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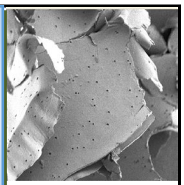

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Heavy Metal Pollution in Water and Sediment of Lohan River, Ranau, Sabah, Malaysia

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ABSTRACT

Lohan River, a small stream near the former Mamut Copper Mine, receives sediment contributions from mine overburden and ultrabasic soils rich in Co, Cr, and Ni. This study investigated heavy metal enrichment in the riverbed sediments. Seven sampling stations were selected along the river, with additional control stations at Lohan Toki River and Moroli River. Heavy metals were extracted using the aqua regia method and analyzed via ICP-OES, with quality control including blanks and SRM digestions. Cr (218–700.68 mg/kg), Ni (238.47–679.22 mg/kg), and Cu (235.19–438.97 mg/kg) concentrations in Lohan River sediments exceeded high guideline values (H-GV) from the Australian and New Zealand Sediment Quality Guidelines (370 mg/kg for Cr, 52 mg/kg for Ni, and 270 mg/kg for Cu). Lohan Toki River sediments also showed Cr and Ni contamination, while Moroli River sediments remained below H-GV. Water samples recorded metal levels below Malaysia's Class IIA/IIB thresholds. Environmental indices classified Lohan River sediments as moderately to heavily polluted with Cr, Cu, and Ni (Igeo Class 3). Enrichment Factor (EF) values ranged from 4.94 to 11.67, indicating significant enrichment. Pollution Load Index (PLI) values showed localized moderate to heavy pollution at Stations 5 and 6. However, the values of Potential Ecological Risk Index (PERI) were below 150, indicating low ecological risk overall. Despite localized contamination, the water's heavy metal levels posed no immediate threat under current standards.

INTRODUCTION

Heavy metals occur naturally in the environment. Although they are naturally occurring elements, their toxicity to human health and the environment cannot be underestimated [1]. For instance, extended exposure to certain heavy metals can disrupt the functioning of critical human organs, including the brain, bone, heart, kidneys, or liver [2]. One characteristic of heavy metals that makes them a significant concern is their non-biodegradability [3]. Sources of heavy metals can be from natural and anthropogenic origin. Natural sources include the weathering of rocks and volcanic eruptions, while anthropogenic origin may come from human activities such as mining, electroplating, and smelting ([2] ;[4]). In the case of the Lohan River, heavy metals pollution in the river comes from the weathering of ultrabasic rocks followed by subsequent erosion during the rainy season which contributes to Co, Cr, and Ni [5-7] and accumulated pollution from the former Mamut Copper Mine through 25 years of operation from 1974 to 1999 which contribute to Cu and Zn.

Heavy metal pollution from the former Mamut Copper Mine originates from the accumulated sediment containing Cu and Zn distributed along the Lohan River stretch, erosion from the overburden dumping site known as the Lohan Dumping Site [8] at the headwater of Lohan River and contribution from the solid tailing storage facility known as Lohan Dam, located at the middle stretch of the Lohan river. Mamut Copper Mine in Ranau, Sabah, Malaysia, was considered to be the largest open pit mining operation in Southeast Asia for copper extraction during its operation time [9]. Open-pit copper mining can have a significant environmental impact, particularly on small streams. The process involves extensive excavation, resulting in soil degradation, loss of vegetation, and pollution of surrounding ecosystems [10]. The environmental impacts on water quality can be severe, with studies documenting elevated levels of heavy metals like copper and zinc and acidity in river water and sediments due to mining activities [11]. Additionally, open-pit mining causes substantial damage to surface vegetation and soil, impacting the overall ecosystem [12]. Even after the cessation of open-pit copper mining operations, the environmental effects on small streams can persist and pose long-term challenges [13].

The creation of pit lakes from abandoned open-cut mines is a common legacy of mining activities, with many of these lakes being toxic and potentially harmful to adjacent communities and ecosystems [14]. These pit lakes can fill with groundwater, surface water, and rainwater, potentially impacting the surrounding environment [15,16]. Mine tailings make up a major component of waste from mining industries. These wastes are hazardous to the environment because they often contain high concentrations of heavy metals and metalloids [17]. Tailings are mixtures of finely ground rock and water left behind after removing the mineral concentrate [18]. Tailing storage affects the nearest river to the drainage location and contaminates water bodies that are far from it due to the water system's interconnectivity [19].

Ultrabasic soils are characterized by deficiencies in essential nutrients such as calcium, nitrogen, phosphorus, potassium, molybdenum, and zinc while containing toxic concentrations of heavy metals like nickel, cobalt, and chromium [20]. The unique geochemistry of ultrabasic rock, which is high in magnesium and toxic metals like chromium, cobalt, and nickel, and low in essential elements like phosphorus, directly influences soil microbial and floristic compositions, especially at higher altitudes where soils retain the chemistry of the parent material more effectively. Studies have shown that ultrabasic soils are often associated with nickel and cobalt deposits, indicating the presence of these metals in such environments [21].

