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Assessing enrichment and contamination of sediments in the effluent canal of the ore processing industry and Naviundu River in Lubumbashi, Democratic Republic of Congo

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Abstract
The Naviundu River is exposed to heavy metal pollution from a mineral processing industry that discharges its effluents into the river. Heavy metals can accumulate in sediments and affect the aquatic ecosystem. The study collected surface sediment samples from the effluent pipe and along the Naviundu River, upstream and downstream of the industry. The samples were analyzed for the concentration of As, Co, Cd, Cr, Cu, Pb, Zn using ICP-OES. The study used various methods and indices to assess the level and source of contamination and the potential ecological risk of the heavy metals in the sediments. The results showed that the mean concentrations of As, Cr, Cu, Pb, and Zn were above the sediment quality guideline values for protection of aquatic life and the probable biological effect level. The enrichment factor and geo accumulation index results indicated sediment contamination in the pipe and downstream by As, Cu, Co, Cd, Pb and Zn. The association of these elements with Cr generated a very high ecological risk for the biocenosis. The study concluded that the sediments of the Naviundu river are highly contaminated with heavy metals. The origin of the heavy metals in the sediments is the effluent from the mineral processing plant.
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Keywords
Enrichment, Metallic trace elements (MTEs), Contamination, Sediments, Naviundu.

Introduction

The Democratic Republic of Congo has a long history of mining, which provides socio-economic benefits for many cities (Ettler, 2016). Lubumbashi, in particular, has grown due to the exploitation and processing of copper and cobalt ores. The mining sector has been liberalized, leading to the emergence of many small and medium-sized enterprises that extract and process minerals (Tshamala, 2008). However, mining also causes serious environmental and landscape impacts, such as soil and water contamination, land degradation and deforestation (Panagos et al., 2013; Petropoulos et al., 2013; Khalil et al., 2014). The region of Central Africa that is rich in copper and cobalt ores is shared by the DRC and Zambia. Industrial waste and mining effluent are the main sources of heavy metal pollution in the aquatic ecosystem of this region (Dusengemungu et al., 2022; Muimba-Kankolongo et al., 2022; Muimba-Kankolongo et al., 2021; Ouma et al., 2022; Tindwa & Singh, 2023). Heavy metals tend to settle on the riverbeds by precipitation or flocculation after being adsorbed by suspended particles, forming

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deposits of heavy metals in the sediments (*Contaminants in the Mississippi River--Heavy Metals in the Mississippi River*, n.d.; Fan et al., 2021; He et al., 2023; Zeng et al., 2019). Heavy metals are not biodegradable or metabolizable, so they can accumulate in the sediments and reach toxic levels (Khalef et al., 2022; Venkatachalam et al., 2009; Zhang et al., 2015). This can pose significant ecological risks for aquatic life. The Naviundu River is affected by the effluent from a mineral processing plant, which has reduced its economic value for activities such as fishing and swimming. This study aims to evaluate the contamination level of the Naviundu River by measuring the concentration of some heavy metals in the surface sediments. To do this, we used the following methods: Geo Accumulation Pollution Index (Igeo), Contamination Factor, Ecological Risk Potential of trace metals, Sediment Quality Guidelines and Enrichment Factor to identify the possible sources of trace metals.

Materials and Methods

The study area

Lubumbashi, the second-largest city in the Democratic Republic of Congo, stands only behind Kinshasa in terms of size. Its establishment in 1910 can be attributed to the uncovering of significant copper reserves and their exploitation by the Union Minière du Haut Katanga (UMHK) ("Congolese Militia Seizes UN Compound in Katanga's Lubumbashi," 2013; Kinshasa, 2023). Situated within the coordinates of 11°36'31.0" South latitude and 27°18'36.4" East longitude, Lubumbashi occupies a square region at an elevation of 1276 m (fig. 1). The climate of this city adheres to the Cw6 classifica-tion according to Koppen's system (*Geography One - the Koppen Climate Classification System - CSS Forums*, n.d.; Gisp, 2020*; Köppen Climate Classification System*, n.d.). This particular tropical climate experiences two distinct seasons, namely the rainy season spanning November to March and the dry season lasting from May to September. It was taken out out a cross-sectional study between November and December 2020 with a mining company that has been processing copper and cobalt ores for 20 years. We collected sediment samples from the effluent pipe and along the Naviundu River, which receives the effluents from the plant.

