

Associations of redox conditions and organic matter with nickel and chromium partitioning in the Bahodopi River, a tropical lateritic mining river in Central Sulawesi

Nadaa Afririzka Manova¹, Indah Rachmatiah Siti Salami^{2*}, Anindrya Nastiti², Dwina Roosmini², Shintya Firna Ningsih¹, Rosetyati Retno Utami³

¹ Master's Program of Environmental Engineering, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia

² Environmental Management Technology Research Group, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia

³ Research Center for Limnology and Water Resources, National Research and Innovation Agency, Bogor 16911, Indonesia

* Corresponding author's e-mail: indahrss@itb.ac.id

ABSTRACT

Lateritic nickel mining can increase the transport of metal-bearing particles into river systems, where sediment–water partitioning governs metal mobility and ecological exposure. Although redox conditions and organic matter are recognized as factors associated with metal partitioning, their relative importance under tropical lateritic mining conditions remains poorly understood. This study examined associations between redox-related and organic matter-related variables and nickel (Ni) and chromium (Cr) partitioning between sediment and water at nine stations along the Bahodopi River, Indonesia, sampled during the dry season, using log-transformed distribution coefficients (logK_d). Oxidation–reduction potential (ORP) showed the strongest association with Ni partitioning ($\rho = 0.756$, $p = 0.018$), while sediment organic matter showed the strongest association with Cr partitioning ($\rho = 0.689$, $p = 0.040$), sediment Fe/Mn ratio and dissolved organic carbon showed weak, non-significant associations with either metal. However, because ORP and logK_d both increased with distance from the upstream station, partial correlation analysis showed that the ORP–logK_d association weakened substantially and lost significance once this spatial trend was accounted for, indicating that spatial confounding contributed to the observed relationship. Multiple regression models explained a large share of variance in logK_d for both metals, although only the Ni model was statistically significant, and diagnostics showed that model fit was disproportionately influenced by a small number of stations. These findings suggest that Ni and Cr partitioning may be associated with different environmental variables in this system, but given the small number of stations, single sampling campaign, and evidence of spatial confounding, these associations should be regarded as preliminary and warrant confirmation through spatially and temporally replicated sampling.

Keywords: oxidation–reduction potential, sediment organic matter, distribution coefficient (K_d), nickel mining, tropical river.

INTRODUCTION

The increasing demand for electric vehicles and renewable energy technologies has accelerated the expansion of lateritic nickel mining worldwide, increasing concerns over metal contamination in freshwater ecosystems (Shiquan

and Deyi, 2023; USGS, 2025). Indonesia, which hosts some of the world's largest lateritic nickel resources, has experienced rapid mining development, particularly in Sulawesi, where extensive land disturbance enhances the transport of metal-bearing particles from mining areas into adjacent river systems (Prasetyo, 2016; Yani et al., 2024).

Consequently, understanding the environmental processes governing metal transport in mining near rivers has become increasingly important.

Lateritic nickel deposits contain elevated concentrations of nickel (Ni), chromium (Cr), iron (Fe), manganese (Mn), and other trace metals that can be mobilized through weathering, erosion, surface runoff, and mining disturbances (Laksono et al., 2020; Sufriadin et al., 2015). Once released into aquatic environments, these metals partition dynamically between dissolved and sediment-bound phases, influencing their mobility, transport, bioavailability, and ecological risk (Burgess et al., 2024). Because sediment–water partitioning determines the environmental fate of trace metals, understanding the factors controlling this process is essential for improving water quality assessment and ecological risk evaluation in mining-affected rivers.

Sediment-water partitioning is governed by interacting physicochemical and biogeochemical processes, among which redox conditions and organic matter play particularly important roles (Kluska and Jabłońska, 2023; Zhao et al., 2024). Changes in oxidation-reduction conditions influence the stability of Fe- and Mn-(oxyhydr)oxides that serve as major sorbents for trace metals, thereby regulating metal retention or release between sediment and the dissolved phase. Under reducing conditions, the dissolution of these mineral phases may promote the release of previously adsorbed metals into porewater and overlying water, whereas oxidizing conditions generally enhance metal retention through the formation of stable oxide phases (Hong et al., 2026; Madadi et al., 2023). Organic matter further influences metal partitioning through adsorption, complexation, and organo-mineral associations that modify metal stability and transport (Swanson et al., 2023). Collectively, these processes determine the distribution of metals between dissolved and particulate phases under varying environmental conditions.

Although metal contamination in rivers near mining has been extensively investigated, most studies have focused on metal concentrations in water, sediment, or biota rather than on the environmental processes controlling sediment–water partitioning (Schwantes et al., 2021; Ya’la et al., 2025). Moreover, field-based evaluations commonly rely on indirect sediment geochemical indicators, such as Fe/Mn ratios or sediment organic matter, whereas direct measurements of oxidation–reduction potential (ORP) are less

frequently evaluated alongside these proxies (Yalin and Shenker, 2022). Consequently, the relative importance of redox-related and organic matter-related variables in explaining metal partitioning remains poorly understood, particularly in tropical lateritic mining rivers characterized by strong geochemical heterogeneity (W. Liu et al., 2022; Swanson et al., 2023). Furthermore, no study has investigated the relative importance of redox-related and organic matter-related controls on Ni and Cr sediment–water partitioning in the Bahodopi River, despite the rapid expansion of lateritic nickel mining in the watershed.

