Environmental impacts of nickel extraction and processing in South and Central Sulawesi, Indonesia

Report on water and sediment contamination • May 2025 campaign

Sulawesi, Indonesia

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Executive summary

Indonesia is the world's largest producer of nickel, holding more than 40% of global reserves and contributing over half of global mining output. Since the 2020 ban on raw ore exports, nickel extraction and processing have expanded rapidly, positioning the country at the center of the global electric vehicle and green energy transition. However, this rapid growth has also brought significant environmental and social costs, including land conflicts, overpopulation, unsafe working conditions, and widespread pollution.

To document these impacts, Source International partnered with Friends of the Earth Japan and WALHI South Sulawesi to conduct an independent environmental assessment in South and Central Sulawesi – key hubs for nickel extraction and processing. The project involves two field campaigns designed to collect scientific evidence on water, sediment, and air pollution in the area. These findings will support advocacy efforts targeting the electric vehicle battery industry in Indonesia, Japan, and Europe. This report presents the results of the first field campaign, carried out in May 2025 in Sorowako and Morowali.

The data revealed widespread heavy metal contamination in the area, reflecting the **combined influence of natural laterite geology and anthropogenic inputs from nickel mining and processing**. **Sediments were of particular concern:** concentrations of nickel, chromium, and cobalt were consistently far above international safety guidelines. For instance, nickel was 200 times higher than its Probable Effect Level, with median concentrations one to two orders of magnitude above the European baseline. In surface waters, manganese emerged as the most critical contaminant, exceeding Indonesian regulatory limits in more than 25% of the samples and reaching extreme concentrations – up to 200 times the national Environmental Quality Standard – in the Morowali Industrial Park. Chromium VI, a known human carcinogen, exceeded 10 µg/L in more than half of the water samples and exceeded the Class III Environmental Quality Standard for rivers and lakes (50 µg/L) in two cases. **The villages of Labota, Bahodopi, Nikkel, and Sorowako appeared particularly exposed** to the environmental impacts of nickel mining and processing.

Table of contents

Introduction

The context

Accounting for 42% of the total nickel reserves and 51% global mine production,[1,2] **Indonesia is the world's largest producer of nickel**, a key material in electric vehicle batteries and steel production. Much of these reserves are concentrated in Sulawesi, particularly in Central and Southeast Sulawesi. Following a 2020 export ban on unprocessed nickel ore,[3,4] the country has rapidly expanded its domestic processing capacity, including smelting, high-pressure acid leaching, and refining into high-value products. A focal point of this expansion is the Indonesia Morowali Industrial Park (IMIP) in Central Sulawesi, which has become the largest nickel processing hub in the region.[5–7] As global demand for nickel is projected to rise in the next few years,[2] Indonesia is poised to play an increasingly central role in the green economy transition.

Yet, **this nickel rush comes with profound social and environmental costs**.[5,6,8–10] On the social side, mining operations have significantly disrupted the lives and livelihood of indigenous coastal communities, with Kabaena Island[8] and Labota[5] serving as emblematic cases. The rapid pace of industrialization around nickel hubs has also seen a growth of mining towns. However, this development has been so rapid that it has often outpaced that of essential public services – including waste management, healthcare, education, and electricity supply.[5] Workers also face unsafe conditions due to insufficient occupational protection and exposure to concerning levels of pollution.[5,10]

Figure 1. Aerial view of the Sorowako mining area. Lake Matano and Lake Mahalona are visible in the background. Photo credit: Stefano Sbrulli for Source International, 2025.

These social effects are compounded by severe environmental impacts, ranging from water pollution to deforestation and biodiversity loss.[6–11] For example, a recent study in Kabaena Island (Southeast Sulawesi) found alarming levels of cadmium, zinc, and nickel in seawater around fishing villages – with concentrations in the mg/L range, over two orders of magnitude above the Indonesian Environmental Quality Standards.[8] Meanwhile, nickel refining relies heavily on coal-fed power plants, which have been driving a dramatic increase in coal consumption over the past few years.[6,7] These pressures occur within a habitat that includes endemic flora and fauna, stretches of undisturbed tropical forest, coastal mangrove ecosystems, coral reefs, and key biodiversity areas – such as the KBA Routa, which partially overlaps with Morowali's mining concessions.[7]

General objectives of the project

While national and international stakeholders have started to expose the hidden social and environmental costs of nickel extraction in Indonesia (e.g., in Kabaena Island[8]), much work remains to be done. To contribute to this effort, Source International partnered with Friends of the Earth Japan and the Indonesian Environmental Forum (WALHI) South Sulawesi to **conduct a comprehensive environmental impact assessment** in Sorowako (South Sulawesi) and Morowali (Central Sulawesi), two strategic hubs for nickel extraction and processing.

This report describes the results of the sampling campaign that took place in May 2025, during the wet season.

Location and past work

Sampling took place in two key nickel extraction and processing hubs: Sorowako and Morowali (Figure 1, Figure 2, and Figure 3). This entire region sits on a bedrock of laterite ore,[3] a mineral that contains nickel, iron, cobalt, manganese, and chromium.[12,13]

Sorowako, located inland in South Sulawesi, hosts the third largest nickel mine in Indonesia[14] and has been operating for more than 50 years.[15] The mine is owned by PT Vale Indonesia, which holds more than 70'000 hectares of concessions.[15] The area also includes a processing plant for nickel matte and new projects are being planned for new mine explorations and a smelting facility.[15–17] The local communities, which rely on farming, have a long history of complaints on the industry's impacts – including issues on land ownership, insufficient compensation, and impacts on agricultural productivity.[16] Water quality has also been an issue. Following complaints on increased turbidity in the Asuli village's spring water, in early 2023, FoEJ and WALHI South Sulawesi strengthened a water monitoring campaign that revealed concerning heavy metal pollution – including hexavalent chromium exceeding national and international drinking water standards.[16] In August 2023, FoEJ and HI South Sulawesi crystallized these concerns into a document – later signed by 104 organizations from 23 countries – that urged PT Vale to protect the basic human rights of communities surrounding the Sorowako Nickel Project.[16]

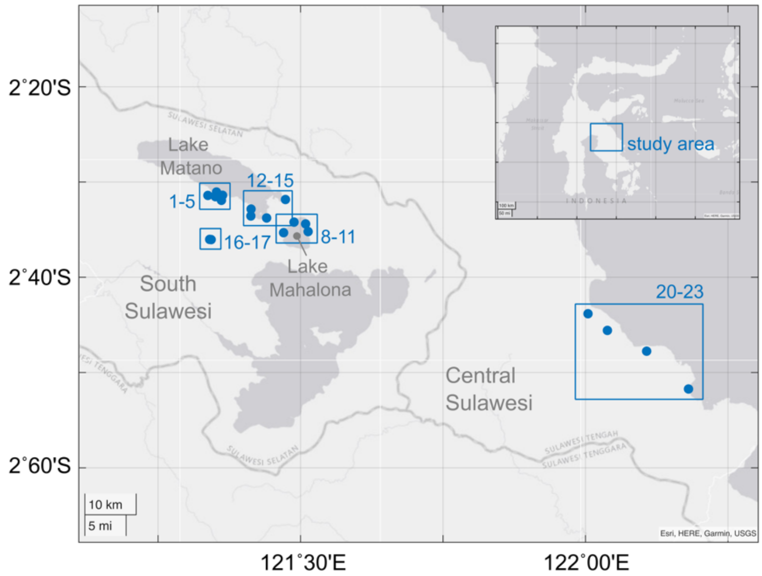


Figure 2. Overview of the sampling area. Samples 1 to 17 were collected in South Sulawesi, while samples 20 to 23 were taken in Central Sulawesi. Figure 3 gives more details of the areas in the blue squares.

The second focal area is the Morowali Regency, on the east coast of Central Sulawesi. This area hosts the Indonesia Morowali Industrial Park (IMIP), which is among the largest nickel processing facilities in Indonesia, and several active mining concessions.[5,7,10] In 2024, IMIP included more than 15 active smelters, high-power acid leach facilities, and several coal-fired power plants for energy supply.[7,10] The district also includes 12 villages, some of which have been severely impacted by industrial operations.[10] Notable examples include Bahodopi, Dampala, and Labota – once a fishing village now surrounded by IMIP's activities.[5,18] Major conflicts include environmental degradation, labor and human rights abuses, overpopulation, illnesses, socioeconomic strains, and militarization.[5,10,18] In January 2024, FoEJ and WALHI Central Sulawesi conducted a water sampling campaign in the area, finding nickel, chromium, and manganese above the Japanese Environmental Quality Standards in several instances.

Normative reference

We interpreted all analytical results in the context of national and international regulatory frameworks. For water, we refer primarily to the **Indonesian Water Quality Standards** for rivers and lakes (Table 1). The normative reference is the Government Regulation No. 22 of 2021 (Annex VI),[19] which sets environmental quality criteria for various inland and coastal waters based on 4 use-based classes – going from raw drinking water (Class I) to water for irrigation (Class IV).

In locations where water is used for drinking or domestic purposes, we interpreted the results in the context of the Indonesian Drinking Water Quality Standards, integrating the 2010 Ministry of Health Regulation No. 492[20] with a following update (Ministry of Health Regulation No. 2 of 2023; Annex I)[21]. The 2/2023 update kept most limits unchanged while setting more stringent standards for manganese (from 400 to 100 µg/L) and iron (from 300 to 200 µg/L) and introducing chromium VI as a mandatory parameter – thus, better aligning with the World Health Organization's Guidelines for Drinking Water Quality.[22]

Table 1 Overview of the normative reference for environmental quality evaluation. Metals not listed in this table are not regulated under the current normative. See main text for references and acronyms. See Table A3 for a detailed breakout of the Class I to IV values for rivers and lakes. † This value is not from the Canadian but from the United States' Environmental Protection Agency (consensus-based guidelines). [a] Introduced or modified in P 2/2023; see main text. [b] Regulated only in Class I waters. [c] 400 – 1'000 mg/L in lake water.