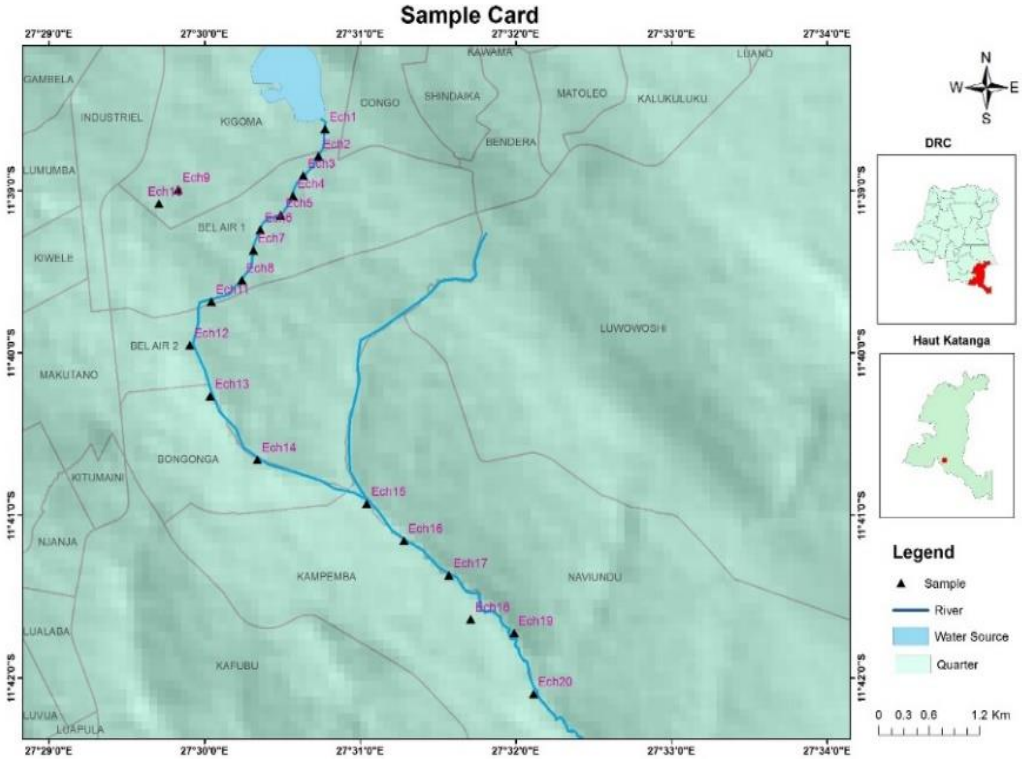

Figure 1
Below shows the map of the study area and the geolocation of sampling on the Naviundu River and the sites where the sediment samples were collected for our study

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Sample collection

It has been established a transect on the Naviundu River and collected surface sediments from 20 points, including 8 points upstream of the plant and 12 points downstream from the plant outlet to the second confluence with the Kamasaka River. We used Eijkelkamp hand augers to collect the samples at a depth of 0 to 50 cm. At each point, we took 3 samples of 200 g of sediment, mixed and homogenized them to form a single composite sample representative of the point. We stored the samples in plastic jars. Table1 shows the GPS coordinates of the sampling points.

Site	Designation	South	East
S2A	At the source of the Naviundu River	11° 38′ 37.3″	27° 29′ 49.9″
S2B	Upstream and 1 km from the factory	11° 38′ 47.4″	27° 29′ 42.4″
S2C	Upstream and less than 1 km from the plant	11° 38′ 54.6″	27° 30′ 2.5″
S2D	Upstream and 700 m from the plant	11° 39′ 2.2″	27° 29′ 54.2″
S2E	Upstream and less than 1 km from the plant	11° 39′ 9.0″	27° 30′ 2.2″
S2F	Upstream and 650 m from the plant	11° 39′ 14.8″	27° 30′ 20.5″
S2G	Upstream and within 600 m of the plant	11° 39′ 22.3″	27° 31′ 2.6″
S2H	Upstream and 500 m from the plant	11° 39′ 33.1″	27° 31′ 17.0″
S1A	Exit from the plant and start of the pipeline	11° 38′ 59.6″	27° 31′ 34.3″
S1B	The pipeline at 100 m from the factory exit	11° 39′ 5.0″	27° 31′ 42.6″
S3A	Sampling at more than 100 m from the cemetery avenue plant	11° 39′ 41.0″	27° 31′ 59.5″
S3B	Sampling point in the industrial district	11° 39′ 57.2″	27° 32′ 6.7″
S3C	Sampling point in the industrial district	11° 40′ 16.0″	27° 30′ 46.4″
S3D	Sampling point in the industrial district	11° 40′ 39.7″	27° 30′ 43.9″
S3E	Sampling point Moise bridge	11° 40′ 55.9″	27° 30′ 38.2″
S3F	Sampling point 100 m befor the confluence	11° 41′ 9.2″	27° 30′ 34.2″
S3G	Sampling point at the confluence	11° 41′ 22.2″	27° 30′ 29.5″
S3H	Sampling point 100 m after the confluence	11° 41′ 38.4″	27° 30′ 21.6″
S3I	Sampling point 200 m after the confluence	11° 41′ 43.4″	27° 30′ 19.1″
S3J	Sampling point at 5 km from the confluence	11° 42′ 6.1″	27° 30′ 14.4″