The Lohan River is surrounded by ultrabasic soil in its headwater. Thus, the erosion of soil during heavy rainfall introduced a substantial amount of Co, Cr, and Ni into the river. The presence of these heavy metals in the river water and sediment renders both media unsuitable for the growth and survival of plants that lack tolerance to heavy metals. The local community relies on water from the Lohan River for agricultural activities, such as paddy plantation and domestic uses [22]. Given that many residential areas are scattered along the Lohan River, the heavy metal concentration in the water and sediment along the Lohan River has to be determined to minimize the potential risk to human health. It is hypothesized that the heavy metal concentration in the water and sediment from the Lohan River deviates from the normal range. This study aims to quantify the accumulation of heavy metals along the Lohan River, evaluate their concentrations against established sediment standards, and assess the pollution indices based on the environmental pollution index for sediment. This work are intended to inform researchers, water users, and local authorities about the heavy metals concentrations in the sediment and water of the Lohan River, enabling them to respond accordingly.

MATERIALS AND METHODS

The study area is a small catchment of the Lohan River located in Ranau, within the West Coast Division of Sabah (**Fig. 1**). The headwaters of the Lohan River originate from the hilly area elevated at 1300–1500 m above sea level, in the northern region that encompasses the former Mamut Copper Mine (MCM) area and surrounding ultrabasic hill. The Lohan River water supply does not directly originate from the Mamut Copper Mine Lake but rather from the river spur from the Lohan Dump cliff (8) and the ultrabasic hills surrounding the headwater.

Water supply to Lohan River might also originate from the MCM main lake because the water level in the lake (1256 m above sea level or asl) is higher than the headwater of Lohan River (837 m asl), potentially allowing slow percolation of seepage water from the lake into the river. The water in the Lohan River flows from southeastward before turning eastward [23]. A dam storing solid tailings from the Mamut Copper Mine was built at Lohan Dam, located in the middle of the Lohan River stretch and very close to the Lohan River. Any spillage from the Lohan Dam poses a risk of contamination of the Lohan River.

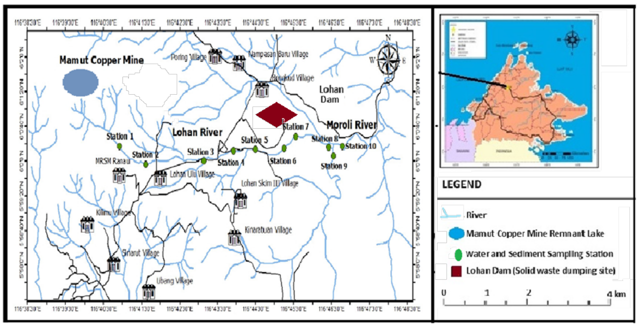

Fig. 1. Location of the Lohan River small water catchment and sampling stations.

Sediment and water sampling and analysis

In total, ten sampling stations were identified in the study area. Seven sediment and water sampling stations (Stations 1, 2, 4, 5, 6, 7, and 8) were chosen along the stretch of Lohan River covering the river's upstream, middle and downstream. For comparison, one sample was obtained from the Lohan Toki River (Station 3), a small stream adjoining the Lohan River, and two samples from the larger Moroli River that are at Station 9 at the upper section and Station 10 at the lower section of the point where Lohan river adjoin Moroli river. Station 10, which is at the lower part of the adjoining point, receives water and sediment from the Lohan River. Five heavy metals, namely Co, Cr, Ni, Cu, and Zn were determined in this exercise.

Heavy metals Co, Cr, and Ni indicate pollution from the surrounding ultrabasic soil, whereas Cu and Zn are indicators of the former copper mine's pollution. River sediments were collected across the river, taking samples from both sides of the river bank and in the middle and made as a composite sample. These samples were kept in a zipped plastic bag in a cool box and transported to the Lab. The samples were spread on a silver tray in the Lab and kept dry at room temperature. Upon drying, the samples were sieved with <63 µm opening sieve. Heavy metals in sediment were extracted from the fine river sediment (<63 µm) using aqua regia $HCl:HNO_3$ (3:1) by the method 3050b [24].

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Heavy metals in the extracted solution and in the river water were determined using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) model Perkin Elmer Optima 5300DV. All apparatus were soaked in acid before use for quality control, including blank and SRM digestion. The Standard Reference Material was the SRM 2711a – Montana II Soil from the National Institute of Standards and Technology.

Heavy metal content in sediment was evaluated using environmental indicators such as geoaccumulation index (Igeo) [25] and contamination factor (CF) [26]. Enrichment factor (EF) using the equation of Buat-Menard and Chesselet [27], pollution load index (Pli) [28], and potential ecological risk index (PERI) [29]. Environmental indexes obtained were referred to their respective class categories. These indices of potential pollution are calculated by normalizing the concentration of one metal in the topsoil relative to a reference element. A reference element is a particularly stable element in the soil, characterized by the absence of vertical mobility and/or degradation phenomena. The chosen reference elements should also be associated with finer particles (grain size) and not be anthropogenically altered. Commonly used reference elements in many studies include Al, Fe, Mn, and Rb, as well as total organic carbon and grain size. For this study, Fe content was used as a reference element.