	Surface water (Indonesian guidelines)		**Sediments** (Canadian guidelines)	
Parameter	**Rivers and lakes (Class I to IV)**	**Drinking water**	**IQSG**	**PEL**
pH	6 – 9	6.5 – 8.5	–	–
Aluminum	–	200 µg/L	–	–
Antimony	–	20 µg/L	–	–
Arsenic	50 – 100 µg/L	10 µg/L	5.9 mg/kg	17 mg/kg
Barium	1000 µg/L	700 µg/L	–	–
Boron	1000 µg/L[b]	500 µg/L	–	–
Cadmium	10 µg/L	3 µg/L	0.6 mg/kg	3.5 mg/kg
Cobalt	200 µg/L	–	–	–
Chromium	–	50 µg/L	37 mg/kg	90 mg/kg
Chromium VI	50 – 1000 µg/L	10 µg/L[a]	–	–
Iron	300 µg/L[b]	200 µg/L[a]	–	–
Manganese	100 µg/L[b]	100 µg/L[a]	–	–
Mercury	1 – 5 µg/L	1 µg/L	0.17 mg/kg	0.49 mg/kg
Molybdenum	–	70 µg/L		
Nickel	50 – 100 µg/L	70 µg/L	–	48.6 mg/kg†
Lead	30 – 500 µg/L	10 µg/L	35 mg/kg	91.3 mg/kg
Copper	20 – 200 µg/L	2000 µg/L	35.7 mg/kg	197 mg/kg
Selenium	10 – 50 µg/L	10 µg/L	–	–
Zinc	50 – 2000 µg/L	3000 µg/L	123 mg/kg	315 mg/kg

Indonesia does not set specific quality criteria for sediments. For this reason, we referred to the **Canadian Environmental Quality Guidelines**,[23] as common in the literature (e.g., Marshall et al.[24]). This framework provides two metrics: the Interim Sediment Quality Guideline (ISQG) and the Probable Effect Level (PEL). The ISQG represents the concentration below which adverse effects on sediment-dwelling organisms are unlikely, while the PEL is the concentration above which adverse effects are likely to occur. For nickel only – which is not included in the Canadian Guidelines but is highly relevant to this project – we used the United States' consensus-based PEL.[25] All values are in Table 1.

As sediments appeared particularly polluted, we further compared our results to median sediment concentrations reported in the **Geochemical Atlas of Europe**.[26] This is a large dataset compiled in the context of the Forum of the European Geological Surveys (FOREGS) Geochemical Baseline Mapping program to establish baseline concentrations of elements in natural soils, stream waters, sediments, and floodplains across Europe. In this report, we used as a comparison the median stream sediment concentrations (“total” or, if not available, “aqua regia”; in mg/kg)[27]. Relevant values are reported directly in the text.

Sampling site and methods

Sampling sites

Sampling was conducted from May 21 to May 25, 2025, at the end of the wet season. We collected 19 water and 16 sediment samples in selected locations in Sorowako and Morowali. Most of these points were sampled in campaigns conducted by FoEJ and WALHI South and Central Sulawesi between 2022 and 2024 (Figure A1 in the Appendix).

In Sorowako, we visited 4 different areas (Figure 2 and Figure 3A). Samples 1 to 5 were collected from streams flowing into Lake Matano and passing through the villages of Sorowako and Nikkel (old Sorowako). Except for site 4, all drain from the main Sorowako mining area. These 5 points were also included in previous campaigns (water only; Figure A1). Samples 8 to 11 were collected in Lake Mahalona, east of the main Sorowako mining area. Although only the northwestern coast of the lake falls within PT Vale Indonesia's concession (red area in Figure 3A)[28], the local community indicated that all sites are impacted by mining in the Petea block or ore processing activities. For example, sample 8 is downstream of the Fiona dam, which was built by PT Vale to collect waste from ore processing. Samples 12 to 15 were from Lake Matano's tributaries away from urban areas. Locations 12 and 13 receive inputs from the main Sorowako mine, while site 15 is downstream of the Petea block on the lake's eastern side. Site 14, located under the access road that connects the Petea block to Sorowako's mining and processing area, appeared to be impacted by erosion (see also Figure 5A-B). Samples 16 and 17 were collected from domestic water sources in Asuli, a village south of the main Sorowako mining area. While most residents now rely on commercial water, some poor families may still rely on these springs also for drinking.

In Morowali, we obtained 4 water and sediment samples from streams receiving inputs from industrial activities and/or mining concessions (Figure 3B). Samples 20 and 21 were taken respectively from the Labota River and Bahodopi River and were impacted by IMIP's operations –

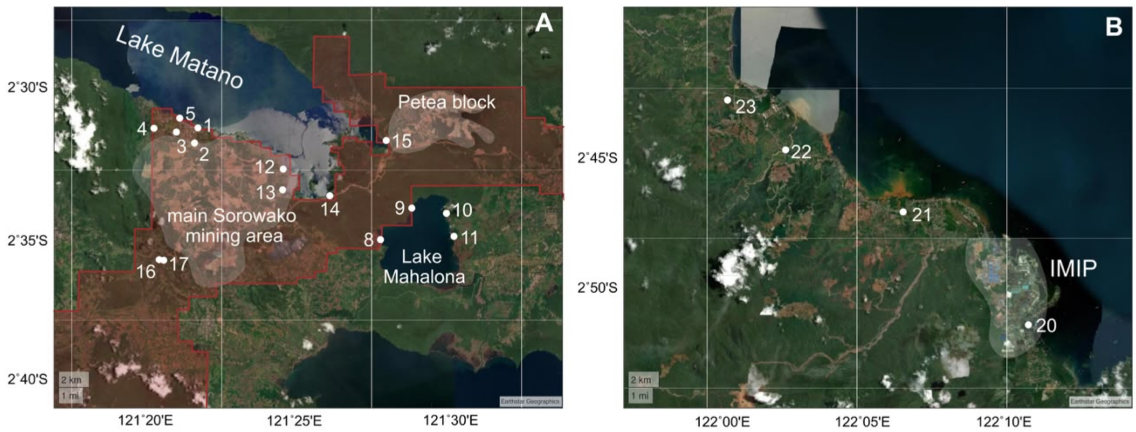


Figure 3. Satellite view of the sampling sites in South (A, samples 1 to 17) and Central (B, samples 20 to 23) Sulawesi. The red area in panel A is the extension of PT Vale Indonesia's Mining Business License Area as provided by the Indonesian Ministry of Energy and Mineral Resources.[28] The maps are from Matlab R2021b (Eastar Geographics).

and, for 21 only, upstream mines (see also Figure 5C-G). In 2024, FoEJ reported a smelter wastewater inflow in the Labota sampling location (sample 20). Sample 22 was collected from the Dampala River near the eponymous village. This site has been historically impacted by upstream mining and is likely to face further impacts from PT Vale's planned mine expansion projects. Last, we took sample 23 in the Onepute Jaya village, which receives inputs from a decommissioned mine within PT Vale Indonesia's concession. Like 22, we expect this site to be impacted by PT Vale Indonesia's upcoming mining operations.

General site and water characterization

In each location, we recorded the GPS position with a Garmin Fenix 7 watch and measured general water quality parameters with a multiparametric field probe (Hanna, HI 98194). The probe's pH and conductimetry sensors were calibrated daily with new standard solutions, namely pH 4 and 7 buffers and a 1413 µS/cm conductivity solution. The temperature probe was used uncalibrated. We placed the multiparametric probe in running water and recorded temperature, pH, and conductivity values after stabilization. We then rinsed the probe thoroughly with deionized water and stored it in its case.

Water and sediment sampling

We collected 19 water samples, of which 13 from streams, 4 from lake sides, and 2 from drinking water sources (Table A2). In each location, we obtained 2 sub-samples: one for the determination of heavy metals and the other for chromium VI. For heavy metals, we filtered approximately 50 mL of water into a Falcon tube using a 0.45 µm syringe filter and acidified it with ~ 0.5 mL of concentrated nitric acid (70%). For chromium VI, we filled a 50 mL Falcon tube with unfiltered water and added 1 mL of ammonium sulfate buffer.

In 16 locations, we also collected sediment samples (Table A2). Using a plastic scoop, we gathered surface sediments (0–10 cm) from exposed riverbeds and homogenized them inside a plastic container. They were quartered and ~ 100–150 g were placed into a clean sampling bag.

After collection, we stored all samples away from direct sunlight and put them in a refrigerator (4 ˚C) as soon as possible. During national and international transports, samples stayed at room temperature in the dark.

Chemical analyses

Water and sediment analyses were performed by an accredited laboratory (by ACCREDIA) within 15 days of collection. Filtered and acidified water samples were analyzed for 21 heavy metals following the procedure UNI EN ISO 17294-2:2023 (inductively coupled plasma mass spectrometry, ICP-MS). Unfiltered water samples were used to determine chromium VI via the EPA 7199 1996 method (ion chromatography with post-column derivatization and spectrophotometric detection).

Heavy metals in sediments were analyzed according to the combined method EPA 3051 A 2007 (microwave digestion) + EPA 6020 B 2014 (ICP-MS). Sediments were also analyzed for chromium VI via EPA 3060 A 1996 (basic extraction) + EPA 7196 A 1992 (colorimetric via spectrophotometric detection).

Table A1 reports the limits of detection (LoD) for the 22 analytes as provided by the laboratory. Estimated measurement uncertainties are on average 25% (6% to 36%) and 28% (range 20% to 50%) of the measured value for waters and sediments, respectively. These values are extrapolated from the measurement uncertainties provided in the laboratory test reports.