Table 1
***A**bove shows the geolocation of the samples from the effluent pipe and the Naviundu River*

Sample analysis technique

It was dried the sediment samples in an oven at 50 °C, then ground and homogenized them into a fine powder using an agate mortar. It was filtered the sample through a polyethylene sieve with a pore size of 63 µm. It was digested about 200 mg of surface sediment samples in a Teflon reactor by adding 5 ml hydrofluoric acid (40%), 5 ml hydrochloric acid (37%) and 2.5 ml nitric acid (69%). It was performed mineralization in a microwave (CEM Corporation, Mars 5x-pres) at 180 °C for 25 minutes and neutralized hydrofluoric acid by adding boric acid (4%). It was filtered the mixture and transferred the mineralized part to a 50 ml Teflon tube, which we topped up with ultrapure water.

It was analyzed the digested samples by inductively coupled plasma atomic emission spectroscopy (ICP-OES, Perkin Elmer ICP Optima 8300) at a metal-specific wavelength. It was analyzed the concentrations of the following heavy metals and nonmetals: Arsenic (As), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Lead (Pb) and Zinc (Zn). It was prepared standard solutions at different concentrations (0, 0.5, 1, 2, 3, 4, and 5 mg L-1) from Perkin Elmer multi-element standard solution (100 mg/L) for calibration. The limit of detection (LOD) was calculated as 3 times the standard deviation of blanks and was less than 1 µg L^{-1} for all elements analyzed. The certified reference material BCR-032 (Table-3) was used to verify the sen-

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sitivity of the instrument and the reliability of the results. The relative standard deviations of 3 repeated measurements were less than 4%. Concentrations are in mg kg-1 (ppm) dry weight (dw).

Methods for assessing sediment pollution

Sediment pollution assessment methods We used the sediment quality guidelines established by the National Oceanic and Atmospheric Administration (NOAA) and different pollution indices to assess sediment quality (*Ecological Risk Assessment Screening Benchmarks | Region 5 Superfund | US EPA*, n.d.; Hübner et al., 2009; Sinu, 2022).

Operational definitions

Enrichment factor. Operational definitions Enrichment factor The enrichment factor (EF) is used to assess the intensity of anthropogenic metal pollution by separating the anthropogenic signal from the natural signal (Abdullah et al., 2020; Ali et al., 2019; Álvarez-Vázquez et al., 2020; Assabar et al., 2023; Hızlı et al., 2023; Khalilova & Mammadov, 2016; Wu et al., 2023; Zahra et al., 2014). In this study, we used scandium(Sc) as a conservative element for geochemical normalization, Kilunga et al.,2017 (Ngweme et al., 2021; Salah et al., 2021; Tshibanda et al., 2021) and the UCC (Upper Continental Crust) value as a geochemical background as described by Mwanamoki et al.,2014. The enrichment factor was calculated according to the equation [1] given by Mwanamoki et al.,2014; Sakan et al.,2009; Kilunga et al., 2017:

$$FE = [M1] / [Sc1] / [Sc2] / [M2] \quad [1]$$

The given equation employs the following notations: $[M_1]$ denotes the concentration of element M in the sample, $[Sc_1]$ represents the concentration of Sc in the sample, $[M_2]$ indicates the concentration of element M in the geochemical background, and $[Sc_2]$ signifies the concentration of Sc in the geochemical background. According to Sakan et al. (2009) and Mwanamoki et al. (2014), the Enrichment Factor (EF) is classified into various ranges:

FE < 0	No enrichment
FE < 3	Minor enrichment
FE 3-5	Moderate enrichment
FE 5-10	Moderately severe enrichment
FE 10-25	Severe enrichment
FE 25-50	Very severe enrichment
FE > 50	Extremely serious enrichment

Geo Accumulation Index (Igeo). The evaluation of sediment pollution caused by heavy metals was conducted through the implementation of the Index of Geoaccumulation (Igeo) (Hao et al., 2021; Ma et al., 2022). This assessment method was initially established by Müller in 1979 and has since been extensively employed in environmental research. The Igeo relies on a comparative analysis between the metal concentration in the sediment and the corresponding geochemical baseline concentration for the metal. This comparison is achieved using the following equation [2]:

$$Igeo = \log_2 (C_n / 1.5\ B_n) \quad [2]$$

Where; C_n represents the concentration in the sediment for element n; B_n represents background for element n; $\log_2$: logarithm to base 2; coefficient 1.5: correction factor that allows to take into account the natural fluctuations of the content of a given metal that can be attributed to mineralogical changes in the sediment Scale of pollution intensity from the Igeo according to Müller [1979].

Igéo ≤ 0	Unpolluted
0 < Igéo < 1	Unpolluted to moderataly polluted
1 < Igéo < 2	Moderately polluted
2 < Igéo < 3	Moderately to heavily polluted
3 < Igéo < 4	Heavily pollutrd
4 < Igéo < 5	Heavily to extremely polluted
Igéo > 5	Extremely polluted

The contamination factor (Cf). It is used to show the level of contamination of potentially toxic elements in sediments. The contamination factor is calculated according to the following equation [3]:

$$Cf = \frac{C_{sample}}{C_{background}} \quad [3]$$

where C_{sample} is the concentration of metal in a specific sediment sample and $C_{background}$ is the concentration of the same element. The classifications of contamination factors are as follows:

Cf < 1	Low contamination
1 < Cf < 3	Moderate contamination
3 < Cf < 6	High contamination
Cf > 6	Very high contamination

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Potential Ecological Risk Index (PERI). To evaluate the contamination of sediments by heavy metals the potential ecological risk index was determined using the following equations [4] and [5]

$$Er = Ti \times \frac{Ci}{Cn} \quad [4]$$

$$RI = \sum_{i=1}^{n=7} \left(T_i \times \frac{C_i}{C} \right) \quad [5]$$

where *RI* is the risk index that is the sum of all risk factors for the sediment samples. *Er* is the individual poten tial ecological risk; *Ti* is the metal toxic response from the literature including : Cd=30, As=10, Cu=5, Co=5, Pb=5, Cr=2, Zn=1. *Ci* is the measured metal concentration in the sediment sample, and *Cn* is the reference metal value of the upper continental crust. RI values were classified as follows:

RI < 150	Low ecological rosk
150 < RI ≤ 300	Indicates moderate ecological risk
300 ≤ RI < 600	Indicates considerable ecological
RI ≥ 600	Indicates very high ecological risk to sediment

Results

Table 2 above shows the ICP-OES recovery values. We observe that the triplicate measurements of the reference material (BCR-032) were similar with the provided certified values and above 90.5% for all elements.

Element	Certified value BCR-032	Measured value (n=3)	Recovery
As	32.50 ± 1.19	29,42 ± 3.42	90.52
Co	40.35 ± 2.04	35.75 ± 4.03	93.56
Cd	22.18 ± 1.05	20.33 ± 1.28	91.66
Cr	257,42 ± 3.23	252.10 ± 4.05	97.93
Cu	35,27 ± 2,29	32.05 ± 1.44	90.87
Sc	Not certified	---	---
Pb	Not certified	---	---
Zn	254.35	245.07 ± 5.54	96.35

Table 2. *Recovery values of the certified reference material BCR-032 (in mg kg^{-1})*

In our study, site 1 represents the sampling points at the Naviundu River pipeline, site 2 represents the sampling points upstream of the Naviundu River and site 3 represents the sampling points downstream of the Naviundu River. Table 3 above shows the heavy metal and organic