The Bahodopi River in Morowali Regency, Central Sulawesi, provides an ideal natural system for investigating these processes because it flows through a tropical region undergoing active lateritic nickel mining, including open-pit operations. Runoff and erosion from disturbed landscapes introduce metal-bearing sediments into river while creating dynamic physicochemical conditions that influence sediment–water interactions (Cuevas et al., 2024; Qiao et al., 2023). These characteristics make the river suitable for evaluating environmental controls on Ni and Cr partitioning.

To address these knowledge gaps, this study compared associations between redox-related variables (oxidation–reduction potential and sediment Fe/Mn ratio) and organic matter-related variables (dissolved organic carbon and sediment organic matter) and Ni and Cr sediment–water partitioning in the Bahodopi River. Because longitudinal river sampling designs are prone to confounding between co-occurring environmental gradients, this study also evaluated whether the observed associations between redox conditions and metal partitioning held after accounting for spatial position along the river. By integrating direct measurements of redox conditions with conventional sediment geochemical proxies in a tropical lateritic mining river, this study offers field-based insight into the relative importance of these variables and highlights considerations relevant to designing more robust environmental monitoring frameworks in mining-affected watersheds.

MATERIALS AND METHODS

Study area

This study was conducted in the Bahodopi River, Morowali Regency, Central Sulawesi,

Indonesia, a watershed located in the vicinity of lateritic nickel mining activities. The river system lies within a landscape shaped by open-pit extraction and ore-processing operations, with several sections located in close proximity to mining facilities. The river flows downstream toward coastal environments, making it a suitable system for investigating metal transport and transformation processes in areas near mining activity. The distribution of sampling stations and the geographical setting of the study area are illustrated in Figure 1.

Sampling stations were established longitudinally along the river, extending from upstream areas located near mining activities to downstream sections. This spatial design enabled the assessment of variations in physicochemical conditions, metal concentrations, and sediment–water partitioning along the river’s continuum. The geographic coordinates and distance from the upstream station for each of the nine sampling stations are presented in Table 1.

Sampling was conducted in September 2025, during the dry season, when river discharge and dilution capacity are typically lower and metal concentrations in sediment and water are more likely to reflect ongoing geochemical processes rather than being diluted by high-flow conditions, as similarly reported for dry-season sediment

sampling in mining-affected tropical catchments, where moderate Cr and Ni contamination was linked to nearby mining activity and adjacent human settlements (Cáceres Obada et al., 2025). Land use adjacent to the sampling stations consisted predominantly of residential settlements along the river corridor, with an active open-pit nickel mining area located near the upstream station (0 km), reflecting the mixed residential–mining land-use pattern common in tropical nickel-mining watersheds.

Water sampling and physicochemical measurements

Surface water samples were collected from the midstream section at each station using pre-cleaned polyethylene bottles. Two field-duplicate water samples were collected per station ($n = 18$ water samples total across 9 stations) to assess sampling precision. Sampling containers were soaked in 10% HNO_3 and rinsed with deionized water prior to use to minimize contamination.

Physicochemical parameters, including oxidation–reduction potential (ORP), were measured in situ using a PHT-027 Multi Parameter Water Quality Monitor, calibrated prior to fieldwork using standard calibration solutions in accordance with SNI 8995:2021. These parameters were