Data analysis

We analyzed all data with Excel and Matlab (R2012b). We computed boxplots, median, max, and min values using all available concentrations, also if below their limit of detection or not detected (n.d.; value set to 0; raw data in Table A3 and Table A4). We performed exploratory principal component analysis (PCA) in Matlab inputting standardized data matrices (via the "zscore" function) into the "pca" function.

For data analysis purposes, we converted GPS locations in degrees, minutes, and seconds as provided by the Garmin watch into decimal degrees (DD) using the following equation.

$$\mathrm{DD} = \mathrm{degrees} + \frac{\mathrm{minutes}}{60} + \frac{\mathrm{seconds}}{3600}$$

Last, we converted the Indonesian limit for total dissolved solids (TDS, 300 mg/L) in drinking water into an approximate electrical conductivity (EC) value using the equation $\mathrm{EC} = \mathrm{TDS}/k$, where k is an empirical constant ranging from 0.55 to 0.75.[29] k varies depending on the water's electric conductivity, being lower in freshwater and higher in saline environments. As a conservative estimate, we used $k = 0.55$, which works well in the conductivity range 300 to 800 µS/cm. This calculation yielded 300 mg/L ~ 545 µS/cm.

Past data

In this report, we also mention a few water quality data collected by FoEJ and WHALI South and Central Sulawesi between October 2022 and January 2024. For data selection, we focused on reports that included heavy metals analyses performed via ICP-MS. We plotted the GPS coordinates onto a map (Figure 1A) and selected the locations that were also visited in the May 2025 campaign. The ICP-MS analyses performed in the past included 15 heavy metals; here, we primarily focused on nickel, (total) chromium, and manganese. A more in-depth analysis will be included in the final report. Chromium VI was detected with a semi-quantitative colorimetric kit and was not included in the discussion.

Results

General water chemistry parameters

Water samples' pH ranged from 6.9 to 8.3, with a median of 8.0 (Figure 4A and Table A2). All values fall within the Indonesian regulatory limits (Table 1).

Conductivity was between 90 and 1486 µS/cm, with a median of 261 µS/cm (Figure 4B and Table A2). Samples 12, 20, and 21 were outliers, each exceeding 1000 µS/cm. While conductivity is not included in the Indonesian Water Quality Standards,[19] the national drinking water normative sets total dissolved solids < 300 mg/L.[20,21] For comparison, we converted this limit into conductivity units,[29] yielding an approximate value of 545 µS/cm (see section Sampling site and methods for details). Indeed, all 3 outliers exceeded this benchmark (dashed pink line in Figure 4B). While none of these sites serve as drinking water sources, their high conductivity suggests potential anthropogenic contamination.

Water temperature was between 24 and 32 ˚C (median of 27 ˚C), with variations related to day-to-day changes in meteorological conditions and sampling time.

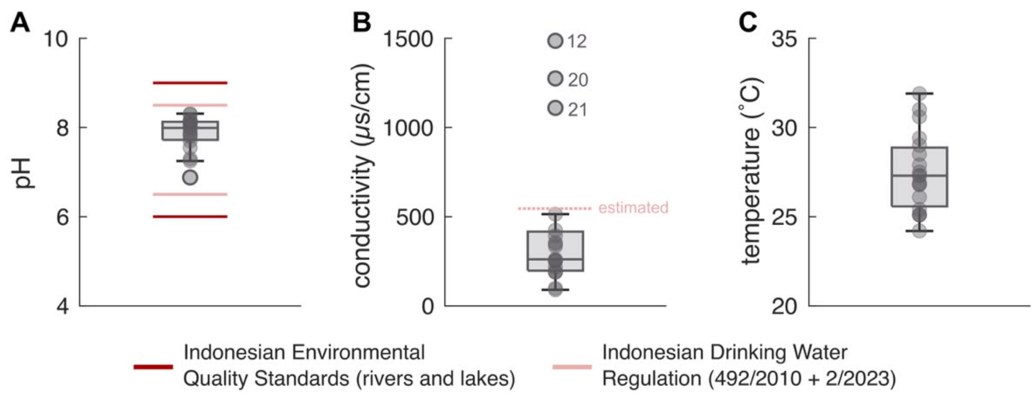


Figure 4. Overview of general water chemistry parameters. The lines in panel A are the Indonesian Environmental Quality Standards for river and lake water (red) and drinking water (pink). The dashed pink line in panel B is a conductivity limit estimated from the Indonesian reference levels for total dissolved solids as explained in the text. Raw data are in the Appendix (Table A2).

Heavy metals in waters and sediments

Water – Of the 21 analyzed, we detected 19 metals, of which 12 were present in 90 to 100% of samples (Table A3). In addition to iron, aluminum, and manganese, which are ubiquitous in nature, we found relatively high concentrations (medians from 13 to 19 µg/L) of barium, boron, chromium (including chromium VI), and nickel. We never detected beryllium nor tin, while arsenic, cadmium, mercury, molybdenum, lead, copper, selenium, thallium, and vanadium were above their limit of detection only in a handful of samples (Table A3).

When considered in the context of the regulatory framework, **manganese is the only metal that surpassed the national limits in more than a quarter of the samples** (Table A3). Samples 20 and 21 were particularly concerning, surpassing ~ 80 to 200 times the national Environmental Quality Standard (EQS) of 100 mg/L (set only for Class I rivers; Table 1). These locations were within the Morowali Industrial Park and showed alarming manganese concentrations also in a past campaign (1300 to 2050 µg/L in January 2024). A few sources[5,30] – including IMIP's official website[31] – report the presence of manganese processing units in the industrial area, which are likely responsible for this contamination.

Chromium VI was also above the Class III Environmental Quality Standards in 2 samples (3 and 5), and above the drinking water limit (10 µg/L) in other 9 samples not used for drinking purposes (Table A3). Samples 3 and 5, collected in Nikkel, receive inputs from upstream nickel mines within the main Sorowako PT Vale Indonesia's concession and had also the highest reported concentrations of total chromium (130 and 110 µg/L, respectively). These samples were also contaminated with (total) chromium in past sampling campaigns – though the values observed in May 2025 were the highest to date. **Chromium VI and total chromium were high across the entire dataset** (median of 12 and 19 µg/L, respectively), hinting at a natural background that adds to the anthropogenic inputs – this has been observed in other areas with chromium-rich bedrocks[12,32,33] and is also visible in the sediment data (see below). Despite these overall high levels, their concentration in the two domestic water sources was below the drinking water standard (chromium VI: < 10 µg/L vs. 7.1–7.7 µg/L; total chromium: < 50 µg/L vs. 7.4 µg/L; Table A3). Within our dataset, chromium VI in water was always ~ 60% of total chromium, in agreement with its biogeochemical behavior.[34]

Antimony, iron, nickel, selenium, and zinc exceeded the national regulatory limits only in 1 sample (Table A3). **Sample 14 was particularly striking, as it exceeded the limits for nickel** (830 µg/L, exceeding the Class VI limit) **and other common metals** – namely, iron (2100 µg/L, exceeding the Class I EQS), manganese (360 µg/L, also exceeding the Class I EQS), and aluminum (310 µg/L, exceeding the drinking water standard). While below the regulatory standards, cobalt was also significantly higher than the median of the dataset (49 vs. 0.79 µg/L). This sample was collected below the access road that connects the main Sorowako mining and processing area to the Petea block (Figure 3 and Figure 5A-B) and showed concerning pollution also in its sediments (see below). FoEJ and WALHI South Sulawesi sampled this site also in October 2022 – though further away from the coast – finding overall acceptable water quality. This data suggests that location 14 has been impacted by a relatively recent pollution event, possibly caused (or worsened) by seasonal rain compounded by a lack of thorough planning in road construction.

In addition to site 14, **samples 20, 21, and 16 had at least one relevant regulatory exceedance and were overall different from the others** (as assessed via an exploratory principal component analysis; see Figure A2). Sample 20, impacted by IMIP's operations or smelters, had the highest measured concentrations of arsenic (3.4 µg/L), cadmium (0.11 µg/L), molybdenum (3.0 µg/L), copper (7.9 µg/L), selenium (320 µg/L), thallium (4.9 µg/L), and vanadium (8.3 µg/L). Selenium exceeded almost 6 times the EQS for Class IV rivers and lakes (50 µg/L; Table 1). While being overall less polluted, sample 21 had the highest measured concentrations of manganese (19000 µg/L) and boron (280 µg/L). This site is affected by mining activities that supply IMIP with nickel ores – thus, this contamination is not surprising. Both locations stood out also for their conductivity (Table A2) and sediment composition (Table A4), indicating consistent contamination of all environmental matrices. Last, sample 16 was collected from a communal spring in the Asuli village and had the highest measured levels of antimony (21 µg/L, above the national limit), barium (150 µg/L), and zinc (61 µg/L). (This spring is used primarily for domestic purposes; however, as some families may still use it as their drinking water, we refer to the national normative for drinking water.) Sample 17, which was collected nearby, had a similar elemental composition but no exceedances.

Figure 5. Photos of the most polluted sites visited in this campaign, namely site 14 (panels A and B), 20 (panels C, D, and E), and 21 (panel F and G).

Sediments – Of the 21 analyzed, we detected 20 metals, of which 12 in all sediments – namely, aluminum, arsenic, barium, cobalt, chromium, iron, manganese, mercury, nickel, copper, vanadium, and zinc (Figure 6 and Table A4). Antimony was the only metal that was never observed, while arsenic, boron, cadmium, molybdenum, selenium, and tin were detected or above their limit of detection in less than a quarter of samples.