Sampling site	Sample	As	Co	Cd	Cr	Cu	Sc	Pb	Zn	Mo
Site 2	S2A	0.7	11.5	0.001	21.4	15.3	3.0	3.20	31.3	4.59
	S2B	0.7	11.6	0.001	30.7	15.1	3.1	3.80	35.1	4.52
	S2C	1.0	25.6	0.001	45.6	23.5	7.0	3.40	90.5	5.79
	S2D	1.6	25.7	0.001	48.5	23.4	7.0	40.7	92.3	5.65
	S2E	3.0	26.7	0.001	48.5	23.4	9.6	42.2	94.2	4.46
	S2F	3.5	26.2	0.001	48.5	23.4	9.6	42.1	94.2	4.84
	S2G	2.0	24.5	0.001	40.6	18.5	6.0	40.6	85.5	7,25
	S2H	2.5	20.5	0.001	70,3	18.3	6.5	41,4	85.6	6.29
Site 1	S1A	12.2	1578.6	0.90	147.3	1678.3	3.6	218.1	552.6	6.45
	S1B	20.8	643.7	0.80	137.6	687.6	6.7	219.1	552,2	10.34
Site 3	S3A	17.0	760.2	0.50	128.6	680.5	6,0	220.3	507.2	6.42
	S3B	18.0	655.8	0.50	123.2	674.3	6.6	212.8	501.4	5.56
	S3C	11.0	358.1	0.20	80.3	430.4	4.1	208.1	325.7	10.23
	S3D	9.2	315.4	0.01	61.3	341.3	3.4	178.7	242.8	6.37
	S3E	9.5	309.8	0.01	61.4	310.8	3.5	164.6	241.4	8.63
	S3F	9.1	281.6	0.01	61.8	189.6	3.8	156.3	228.7	9.61
	S3G	5.8	205.1	0.01	60.4	143.1	3.1	89.3	158.6	7.35
	S3H	5.6	189.3	0.01	55.2	143.2	3.2	53.4	135.2	6.43
	S3I	4.5	158.2	0.01	50.8	105.7	3.1	48.4	135.2	4.91
	S3J	3.8	158.1	0.01	50.4	97.4	3.1	48.4	135.2	4.78
	Average	7.1	289.3	0.14	69.6	282.2	---	101.7	216.2	---
	RQS	5.9	---	0.59	37.3	35.7	---	35.0	123.0	---
	PEL	17	---	3.50	90.0	197.0	---	91.3	315.0	---

Table 3
Levels (mg/kg) of heavy metals and organic matter in the sediments of the Naviundu.

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matter contents in the sediment samples according to the sampling sites along the Naviundu River and the pipeline. Colored levels are those that are above the sediment quality guideline (SQG) for the protection of aquatic life and the probable biological effect level. Table 4 above presents the enrichment factor and geo accumulation index. It appears from this table that upstream of the Naviundu River the values of EF and Igeo are low ; indicating no pollution and enrichment to minor enrichment and unpolluted to moderately polluted sediment. Downstream the values varied from moderate to extremely severe enrichment with the level varying from moderately polluted to extremely polluted.

Table 4. *The FE and Igeo Values*

Sites	Samples	FE						Igeo					
		As	Co	Cr	Cu	Pb	Zn	As	Co	Cr	Cu	Pb	Zn
Site 2 Upstream of the Naviundu River	S2A	0.81	2.23	1.42	2.55	0.43	1.40	-2.09	-0.64	-1.29	-0.45	-2.99	-1.31
	S2B	0.79	2.18	1.98	2.43	0.50	1.52	-2.09	-0.63	-0.77	-0.47	-2.74	-1.15
	S2C	0.50	2.13	1.30	1.87	0.20	1.74	-1.58	0.50	-0.20	0.16	-2,90	0.21
	S2D	0.80	2.14	1.38	1.67	2.40	1.77	-0.90	0.51	-0.11	0.15	0.67	0.24
	S2E	1.09	1.62	1.01	1.21	1.81	1.32	0.00	0.56	-0.11	0.15	0.72	0.27
	S2F	1.27	1.59	1.01	1.21	1.81	1.32	0.22	0.54	-0.11	0.15	0.72	0.27
	S2G	1.16	2.38	1.35	1.54	2.79	1.91	-0.58	0.44	-0.37	-0.18	0.67	0.13
	S2H	1.34	1.84	2.16	1.40	2.63	1.77	-0.26	0.18	0.42	-0.19	0.69	0.13
Site 1 the pipeline	S1A	11.89	255.83	8.18	233.09	24.94	20.66	2.02	6.45	1.48	6.32	3.09	2.82
	S1B	10.89	56.18	4.10	51.31	13.51	11.09	2.79	5.16	1.39	5.03	3.10	2.82
Site 3 Downstream of the Naviundu River	S3A	9.94	73.92	4.28	56.70	15.17	11.38	2.50	5.40	1.29	5.01	3.11	2.70
	S3B	9.56	57.97	3.73	51.08	13.32	10.22	2.58	5.18	1.23	5.00	3.06	2.68
	S3C	9.41	50.95	3.91	52.48	20.97	10.69	1.87	4.31	0.61	4.35	3.02	2.06
	S3D	9.49	54.24	3.60	49.19	21.71	9.61	1.61	4.13	0.22	4.02	2.80	1.63
	S3E	9.52	51.76	3.50	44.40	19.43	9.28	1.66	4.10	0.22	3.88	2.69	1.62
	S3F	8.40	43.23	3.25	24.94	16.99	8.10	1.60	3.96	0.23	3.17	2.61	1.55
	S3G	6.56	38.60	3.89	23.08	11.90	6.88	0.95	3.51	0.20	2.76	1.80	1.02
	S3H	6.14	33.41	3.45	22.37	6.89	5.68	0.90	3.39	0.07	2.76	1.06	0.79
	S3I	5.09	29.77	3.27	17.04	6.45	5.87	0.58	3.13	-0.04	2.33	0.92	0.79
	S3J	4.30	29.75	3.25	15.70	6.45	5.87	0.34	3.13	-0.05	2.21	0.92	0.79