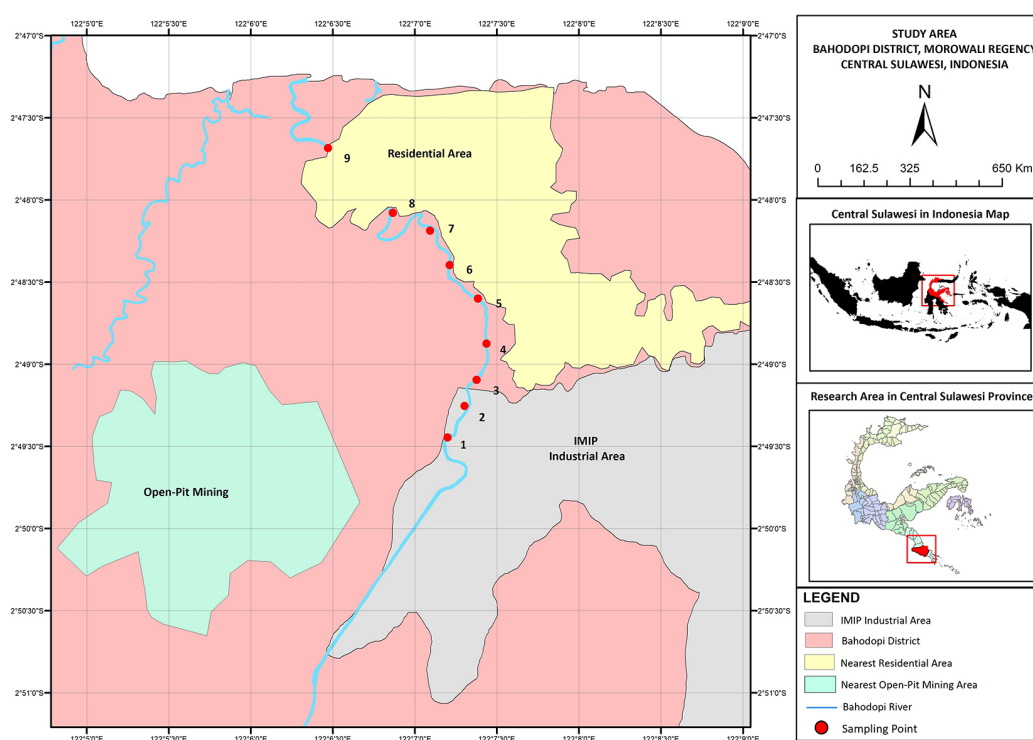


Figure 1. Location of the study area and sampling stations along the Bahodopi River

Table 1. Coordinates and distance for each sampling stations

Distance from mining (km)	Station	Coordinates
0	1	2°49'26.7"S 122°07'12.0"E
0.5	2	2°49'15.2"S 122°07'18.2"E
1.5	3	2°49'5.6"S 122°07'22.7"E
2	4	2°48'52.4"S 122°07'26.3"E
2.5	5	2°48'35.9"S 122°07'23.1"E
3	6	2°48'23.8"S 122°07'12.8"E
4	7	2°48'11.1"S 122°07'5.7"E
5	8	2°48'4.7"S 122°06'52.0"E
6	9	2°47'41.0"S 122°06'28.3"E

selected because they influence metal speciation, adsorption–desorption reactions, and metal mobility in aquatic environments (Kluska & Jabłońska, 2023; Zhao et al., 2024)

Water samples for dissolved metal analysis were filtered in situ through 0.45 µm membrane filters to obtain the dissolved fraction. Filtrates were acidified to pH < 2 using ultrapure nitric acid and stored at 4°C until laboratory analysis.

Dissolved organic carbon (DOC) concentrations were determined using a total organic carbon (TOC) analyzer. DOC was included as an explanatory variable because dissolved organic ligands can form complexes with metal ions and influence their transport, mobility, and bioavailability in aquatic systems (P. Wu et al., 2024; Xie et al., 2025).

Sediment sampling and analysis

Surface sediment samples (0–5 cm) were collected from depositional zones using a stainless-steel scoop, following SNI 6989.58:2008. Water depths at the sampling stations ranged from approximately 20 to 50 cm, and the shallow flow conditions did not allow meaningful depth stratification of the water column or surface sediment. Therefore, composite sampling across lateral positions within each station was used to obtain a representative sample of the depositional area. Following standard sediment-sampling guidance, sub-samples were collected from multiple

depositional zones, including the left bank, right bank, and center channel, and combined into a single composite sample for each station. Two field-duplicate composite samples were collected at each station to assess sampling precision, resulting in 18 sediment samples from nine stations.

Sediment organic matter content was determined using the loss-on-ignition (LOI) method following ASTM D2974-20. Approximately 5 g of dried sediment was combusted at 650 °C for 4 hours, and organic matter content was calculated from mass loss during ignition. LOI was included because sediment organic matter can influence metal binding capacity and modify redox micro-environments within sediments.

Sediment organic matter was estimated using the LOI method, which was selected for its simplicity, low cost, and wide applicability in comparative field-based geochemical studies. As with other applications of LOI in mineral-rich sediments, measured values may include a minor contribution from the loss of structural (bound) water in clay minerals and Fe-(oxyhydr)oxides during combustion, a well-documented characteristic of the method rather than an error specific to this study. Accordingly, %LOI values in this study are interpreted as a relative, comparative indicator of sediment organic content across stations, consistent with its common use in similar geochemical partitioning studies (Howard and Howard, 1990).

Metal analysis

Dissolved concentrations of Ni, Cr, Fe, and Mn in water samples were determined using Inductively Coupled Plasma–Optical Emission Spectrometry (ICP–OES) following acid preservation and filtration. Prior to analysis, water samples were filtered through 0.45 µm membrane filters and acidified to pH < 2 with ultrapure HNO₃. Sediment samples were digested using a microwave-assisted acid digestion procedure with concentrated HNO₃ and HCl in accordance with USEPA Method 3051A to obtain acid-extractable metal concentrations. The resulting digestates were analyzed using ICP–OES under appropriate quality control procedures. In this study, Fe and Mn were determined as total (acid-extractable) concentrations following USEPA Method 3051A digestion, and therefore the resulting Fe/Mn ratio reflects bulk elemental abundance rather than the speciation of specific Fe/Mn mineral phases or oxidation states. This

ratio should accordingly be interpreted as an indirect, integrative proxy rather than direct evidence of specific redox transformations.

Chromium was quantified as total dissolved and total acid-extractable Cr using ICP–OES, which does not distinguish between Cr(III) and Cr(VI) species. This is consistent with common practice in environmental monitoring, where accurate assessment of chromium contamination in mining-influenced watersheds requires distinguishing between the environmentally contrasting Cr(III) and Cr(VI) species, yet environmental monitoring and risk assessments still rely predominantly on total chromium concentrations (Kutlu et al., 2026).