RESULT AND DISCUSSION

Heavy metals content in sediment and water

Heavy metals (Co, Cr, Ni, Cu, dan Zn) concentrations in the sediment of the Lohan River, Lohan Toki, and Moroli River and their comparison with established standards are shown in **Table 1** and **Fig. 2**. The Lohan Toki River originates from an ultrabasic hill in the western part of the Lohan River catchment and does not receive sediment from the former Mamut Copper Mine (MCM). Consequently, its sediment contains a high concentration of Cr and Ni which are associated with ultrabasic soil. At station 10, located at the lower part of the Moroli River, the Cr and Ni concentrations exceed the maximum allowable concentration (MAC) suggested by [30], the USEPA SQG threshold for heavily polluted conditions, and the Canadian ISQs Probable Effect Level (PEL) [31]. However, these concentrations are still below the Australian & New Zealand ISQG High Guideline Value (H-GV). This value depicts the influence of Lohan River effluent on sediment in the immediate reach of the Moroli River.

All stations recorded Cr, Ni, and Cu concentrations that exceeded the Australian and New Zealand (HG-V) except for Stations 1 and 2 for Cr and Cu in the sediment along the Lohan River stretch. The concentrations of Zn and Co were below the MAC value. The levels of Cr, Ni, and Cu concentrations fluctuated along the river stretch. Stations 1 and 2 in the headstream showed lower concentrations of Cr, Ni, and Cu compared to downstream stations. In general, heavy metal concentrations at station 4 to station 8 decreased slightly, though not significantly.

The range of concentrations from station 1 to station 8 for Co, Cr, Ni, Cu, and Zn were 4.21 to 23.84 mg/kg, 218.23 to 700.68 mg/kg, 238.47 to 679.22 mg/kg, 235.19 to 438.97 mg/kg, and 28.89 to 60.21 mg/kg, respectively. All heavy metals concentrations from stations 1 to 8 exceeded the Canadian ISQ probable Effect Level (PEL) and the Australian & New Zealand ISQG High Guidelined Value (H-GV), except at stations 1 and 2, which are only lower than the Australian & New Zealand ISQG High Guidelined Value (H-GV). The concentrations of Co and Zn in the sediment of the Lohan River are comparable to the values reported by [34] for the Mamut River. However, Cu concentration in the Mamut River is up to three times higher than in the Lohan River.

Table 1. Concentrations of various heavy metals in the sediment from all stations along the Lohan river.

Station	Heavy Metal Concentration (mg/kg)				
	Co	Cr	Ni	Cu	Zn
1	8.84 ± 6.91	218.23 ± 45.75	272.16 ± 71.89	252.07 ± 59.33	53.89 ± 21.00
2	4.21 ± 7.29	270.83 ± 161.25	238.47 ± 119.88	235.19 ± 47.44	28.89 ± 7.66
3 Control Lohan Toki	28.49 ± 8.40	865.34 ± 189.61	668.99 ± 124.82	22.98 ± 27.65	45.58 ± 11.45
4	20.86 ± 20.81	700.68 ± 344.27	547.81 ± 272.34	363.83 ± 176.42	57.44 ± 22.62
5	23.84 ± 14.90	641.25 ± 186.21	679.22 ± 191.35	438.97 ± 140.33	60.21 ± 15.73
6	9.03 ± 9.99	524.84 ± 116.78	460.25 ± 147.77	396.11 ± 91.70	39.40 ± 18.97
7	15.64 ± 12.74	516.95 ± 137.94	540.16 ± 171.96	394.24 ± 124.04	45.42 ± 19.66
8	10.14 ± 16.34	452.43 ± 275.24	431.66 ± 257.03	296.28 ± 193.90	34.94 ± 33.47
9 Control Moroli upper part	ND	15.50 ± 15.35	4.28 ± 7.41	ND	ND
10 Control Moroli lower part	ND	109.65 ± 146.27	107.55 ± 157.95	53.48 ± 91.01	1.39 ± 2.41
Lohan River 2007 [32]	72.28	550.66	621.10	3147.50	365.74
Lohan River 2009 [32]	43.94	535.13	507.31	1223.78	169.10
Main Lake 2007 [32]	51.93	839.78	828.44	2178.02	119.84
*MAC [30]	25 - 50	75 - 100	100	60 - 125	70 - 400
#USEPA SQGs (Heavily Polluted)	-	>75	>50	>50	>200
Canadian ISQGs (PEL) [31]	-	90	47 (OEL)	197	315
Australian & NZ (H-GV) [33]	-	370	52	270	410

*Maximum Allowable Concentration - Source: [30]
#USEPASQGs – Heavily polluted
Canadian ISQGs Probable Effect Level (PEL) [31]
Australia & New Zealand ISQG – High Guidelines Value (H-GV) [33]