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Table 5. Contamination Factor (CF) values, Individual Potential Ecological Risk (Er) and Individual Potential Ecological Risk Index (IR).

Sites	Samples	Cf							Er							RI
		As	Co	Cd	Cr	Cu	Pb	Zn	As	Co	Cd	Cr	Cu	Pb	Zn	
Site 2 Upstream of the Navinadu River	S2A	0.35	0.95	0.01	0.61	1.09	0.18	0.60	3.5	4.79	0.30	1.22	5.46	0.94	0.60	16.82
	S2B	0.35	0.96	0.01	0.87	1.07	0.22	0.67	3.5	4.83	0.30	1.75	5.39	1.11	0.67	17.57
	S2C	0.50	2.13	0.01	1.30	1.67	0.20	1.74	5.0	10.66	0.30	2.60	8.39	1.00	1.74	29.70
	S2D	0.80	2.14	0.01	1.38	1.67	2.39	1.77	8.0	10.70	0.30	2.77	8.35	11.97	1.77	43.88
	S2E	1.50	2.22	0.01	1.38	1.67	2.48	1.81	15.0	11.12	0.30	2.77	8.35	12.41	1.81	51.77
	S2F	1.75	2.18	0.01	1.38	1.67	2.47	1.81	17.5	10.91	0.30	2.77	8.35	12.38	1.81	54.03
	S2G	1.00	2.04	0.01	1.16	1.32	2.38	1.64	10.0	10.20	0.30	2.32	6.60	11.94	1.64	43.02
	S2H	1.25	1.70	0.01	2.00	1.30	2.43	1.64	12.5	8.54	0.30	4.01	6.53	12.17	1.64	45.71
Site 1 the pipeline	S1A	6.10	131.55	9.00	4.20	119.87	12.82	10.62	61.0	657.75	270.0	8.41	599.39	64.14	10.62	1671.3
	S1B	10.40	53.64	8,00	3.93	49.11	12.88	10.61	104.0	268.20	240.0	7.86	245.57	64.44	10.61	940.70
Site 3 Downstream of the Navinadu River	S3A	8.50	63.35	5.00	3.67	48.60	12.95	9.75	85.0	316.70	150.0	7.34	243.03	64.79	9.75	876.68
	S3B	9.00	54.65	5.00	3.52	48.16	12.51	9.64	90.0	273.25	150.0	7.04	240.82	62.58	9.64	833.34
	S3C	5.50	29.84	2.00	2.29	30.74	12.24	6.26	55.0	149.20	60.0	4.58	153.71	61.20	6.26	489.98
	S3D	4.60	26.28	0.10	1.75	24.37	10.51	4.66	46.0	131.41	3.0	3.50	121.89	52.55	4.66	363.04
	S3E	4.75	25.81	0.10	1.75	22.20	9.68	4.64	47.5	129.08	3.0	3.53	111.00	48.41	4.64	347.14
	S3F	4.55	23.46	0.10	1.76	13.54	9.19	4.39	45.5	117.33	3.0	3.45	67.71	45.97	4.39	287.44
	S3G	2.90	17.09	0.10	1.72	10.22	5.25	3.05	29.0	85.45	3.0	3.44	51.10	26.26	3.05	201.33
	S3H	2.80	15.77	0.10	1.57	10.22	3.14	2.60	28.0	78.87	3.0	3.15	51.14	15.70	2.60	182.47
	S3I	2.25	13.18	0.10	1.45	7.55	2.84	2.60	22.5	65.91	3.0	2.90	37.75	14.23	2.60	148.90
	S3J	1.90	13.17	0.10	1.44	6.95	2.84	2.60	19.0	65.87	3.0	2.88	34.78	14.23	2.60	142.37