Besides aluminum and iron, manganese, nickel, chromium, and cobalt were the most abundant metals within the dataset. This data is particularly concerning when considered in the context of the available environmental guidelines. **Chromium and nickel were well above their Probable Effect Levels (PEL) at all sampling sites** (Figure 6 and Table A4). Values ranged from 160 to 1600 mg/kg (median of 1500 mg/kg) for total chromium and from 600 to 11000 mg/kg (median of 2500 mg/kg) for nickel, and were respectively ~2–20 and ~10–200 times higher than their PEL (90 mg/kg and 48 mg/kg, respectively; Table 1). For nickel, most of these concentrations were above the highest

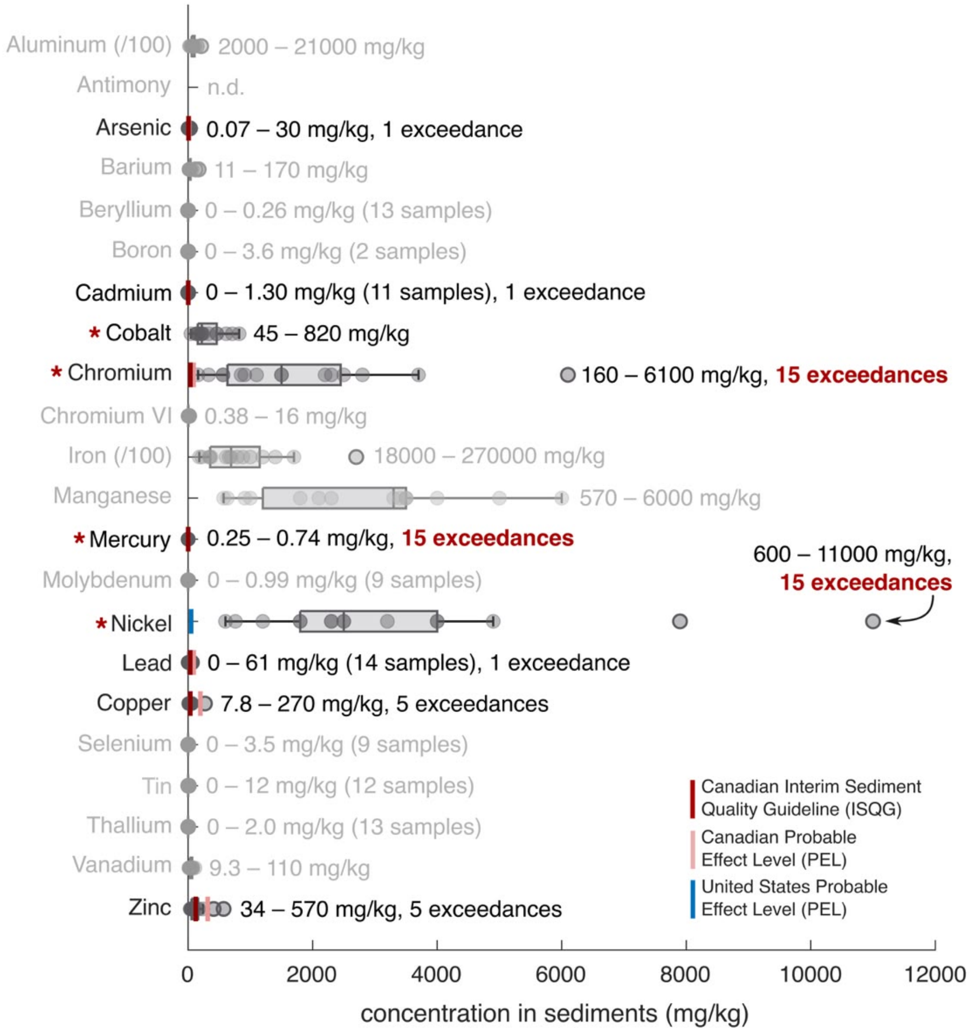


Figure 6. Overview of heavy metal concentration in sediments. The text on the right gives the range of measured concentrations, the number of samples in which the metal was detected (if not specified, it was detected in 100% of the samples; $N = 16$), and the number exceedances to the reference levels for sediments. Entries in grey were either never detected (n.d.) or were detected but have no reference levels (cadmium is an exception; see text). Elements that are concerning are flagged with a red asterisk and discussed in the text. Data for aluminum and iron are divided 100-fold to fit the figure's scale. Raw data are in the Appendix (Table A4).

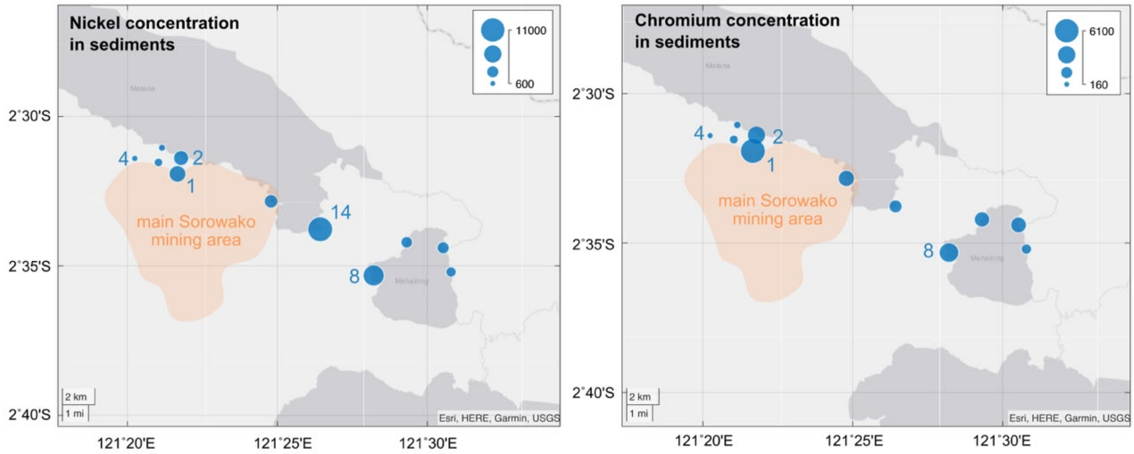


Figure 7. Spatial distribution of nickel (left) and chromium (right) in sediments in the Sorowako area. The size of the data points is proportional to the concentration as indicated in the upper right legends (units of mg/kg). Locations identified with numbers are discussed in the main text.

sediment concentrations reported in a recent global review (5200 mg/kg).[35] Unlike surface water, chromium VI was virtually absent, representing 0.03–0.43% of total chromium. This finding agrees with chromium's redox behavior in anoxic environments (including sediments)[34] and previous literature.[36] Mercury was also above the Canadian Interim Sediment Quality Guideline (ISQG) in 100% of the samples and above the PEL in 11 samples (73%). Mercury is not a natural component of laterite. While it may be released by other activities occurring in the area (e.g., coal burning), its spatial distribution does not provide clear insights into its source. Copper and zinc were also above their Canadian ISQG and PEL in 5 and 1–2 samples, respectively.

Cobalt was another element of concern, ranging from 45 to 820 mg/kg, with a median of 220 mg/kg. As PEL and ISQG values were not available, we used as comparison the median from the FOREGS database for river sediments. Median cobalt loads in Europe were 8 mg/kg,[27] which is ~30 times lower than ours. While not as concerning, median manganese levels (3300 mg/kg) were also 7 times higher than in Europe (452 mg/kg)[27].

Below 400–600 mg/kg of nickel, we also noted significant positive correlations with iron, chromium, and cobalt ($R^2 > 0.9$; Figure A3), indicating the presence of either a common contamination source, a natural background, or both. Sulawesi's laterite ore contains iron (~17%) and nickel (~2%) as predominant elements, and minor amounts of chromium (as chromium oxide; ~1%), manganese (~0.4%), and cobalt (~0.04%).[13] As for water, an exploratory principal component analysis showed a rather homogeneous heavy metal composition across the dataset (Figure A4), with only 2 samples acting as outliers (sample 8 and, again, sample 20). When considering the geographic distribution (Figure 7), we found the highest sediment concentrations of nickel and chromium in areas with known mine-related disturbances. Particularly emblematic is location 4, which was considered a "control" site also in previous campaigns. While being above the regulatory thresholds and European medians, this site had the lowest concentrations of the entire dataset for several key indicators of nickel mining pollution – including nickel (600 vs. a median of 2500 mg/kg), chromium

(160 vs. a median of 1500 mg/kg), and cobalt (45 vs. a median of 220 mg/kg). Overall, **these observations support the hypothesis of anthropogenic pollution that adds up to an already significant natural background of specific heavy metals.**

Key findings

Our results point to **strong anthropogenic inputs associated with laterite extraction and processing layered on top of a natural background** of selected heavy metals. This natural background has been observed in other areas with similar geology[12] and with other types of chromium-rich rocks[32,33], highlighting the need for an even more thorough and mindful management of mine operations and associated industrial processes than normally required. **These metals have well-documented adverse effects on organisms and are released in areas of exceptional ecological significance.** Integration of these findings with future and past sampling campaigns will strengthen these conclusions, providing a strong case for national and international advocacy efforts.

Surface water contamination

Heavy metal concentrations in water samples were significant but concerning only for specific metals and/or locations (Table A3)**. Manganese** was the only compound exceeding the Indonesian water quality standards in more than 25% of the sites. Samples 20 and 21, collected within the IMIP area, were particularly extreme, exceeding almost 80 to 200 times the Indonesian Environmental Quality Standard for rivers and lakes (Class I). **Chromium VI** was also detected at 11 sites (57%) in concentrations above 10 µg/L. In 2 samples collected in Nikkel, downstream of the main mining area in Sorowako, chromium VI was also higher than the Indonesian EQS for rivers and lakes (Class III; samples 3 and 5).

While water chemistry was overall constant within the dataset, 4 samples (14, 16, 20, and 21) stood out as outliers with multiple exceedances and distinct signatures. **Samples 20 and 21** were collected in proximity to nickel processing areas, while **sample 14** was taken under PT Vale's access road, a site that showed significant signs of erosion (Figure 5A-B). Overall, their chemical composition was consistent with the identified anthropogenic disturbance. At these sites, general water chemistry parameters and sediments' heavy metal concentrations also showed clear signs of mine-related pollution.

