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Evaluation of Sediment and Soil Contamination by Acidic Mine Drainage from Waste Rock of the Largest Copper Mine in India

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Abstract

Mining activity causes displacement of rockmass from its original location in lithosphere. This action exposes rockmass to environmental forces such as air, water, micro-organisms and generates a discharge known as acidic mine drainage (AMD). Due to high solubility owing to acidic nature, AMD is rich in heavy metals. Through various drainage channels this metal rich discharge is transported to adjacent water bodies such as streams, rivers, ponds etc. This is a detailed study to include 38 sample sites to assess the heavy metal pollution of soil and stream sediments near the largest copper mining area in central India. Stream sediments and soil samples were systematically collected from the mining area within a span of 10 km from the mine site. The samples were analyzed for copper (Cu), manganese (Mn), cobalt (Co), zinc (Zn), nickel (Ni), lead (Pb). The contamination level of the samples was assessed by Enrichment Factor (EF), Contamination Factor (CF), Pollution Load Index (PLI). Mean value of Enrichment factor (EF) was 15.6 and Contamination factor (CF) was 11.1,which were highest for copper. Contamination of Cu was observed in majority (68%) of sample sites in the study area. The elevation of other heavy metals such as Co and Pb was also observed in more than 50% i.e., 19 samples location. Mapping of PLI reveals polluted sites near mine waste dump and tailing storage facility. This study reveals and evaluates the contamination by acidic mine drainage due to mining activity.

Keywords: *Leaching, Sediment Contamination, Soil Contamination, Enrichment Factor, Contamination Factor, Pollution Load Index, Acid Mine Drainage.*

1.0 Introduction

The removal of rocks from beneath the surface of the earth is an essential step in the mining process, which is used to extract minerals. After excavation, the rockmass is brought up to the surface, which is where the excavated mineral may undergo chemical reactions with the surrounding air and water (in the form of moisture). If the rock that was excavated contains sulfide minerals, particularly iron pyrite (FeS_2), then the formation of AMD may take place upon the rock's exposure to the surrounding atmosphere. Sulfide mineral deposits are associated with most copper mines found around the world[1]. Large open pit mines in porphyry copper deposits, which contain between 0.4 and 1.0 per cent copper, are the source of a significant amount of copper that is extracted in the form of copper sulfides[2]. Therefore, mining

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project producing copper ore are probable sites for generation and discharge of AMD[3].

Acid mine drainage is one of the primary contributors of heavy metals found in sediments, soil and bodies of water in the vicinity of mining operations. The ability of AMD to leach causes metals that were previously trapped in rockmass to be freed into the environment, thereby making it possible for these metals to accumulate in natural environments[4].

1.1 Study Area

The mining project that serves as the study area can be found in the central-eastern region of India. It is the single most important source of copper iron sulfide ore ($CuFeS_2$) production in India and accounts for approximately 40 per cent of the country's total copper reserves[5]. The project contains an opencast copper mine and an ore concentration/ beneficiation plant with their waste disposal sites named as mines waste dump (MWD) and tailing storage facility (TSF)/ tailing dam (TD) respectively, as shown in Google® Earth Pro™ image. (Figure 1).The principal ore mined is chalcopyrite ($CuFeS_2$) with 1.0% copper content. The length of the pit is 2.2 km in strike direction with an average width of 500 m.The study area lies between longitude 80.656717° E and 80.760728° E and latitude 21.940692° N to 22.083680^0 N.

Two important rivers flow in the vicinity of the project namely, 'Banjar' river due north-east of the study area and 'Son' river due south of the study area (Figure 2).

The northern part of study area has gentler topography as compared to southern part of the study area. The mining project is positioned at a relatively higher topographic level than nearby water bodies so, any wastewater that is generated by mining activity flows outwards from the mining project through various small tributaries or drains. The basin demarcation for both the rivers was performed using SRTM DEM of the area and QGIS software. It showed no intersection between the two revers thereby avoiding any cross contamination. Figure 3 shows Banjar river basin (north-east of copper mine) and Son river basin (south-west of copper mine) overlaid over Google Earth image of the study area.