Statistical analysis

Table-6 presents the Pearson matrix ; the results show a strong positive correlation between all elements (As, Co, Cd, Cr, Cu, Pb and Zn). This observation proves .that heavy metals probably have a common source. On the other hand, organic matter shows a weak correlation with Co, Cd, Cu and Cr ; where as with As and Zn the correlation is positive. However with Pb a strong correlation is observed.

	As	Co	Cd	Cr	Cu	Pb	Zn	Mo
As	1							
Co	.738**	1						
Cd	.808**	.902**	1					
Cr	.895**	.890**	.940**	1				
Cu	.722**	.994**	.910**	.882**	1			
Pb	.934**	.787**	.736**	.847**	.780**	1		
Zn	.956**	.889**	.918**	.967**	.880**	.928**	1	
Mo	.554*	.281	.315	.394	.285	.627**	.472*	1

Table 6
Pearson correlation matrix between the elements studied

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Statistical analysis

We used principal component analysis (PCA) for data analysis on a spss software. This allowed us to determine the source of heavy metal contamination in the sediments of the Naviundu River. The rotated component matrix of the PCA is presented in Table 7. The first two principal components of the samples are presented in the diagram shown in Figure 1.-

Elements	Component	
	1	2
As	.926	.203
Co	.925	-.285
Cd	.931	-.232
Cr	.967	-.102
Cu	.921	-.288
Pb	.926	.257
Zn	.991	.004
Mo	.505	.816
% of variance	80.734	12.509
Cumulative %	80.734	93.242

Table 7. *Principal component, percentage variance explained after varimax rotation.*

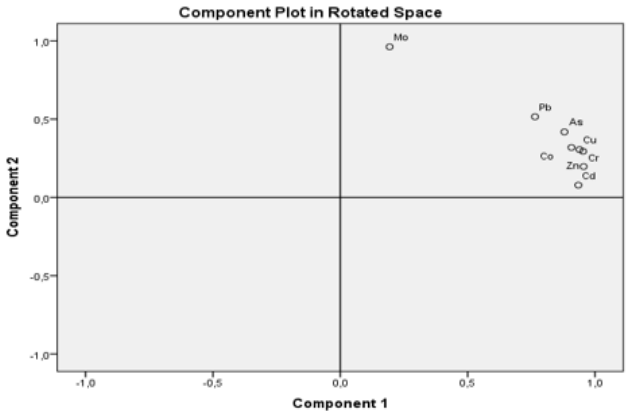

Figure 1. *Plot of results for the two main components of heavy metals (As, Co, Cd, Cu, Cr, Pb, Zn and Mo) in surface sediments.*

Principal component analysis gave the matrix has 2 components whose cumulative total variance of 93.243%. The first component has 80.734% of the total variance revealing a strong positive loading of metals. This indicates that the metals have a common source. The second component has 12.509% of the total variance.

Discussion

Ore-processing plants contribute significantly to the increase in heavy metals in sediments through their wastewater. Our research found that the sediments in the Naviundu River had unusually high levels of heavy metals at two specific locations, labeled as 1 and 3. However, the sediments collected at site 2 contained acceptable levels of heavy metals. We discovered an extremely severe enrichment of cobalt (Co) and copper (Cu) in the sediments, which aligns with the findings of Atibu et al's study in 2016. Surprisingly, our results contradict a study conducted in the same area by Bamba et al in 2017. We observed severe enrichment of arsenic (As), lead (Pb), and zinc (Zn), a finding also reported by Nour et al for Pb, Erika et al for As, and Patrick V et al for Zn. Chromium (Cr) showed a moderate level of enrichment, consistent with the findings of Yaser V et al (Vakilzadeh et al., 2022).