Sediment contamination

We found highly concerning concentrations of nickel, chromium, and cobalt in sediments across the entire sampling area (Figure 6 and Table A4). Specifically, nickel and chromium were respectively ~10 to 200 and 2 to 20 times higher than their PEL. The median concentrations of nickel, chromium, and cobalt were also, respectively, 119, 24, and 28 times higher than the median stream sediment concentrations in Europe. While the widespread contamination and its chemical signature hint at a natural background – nickel, chromium, cobalt, and manganese are common constituents of laterite[13] – **their spatial distribution underscores clear additional contributions of anthropogenic sources** (e.g., Figure 7).

Environmental and human health impacts

All heavy metals above regulatory standards in water and sediments have known adverse effects on human health. **Particularly concerning are organic and inorganic nickel compounds and chromium VI, which are Class I carcinogens** – i.e., established human carcinogens – according to the International Agency for Research on Cancer.[37] While our analyses detected only *total* nickel, under natural conditions, this metal is primarily present in its +2 oxidation state[35,38] – thus, not as the less toxic metallic element but as a component of organic and inorganic compounds. On the other hand, we have direct evidence of the widespread presence of chromium VI, the most dangerous form of chromium. For both metals, we found more exceedances in sediment samples than in surface water. This, however, must not be seen as a low-risk scenario, as changes in environmental conditions (e.g., pH, oxygen levels, etc.) can release significant quantities of these heavy metals from sediments into overlaying water.[34–36]

Nickel, chromium, and manganese also have a range of additional adverse impacts on humans – causing, among other things, developmental, neurological, immunological, and reproductive disorders[39–41] – **and other organisms**.[37,38,42] **Given the high ecological and cultural significance of the area, their negative impact on biota is particularly concerning**. Lake Matano[43] and Lake Mahalona[44] have been formally identified as Global Key Biodiversity Areas due to their richness of endemic species. Both lakes have also been part of national conservation areas since 1979 and have been important sites for indigenous culture for centuries.[9,45] Likewise, the whole Sulawesi coastal region – including Morowali – is part of the Coral Triangle, a global center of marine biodiversity featuring exceptionally high coral and reef-fish diversity.[46] Alongside corals, the coast is also a place for rich mangrove forests and seagrass beds, which are not yet adequately protected despite their high ecological significance[47] and have already suffered severe degradation due to IMIP's activities.[7]

Overall, our findings underscore the urgent need for stronger environmental oversight and mitigation measures to prevent further harm to both human communities and the region's uniquely fragile ecosystems.

References

(1) McRae, M. E. *Nickel*; Mineral Commodity Summaries 2024; U.S. Geological Survey, 2024. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-nickel.pdf.

(2) International Nickel Study Group. The World Nickel Factbook 2024, 2024. https://insg.org/wp-content/uploads/2024/09/publist_The-World-Nickel-Factbook-2024.pdf (accessed 2025-11-26).

(3) Peh, G. *Indonesia's Nickel Companies: The Need for Renewable Energy amid Increasing Production*; Institute for Energy Economics and Financial Analysis, 2024. https://ieefa.org/resources/indonesias-nickel-companies-need-renewable-energy-amid-increasing-production (accessed 2025-08-18).

(4) Gupta, K. *Indonesia doubles down on nickel export bans and downstreaming | East Asia Forum*. https://eastasiaforum.org/2023/12/07/indonesia-doubles-down-on-nickel-export-bans-and-downstreaming/ (accessed 2025-08-18).

(5) Yeung, P. Workers Are Dying in the EV Industry's 'Tainted' City. *Wired*. February 2023. https://www.wired.com/story/workers-are-dying-in-the-ev-industrys-tainted-city/ (accessed 2025-08-18).

(6) Business & Human Rights Resource Center. *Powering Electric Vehicles – Human Rights Impacts of Indonesia's Nickel Rush*; 2024. https://media.business-humanrights.org/media/documents/2024_EV_supply_chains.pdf.

(7) IMVO Covenant for the Renewable Energy Sector. *Nickel Mining-Related Sustainability Impact at Landscape-Level in Morowali, Indonesia – Final Report*; 2025. https://www.iucn.nl/app/uploads/2025/07/Morowali-report-IUCN-NL-finale-versie-high-res.pdf.

(8) Alfalah, D.; Afra, S.; Hardiana, D. *How the Nickel Rush Ravaged Kabaena Island and the Bajau People's Livelihood*; Satya Bumi, 2024. https://satyabumi.org/report-nickel-rush-kabaena-bajau/ (accessed 2025-02-05).

(9) *Karonsi'e Dongi people and Vale mine in Sorowako, Sulawesi, Indonesia – Ej Atlas*. Environmental Justice Atlas. https://ejatlas.org/conflict/karonsie-dongi-people-and-vale-mine-in-sorowako-sulawesi-indonesia (accessed 2025-08-18).

(10) *Indonesia Morowali Industrial Park (IMIP), Central Sulawesi, Indonesia – Ej Atlas*. Environmental Justice Atlas. https://ejatlas.org/conflict/indonesia-morowali-industrial-park-imip1 (accessed 2025-08-19).

(11) Lo, M. G. Y.; Morgans, C. L.; Santika, T.; Mumbunan, S.; Winarni, N.; Supriatna, J.; Voigt, M.; Davies, Z. G.; Struebig, M. J. Nickel Mining Reduced Forest Cover in Indonesia but Had Mixed Outcomes for Well-Being. *One Earth* **2024**, *7* (11), 2019–2033. https://doi.org/10.1016/j.oneear.2024.10.010.

(12) Delina, R. E.; Perez, J. P. H.; Roddatis, V. V.; Stammeier, J. A.; Prieur, D.; Scheinost, A. C.; Tan, M. M.; Garcia, J. J. L.; Arcilla, C. A.; Benning, L. G. Immobilization of Chromium by Iron Oxides in Nickel–Cobalt Laterite Mine Tailings. *Environ. Sci. Technol.* **2025**, *59* (11), 5683–5692. https://doi.org/10.1021/acs.est.4c05383.

(13) Zhang, Y.; Qie, J.; Wang, X. F.; Cui, K.; Fu, T.; Wang, J.; Qi, Y. Mineralogical Characteristics of the Nickel Laterite, Southeast Ophiolite Belt, Sulawesi Island, Indonesia. *Min. Metall. Explor.* **2020**, *37* (1), 79–91. https://doi.org/10.1007/s42461-019-00147-y.

(14) Carmen. *The five largest nickel mines in operation in Indonesia*. Mining Technology. https://www.mining-technology.com/marketdata/five-largest-nickel-mines-indonesia/ (accessed 2025-08-18).

(15) *Indonesia – About PT Vale*. https://vale.com/indonesia/about-pt-vale (accessed 2025-08-19).
(16) *Protecting the Basic Human Rights of Communities Impacted by the Sorowako Nickel Development in Indonesia! – Request Submitted to Major Shareholders of Vale for Appropriate Action to Prevent Complicity in Human Rights Abuses (endorsed by 104 organizations from 23 countries over the world)*. Friends of the Earth Japan. https://foejapan.org/en/issue/20230818/13949/ (accessed 2025-02-05).
(17) *Responsible Mining Map – Sorowako*. https://map.responsiblemining.net/ (accessed 2025-08-19).
(18) Lotulung, G. Nickel in Sulawesi: The Price of the Green Economy - Alternatives Humanitaires. *Alternatives Humanitaires*. March 21, 2024. https://www.alternatives-humanitaires.org/en/2024/03/21/nickel-in-sulawesi-the-price-of-the-green-economy/ (accessed 2025-08-08).
(19) *PP No. 22 Tahun 2021*. Database Peraturan | JDIH BPK. http://peraturan.bpk.go.id/Details/161852/pp-no-22-tahun-2021 (accessed 2025-08-19).
(20) *Permenkes No 492 Tahun 2010 tentang Persyaratan Kualitas Air Minum*. https://www.academia.edu/11395046/PerMenkes_tentang_Persyaratan_Air_minum (accessed 2025-08-19).
(21) *Permenkes No. 2 Tahun 2023*. Database Peraturan | JDIH BPK. http://peraturan.bpk.go.id/Details/245563/permenkes-no-2-tahun-2023 (accessed 2025-08-19).
(22) World Health Organization. *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda.*; Geneva, 2022.
(23) Canadian Council of Ministers of the Environment. *Resources*. https://ccme.ca/en/resources (accessed 2025-08-19).
(24) Marshall, B. G.; Veiga, M. M.; Kaplan, R. J.; Adler Miserendino, R.; Schudel, G.; Bergquist, B. A.; Guimarães, J. R. D.; Sobral, L. G. S.; Gonzalez-Mueller, C. Evidence of Transboundary Mercury and Other Pollutants in the Puyango-Tumbes River Basin, Ecuador–Peru. *Environ. Sci. Process. Impacts* **2018**, *20* (4), 632–641. https://doi.org/10.1039/C7EM00504K.
(25) Ingersoll, C. G. *Prediction of Sediment Toxicity Using Consensus-Based Freshwater Sediment Quality Guidelines*; EPA 905/R-00/007; United States Geological Survey, 2000. https://doi.org/10.1201/9781420062236.
(26) *Foregs Geochemical Atlas*. http://weppi.gtk.fi/publ/foregsatlas/index.php (accessed 2025-08-19).
(27) *Maps*. http://weppi.gtk.fi/publ/foregsatlas/maps_table.php (accessed 2025-08-19).
(28) *ESDM One Map - Exploring Energy and Mineral Resources of Indonesia*. https://geoportal.esdm.go.id/home/map/minerba (accessed 2025-09-15).
(29) Rusydi, A. F. Correlation between Conductivity and Total Dissolved Solid in Various Type of Water: A Review. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *118* (1), 012019. https://doi.org/10.1088/1755-1315/118/1/012019.
(30) *Indonesia: Labour exploitation, economic injustices, and environmental degradation plague Morowali Industrial Park, campaigners say*. Business & Human Rights Resource Centre. https://www.business-humanrights.org/my/%E1%80%9E%E1%80%90%E1%80%84/indonesia-labour-exploitation-economic-injustices-and-environmental-degradation-plague-morowali-industrial-park-campaigners-say/ (accessed 2025-08-18).
(31) *PT Sulawesi Manganese Recycle*. PT Indonesia Morowali Industrial Park. https://imip.co.id/pt-sulawesi-manganese-recycle/ (accessed 2025-08-19).