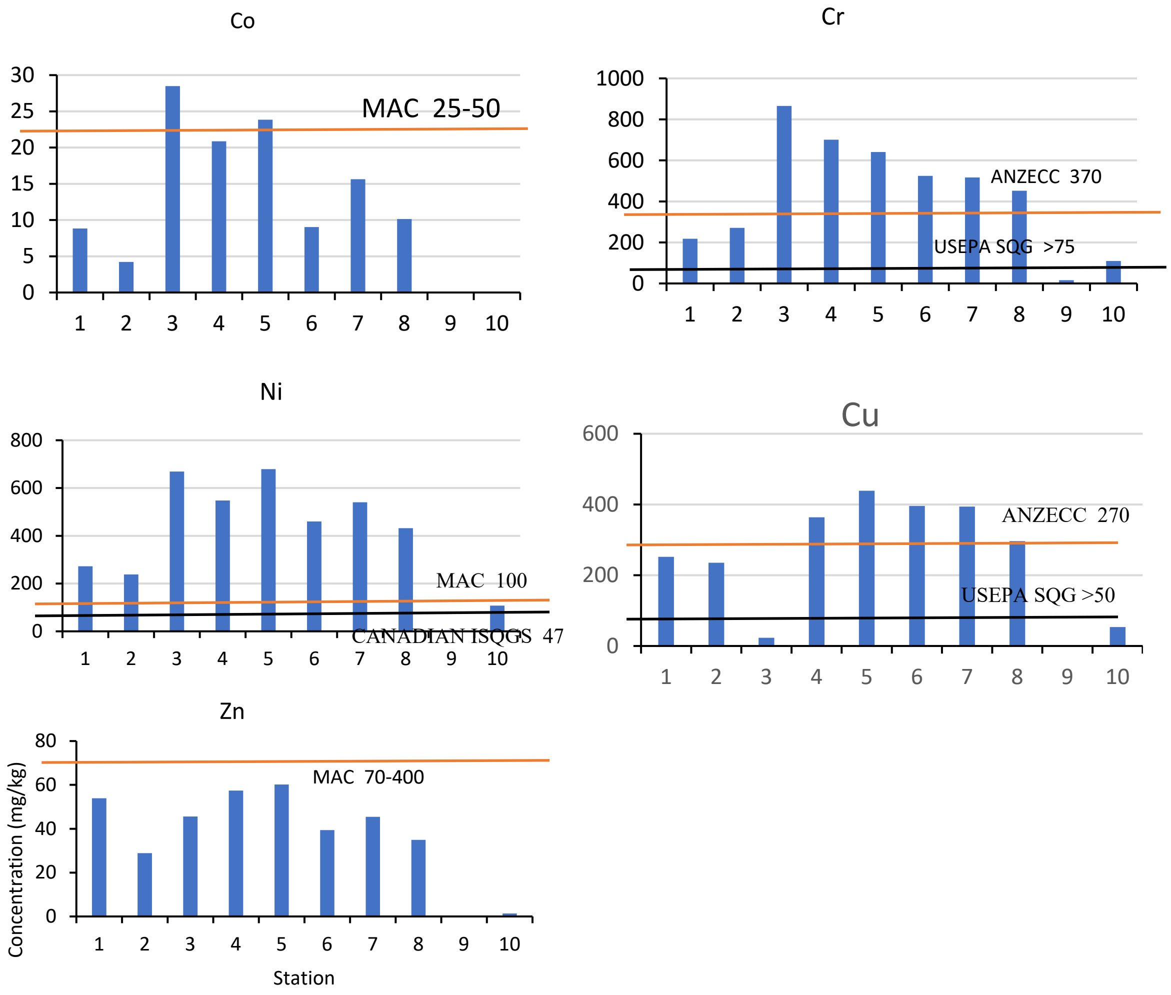

Fig. 2. Heavy metals in sediment vs established Standard

In contrast, Ni concentrations in the sediment of the Lohan River were approximately twice as high as those in the Mamut River. This shows that the Mamut River is highly polluted with Cu from the copper mine, whereas the Lohan River is more heavily polluted with Ni from the surrounding ultrabasic hills. The heavy metals content in water, as shown in **Table 2**, indicates that the control Station 3 contains low concentrations of Cr, Ni, and Zn, while Co and Cu are not detectable. For the control stations at Moroli River, Station 9 contains Zn, whereas Station 10 located at the lower part of the adjoining point, contains both Ni and Zn. Co and Cr are not detectable at any station in the Lohan River. Nickel and Zn can be detected in all sampling stations except Ni in Station 9. This shows that Zn is a very common metal that is easily detectable in water, whereas Ni is undetectable in Station 9 because Ni-bearing sources from the Lohan River do not influence the water.

Copper is detectable only at Stations 1 and 2, and is not present in the remaining stations. All heavy metals concentrations in the control stations and Lohan River are below Class IIA and IIB thresholds in the Malaysian National Water Quality Standard (NWQS). The recorded values are also comparable to the pristine river water of the Eucalyptus River in the Maliau basin [35]. Lohan River water is suitable for recreational use based on the heavy metal concentration alone. Heavy metal pollution in small river catchments can arise from various sources within or around the catchment area. One significant source is the historical pollution accumulated in sediments over time, which can be remobilized during flood events, contributing to high metal loads in the suspended matter [37]. Heavy metals recorded in Lohan River water through time [34] showed that the concentration of Cu in water gradually decreased after the MCM ceased operation in 1999. However, Zn concentration shows an increasing trend with time but is still lower than the data in 1999 when the mine ceased to operate (**Table 3**).

Table 3. Previous research on heavy metal content in water of the Lohan River.

Station	Concentration (mg/L)					Reference
	Co	Cr	Ni	Cu	Zn	
Lohan River 2007	0.0016	0.0068	0.0322	0.0020	0.0139	[32]
Lohan River 2009	0.85	0.0021	0.0135	0.0030	0.0126	[32]
Lohan River 2012	na	0.026	na	0.034	0.032	[34]
Lohan River 2020	na	na	na	0.0063	0.0415	[38]
Lohan River 2024	ND	ND	0.0055	0.0010	0.0867	This work, 2024
Mamut Main Lake 2007	0.21	0.0083	0.63	3.36	1.63	[32]
Mamut Main Lake 2009	0.209	0.0048	0.48	3.06	0.87	[32]
Mamut Main Lake 2020	0.206	0.017	0.414	2.76	1.61	[39]

Table 2. The concentration of heavy metals in the water of the Lohan River stretch.