Sediment redox proxy (Fe/Mn ratio)

The sediment Fe/Mn ratio was used as an indirect geochemical indicator of redox conditions. Fe&Mn exhibit different redox sensitivities, with manganese generally becoming mobilized under reducing conditions more readily than iron. Consequently, variations in sediment Fe/Mn ratios may reflect changes in redox status and metal cycling processes within sediments (Sivan et al., 2026; C. Zhang et al., 2014). Unlike ORP measurements, which represent real-time redox conditions, Fe/Mn ratios provide an integrated indication of longer-term sediment redox conditions.

Sediment and water metal partitioning

Metal partitioning between sediment and water phases was evaluated using the distribution coefficient (K_d) as shown in Equation 1:

$$K_d = \frac{C_{\text{sediment}}}{C_{\text{water}}} \quad (1)$$

where: C_{sediment} is the metal concentration in sediment (mg kg^{-1}) and C_{water} is the dissolved metal concentration in water (mg L^{-1}). K_d values were expressed in L kg^{-1} and log-transformed ($\log K_d$) prior to statistical analysis.

The distribution coefficient is widely used to evaluate metal mobility and partitioning behavior, where higher values indicate stronger sediment association and lower values indicate greater mobility in the dissolved phase. This approach is consistent with field-based K_d estimates

reported elsewhere for river systems, where partitioning coefficients between dissolved and particulate/sediment phases are calculated directly from measured concentrations rather than derived from equilibrium modeling (Grard and Delière, 2023), and the resulting values should be interpreted as station-scale, not micro-scale, partitioning estimates.

Statistical analysis

Prior to inferential analyses, data normality was assessed using the Shapiro–Wilk test because of the relatively small sample size ($n = 9$). Variables with p-values greater than 0.05 were considered normally distributed, whereas variables with p-values below 0.05 were considered non-normal. Depending on data distribution, Pearson correlation analysis was applied to normally distributed variables, whereas Spearman rank correlation analysis was used when normality assumptions were not satisfied. Correlation analyses were conducted to evaluate relationships between $\log_{10} K_d$ and environmental variables, including ORP, Fe/Mn ratio, DOC, and sediment organic matter (%LOI). 95% confidence intervals for Spearman correlation coefficients were calculated to assess the precision of the estimated associations, particularly for relationships near the conventional significance threshold ($p \approx 0.05$). Given the wide observed range in DOC concentrations, a sensitivity analysis was additionally performed by recalculating correlation and regression results after excluding the station with the highest DOC value, to evaluate whether this observation disproportionately influenced the reported relationships.

To evaluate the relative contribution of redox and organic matter variables to metal partitioning, multiple linear regression analyses were conducted using $\log K_d$ for Ni and Cr as response variables and ORP, Fe/Mn ratio, DOC, and OM as predictor variables (Madadi et al., 2023; Zhao et al., 2024). Because ORP and $\log K_d$ both showed an apparent increase with distance from the upstream station, a partial Spearman correlation was additionally performed to determine whether the ORP– $\log K_d$ relationship remained after accounting for this shared longitudinal trend, following approaches used to disentangle spatially confounded environmental gradients in river systems (N. Liu et al., 2026). To further assess the reliability of the regression models given the small

number of observations relative to the number of predictors, standardized coefficients, 95% confidence intervals, and variance inflation factors (VIF) were calculated to check for multicollinearity among predictors, and Cook's distance was used to identify individual stations with disproportionate influence on the model fit (Belsley et al., 2005). A VIF below 5 was considered indicative of acceptable multicollinearity, and stations with Cook's distance exceeding $4/n$ were flagged as potentially influential.

Quality assurance and quality control

Quality assurance and quality control (QA/QC) procedures for metal analysis were implemented by the certified analytical laboratory according to its established standard operating procedures for ICP–OES analysis. Instrument calibration, sample preparation, and metal determination were conducted by the laboratory following its routine analytical procedures, with sediment digestion based on USEPA Method 3051A (USEPA, 2018). Field duplicate samples were collected for both water and sediment at each sampling station to assess sampling and handling consistency. However, batch-specific laboratory QA/QC information, including method detection limits (MDLs), procedural blank results, laboratory duplicate precision, and certified reference material (CRM) recoveries, was not included in the analytical results provided to the authors. Consequently, these laboratory QA/QC parameters could not be independently assessed in the present study. The reported metal concentrations were therefore used as provided by the certified analytical laboratory and interpreted based on the documented analytical methods, acknowledging that batch-specific laboratory QA/QC parameters could not be independently verified.

RESULTS

The spatial distribution of sediment–water partitioning coefficients (logKd) and environmental variables along the Bahodopi River is shown in Figure 2. Both logKd Ni and logKd Cr generally increased from upstream to downstream, a pattern broadly mirrored by ORP, which became progressively less reducing along the river. In contrast, sediment Fe/Mn ratio, DOC, and OM showed greater spatial

variability without a clear longitudinal trend, including a localized peak in Fe/Mn ratio at the 2 km station that was not matched by a corresponding rise in logKd.