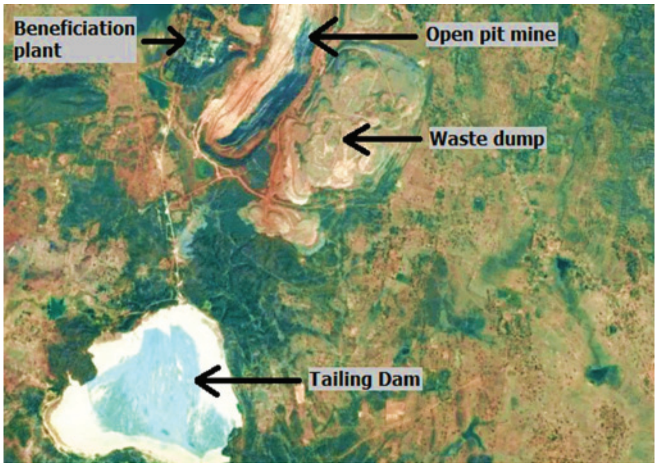

Figure 1: Study Area (Courtesy: Google Earth)

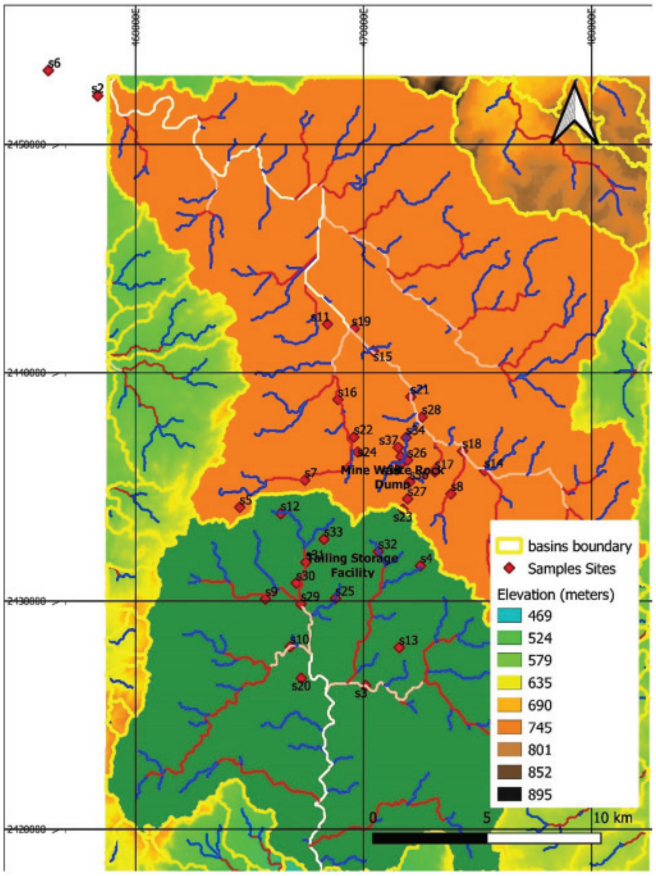

Figure 2: SRTM digital elevation model clipped to study area and drainage channels

2.0 Materials and Methods

2.1 Sample Collection and Analysis

The digital elevation model (DEM) was prepared from SRTM rasters (N21E080.SRTMGL1.hgt and N22E080.SRTMGL1.hgt) acquired from "Earth data" web portal of NASA. The DEM was prepared using QGIS software LTR 3.10.

In order to track the potential movement of metals as they are transported from the mine site, the sampling sites were strategically placed along the drainage network throughout the area. The sample stations were positioned along the principal flow and deposition pathways in both the rivers and their tributaries. A few roadside/open soil samples were also