Station	Concentration (mg/L)				
	Co	Cr	Ni	Cu	Zn
1	ND	ND	0.0092 ± 0.0074	0.0011 ± 0.0019	0.0972 ± 0.0637
2	ND	ND	0.0113 ± 0.0019	0.0009 ± 0.0015	0.1094 ± 0.0020
3	ND	0.0016 ± 0.0001	0.0012 ± 0.0022	ND	0.0486 ± 0.0742
4	ND	ND	0.0059 ± 0.0029	ND	0.1136 ± 0.0142
5	ND	ND	0.0030 ± 0.0011	ND	0.0434 ± 0.0488
6	ND	ND	0.0029 ± 0.0027	ND	0.0854 ± 0.0692
7	ND	ND	0.0051 ± 0.0023	ND	0.1173 ± 0.0047
8	ND	ND	0.0009 ± 0.0016	ND	0.0404 ± 0.0567
9	ND	ND	ND	ND	0.1062 ± 0.0056
10	ND	ND	0.0016 ± 0.0017	ND	0.1135 ± 0.0082
Eucalyptus river [35]	$<5^{-6}$	0.0003	0.0017	0.0018	0.0239
NWQS – IIA/IIB [36]	Not mentioned	0.05	0.05	0.02	5

Note:
Stations 1, 2, 4, 5, 6, 7 and 8: Lohan River
Station 3: Lohan Toki River (Control)
Stations 9 and 10: Moroli River (Control)

In the case of the Lohan River, the remobilization of accumulated sediment is caused by flooding and the stone quarrying activities between Station 1 and Station 3. Quarrying stones in riverbeds and floodplains can significantly affect the remobilization of river systems. The alteration of flow regimes due to quarrying activities can lead to increased flooding, erosion, and drainage, thereby heightening the risk of heavy metal remobilization in floodplains [40]. This can result in the erosion and redeposition of sediment-associated metal loads, particularly in areas with low gradients and wide valley floors [37].

Studies have shown that changes in metal concentrations and sediment stratigraphy in floodplains, stream channels, and other water bodies can indicate rapid metal load changes downstream during and after mining activities [37]. During flooding events, contaminants in river sediments, including heavy metals, can be remobilized, washed out from industrial and mining sites, and transported to and accumulated in floodplain ecosystems [41]. The remobilization of recently deposited sediment on river floodplains during inundation events has been identified as an important process, emphasizing the importance of understanding sediment transport dynamics in river systems.

Additionally, the mobility of metals in floodplains impacted by mining activities underscores the long-term consequences of historical anthropogenic influences on metal distribution and remobilization [37]. Overall, the interaction between quarrying activities, flood events, and the natural dynamics of river systems can lead to the remobilization of sediment and metals, impacting water quality, ecosystem health, and the long-term storage and redistribution of contaminants in river environments. The significant increase in station 2 for Cu, Cr, and Ni ($p < 0.05$) from 270.83 mg/kg, 238.47 mg/kg, and 235.19 mg/kg to 700.68 mg/kg, 547.81 mg/kg and 363.83 mg/kg in station 4 indicates the effect of such activity. These elevated concentrations remain high up to the last sampling point at Station 8 in the Lohan River.

Specific point sources within the catchment, such as tributaries or industrial mining activities, can introduce heavy metals into the river system [42]. In the case of the Lohan River, small river tributaries occur at Station 3, which is the Lohan Toki River. Sediment from the Lohan Toki River itself recorded very high concentrations of Cr and Ni, indicating the ultrabasic soil origin of its headwater. This occurrence might also contribute to the subsequent stations' high Cr and Ni content. Stations 6 and 7 are located right opposite the Lohan Dam, which stores the solid tailing of the former Mamut Copper Mine. Erosion of soil containing high Cu concentration from the embankment edge to Lohan River contributes to the elevated Cu content in sediment.

After the cessation of mining activities, the activation of polluted soils and sediments during rainy periods caused an increase in metal concentrations of river waters and sediment [43]. In conclusion, heavy metals pollution in small river catchments such as the Lohan River can stem from historical pollution, urbanization, agricultural practices, mining, and natural sources within the catchment area.

The trend of heavy metals in water and sediment

The general trend of heavy metals concentrations in water, in decreasing order, is Zn, Ni, Cu, Cr, and Co (**Table 4**). The most abundant heavy metal commonly found in all stations along Lohan River as well as the control station, was zinc, followed by nickel. The concentration of Zn in the water column of Lohan River was consistently the highest across the different stations, even though its concentrations in sediment were low. This resulted from the higher mobility of Zn compared to other heavy metals such as Ni, Cu, and Cr in the water column [44]. The finding by [38] concluded that Zn prefers staying soluble in the water rather than being adsorbed unto sediment.