Higher downstream logKd values indicate a greater proportion of Ni and Cr associated with the sediment phase relative to the dissolved phase. This pattern coincided with progressively higher ORP values along the river, whereas no comparable longitudinal trends were evident for sediment Fe/Mn ratio, DOC, or OM.

Data normality was checked using the Shapiro–Wilk test before correlation analysis. ORP and DOC were normally distributed, while Fe/Mn ratio, OM, logKd Ni, and logKd Cr were not. Since both logKd variables were non-normal, Spearman correlation was used consistently across all variable pairs. Correlation results are visualized in Figure 3, with exact values summarized in Table 2.

To complement this visual overview, the corresponding Spearman correlation coefficients (ρ) and significance levels (p-values) are summarized in Table 2.

ORP showed the strongest association with logKd Ni, while sediment organic matter showed the strongest association with logKd Cr (Table 2). Fe/Mn ratio and DOC were weakly and non-significantly related to logKd for either metal. All ORP readings were negative throughout the study area, indicating generally reducing conditions. It is worth noting that the confidence intervals for most correlations were fairly wide, which is expected given the small number of sampling stations ($n = 9$) and suggests that these associations should be interpreted with some caution.

Because both ORP and logKd increased along the river, we checked whether this relationship still held once distance from the upstream station was taken into account. After this adjustment (partial correlation controlling for distance), the ORP–logKd association weakened for both metals for Cr, ρ dropped from 0.664 ($p=0.051$) to 0.367 ($p=0.371$), for Ni, ρ dropped from 0.756 ($p=0.018$) to 0.613 ($p=0.106$) and was no longer statistically significant for either metal, suggesting that part of the apparent relationship between ORP and metal partitioning may simply reflect their shared spatial pattern along the river rather than a direct effect of redox conditions alone.

Multiple regression models using ORP, Fe/Mn ratio, DOC, and OM as predictors explained a large share of the variation in logKd for both

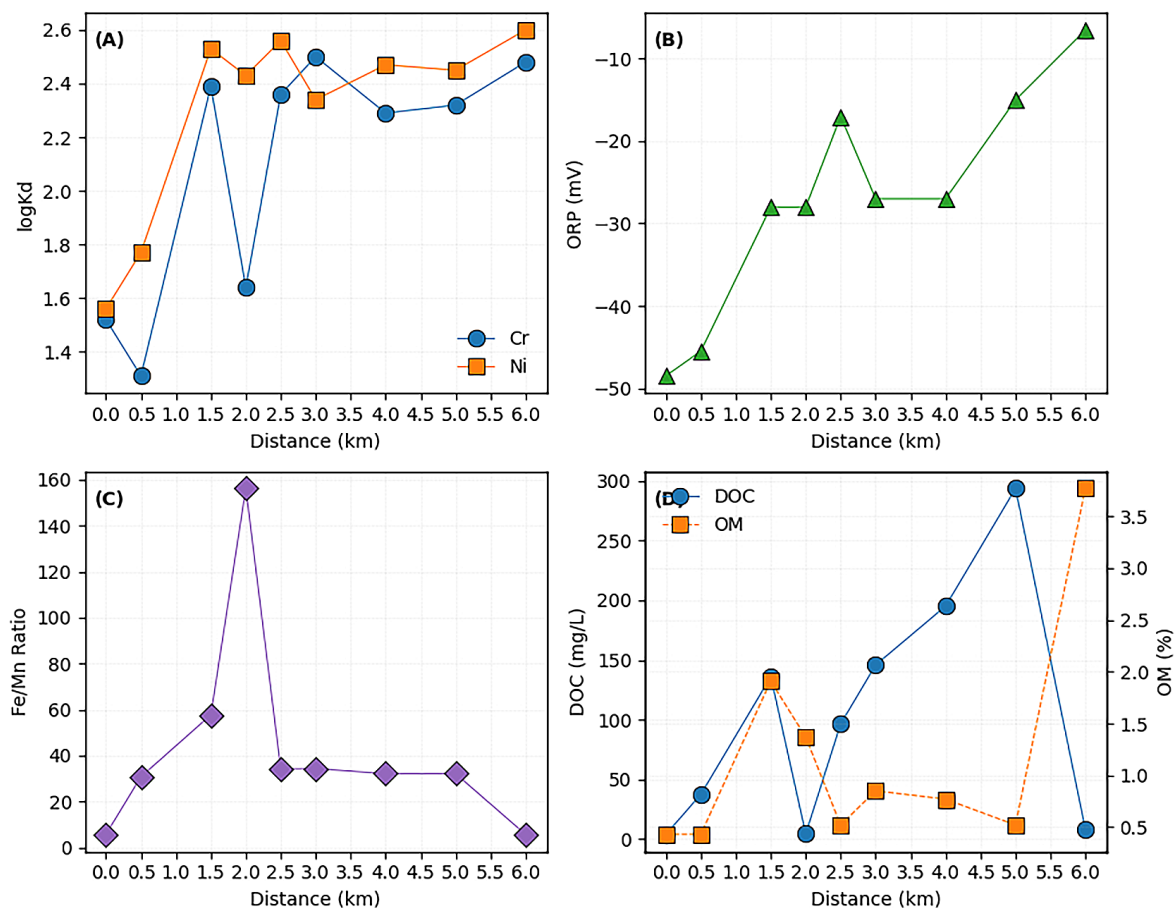


Figure 2. Spatial variation of environmental variables and sediment–water metal partitioning along the Bahodopi River: (A) logKd of Ni and Cr; (B) ORP; (C) sediment Fe/Mn ratio; and (D) DOC and sediment OM