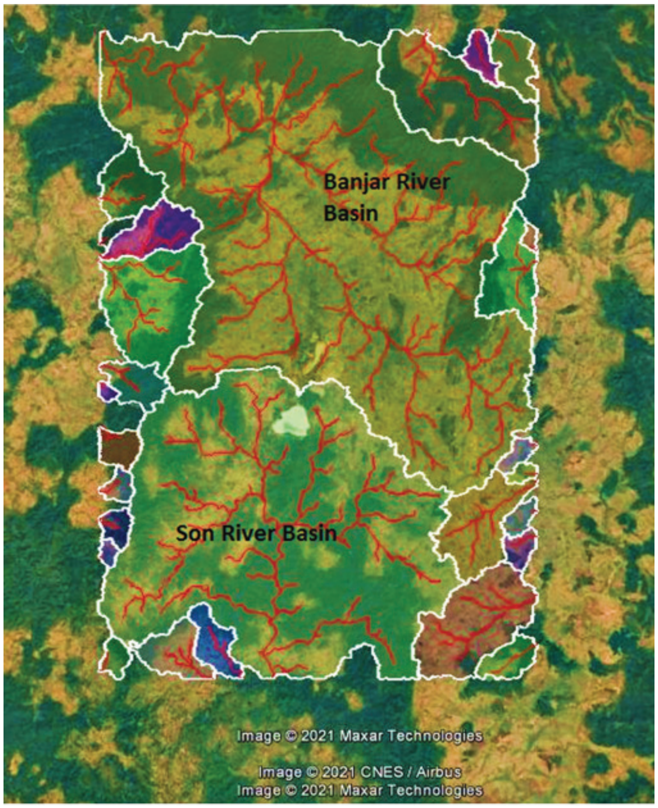

Figure 3: Banjar River basin with MWD and Son river basin with TSF

collected to provide additional insight into contamination around the study area. A total of thirty-eight samples were collected in duplicate at a depth of 10 cm along the river channels and tributaries (Figure 4).

The 35 sample locations are located within 10-kilometer radius and three samples were located outside the 10-kilometer radius. The 3 samples were collected for the purpose of eliminating any other source of contamination apart from the mining project. The minimum elevation of the study area is 507.005 m, maximum elevation is 700.000 m with the mean elevation of 576.831 m above sea level. The mine waste dump (MWD) and tailing storage facility (TSF) are located at elevation range of 590m to 635m well above the neighbouring waters bodies.

The sediment samples collected from rivers and tributaries were taken as close to the middle of the river channels as was practically possible. In addition to this, it was made certain that samples were gathered at locations where convergence of streams was observed. In order to avoid contamination, the collection was done in duplicate with a separate plastic scrape and placed in a pre-labelled polyethylene Ziploc sampling bag. At each of the sample sites GPS coordinates were recorded.

Pebbles, rock-chips and botanical bits were separated from the sample mass. The samples were processed in the following order: grinding was done using agate mortar, pulverized, and forwarded through 200 mesh sieves, and were kept in polyethylene bottles pre-washed using nitric acid and distilled water (3:1).

Every sample was completely dried at 108^0 C to constant weight. After all the samples had been dried,1g of each sample was then subjected to digestion in accordance with the standard procedure[6]. The leachate analysis was done using Atomic Absorption Spectroscope (AAS) of Labindia make. The AAS instrument was calibrated before every analysis. The samples were analyzed for copper (Cu), manganese (Mn), cobalt (Co), zinc (Zn), nickel (Ni), lead (Pb).

2.2 Calculation of Pollution Levels

(a) Enrichment Factor

Enrichment factor (EF) is a means of quantifying variation of contaminant element over a user defined background level of reference element. It is expressed as follows:

$$Ef = \frac{\left[\frac{Cn}{Cref}\right]_{Sample}}{\left[\frac{Cn}{Cref}\right]_{background}} \qquad \text{... (1)}$$

Where Cn is the content of the element ‘n’ under study and C_{ref} is the content of element selected as reference for this factor[7]. Iron (Fe) has been employed by several authors studying anthropogenic impact on marine and estuarine sediments[8,9].

The C_{ref} value for reference element corresponds to average shale content for the reference element[10]. According to[11], the elements Si, Al, Fe, Sc, Zr, or Ti are the reference elements that are most frequently used in the computation of EF[12]. These are the types of elements whose crustal concentrations are already so high that the effects of anthropogenic activity do not have a significant impact on their concentrations. In the process of computing EF values, various researchers have used a variety of reference elements in their calculations. As an illustration[13], utilized aluminum, whereas[14] relied on calcium as their reference material.

For the purposes of this investigation, the values of EF were calculated using element Fe, which served as the reference element. It was decided to use Fe due to its high mobility in oxidizing environments, its low variability in occurrence, and the fact that it occurs naturally in the environment in trace quantities[15,16,17,18]. The classification of EF is provided in Table 1[19].

