively, indicating strong associations. These patterns suggest that the correlated metals share a common anthropogenic source, such as mining activities, and exhibit similar transport behaviours.

Table 2. Pearson's correlation coefficient matrix between pH and heavy metals for the water sample.

Metal	pH	Cu	Pb	Zn	Ni	Fe	Mn	Cd
pH	1							
Cu	-0.651^{**}	1						
Pb	−.039	0.365	1					
Zn	-0.731^{**}	0.862^{**}	0.123	1				
Ni	-0.780^{**}	0.829^{**}	0.083	0.994^{**}	1			
Fe	-0.512^{*}	0.595^{**}	−.078	0.902^{**}	0.899^{**}	1		
Mn	-0.623^{**}	0.576^{*}	−.094	0.894^{**}	0.903^{**}	0.956^{**}	1	
Cd	-0.735^{**}	0.777^{**}	0.356	0.861^{**}	0.864^{**}	0.668^{**}	0.753^{**}	1

** Correlation is significant at the 0.01 level (2- tailed).
*Correlation is significant at the 0.05 level (2- tailed).

3.3 *Principal component analysis*

PCA was evaluated using varimax normalised rotation to assess the potential contributing sources of heavy metals in the water sample, as shown in Table 3.

Table 3. Principal component analysis of heavy metals in water sample.

Metal	PC1	PC2
Fe	0.969	0.208
Mn	0.914	0.334
Zn	0.822	0.535
Ni	0.803	0.580
pH	−0.309	−0.927
Cd	0.601	0.617
Cu	0.515	0.615
Pb	0.059	0.053
Eigenvalues	5.72	1.27
Variance (%)	71.58	15.94
Cumulative (%)	71.58	87.52

Principal Component Analysis (PCA) depicts two dominant components, PC1 and PC2, with eigenvalues greater than 1, explaining 87.52 % of the total variance. PC1, accounting for 71.58 % of the variance, was primarily associated with Fe, Mn, Zn, Ni, Cd, and Cu, with Fe showing the highest loading of 0.96. PC2, explaining 15.94 % of the variance, exhibited notable loadings for Cd, Cu, Ni, Zn, and Mn, with values of 0.62, 0.61, 0.58, 0.53, and 0.33, respectively. The results indicate that PC1 represents a substantial anthropogenic source, mostly associated with copper mining operations, whereas PC2 suggests a lithogenic origin. These analyses imply that mining has a significant impact on the proportion of Fe, Mn, Zn, Ni, Cd, and Cu in the water close to the mining area. The scree plot (Figure 3) demonstrates a pronounced reduction in eigenvalues following PC2, establishing these first two principal components as the dominant sources of variation within the dataset.

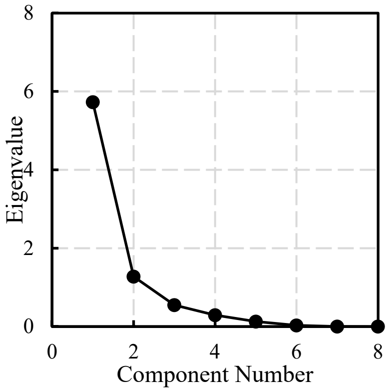

Figure 3. Scree plot of eigenvalues versus principal components.

4 CONCLUSION

Contamination through heavy metals (Cu, Pb, Zn, Ni, Fe, Mn and Cd) around mining sites poses significant environmental and public health risks. Results revealed that the concentration of Cu, Ni and Fe exceeds the permissible limit as per IS:10500 (2012). Pearson correlation analysis shows that a strong positive correlation of Cu with Zn, Ni, Fe and Cd at a significance level of 0.01, suggesting a common origin. Additionally, negative correlation of pH with Cu, Zn, Ni, Fe, Mn and Cd indicates a more acidic environment more release of these metals. Principal component analysis revealed that metal concentrations Fe, Mn, Zn, Ni, Cd and Cu were the dominant contributors, representing 71.58% of the overall variance. Combining Pearson correlation and principal components analysis identified that the mining activity is a major source of Cu, Zn, Ni, and Cd in water around the copper mine area. Low pH promotes cation exchange and mineral dissolution and increases the hydraulic conductivity, and weakens soil strength. These findings indicate the urgent need for a comprehensive response integrating phytoremediation strategies and monitoring programs for water, crops and soil in affected communities.

5 REFERENCES

Akcil, A. and Koldas, S. 2006. Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production* 14(12-13), 1139-1145.

Amiri, M. and Ghasemi, A. 2025. Investigation of the Impact of Heavy Metal Lead on the Geotechnical and Environmental Properties of Marl Soils with a Special Focus on Desorption Behavior in Industrial Areas. *Results in Engineering*, 27(10), p.105957.