Ni is lower in content than Zn and was still detected in water column across all stations, even in smaller concentrations. Ni solubility in the water column can be affected by factors like redox conditions and the presence of organic matter. For instance, the dissolution of iron hydroxides and oxidation of organic matter can increase Ni solubility ([44] ;[45]). Additionally, natural organic matter in water bodies can bind with metals like Ni, reducing their bioavailability to organisms and potentially impacting their toxicity levels [46].

Cobalt was undetectable in all stations, whereas Cr was detected only in Station 3, whilst Cu was present only at Stations 1 and 2. The presence of other competing ions and the interaction between water and sediments could influence the absence of Cr, Co, and Cu in stream water. It could also be attributed to factors such as the sorption capacity of sediments and the preferential flow of water-carrying metals from contaminated sources [47]. Competing ions in the water can affect Co, Cr, and Cu solubility and mobility. Speciation results suggest that high levels of these metals were associated with exchangeable and carbonate-bound fractions, suggesting that they may not be present in detectable concentrations in the stream water due to their association with solid phases [48].

Geochemical interactions between water and sediments can further lead to the adsorption and retention of metals like Co, Cr, and Cu onto solid phases, reducing their presence in the water column [49]. A previous study by [50] in the Lohan River shows the presence of Co and Cr; however, the result of the present study cannot detect Cr and Co. Since Co and Cr were still present in the sediment from all stations of the Lohan River, it was plausible for these heavy metals to be released into the river water again when the physicochemical conditions were favorable [51]. For example, Co could be re-released into the water if the pH of the water changes, thus, Co is highly susceptible to recycling [34]. Cr is also known for having low mobility as it prefers adsorbing to fine sediment with a large surface area, which might explain its absence in the water column and its presence in the sediment [52].

Table 4. The trend of heavy metals in water and sediment from different stations.

Station	Trend of Heavy Metals In water	Trend of Heavy Metals In sediment
1	Zn > Ni > Cu > Cr = Co	Ni > Cu > Cr > Zn > Co
2	Zn > Ni > Cu > Cr = Co	Cr > Ni > Cu > Zn > Co
3	Zn > Cr > Ni > Cu = Co	Cr > Ni > Zn > Co > Cu
4	Zn > Ni > Cu = Cr = Co	Cr > Ni > Cu > Zn > Co
5	Zn > Ni > Cu = Cr = Co	Ni > Cr > Cu > Zn > Co
6	Zn > Ni > Cu = Cr = Co	Cr > Ni > Cu > Zn > Co
7	Zn > Ni > Cu = Cr = Co	Ni > Cr > Cu> Zn > Co
8	Zn > Ni > Cu = Cr = Co	Cr > Ni > Cu > Zn > Co
9	Zn > Ni > Cu = Cr = Co	Cr > Ni > Cu = Zn = Co
10	Zn > Ni > Cu = Cr = Co	Cr > Ni > Cu > Zn > Co
Past Research [50]	Ni > Cu > Zn > Co > Cr	Cu > Ni > Cr > Zn > Co
Past Research [38]	Cu > Zn > Ni	Cu > Ni > Zn

Based on **Table 4**, the general trend of metal content in sediment in decreasing order is depicted as Cr, Ni, Cu, Zn, and Co. The presence of these metals in river sediment is expected because the headwater of the river catchment is surrounded by ultrabasic rock/soil, which is known to contain a high concentration of Co, Cr, and Ni [53]. Besides, the Lohan River once received solid waste tailing from the Lohan Dump site of the former Mamut Copper Mine [8], which supplied sediment containing Cu and Zn into the river bed. The metal concentration trend from Stations 1 to 8, which is considered to not differ significantly, implies that sediment containing these metals is often reworked and remobilized during rainfall and flooding.

Ecological environmental indices evaluation

Environmental indices, as shown in **Table 5**, include the Geoaccumulation Index (Igeo), Contamination Factor (CF), Enrichment Factor (EF), Pollution Load Index (Pli), and Potential Ecological Risk Index (PERI). The Enrichment Factor (EF) and the Geoaccumulation Index (Igeo) are indicators used to assess the presence and intensity of anthropogenic contaminant deposition on surface soil.

The geoaccumulation index (Igeo), developed by [54], evaluates the level of heavy metal and metalloid contamination in sediment by comparing current concentration to pre-industrial levels. The background values used for this assessment refer to the average elemental content in the Earth's crust. The Igeo values for the Lohan River's sediment for Co and Zn at all stations along the Lohan River, including the control stations, are below 0 and fall into Class 0 of the Igeo index classification. This classification indicates that the Lohan, Lohan Toki, and Moroli river sedimenta are unpolluted by both metals. The control stations at Moroli River (Stations 9 and 10) are considered unpolluted (Class 0) for Cr and Ni. Despite being unpolluted with Cu metal Station 3, Lohan Toki River is moderately to seriously polluted with Cr, and Ni. Along Lohan River, Stations 1 and 2 are in Class 1, Unpolluted to Moderately unpolluted with Cr. Stations 6, 7, and 8 are in Class 2, which are moderately polluted with Cr. Stations 1, 2, and 8 are moderately polluted with Ni, and Cu, whereas Station 6 is moderately polluted with Ni. Stations 4 and 5 are in Class 3, which are moderately to seriously polluted with Cr, Ni, and Cu. Station 7 is moderately to seriously polluted with Ni, and Cu, whereas station 6 is moderately to seriously polluted with Cu.