In terms of the geo-accumulation index, our study demonstrated that the sediment samples taken from site 2 (upstream of the plant) and the Naviudu river were not polluted. However, the samples collected from effluent pipe site 1 and pipe site 3 (downstream) exhibited heavy pollution, particularly with Co, Cu, and Pb, and extreme pollution with Co and Cu. The pollution of river sediments in mining areas has been documented by various authors, including Siham et al in 2019 for Pb, Elvine et al in 2022 for Cu, and Banze et al in 2022 for Co. The same sediments showed moderate to high pollution levels of As and Zn, which supports the findings of Seema Rani et al in 2021 for As and Ekabal Siddiqui et al in 2019 for Zn. The sediments also had a moderate pollution level of Cr at sites 1 and 3, consistent with Haixia Li et al's research in 2021.

Regarding the contamination factor (Cf), our results indicated a high level of heavy metal contamination in the sediments. This observation has been supported by other studies, including Omwene et al in 2018. However, Moldovan et al in 2022 did not confirm this finding. Our study revealed that the potential ecological risk (ER) is low upstream (site 2) but very high at site 1 (the pipeline) and downstream of the river (site 3).

Table 8 below shows the comparison between the means of potentially toxic metals from different studies from the literature and our study. Ore-processing plants contribute significantly to the increase in heavy metal levels. We compared the average amounts of trace metals found in the Naviundu River (Table 8) with those in other rivers around the world, as reported in

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Table 8. *The comparison between the means of potentially toxic metals from different studies from the literature and our study.*

Rivières	As	Co	Cd	Cr	Cu	Pb	Zn	Reference
Naviundu River, RDC	7.0	289.8	0.14	69.5	282.1	101,7	216.2	Our study
Talar ruver, Iran	9.8	13.7	0.16	105.2	28.5	18.3	67.9	Vakilzadeh et al., 2022
De Montigny Lake, Canada	---	6.7	0.10	48.3	10.3	14.7	36.4	Vualu and Mambenga, 2021
Karun River, Iran	3.0	---	---	37.6	20.9	9.6	44.6	Rastmanesh et al., 2020
Liaohe River, Cina	9.9	---	1.90	35.1	17.8	10.6	50.2	Ke et al., 2017
Mangonbangon River, Philippines	---	15.3	---	89.4	116.3	---	213.7	Decena et al., 2018
Conceição River Basin, Brazil	13.4	---	2.10	230.5	23.6	22.3	54.0	Leão et al., 2021

various studies. It seems that human-made pollution is linked to the mining industry. The levels of Co, Cu, Pb, and Zn were higher in the Naviundu River compared to all the other rivers mentioned: Talar in Iran (Vakilzadeh et al., 2022), De Montigny in Canada, Karun in Iran (Decena et al., 2018), Liaohe in China (Leão et al., 2021), Mangonbangonen in the Philippines and Conceiçao in Brazil (De Lacerda et al., 1985). On the other hand, As and Cd had lower levels than Talar, Liaohe, and Conceiçao. Cr had lower levels than Talar in Iran, Conceicao in Brazil, and Mangonbangon in the Philippines (Deocaris et al., 2022; Omwene et al., 2018), but higher levels than Montigny (Mambenga, 2021), Karun Iran (Decena et al., 2018), and Liaohe in China (Leão et al., 2021). In our study, the amount of As was higher than that found in Karun, Iran. Similarly, Cr had lower levels than Talar in Iran, Conceicao in Brazil, and Mangonbangon in the Philippines but higher levels than Montigny (Moldovan et al., 2022), Karun Iran (Decena et al., 2018), and Liaohe in China (Leão et al., 2021; Ke et al., 2017; Rastmanesh et al., 2020).

Conclusions

In my research, It was used various methods to measure the pollution levels and identify the sources of contamination. We found that the sediments in the Naviundu River had higher levels of heavy metals than what is considered safe for aquatic life. The concentrations of Co, Cu, Pb, and Zn in this river were much higher compared to other rivers around the world. My analysis showed that Co and Cu were extremely concentrated, while As, Pb, and Zn were highly concentrated in the sediments. The sediments in the Naviundu River were found to be highly polluted with Co and Cu, based on the Igeo values. Additionally, we observed significant contamination of the sediments with As, Co, Cd, Cu, Pb, and Zn, except for Cr. This contamination was.

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