(b) Contamination Factor

Contamination Factor (CF), is also called single metal pollution index. It is defined as follows:

$$Cf_x = {}^{C_n}\!/_{C_{background}} \qquad \text{... (2)}$$

Table 1: Classification of EF

Classification	Sediment contamination
<2	Low enrichment
2 - 5	Moderate enrichment
5 - 20	High enrichment
20 - 40	Very high enrichment
>40	Extremely enrichment

Where C_n is the concentration of the element 'n' under study and $C_{background}$ is the background concentration of same element 'n'[20]. The contamination factors are classified according to their values ranging from 1 to 6. Therefore "if CF_x<1, little or low contamination for element 'x'; 1<CF_x<3, moderate contamination for element 'x'; 3<CF_x<6, considerable contamination for element 'x'; and finally CF_x> 6, very high contamination for element 'x'"[21]

(c) Pollution Load Index (PLI)

PLI provides a measure of pollution taking into consideration the combined effect of several pollutants in the study area[22]. PLI map was generated with inverse distance weighing method using QGIS software. PLI is defined as follows[23,24]:

$$PLI = (CF_1 * CF_2 * \ldots.. * CF_i)^{1/i} \quad \ldots (3)$$

The Pollution load index (PLI) is classified in Table 2 as follows[25]:

Table 2: Classification of PLI

PLI	Pollution level
PLI<1	Low contamination
1dePLI<2	Moderate contamination
2dePLI<3	Considerable contamination
PLI.>3	Very high contamination

3.0 Results and Discussion

3.1 Evaluation of Heavy Metals in the Samples Around Study Area by Enrichment Factor

The basic statistics of heavy metals content (mgkg^{-1}) and the enrichment factors (EF) observed in samples collected from different locations around the mine area are provided in Tables 3 and 4 respectively.

In Table 4, the mean enrichment factors (EF) for heavy metals in the samples collected around the study area were: EF_{Cu} (15.16) >EF_{Co} (2.10) >EF_{Pb} (1.59) >EF_{Mu} (1.19) >EF_{Ni} (0.85) >EF_{Zn} (0.43). The enrichment factor for Cu was the highest, its average value of EF was 15.16, with maximum of 87.19 (sample 's38') indicating presence of highly contaminated samples sites in the study area. Similarly, for Co sample 's32' the maximum enrichment factor was 6.53. The reason for sample s32 and sample s38 exhibiting extremely high enrichment is that these sample sites are in the neighbourhood of AMD sources (TSF and MWD) and receive direct drainage from the the irrespective sources. Table 5 presents frequency and percentage distribution of samples with different classes of enrichment factor.

In Table 5, it can be observed that Cu was beyond high enrichment factor (EF>5) in 17 samples (44%), clearly indicating anthropogenic impact i.e. impact of copper mining operation. Only moderate enrichment was observed for Co, Mn, Pb, Ni with 17 samples (45%), 8 sample (21%), 5 samples (13%) and 1 sample (3%) respectively. Moreover, if we include moderately enriched samples class with high, very high and extreme enriched classes then 55% of samples are enriched with Cu. This may occur as a result of copper bearing rockmass present in mine waste dumps because grade control is not absolute, and some amount copper bearing rockmass may end up with the MWD. The recovery parameter of beneficiation process is less than 100% and therefore tailings generated do contains ore particles which reach the TSF.

Table 3: Basic statistics of heavy metals concentration in the study area

	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Co (mg kg^{-1})	Zn (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})
Mean	502.526	702.00	24.84	24.21	28.76	23.55
Median	83.5	395.00	23.25	23.00	24.00	19.50
Min	5	10.00	7.00	5.00	7.00	5.00
Max	3408	5030.00	55.00	50.00	99.00	97.00
1st Quart	20.75	221.00	14.25	19.00	15.25	13.00
3rd Quart	683	888.25	30.00	28.75	38.00	31.00
Std dev. (n-1)	846.809	898.23	13.20	9.67	18.47	17.23