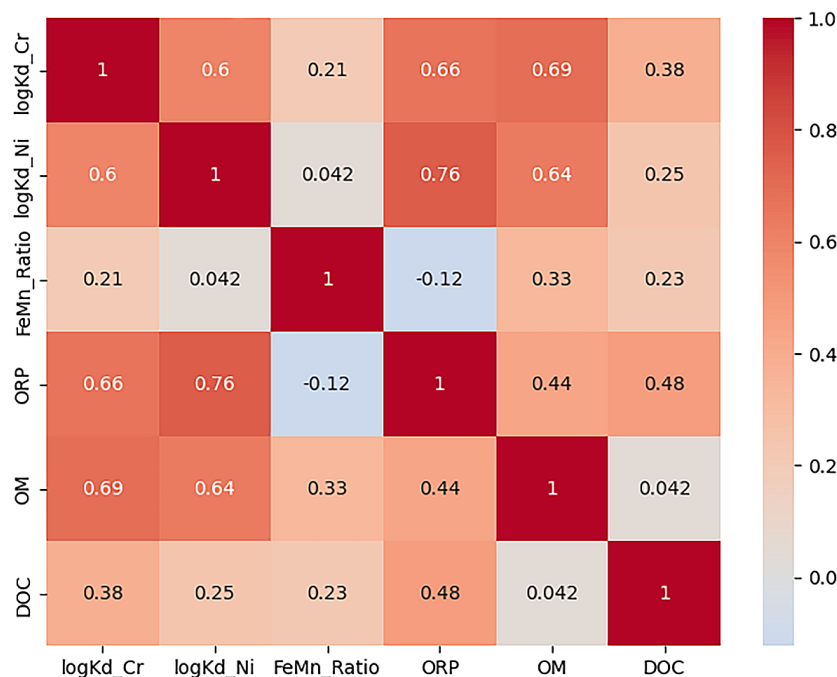


Figure 3. Spearman correlation matrix among environmental variables and metal partitioning coefficients (* $p < 0.05$, ** $p < 0.01$). *Red colors indicate positive correlations, with darker shades representing stronger positive relationships, blue colors indicate negative correlations, with darker shades representing stronger inverse relationships

Table 2. Spearman correlation coefficients between environmental variables and sediment–water metal partitioning coefficients

Variable	ρ (logKd Cr)	p-value	95% CI (Cr)	ρ (logKd Ni)	p-value	95% CI (Ni)
ORP	0.664	0.051	[−0.052, 0.982]	0.756	0.018	[0.063, 1.000]
Fe/Mn	0.209	0.589	[−0.600, 0.953]	0.042	0.915	[−0.738, 0.914]
DOC	0.383	0.308	[−0.459, 0.890]	0.250	0.516	[−0.722, 0.842]
OM	0.689	0.040	[−0.028, 0.971]	0.639	0.064	[−0.191, 0.995]

metals, although only the Ni model was statistically significant overall (Table 3). Even so, none of the individual predictors reached significance on their own, and VIF values below 3 indicated that multicollinearity was not a major concern.

A closer look at model diagnostics showed that a few stations particularly those at 2, 2.5, 5, and 6 km had a disproportionate influence on the regression results, with the 6 km station standing out most strongly in the Cr model. This suggests that the observed relationships were not evenly represented across all nine stations, and that a handful of locations carried more weight in shaping the regression outcome than the rest.

Given the unusually wide range in DOC concentrations, we also checked whether excluding the station with the highest DOC value (5 km; 293.6 mg L^{−1}) changed the results. The weak DOC–logKd correlations remained essentially unchanged with or without this station, indicating that this relationship was not being driven by a single extreme value. However, excluding this station noticeably increased the regression R² for both metals, further supporting the earlier observation that a small number of stations had a stronger-than-average influence on the overall model fit.

DISCUSSION

Among the variables examined, ORP showed the strongest bivariate association with logKd

Ni, while sediment organic matter (OM) showed the strongest association with logKd Cr. However, partial correlation analysis indicated that the ORP–logKd relationship weakened considerably once distance from the upstream station was taken into account, suggesting that this association is, at least in part, confounded by the shared longitudinal pattern between ORP and logKd along the river rather than reflecting an independent redox effect. This pattern illustrates a broader challenge in river studies with a longitudinal sampling design, where multiple physicochemical variables often trend together along the flow path simply because they share a common spatial gradient, making it difficult to separate a genuine mechanistic relationship from co-occurring spatial trends. Spatial autocorrelation of this kind has been increasingly recognized in heavy-metal studies of river and sediment systems, where both geological setting and anthropogenic activity, including mining, can generate strong spatially structured patterns independent of any direct causal linkage between individual variables (N. Liu et al., 2026).