Zinc appears in low concentration at all stations along the Lohan River and at the control stations, resulting in a low contamination factor (CF<1). For the control stations, the contamination factor is low for Co at Stations 9 and 10, low for Cr, Ni, and Cu at Station 9, and low for Cu at Station 3. In moderate contamination factor category 1≤CF<3, Station 10 falls into this range for Ni, Cr, and Cu. Stations 3, 4, and 5 are categorized as very highly contaminated with Cr and Ni. Co's contamination factor (CF) is low at Stations 1, 2, 6, 7, and 8. In the moderate contamination factor category 1≤CF<3, Stations 1 and 2 are placed in this category for Cr. Stations 6, 7, and 8 are considerably contaminated with Cr, whereas Stations 1, 2, and 8 are considerably contaminated with Ni and Cu.

Additionally, Station 8 is notably contaminated with Ni. Stations 4 and 5 are highly contaminated with Cr and Ni, while Stations 4, 5, 6, and 7 are highly contaminated with Cu. The contamination factor is also used to calculate the Pollution Load Index (Pli), which provides an overall assessment of pollution levels in soil and sediment. The PLi values for the Lohan River's sediment ranged from 1.25 (ST2) to 3.40 (ST5). With regards to Pli values, Stations 4 and 5 are categorized as moderately heavily polluted (M-Hp), Stations 6, 7, and 8 are categorized as moderately polluted, whereas Stations 1, and 2 are slightly polluted (Sp). Control Station 3 is categorized as slightly polluted (Sp), while Stations 9 and 10 are categorized as not polluted (Up).

Based on the enrichment factor (EF), Co and Zn fall into deficiency to minimal enrichment (DME, EF<2) at all stations along Lohan River and the control stations. For the control stations, deficiency to minimal enrichment also occurs for Cr at Stations 9, Ni at Stations 9 and 10, and Cu at Stations 3 and 9. Moderate enrichment occurs for Cr at Stations 1 and 10 and for Cu at Station 10. Significant enrichment (EF = 5 – 20), occurs at Station 3 for Cr and Ni. Along the Lohan River, the enrichment factor starts from Moderate enrichment, which occurs for Cr at Station 1. Significant enrichment (SE) occurs for Cr, Ni, and Cu at Stations 2, 4, 5, 6, 7, and 8. Station 1 is significantly enriched with Ni and Cr.

Results from the PERI calculation indicate that all stations fall into the low-risk category. The PERI method assesses the potential ecological danger posed by heavy metal pollutants and evaluates the combined influence of other environmental contaminants. One key factor included in the PERI evaluation is the potential toxicity of the respective metals, which reduces the overall toxicity potential of heavy metals as stipulated by established standards. This includes the Maximum Allowable Concentration (MAC) suggested by [30], the USEPA SQG heavily polluted, the Canadian ISQG probable Effect Level (PEL) (31), and the Australian New Zealand ISQG High Guideline Value (H-GV).

The control station, Station 3 at the Lohan Toki River, and Stations 9 and 10 at the Moroli River fall into the slightly polluted and unpolluted categories based on the pollution load index calculation. The Pli considers the combined effect of all studied metals. However, in the Igeo index and contamination factor index (CF), which evaluate individual metals, Station 3 is categorized as seriously contaminated and has a very high pollution factor for Cr and Ni. Along the Lohan River, from Stations 1 to Station 8, the heavy metals Cr, Ni, and Cu are categorized as seriously contaminated in the Igeo index and display very high pollution factors for the pollution factor index. The Pli index categorizes the Lohan River as moderately polluted with Cr, Ni, and Cu. Despite these findings, the Possible Environmental Risk Index (PERI) categorized the pollution in the Lohan River as low risk.

CONCLUSIONS

The Lohan River is contaminated with high concentrations of Cr, Ni, and Cu, as observed at all stations along the river stretch. The metal concentrations exceed the Maximum Allowable Concentration (MAC) suggested by [30], the USEPA SQG threshold for heavily polluted conditions, the Canadian ISQs Probable Effect Level (PEL), and the Australian & New Zealand ISQG High Guidelines Value (H-GV). The consistent presence of heavy metals in the river sediment along the Lohan River is attributed to the long history of metal accumulation, disturbances in sediment by stone quarrying of the river, remobilization, and redistribution during flood. Accumulated heavy metals that cause pollution in the Lohan River sediment are contributed by the former Mamut Copper Mine (MCM) activity for Cu and Zn and from erosion of soil from ultrabasic hills surrounding the river catchment for Co, Cr, and Ni. Ecological risk indices that look into individual heavy metals, such as the Igeo and Contamination factor indexes, classify the Lohan River as seriously contaminated and very high pollution with Ni, Cr, and Cu. Despite the high heavy metal content in sediment, the heavy metal concentrations in Lohan River water are still low and comparable with pristine river water in Sabah. Furthermore, the metal concentrations in the water are below the Class IIA/IIB thresholds of the Malaysian NWQS, thus fit for recreational purposes.

Table 5. Environmental indices for sediment pollution levels in the Lohan River.