Table 4: The enrichment factor (EF) for the samples

Sample #: - Location	Cu	Mn	Co	Zn	Ni	Pb
	EF	EF	EF	EF	EF	EF
s1:-MWD	0.20	0.78	0.76	0.38	0.58	1.18
s2:-MWD	0.27	1.03	1.26	0.48	0.72	1.20
s3:-TSF	0.29	1.13	1.94	0.56	0.79	0.79
s4:-TSG	0.48	1.82	2.09	0.68	0.79	1.26
s5:-TSF	0.54	0.40	0.89	0.99	0.82	1.82
s6:-MWD	0.44	1.17	1.73	0.50	0.56	1.31
s7:-MWD	0.85	1.69	4.78	0.50	0.83	1.44
s8:-MWD	1.07	2.40	4.08	0.66	0.74	1.48
s9:-TSF	0.65	0.94	2.47	0.73	0.63	1.36
s10:-TSF	1.01	1.08	3.40	0.60	0.82	1.59
s11:-MWD	0.66	0.91	1.32	0.52	0.52	0.84
s12:-TSF	1.28	2.05	2.91	0.47	1.60	2.24
s13:-TSF	1.46	1.39	2.59	0.40	1.18	1.51
s14:-MWD	1.37	1.10	1.73	0.35	1.03	1.76
s15:-MWD	1.85	0.18	1.53	0.28	0.86	1.80
s16:-MWD	2.78	1.82	1.56	0.30	0.88	1.87
s17:-MWD	7.40	0.68	2.19	0.29	0.78	1.39
s18:-MWD	1.70	0.21	2.36	0.30	1.17	1.85
s19:-MWD	3.50	0.59	1.53	0.41	0.97	1.69
s20:-TSF	5.35	0.03	1.68	0.32	0.52	1.77
s21:-MWD	15.31	1.48	2.52	0.54	0.89	1.59
s22:-MWD	1.25	0.13	0.68	0.11	0.33	1.07
s23:-MWD	22.30	1.81	2.30	0.41	1.08	1.53
s24:-MWD	2.76	1.92	2.17	0.22	1.48	1.84
s25:-TSF	2.54	0.05	0.78	0.14	0.32	1.24
s26:-MWD	6.60	0.63	1.00	0.32	0.81	1.67
s27:-MWD	42.44	2.87	3.63	0.56	2.81	4.36
s28:-MWD	33.84	1.03	2.72	0.36	0.76	1.38
s29:-TSF	7.12	0.28	0.93	0.17	0.46	0.69
s30:-TSF	8.09	0.29	0.87	0.14	0.28	1.00
s31:-TSF	9.48	2.77	1.25	0.12	0.36	2.27
s32:-TSF	56.12	2.85	6.53	1.09	0.91	1.20
s33:-TSF	19.76	0.02	1.08	0.27	0.65	1.67
s34:-MWD	27.82	2.75	2.75	0.25	1.17	1.85
s35:-MWD	41.07	2.27	1.37	0.29	0.84	2.05
s36:-MWD	78.16	2.20	3.97	0.37	0.85	2.21
s37:-MWD	81.24	0.51	1.77	0.54	0.61	1.01
s38:-MWD	87.19	0.29	0.91	0.61	0.90	1.78
Mean	15.16	1.19	2.10	0.43	0.85	1.59
Median	2.77	1.06	1.75	0.39	0.82	1.56
Min	0.20	0.02	0.68	0.11	0.28	0.69
Max	87.19	2.87	6.53	1.09	2.81	4.36
Std dev. (n-1)	24.18	0.89	1.25	0.22	0.44	0.61

Table 5: Frequency and percentage distribution of EF

		EF(Cu)	EF(Mn)	EF(Co)	EF(Zn)	EF(Ni)	EF(Pb)
	EF Range	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)
Low enrichment	0-2	17 (45%)	30 (79%)	21 (55%)	38 (100%)	37 (97%)	33 (87%)
Moderate enrichment	2-5	4 (11%)	8 (21%)	16 (42%)		1 (3%)	5 (13%)
High enrichment	5-20	8 (21%)		1 (3%)			
Very high enrichment	20-40	3 (8%)					
Extreme enrichment	40<	6 (15%)					
	Total	38 (100%)	38(100%)	38(100%)	38(100%)	38(100%)	38(100%)

3.2 Single Pollution Index Analysis of Heavy Metals (contamination factor) in the Sediments Around Study Area

According to the calculation results for contamination factors (Table 6) for heavy metals in the study area, the mean contamination factors were $CF_{Cu}>CF_{Co}>CF_{Pb}>CF_{Mn}>CF_{Ni}>CF_{Zn}$ and variation coefficient was Cu > Mn > Pb > Ni > Co > Zn, this indicates that the seepage from MWD and TSF have caused variation of Cu and Mn from their natural setting in the sediment system.