(32) McClain, C.; Maher, K.; Fendorf, S. A Hydrological and Geochemical Analysis of Chromium Mobilization from Serpentinized Ultramafic Rocks and Serpentine Soils at the McLaughlin Natural Reserve, Lake County, California. *AGU Fall Meet. Abstr.* **2011**, *2011*, H43J-1373.
(33) Vasileiou, E.; Papazotos, P.; Dimitrakopoulos, D.; Perraki, M. Hydrogeochemical Processes and Natural Background Levels of Chromium in an Ultramafic Environment. The Case Study of Vermio Mountain, Western Macedonia, Greece. *Water* **2021**, *13* (20), 2809. https://doi.org/10.3390/w13202809.
(34) Gorny, J.; Billon, G.; Noiriel, C.; Dumoulin, D.; Lesven, L.; Madé, B. Chromium Behavior in Aquatic Environments: A Review. *Environ. Rev.* **2016**, *24* (4), 503–516. https://doi.org/10.1139/er-2016-0012.
(35) Rinklebe, J.; Shaheen, S. M. Redox Chemistry of Nickel in Soils and Sediments: A Review. *Chemosphere* **2017**, *179*, 265–278. https://doi.org/10.1016/j.chemosphere.2017.02.153.
(36) Gunkel-Grillon, P.; Laporte-Magoni, C.; Lemestre, M.; Bazire, N. Toxic Chromium Release from Nickel Mining Sediments in Surface Waters, New Caledonia. *Environ. Chem. Lett.* **2014**, *12* (4), 511–516. https://doi.org/10.1007/s10311-014-0475-1.
(37) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans – Chromium, Nickel and Welding*; Lyon, 1990; Vol. 49.
(38) Begum, W.; Rai, S.; Banerjee, S.; Bhattacharjee, S.; Mondal, M. H.; Bhattarai, A.; Saha, B. A Comprehensive Review on the Sources, Essentiality and Toxicological Profile of Nickel. *RSC Adv.* **2022**, *12* (15), 9139–9153. https://doi.org/10.1039/d2ra00378c.
(39) *Chromium | Toxic Substances | Toxic Substance Portal | ATSDR*. https://wwwn.cdc.gov/TSP/substances/ToxSubstance.aspx?toxid=17 (accessed 2025-08-27).
(40) *Manganese | Toxic Substances | Toxic Substance Portal | ATSDR*. https://wwwn.cdc.gov/TSP/substances/ToxSubstance.aspx?toxid=23 (accessed 2025-08-27).
(41) *Nickel | Toxic Substances | Toxic Substance Portal | ATSDR*. https://wwwn.cdc.gov/TSP/substances/ToxSubstance.aspx?toxid=44 (accessed 2025-08-27).
(42) *Manganese in Drinking-Water – Background Document for Development of the WHO Guidelines for Drinking-Water Quality*; World Health Organization, 2011. https://www.who.int/docs/default-source/wash-documents/wash-chemicals/manganese-background-document.pdf.
(43) *Key Biodiversity Areas factsheet: Feruhumpenai - Matano*. https://www.keybiodiversityareas.org/site/factsheet/16384 (accessed 2025-08-28).
(44) *Key Biodiversity Areas factsheet: Danau Mahalona*. https://www.keybiodiversityareas.org/site/factsheet/44816 (accessed 2025-08-28).
(45) Robinson, K. A Mining Theme Park—Cultural Competition and the Politics of Identity Claims in an Indonesian Mining Town. *Asia Pac. J. Anthropol.* **2023**, *24* (5), 365–380. https://doi.org/10.1080/14442213.2023.2277401.
(46) *The Coral Triangle - Coral Triangle Atlas*. http://ctatlas.coraltriangleinitiative.org/About (accessed 2025-08-28).
(47) Gokkon, B. Indonesia's 'Essential' Mangroves, Seagrass and Corals Remain Unprotected. *Mongabay Environmental News*. December 30, 2022. https://news.mongabay.com/2022/12/indonesias-essential-mangroves-seagrass-and-corals-remain-unprotected/ (accessed 2025-08-28).

Appendix

Table A1. Overview of the analytical methods' limit of detection (LoD) for the 22 heavy metals (values provided by the laboratory). When not available (n.a.), 100% of the measurements were above their LoD.

LoD in…	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium IV	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Vanadium	Zinc
Water (µg/L)	25	0.1	1	2.5	0.1	n.a.	0.1	1	n.a.	n.a.	n.a.	n.a.	0.5	1	n.a.	1	1	1	1	0.1	1	5
Sediment (mg/kg)	n.a.	0.1	0.5	n.a.	0.1	0.5	0.1	n.a.	n.a.	1	n.a.	n.a.	n.a.	0.5	n.a.	10	n.a.	0.5	1	0.025	n.a.	n.a.

Table A2. Overview of sample's location and general water chemistry parameters. The conductivity values highlighted are likely to exceed the Indonesian normative for drinking water quality (the conductivity reference level is estimated from that of 300 mg/L for total dissolved solids; details in text). (n.a. = not available)

ID	Sampling date	Sampling time	Samples type	Nearby village / operation	Latitude	Longitude	pH	Conductivity (µS/cm)	Temperature (°C)
1	21/05/2025	8:00	river water + sediments	Sorowako / mine	-2.52319	121.36315	7.84	424	26.1
2	21/05/2025	9:00	river water + sediments	Sorowako / mine	-2.53204	121.36114	7.7	514	26.9
3	21/05/2025	11:30	river water + sediments	Nikkel / mine	-2.52562	121.35056	7.79	251	25.1
4	21/05/2025	12:00	river water + sediments	Kampung Dongi	-2.52344	121.33739	8.16	261	24.2
5	21/05/2025	13:00	river water + sediments	Nikkel / mine	-2.51749	121.35250	7.93	257	25.4
8	22/05/2025	13:00	lake water + sediments	(Tole) / industry	-2.58868	121.47021	8.03	191	30.6
9	22/05/2025	14:00	lake water + sediments	(Tole) / mine	-2.57018	121.48857	8.05	191	31
10	22/05/2025	14:30	lake water + sediments	(Tole) / mine	-2.57326	121.50886	8.13	188	29.4
11	22/05/2025	15:30	lake water + sediments	(Tole) / mine	-2.58672	121.51326	8.12	216	27.3
12	25/05/2025	9:00	river water + sediments	(Nikkel) / mine	-2.54733	121.41316	6.88	**1486**	27.9
13	25/05/2025	10:30	river water	(Nikkel) / mine	-2.55945	121.41280	7.3	355	29
14	25/05/2025	11:30	river water + sediments	(Nikkel) / access road	-2.56292	121.44048	7.55	346	31.9
15	25/05/2025	13:00	river water	(Nikkel) / mine	-2.53059	121.47352	8.15	334	28.5
16	25/05/2025	17:00	spring water	Asuli / mine	-2.60074	121.34313	7.25	99	25.1
17	25/05/2025	18:30	spring water	Asuli / mine	-2.60040	121.34044	7.85	90	25.1
20	24/05/2025	n.a.	river water + sediments	Labota / IMIP	-2.86214	122.18071	8.29	**1275**	27.3
21	24/05/2025	n.a.	river water + sediments	Bahodopi / IMIP, mine	-2.79599	122.10729	7.99	**1110**	27.5
22	24/05/2025	n.a.	river water + sediments	Dampala / mine	-2.75965	122.03841	8.31	393	26.8
23	24/05/2025	n.a.	river water + sediments	Onepute Jaya / mine	-2.73048	122.00438	8.1	250	26.8

Table A3. Heavy metal concentrations in surface water (in µg/L) and Indonesian Environmental Quality Standards for rivers and lakes (EQS, classes I to IV) and drinking water quality (DW; see Table 1). Values exceeding the relevant reference levels are bold and highlighted in dark red. Cells highlighted in bold and grey have values above reference levels that are not directly relevant for the specific water use. Values in grey were either not detected ("n.d.", reported as zeros by the laboratory) or ≤ their limit of detection (values in Table A1).