		Co	Cr	Ni	Cu	Zn	PLi	PERI
ST1	Igeo	-1.76	0.54	1.18	1.75	-1.06	1.64 Slightly polluted, Sp	49.51 Low risk
	CF	0.44	2.18	3.40	5.04	0.72		
	EF	1.00	4.94	7.71	11.42	1.63		
ST2	Igeo	-2.83	0.85	1.01	1.65	-1.96		
	CF	0.21	2.71	3.01	4.70	0.39	1.25 Slightly polluted, Sp	54.94 Low risk
	EF	0.52	6.72	7.40	11.67	0.96		
ST3	Igeo	-0.07	2.53	2.48	-1.71	-1.30		
	CF	1.42	8.65	8.36	0.46	0.61	1.96 Slightly polluted, Sp	97.54 Low risk
	EF	1.88	11.45	11.07	0.61	0.80		
ST4	Igeo	-0.52	2.22	2.19	2.28	-0.97		
	CF	1.04	7.01	6.85	7.28	0.77	3.08 Moderately-heavily polluted	114.70 Low risk
	EF	1.18	7.90	7.72	8.21	0.86		
ST5	Igeo	-0.33	2.10	2.50	2.55	-0.90		
	CF	1.19	6.41	8.49	8.78	0.80	3.40 Moderately-heavily polluted	128.38 Low risk
	EF	1.31	7.02	9.30	9.62	0.88		
ST6	Igeo	-1.73	1.81	1.94	2.40	-1.51		
	CF	0.45	5.25	5.75	7.92	0.53	2.24 Moderately polluted, Mp	99.50 Low risk
	EF	0.59	6.89	7.55	10.40	0.69		
ST7	Igeo	-0.94	1.79	2.17	2.39	-1.31		
	CF	0.78	5.17	6.75	7.88	0.61	2.65 Moderately polluted, Mp	105.97 Low risk
	EF	1.01	6.66	8.70	10.16	0.78		
ST8	Igeo	-1.56	1.59	1.85	1.98	-1.69		
	CF	0.51	4.52	5.40	5.93	0.47	2.03 Moderately polluted, Mp	84.09 Low risk
	EF	0.74	6.61	7.89	8.66	0.68		
ST9	Igeo	ND	-3.27	-4.81	ND	ND		
	CF	ND	0.16	0.05	ND	ND	0.38 Unpolluted, Up	1.04 Low risk
	EF	ND	0.59	0.20	ND	ND		
ST10	Igeo	ND	-0.45	-0.16	-0.49	-6.34		
	CF	ND	1.10	1.34	1.07	0.02	0.49 Unpolluted, Up	17.65 Low risk
	EF	ND	3.55	4.35	3.46	0.06		
		Co	Cr	Ni	Cu	Zn	PLi	PERI
Notes	Igeo	All stations are Unpolluted, Up Igeo < 0	Up, ST9,10; Up-Mp ST1,2; Mp ST6,7,8 Mp-Sp, ST3,4,5	Up, ST9,10; Mp ST1,2,6,8 Mp-Sp, ST3,4,5,7	Up, ST3,9,10; Mp ST1,2,8; Mp-Sp, ST4,5,6,7	All stations are Unpolluted, Up Igeo < 0	Up ST9,10 Sp ST1,2,3 Mp ST6,7,8 M-Hp ST4,5	All stations are low risk of environmt pollution RI < 150
	CF	LCF, ST1,2,6,7,8, 9,10 MCF, ST3,4,5	LCF, ST9 MCF, ST1,2,10 CCF, ST6,7,8 VHCF, ST3,4,5	LCF, ST9 MCF, ST10 CCF, ST1,2,6,8 VHCF, ST3,4,5	LCF, ST3,9 MCF, ST10 CCF, ST1,2,8 VHCF, ST4,5,6,7	All stations Low Pollution, CF<1		
	EF	All station, Deficiency to minimal enrichment (DME) EF < 2	DME, ST9; ME, ST1,10; SE, ST2,3,4, 5,6,7,8	DME, ST9;10 SE, ST1,2,3,4, 5,6,7,8	DME, ST3,9 ME, ST10 SE, ST1,2,4, 5,6,7,8	All stations, Deficiency to minimal enrichment (DME) EF < 2		

Note: Geo accumulation index, Igeo – Class 0 - Up, Unpolluted Igeo<0; Class 1 - Up-Mp, Unpolluted-moderately unpolluted Igeo 0-1; Class 2 - Mp, Moderately polluted, Igeo 1-2; Class 3 - Mp-Sp, Moderately polluted-Seriously polluted, Igeo 2-3. Pollution factor (CF), LCF, Low contamination factor LCF<1; MCF, Moderate contamination factor 1≤CF<3; CCF, Considerable contamination factor 3≤CF<6; VHCF, Very high contamination factor CF ≥ 6. Enrichment Factor (EF), DME, Deficiency to minimal enrichment EF<2; ME, Moderate enrichment, EF = 2 – 5; SE, Significant enrichment, EF = 5 – 20. Pollution Load Index (Pli), Class 0 - Up - Unpolluted, PLi < 1; Class 1 - SP, Slightly polluted, 1 < PLI < 2; Class 2 - Mp, Moderately polluted, 2 < PLI < 3. Potential Ecological Risk Index, PERI – LR, Low-Risk RI < 150; MR, Moderate risk 150 ≤ RI < 300/

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