In northern part of study area, the samples located adjacent to MWD and receiving direct seepage are s34, s35, s36, s37, s38, s23, s27 exhibit very high contamination factor for copper greater than 15. Similarly, in southern part of study area where TSF is located, samples s29, s30, s31, s32 and s33 lying in the source of drainage pattern near TSF recorded high contamination values greater than 10. Table 7 provides the overall picture of distribution of contamination factor.

In Table 7, it can be observed that Cu was above the enrichment factor of 6 in 13 samples (34%), clearly indicating that sample namely, s23, s27 through s38 were significantly affected by mining activity. Only 12 sample sites (32%) were in the low contamination category. Pb&Co also showed moderate to considerable contamination in 50% and 66% of sampling sites respectively. Zinc which is an important micronutrient for plants showed CF below 1, indicating replacement of Zn in samples by other metal species like Cu, Co, Pb. The over limit ratio is in order Cu (68%) > Co (66%) > Pb (50%) > Mn (29%) > Ni (11%) > Zn (0%) indicating the Cu, Co and Pb were among the main pollutants.

PLI provides a measure of pollution taking into consideration the combined effect of several pollutants in the study area. PLI score of more than 1 indicates pollution. A total of 12 sampling sites exhibit PLI greater than 1 with samples s31 and s34 exhibit PLI greater than 2 indicating considerable pollution. This may be due to the proximity of samples site s31 (PLI=2.6) and s34 (PLI=2.14) to the TSF and MWD respectively as shown in PLI map (Figure 4) generated with inverse distance weighing method using QGIS software.