Sample ID	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium IV	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Vanadium	Zinc
1	3.2	n.d.	n.d.	2.1	n.d.	37	n.d.	0.99	20	**12**	74	39	0.1	0.12	21	n.d.	0.2	0.53	n.d.	n.d.	n.d.	3.6
2	1.5	0.94	n.d.	5.7	n.d.	39	n.d.	2.4	14	**11**	46	**180**	n.d.	0.24	36	n.d.	0.16	0.94	n.d.	n.d.	n.d.	1.7
3	9.7	0.2	n.d.	9.9	n.d.	20	n.d.	0.48	**130**	**81**	39	19	n.d.	n.d.	6.9	0.38	0.29	n.d.	n.d.	n.d.	0.42	n.d.
4	12	1.4	n.d.	26	n.d.	18	n.d.	0.12	11	9.9	29	2.5	n.d.	0.14	3.7	n.d.	0.27	0.21	n.d.	n.d.	2.2	3.9
5	13	2.5	n.d.	20	n.d.	16	n.d.	0.7	**110**	**80**	51	39	n.d.	n.d.	8.1	n.d.	0.32	n.d.	n.d.	n.d.	0.45	4
8	32	0.83	n.d.	20	n.d.	15	n.d.	0.62	13	8.1	130	9.8	n.d.	n.d.	14	0.22	0.7	n.d.	n.d.	n.d.	0.34	13
9	50	3	n.d.	38	n.d.	15	n.d.	0.89	10	6.6	**290**	12	n.d.	n.d.	17	n.d.	0.37	n.d.	n.d.	n.d.	0.49	18
10	9.6	0.79	n.d.	28	n.d.	15	n.d.	0.27	5.7	5.5	34	5.4	n.d.	n.d.	7	n.d.	0.14	n.d.	n.d.	n.d.	0.3	11
11	110	0.11	n.d.	0.81	n.d.	9.4	n.d.	0.45	10	7.3	**220**	34	n.d.	n.d.	11	n.d.	0.52	n.d.	n.d.	n.d.	2.4	4.5
12	22	0.16	n.d.	3.3	n.d.	9.9	n.d.	0.34	23	**20**	15	6.5	n.d.	n.d.	26	n.d.	0.2	0.56	n.d.	n.d.	n.d.	2.6
13	25	1.7	n.d.	8.9	n.d.	26	n.d.	2.9	43	**12**	180	**100**	n.d.	n.d.	19	n.d.	0.37	0.82	n.d.	n.d.	n.d.	14
14	**310**	0.34	n.d.	33	n.d.	23	n.d.	49	45	9.6	**2100**	**360**	n.d.	n.d.	**830**	n.d.	1.6	0.46	n.d.	n.d.	0.73	24
15	25	n.d.	n.d.	0.41	n.d.	15	n.d.	1.2	19	**17**	72	51	n.d.	n.d.	21	n.d.	0.15	0.36	n.d.	n.d.	n.d.	3.2
16	61	**21**	n.d.	**150**	n.d.	16	n.d.	0.53	7.4	7.1	85	34	n.d.	0.13	24	n.d.	2.1	n.d.	n.d.	n.d.	2.9	**61**
17	33	0.28	n.d.	7.3	n.d.	15	n.d.	0.1	7.4	7.7	15	2.1	n.d.	0.11	2.5	n.d.	0.33	n.d.	n.d.	n.d.	2	6.5
20	160	1.2	3.4	35	n.d.	180	0.11	1.8	35	**33**	130	**820**	n.d.	3	17	n.d.	7.9	**320**	n.d.	4.9	8.3	31
21	34	0.45	n.d.	33	n.d.	280	n.d.	3.6	43	**36**	52	**19000**	n.d.	2	33	n.d.	0.46	3.3	n.d.	n.d.	0.85	8.6
22	41	0.79	n.d.	13	n.d.	18	n.d.	0.79	15	**14**	56	13	n.d.	n.d.	8.4	n.d.	0.39	0.2	n.d.	n.d.	1.1	5.2

23	24	0.48	n.d.	4.7	n.d.	13	n.d.	1.3	20	**15**	180	56	n.d.	0.12	15	n.d.	0.29	n.d.	n.d.	n.d.	0.34	4.1
EQS (I)			50	1000		1000	10	200		**50**	**300**	**100**	1		50	30	20	10				**50**
EQS (II)			50	1000		–	10	200		**50**	–	–	2		50	30	20	50				**50**
EQS (III)			50	1000		–	10	200		**50**	–	–	2		50	30	20	50				**50**
EQS (IV)			100	1000		–	10	200		1000	–	–	5		**100**	500	200	**50**				2000
DW	200	**20**	10	700		500	3		50	10	200	100	1	70	70	10	3000	10				3000

Table A4. Heavy metal concentrations in sediments (in mg/kg) and Canadian Environmental Quality Guidelines (ISQG = Interim Sediment Quality Guidelines; PEL = Probable Effect Level). Values exceeding ISQG values are highlighted in dark red. Values in grey were either not detected ("n.d.", reported as zeros by the laboratory) or ≤ their limit of detection (values in Table A1). We did not collect sediments in locations 13, 15, 16, and 17; these samples are thus not included in the table. † United States consensus-based PEL.

Sample ID	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium IV	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Vanadium	Zinc
1	5800	n.d.	0.59	41	0.13	n.d.	0.31	330	2800	1	100000	3500	0.7	0.2	4000	25	53	0.41	2.6	0.1	34	570
2	7200	n.d.	0.56	39	0.095	n.d.	0.39	460	6100	5	170000	3400	0.68	0.13	4900	6	28	n.d.	0.09	0.1	35	410
3	3100	n.d.	0.27	40	0.13	n.d.	0.095	240	560	0.84	34000	2100	0.37	n.d.	1200	3	14	n.d.	0.18	0.077	19	37
4	4200	n.d.	1.1	68	0.22	n.d.	0.094	45	160	0.43	18000	1000	0.5	0.3	600	4.7	21	0.34	1.5	0.037	22	34
5	2000	n.d.	0.19	16	0.085	n.d.	0.027	130	330	0.52	22000	910	0.25	0.047	760	2.1	7.8	0.19	0.1	0.021	9.3	42
8	21000	n.d.	0.094	24	0.18	n.d.	0.09	710	3700	16	270000	6000	0.58	n.d.	7900	2.7	63	0.68	0.086	0.18	110	170
9	5600	n.d.	0.11	22	n.d.	n.d.	n.d.	220	2200	0.74	69000	570	0.58	n.d.	2300	2.5	9.9	n.d.	0.85	n.d.	19	56
10	8600	n.d.	0.58	120	0.26	n.d.	0.31	150	2300	7.8	35000	630	0.73	0.097	2500	4.3	53	3.5	0.58	0.078	75	96
11	15000	n.d.	0.37	25	0.084	n.d.	0.094	170	850	0.65	61000	3300	0.74	0.084	1800	1.4	56	n.d.	0.069	n.d.	77	66
12	15000	n.d.	0.1	11	0.068	n.d.	n.d.	460	2500	4.7	140000	3500	0.68	n.d.	3200	4.3	34	n.d.	0.084	0.12	71	67
14	5600	n.d.	0.073	19	n.d.	3.6	0.14	610	1500	0.64	120000	4000	0.6	0.43	11000	n.d.	25	0.2	n.d.	0.095	43	130
20	6900	n.d.	30	170	0.13	n.d.	1.3	140	560	0.38	37000	3500	0.53	0.99	1800	61	270	1.8	0.77	2	34	240
21	11000	n.d.	0.9	21	0.1	n.d.	0.064	200	910	3.7	66000	2300	0.47	0.043	2300	2	33	0.56	n.d.	0.082	47	53
22	8800	n.d.	0.37	19	0.071	0.28	n.d.	220	1100	4.3	79000	1800	0.41	n.d.	2500	1.9	33	n.d.	n.d.	0.052	50	56
23	7900	n.d.	0.24	19	0.078	n.d.	n.d.	820	1500	2	88000	5000	0.69	n.d.	4000	3.4	22	0.24	12	0.11	39	74
ISQG			5.9				0.6		37.3				0.17			35	35.7					123
PEL			17				3.5		90				0.486		48.6†	91.3	197					315

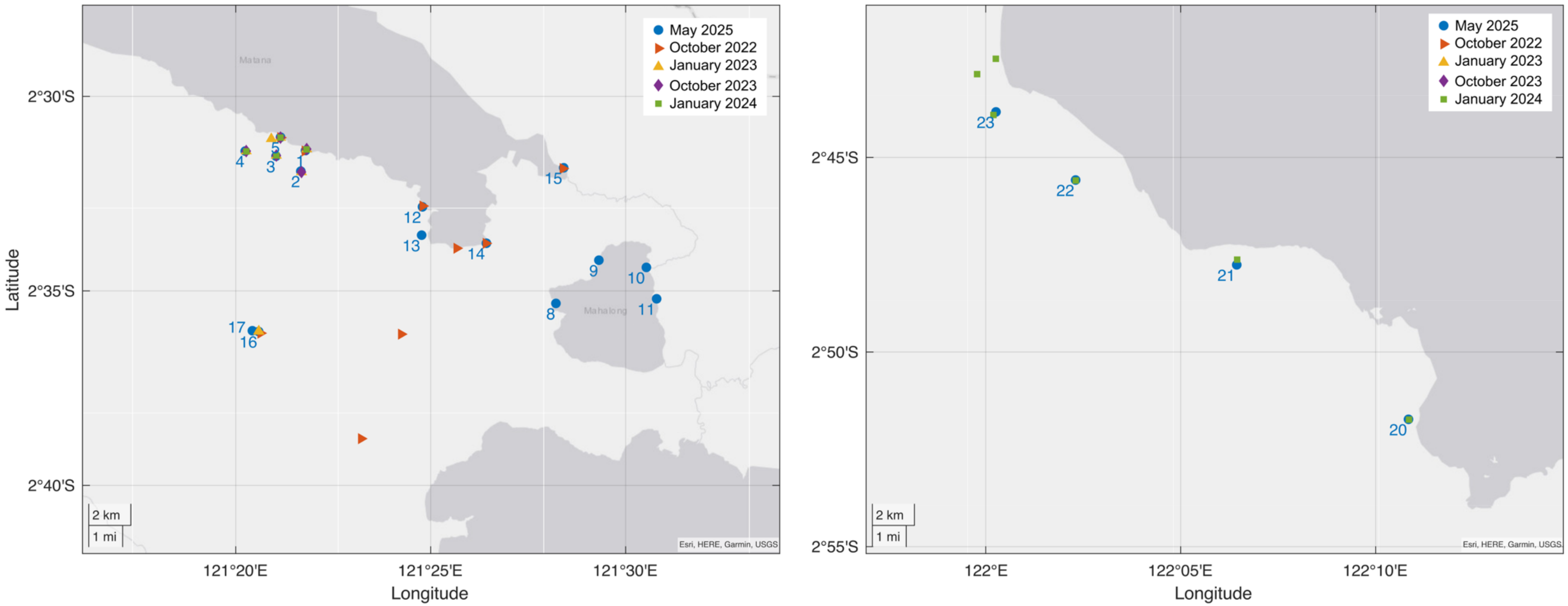
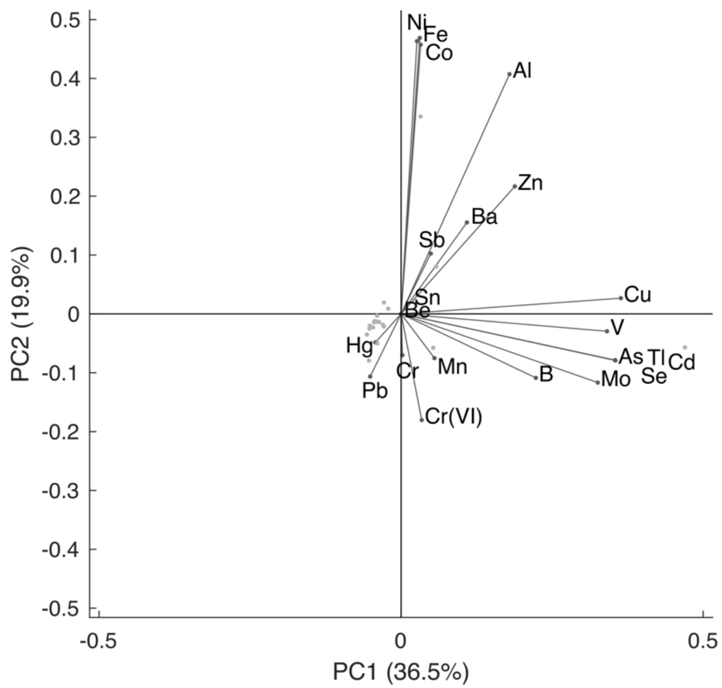