Barakat, A., El Baghdadi, M., Rais, J., Aghezzaf, B., and Slassi, M. 2016. Assessment of spatial and seasonal water quality variation of Oum Er Rbia River (Morocco) using multivariate statistical techniques. *International Soil and Water Conservation Research*, *4*(4), 284-292.

Bempah, C. K., and Ewusi, A. 2016. Heavy metals contamination and human health risk assessment around Obuasi gold mine in Ghana. *Environmental Monitoring and Assessment*, *188*(5), 261.

Boateng, T. K., Opoku, F., and Akoto, O. 2019. Heavy metal contamination assessment of groundwater quality: a case study of Oti landfill site, Kumasi. *Applied Water Science*, *9*(2), 33.

Equeenuddin, S. M., Panda, A., Singh, V., Sahoo, P. K., Sahu, S., and Basantray, S. K. 2017. Geochemical appraisal of mine discharge and tailing at Malanjkhand copper mine, India. *Journal of the Geological Society of India*, *90*(2), 209-216.

Hai, X. U., Lin-Zhang, Y. A. N. G., Geng-Mao, Z. H. A. O., Jia-Guo, J. I. A. O., Shi-Xue, Y. I. N., and Zhao-Pu, L. I. U. 2009. Anthropogenic impact on surface water quality in Taihu Lake region, China. *Pedosphere*, *19*(6), 765-778.

Indian Minerals Yearbook-2022, 61st edition, 2024. Mineral-based Industries (advance release). *Indian Bureau of Mines, Ministry of Mines,* Government of India.

Kazi, T. G., Arain, M. B., Jamali, M. K., Jalbani, N., Afridi, H. I., Sarfraz, R. A., and Shah, A. Q. 2009. Assessment of water quality of polluted lake using multivariate statistical techniques: A case study. *Ecotoxicology and environmental safety*, *72*(2), 301-309.

Kefeni, K. K., Msagati, T. A., and Mamba, B. B. 2017. Acid mine drainage: Prevention, treatment options, and resource recovery: A review. *Journal of Cleaner Production*, *151*, 475-493.

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. and Hudson-Edwards, K.A. 2014. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Applied geochemistry*, *51(17)*, pp.229-245.

Kumarasamy, P., Arthur James, R., Dahms, H. U., Byeon, C. W., and Ramesh, R. 2014. Multivariate water quality assessment from the Tamiraparani river basin, Southern India. *Environmental Earth Sciences*, *71*(5), 2441-2451.

Ma, Q., Wu, N.Z., Xiao, H.L., Li, W.T. and Xiang, J.C. 2022. Effect of Zn2+-Cu2+ combined heavy metal on mechanical properties and microstructure of clayey soil. *Journal of Mountain Science*, 19(9), pp.2556-2569.

Panigrahi, M. K., Naik, R. K., Pandit, D., and Misra, K. C. 2008. Reconstructing physico-chemical parameters of hydrothermal mineralisation of copper at the Malanjkhand deposit, India, from mineral chemistry of biotite, chlorite and epidote. *Geochemical Journal*, *42*(5), 443-460.

Phung, D., Huang, C., Rutherford, S., Dwirahmadi, F., Chu, C., Wang, X., and Dinh, T. A. D. 2015. Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: a study in Can Tho City, a Mekong Delta area, Vietnam. *Environmental Monitoring and Assessment*, *187*(5), 229.

Prasad, B., Maiti, D., and Singh, K. K. K. 2019. Impact of fly ash placement in an abandoned opencast mine on surface and ground water quality: a case study. *Mine Water and the Environment*, *38*(1), 72-80.

Sharma, M., Kansal, A., Jain, S., and Sharma, P. 2015. Application of multivariate statistical techniques in determining the spatial temporal water quality variation of Ganga and Yamuna Rivers present in Uttarakhand State, India. *Water Quality, Exposure and Health*, *7*(4), 567-581.

Singh, A. K., and Mishra, A. 2023. Stability of Copper Mine Tailings Dam for Upstream, Downstream, and Centreline Construction Methods: Numerical Analysis. *Proc. 9th International Congress on Environmental Geotechnics,* Greece, 285-294.

Stein, H. J., Hannah, J. L., Zimmerman, A., Markey, R. J., Sarkar, S. C., and Pal, A. B. 2004. A 2.5 Ga porphyry Cu–Mo–Au deposit at Malanjkhand, central India: implications for Late Archean continental assembly. *Precambrian Research*, *134*(3-4), 189-226.

Wu, M. L., and Wang, Y. S. 2007. Using chemometrics to evaluate anthropogenic effects in Daya Bay, China. *Estuarine, Coastal and Shelf Science*, *72*(4), 732-742.

Zhang, G., Liu, T., Li, H., Wang, Z., Huang, X., Yi, X. and Yan, D. 2024. Experimental study on the effects of heavy metal pollution on soil physical properties and microstructure evolution. *Applied Sciences*, *14*(5), p.2022.