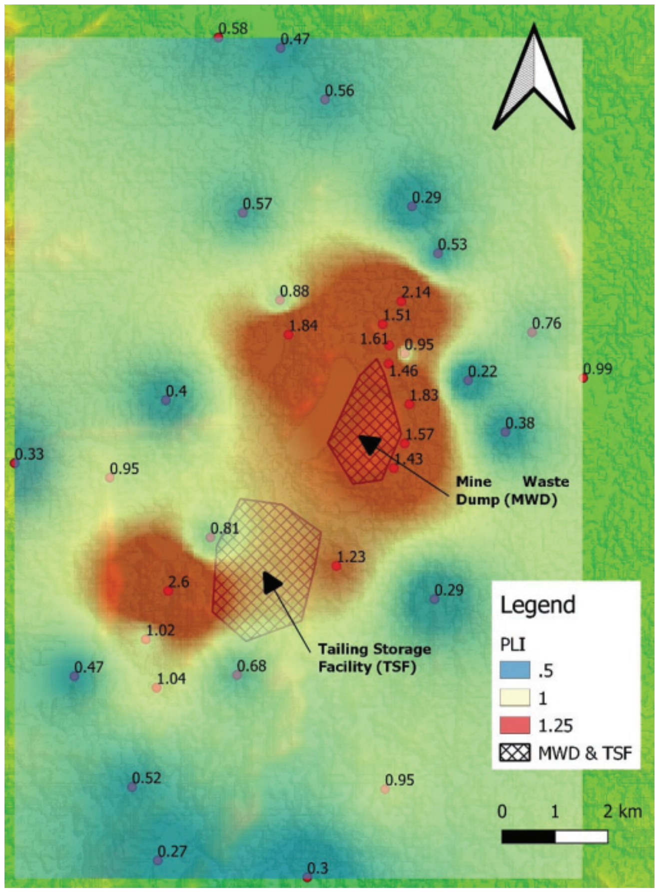

Figure 4: Pollution Load Index Map for the study area

Table 6: Contamination factors for samples

Samples	CF(Cu)	CF(Mn)	CF(Co)	CF(Zn)	CF(Ni)	CF(Pb)	PLI
s1	0.11	0.43	0.42	0.21	0.32	0.65	0.31
s2	0.11	0.43	0.53	0.20	0.30	0.50	0.30
s3	0.11	0.43	0.74	0.21	0.30	0.30	0.30
s4	0.13	0.50	0.58	0.19	0.22	0.35	0.29
s5	0.22	0.16	0.37	0.41	0.34	0.75	0.33
s6	0.27	0.72	1.05	0.31	0.34	0.80	0.51
s7	0.27	0.53	1.50	0.16	0.26	0.45	0.40
s8	0.29	0.65	1.11	0.18	0.20	0.40	0.38
s9	0.31	0.45	1.18	0.35	0.30	0.65	0.47
s10	0.44	0.48	1.50	0.26	0.36	0.70	0.52
s11	0.51	0.71	1.03	0.40	0.40	0.65	0.58
s12	0.80	1.28	1.82	0.29	1.00	1.40	0.95
s13	1.11	1.06	1.97	0.31	0.90	1.15	0.95
s14	1.24	1.00	1.58	0.32	0.94	1.60	0.99
s15	1.33	0.13	1.11	0.20	0.62	1.30	0.56
s16	1.27	0.83	0.71	0.14	0.40	0.85	0.57
s17	1.33	0.12	0.39	0.05	0.14	0.25	0.22
s18	1.42	0.18	1.97	0.25	0.98	1.55	0.76
s19	1.44	0.24	0.63	0.17	0.40	0.70	0.47
s20	2.27	0.01	0.71	0.14	0.22	0.75	0.27
s21	2.40	0.23	0.39	0.08	0.14	0.25	0.29
s22	2.76	0.29	1.50	0.23	0.72	2.35	0.88
s23	16.07	1.30	1.66	0.29	0.78	1.10	1.43
s24	3.69	2.57	2.89	0.29	1.98	2.45	1.84
s25	4.09	0.08	1.26	0.23	0.52	2.00	0.68
s26	5.73	0.54	0.87	0.27	0.70	1.45	0.95
s27	17.53	1.19	1.50	0.23	1.16	1.80	1.57
s28	9.82	0.30	0.79	0.11	0.22	0.40	0.53
s29	10.87	0.42	1.42	0.26	0.70	1.05	1.04
s30	12.51	0.45	1.34	0.22	0.44	1.55	1.02
s31	20.29	5.92	2.68	0.26	0.76	4.85	2.60
s32	21.04	1.07	2.45	0.41	0.34	0.45	1.23
s33	23.02	0.02	1.26	0.32	0.76	1.95	0.81
s34	27.11	2.68	2.68	0.24	1.14	1.80	2.14
s35	33.07	1.83	1.11	0.23	0.68	1.65	1.61
s36	51.33	1.44	2.61	0.24	0.56	1.45	1.83
s37	72.29	0.45	1.58	0.48	0.54	0.90	1.51
s38	75.73	0.25	0.79	0.53	0.78	1.55	1.46
Mean	11.167	0.826	1.307	0.254	0.575	1.178	0.88
Median	1.855	0.465	1.220	0.240	0.480	0.975	0.72
Minimum	0.110	0.010	0.370	0.050	0.140	0.250	0.22
Maximum	75.730	5.920	2.890	0.530	1.980	4.850	2.60
Standard deviation (n-1)	18.818	1.057	0.694	0.102	0.369	0.862	0.59
Range	75.620	5.910	2.520	0.480	1.840	4.600	2.38

Table 7: Frequency and percentage distribution of CF

		CF(Cu)	CF(Mn)	CF(Co)	CF(Zn)	CF(Ni)	CF(Pb)
	CF Range	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)	Frequency and (%)
Low contamination	0-1	12 (32%)	27 (71%)	13 (34%)	38 (100%)	34 (89%)	19 (50%)
moderate contamination	1-3	10 (26%)	10 (26%)	25 (66%)		4 (11%)	18 (47%)
considerable contamination	3-6	3 (8%)	1 (3%)				1 (3%)
very high contamination	6<	13 (34%)					
Over-limit ratio/ %		68%	29%	66%	0%	11%	50%

4.0 Conclusions

According to the findings of this study, the release of copper into sediments caused by acidic mine drainage can have a negative impact. In the course of the field survey that was carried out in the study area, it was discovered that TSF and MWD are potential AMD sites in the study area. It could be seen that the contamination factor for Cu was more than 1 in majority (68%) of sample sites in the study area. The elevation of other heavy metals such as Co and Pb was also observed with contamination factor exceeding 1 in more than 50% i.e., 19 samples location. The average value of contamination factor for Zn was less than 1 with no sampling site exhibiting CF more than 1 indicates replacement of Zn in the soil matrix by other metal received from acidic mine drainage. The mine waste is a potential environment hazard and therefore, it must be treated with importance. Two major sources of AMD in the study area were TSF and MWD. The sampling sites near TSF and MWD were significantly impacted by mining waste. These areas must be isolated from nearby drainage channels and the discharge of such sources must be contained in the mine site itself.

5.0 Conflict of Interest

All authors declare that they have no conflicts of interest.

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