Figure A1. Overview of previous sampling locations. The campaigns were conducted by FoEJ and WHALI between October 2022 and January 2024. We included only campaigns that involved water sampling followed by heavy metal analyses via ICP-MS. The sampling locations were taken from reports shared by FoEJ.



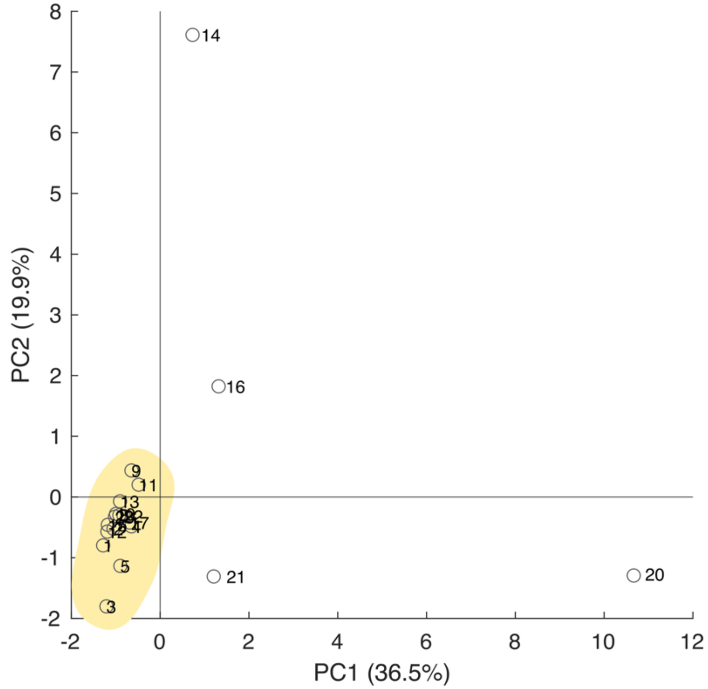


Figure A2. Exploratory principal component analysis of surface water samples (biplot on the left, scores on the right). Overall, the first two principal components (PC) explained 56.4% of the variance. Most samples fall in the yellow areas, indicating similar water composition. Samples 20, 21, 14, and 16 had a significantly different composition.

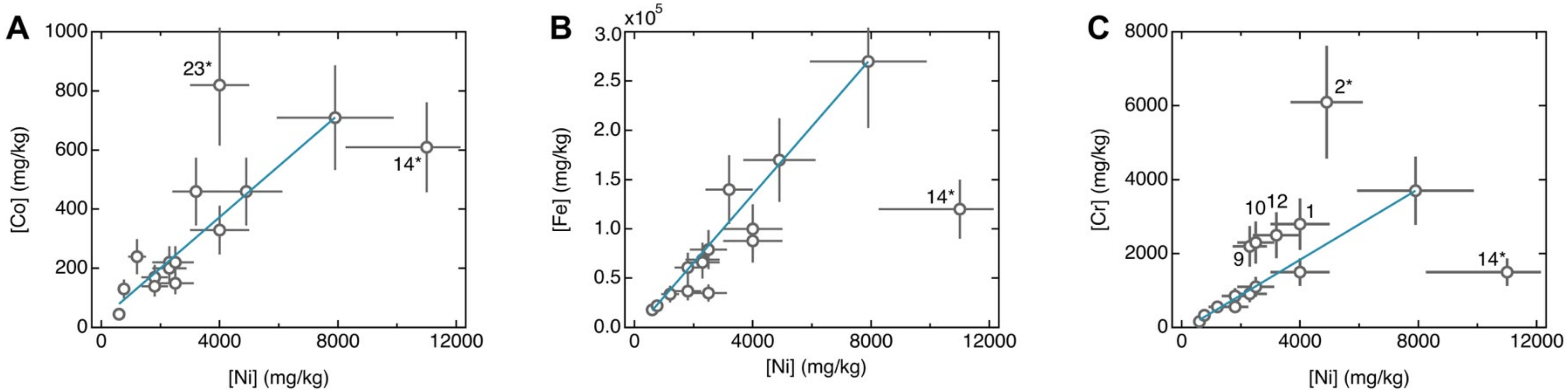


Figure A3. Correlation between nickel and cobalt, iron, and chromium in sediments. Error bars are calculated as 25% of the concentration value. Datapoints labeled with a number (sample number) and asterisk were excluded from the linear fit. Blue lines are linear fits; their R^2 is > 0.99 in all cases. Data analysis was performed with Igor 8.0.

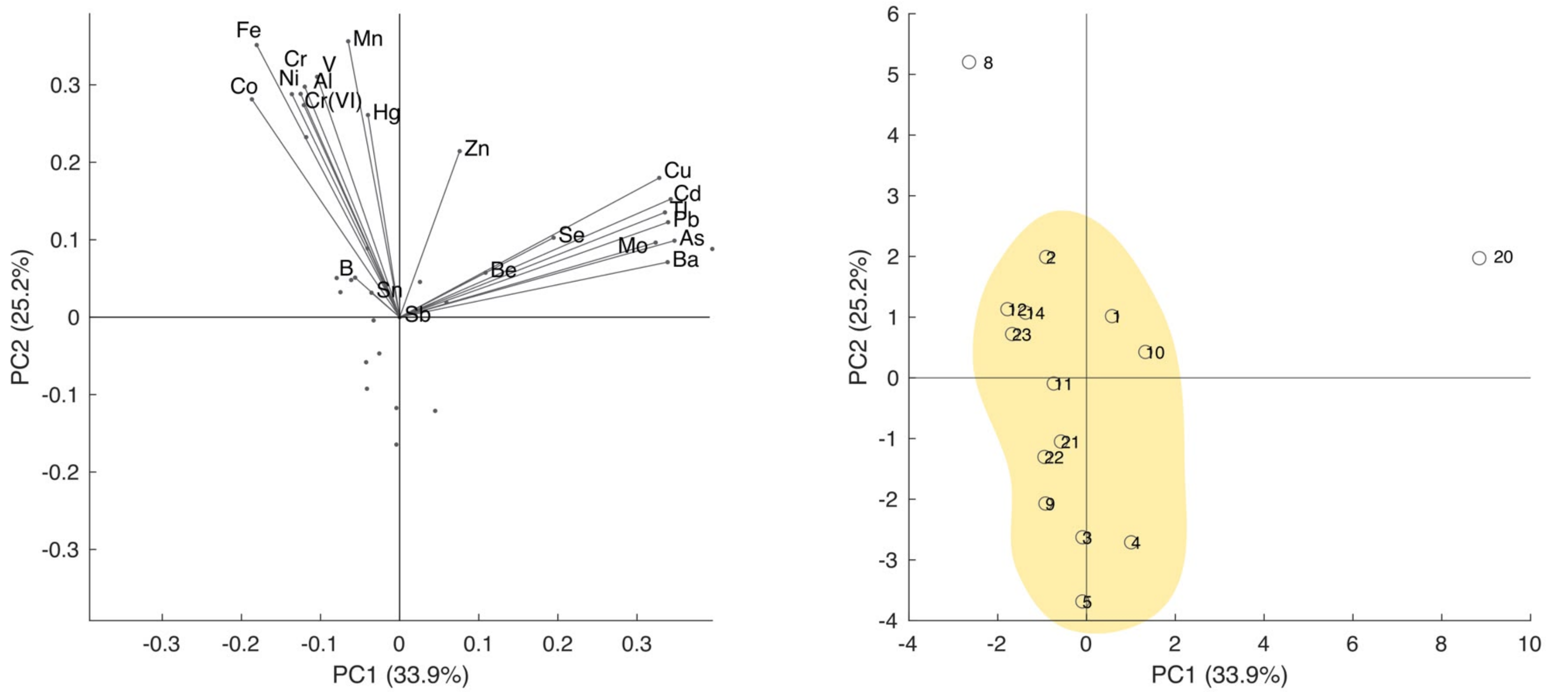


Figure A4. Exploratory principal component analysis of sediment samples (biplot on the left, scores on the right). Overall, the first two principal components (PC) explained 59.1% of the variance. Most samples fall in the yellow areas, indicating similar chemical composition. Samples 20 and 8 had a significantly different chemical composition.