Even so, a mechanistic role for redox conditions in Ni and Cr partitioning remains plausible and is consistent with the broader geochemistry of lateritic mining environments, where Fe-(oxy) hydroxides such as goethite and ferrihydrite are major hosts for Ni and other trace metals (Santoro et al., 2022). Under reducing conditions, reductive dissolution of these Fe-bearing phases can release

Table 3. Statistical performance of regression models predicting metal partitioning (logKd) for Cr and Ni

Predictor	Cr: Coef. (SE)	Cr: 95% CI	Cr: Std. β	Cr: VIF	Ni: Coef. (SE)	Ni: 95% CI	Ni: Std. β	Ni: VIF
Constant	2.328 (0.692)	[0.408, 4.249]	—	—	2.535 (0.380)	[1.481, 3.589]	—	—
ORP	0.0179 (0.013)	[−0.019, 0.055]	0.524	2.84	0.0193 (0.007)	[−0.001, 0.040]	0.703	2.84
Fe/Mn	−0.0017 (0.002)	[−0.008, 0.005]	−0.162	1.06	0.0026 (0.001)	[−0.001, 0.006]	0.319	1.06
DOC	0.0019 (0.002)	[−0.003, 0.006]	0.420	2.22	0.0010 (0.001)	[−0.001, 0.003]	0.270	2.22
OM	0.0996 (0.166)	[−0.361, 0.560]	0.235	2.84	0.0599 (0.091)	[−0.193, 0.313]	0.176	2.84
R ² (Adj. R ²)	0.783 (0.566)	—	—	—	0.899 (0.798)	—	—	—
F (model p)	3.613 (0.121)	—	—	—	8.913 (0.029)	—	—	—

previously sorbed metals into the dissolved phase, while more oxidizing conditions tend to stabilize them and favor metal retention in sediment (Hong et al., 2026; Madadi et al., 2023). All stations in this study showed negative ORP values, indicating persistently reducing conditions, which may be related to the intensive land disturbance from open-pit nickel mining activity near the upstream station (0 km), as well as fine sediment inputs from surrounding residential and mining land use that can limit oxygen exchange at the sediment–water interface (Cuevas et al., 2024; Qiao et al., 2023). This mechanism offers a plausible explanation for the observed ORP gradient, though confirming it as an active driver of metal partitioning independent of spatial position would require sampling designs that decouple redox variation from longitudinal distance, such as repeated measurements at fixed stations over time or a non-linear spatial arrangement of sampling points.

It is also worth noting that ORP was measured in the surface water column rather than directly within the sediment or porewater. Given the shallow water depth at the sampling stations (approximately 20–50 cm), the water column was unlikely to be thermally or chemically stratified, so surface ORP readings likely reflect conditions throughout the water column at each station. However, water-column ORP and sediment or porewater redox potential (Eh) are not necessarily equivalent, since redox conditions at the sediment–water interface can differ from those in the overlying water due to microbial activity and organic matter decomposition within the sediment itself (Chen et al., 2022). The associations reported between ORP and metal partitioning should therefore be understood as reflecting water-column redox conditions, which may only partly capture the redox environment directly governing sediment-bound metal behavior.

ORP showed a somewhat stronger association with logKd Ni than with logKd Cr, which may reflect differences in how the two metals behave geochemically. Nickel in lateritic systems is predominantly associated with Fe-(oxy)hydroxides and is therefore expected to be more sensitive to redox-driven transformations, whereas Cr partitioning is additionally influenced by processes such as oxidation state changes and interactions with organic matter (Delina et al., 2024). This distinction is broadly consistent with other studies reporting that Ni mobility tends to be more closely tied to Fe-phase transformations, while

Cr behavior is often governed by a wider range of interacting mechanisms (Wang et al., 2024). Nonetheless, in light of the spatial confounding identified above, this difference between Ni and Cr should be regarded as a descriptive pattern in the present dataset rather than confirmed evidence of contrasting redox sensitivities.

Sediment Fe/Mn ratio showed no meaningful relationship with logKd for either metal, including at the 2 km station, where a pronounced Fe/Mn peak was not accompanied by any corresponding change in logKd. Because Fe and Mn were measured as total acid-extractable concentrations rather than by mineral phase or oxidation state, the resulting ratio reflects bulk elemental abundance and may be more strongly shaped by sediment provenance and depositional history in this catchment located near active nickel mining than by ongoing redox processes (He et al., 2023; Yalin and Shenker, 2022). Similar limitation of bulk elemental ratios as redox proxies has been reported in other mining-affected sediment systems: in the Coeur d’Alène Lake system, Fe and Mn oxidation states and bonding environments in legacy-mining sediments were found to be primarily governed by in situ redox and organic matter dynamics rather than by bulk elemental ratios (Swanson et al., 2023). These results suggest that, at least in this river, the sediment Fe/Mn ratio is not a reliable stand-in for direct redox measurement, though this does not rule out its usefulness under different depositional settings.

Sediment organic matter showed a significant and comparatively robust association with logKd Cr, and, unlike ORP, did not display a strong longitudinal trend along the river, making this relationship less likely to be driven by the same spatial confounding. This association is consistent with known mechanisms of trace-metal binding to sediment organic matter, including complexation through carboxyl, phenolic, and hydroxyl functional groups (Delina et al., 2024; J. Zhang et al., 2023) and the formation of Fe–organic mineral associations that further stabilize sediment-bound metals (Zhu et al., 2022). Chromium is generally understood to interact more strongly with particulate organic matter and mineral–organic complexes than Ni, whereas Ni partitioning is thought to be more closely tied to Fe-oxide sorption and redox cycling. Organic matter therefore appears to be a supplementary, but not dominant, factor associated with metal retention in the Bahodopi River, consistent with a working hypothesis in

which OM helps stabilize sediment-bound Cr through direct complexation and Fe–OM associations, while exerting a comparatively weaker effect on the more redox-sensitive behavior of Ni. Given the sample size and observational nature of this study, this pattern should be treated as an association warranting further investigation rather than an established mechanism.

DOC, in contrast, showed weak and non-significant relationships with logK_d for both metals, and a sensitivity analysis confirmed that this weak relationship was not simply an artifact of the one station with an unusually high DOC value. While DOC is known to influence metal speciation through aqueous complexation (Li et al., 2024; Luko-Sulato et al., 2024). DOC concentration alone did not appear to explain metal partitioning patterns in this river. This is consistent with evidence that the composition and ligand-binding capacity of DOC, rather than its total concentration, are more important in governing its interaction with trace metals (F. Liu and Wang, 2022), an aspect that was not evaluated in the present study and remains a useful direction for future work.

Taken together, these findings suggest that Ni and Cr partitioning in the Bahodopi River may be associated with different environmental variables, ORP for Ni and sediment organic matter for Cr, but the present nine-station spatial dataset does not allow these associations to be confirmed as dominant or causal controls, particularly for ORP given its apparent confounding with longitudinal position. Rather than pointing to a single dominant redox-driven mechanism, the results are more consistent with multiple, metal-specific environmental influences that would benefit from confirmation through spatially and temporally replicated sampling, together with direct sediment or porewater redox measurements and speciation analysis for Cr.

These findings nonetheless carry practical relevance for monitoring rivers located near lateritic nickel mining activity. Since ORP showed a stronger association with metal partitioning than the sediment Fe/Mn ratio, incorporating direct ORP measurements alongside conventional sediment indicators may help capture near-real-time changes in metal mobility, for instance, following heavy rainfall events that introduce organic-rich sediment and promote more reducing conditions (Santoro et al., 2022), although this application would benefit from validation in future studies

with a larger number of stations and repeated temporal sampling.

Given the association observed between redox conditions and metal partitioning, maintaining more oxidizing conditions could, in principle, help limit the downstream mobility of Ni and Cr, and passive treatment approaches such as settling ponds and constructed wetlands have been used elsewhere to promote favorable biogeochemical conditions for metal immobilization (Opitz et al., 2021; Soda and Nguyen, 2023; Swanson et al., 2023). However, constructed wetlands are known to contain a mosaic of oxic and anoxic microzones rather than a uniformly oxidizing environment, so their performance for Ni and Cr retention depends on interacting redox, sorption, and organic matter processes rather than on redox management alone (H. Wu et al., 2023). Such approaches should therefore be considered a plausible management direction worth piloting in tropical nickel-mining watersheds like those in Indonesia, rather than a confirmed solution based on the present findings.

Collectively, these findings indicate that Ni and Cr partitioning in the Bahodopi River is associated with different geochemical factors, with Ni linked to water-column ORP and Cr to sediment organic matter. This suggests that metal mobility is controlled by multiple processes rather than by a single redox mechanism. Although these relationships are consistent with the known roles of Fe-(oxy)hydroxides and organic matter in metal binding, they should be considered exploratory due to the limited sampling stations, single sampling campaign, and potential influence of longitudinal position on ORP. These findings further suggest that monitoring metal mobility in tropical lateritic nickel-mining watersheds should consider multiple environmental indicators, including redox conditions, organic matter, and metal speciation, supported by repeated spatial and temporal sampling.

CONCLUSIONS

This nine station spatial survey found that ORP showed the strongest association with Ni partitioning, while sediment organic matter showed the strongest association with Cr partitioning, in the Bahodopi River, a tropical river located near lateritic nickel mining. However, partial correlation analysis showed that the ORP–logK_d association weakened and lost statistical significance

once distance from the upstream station was accounted for, indicating that this relationship was confounded, at least in part, by the shared longitudinal trend between ORP and river distance. The present dataset therefore does not support ORP as an independent or dominant driver of metal partitioning; rather, Ni and Cr appear to be associated with different environmental variables, pointing to multiple, metal-specific influences rather than a single dominant redox mechanism.

These findings should be interpreted as preliminary, given the single dry-season sampling campaign, the use of water-column rather than sediment/porewater ORP, the absence of Cr speciation, and the small number of stations relative to the number of predictors evaluated. Future studies incorporating spatially and temporally replicated sampling, direct sediment or porewater redox measurements, and Cr speciation analysis would help determine whether these associations reflect genuine mechanistic controls or remain shaped by the spatial gradient along the river. Even so, the associations identified here support incorporating multiple environmental indicators, including ORP and organic matter, rather than relying on a single proxy, into monitoring efforts for rivers located near tropical lateritic nickel mining.

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