Mining impacts on aquatic environments in the Copper-Cobalt Belt, Democratic Republic of Congo

Assessment of water and sediment quality in Lualaba's frontline communities • October 2025 sampling campaign

Province of Lualaba, DRC

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Executive summary

This report presents the results of a water and sediment monitoring campaign carried out by Source International in the Lualaba Province (Democratic Republic of Congo), a region that supplies more than 75% of the world's cobalt – and is thus central to the green and digital transition. The study contributes to ongoing investigations led by RAID, Afrewatch, and the University of Lubumbashi into the environmental, social, and human rights impacts of copper and cobalt extraction in the DRC.

In October 2025, we collected 12 surface water samples and 9 sediment samples from streams, rivers, and lakes across Kolwezi, Lake Kando and surrounding areas, and Fungurume. Sites included locations directly impacted by mining activities associated with COMMUS, MUMI, and TFM, plus pristine sites that served as controls. We additionally collected water samples from 5 wells that residents in Pierre Muteba II and villages near Lake Kando use for domestic purposes.

Our results provide **compelling evidence that mining activities are contributing to environmental contamination of surface waters and sediments** in a region where natural background concentrations are already elevated. **Copper emerged as the most critical contaminant across all environmental media**, exceeding multiple international standards and guidelines. **Cobalt and manganese were also consistently high across the dataset**, often exceeding by more than an order of magnitude median concentrations reported in Europe. Despite being essential trace nutrients, these metals are toxic to aquatic organisms at high concentrations. **Fish are highly sensitive to copper and manganese**, leading to behavioral changes and reduced growth. While our data did not allow to establish a direct causal link, nearly all communities in the area reported a consistent decline in fish abundance and size over recent years. At most sites, **manganese levels also exceeded several drinking water guidelines and standards**, indicating a potential health risk for local communities relying on surface waters for domestic purposes.

Kolwezi emerged as the most affected location in 2025, with clear links between pollution sources and ecosystem impacts. Fungurume showed a more complex contamination profile, likely reflecting the presence of multiple and overlapping contamination sources. Surface waters in and near Lake Kando were generally of good quality; still, comparison between water and sediment data suggest this area may have experienced higher levels of contamination in past years.

Well water was generally safe for human consumption, having low conductivity and low concentrations of dissolved metals. However, **all samples were consistently more acidic than recommended by international guidelines**. Acidic water can dissolve toxic metals from utensils and containers, leading to indirect health effects not captured by our sampling approach. Furthermore, **manganese was 3–20 times above all health-based standards and guidelines** in a well in Pierre Muteba II located less than 200 m from the COMMUS tailing storage facility. Although we did not univocally identify the origin of this contamination, its vicinity to the mining facility hints to a possible leak.

Comparison with results from the University of Lubumbashi (2024–2025) and past work by Atibu et al. shows strong convergence in identifying copper, cobalt, and manganese as key contaminants associated with local mining activities.

Overall, our water and sediment monitoring results do point to a single causal factor behind the increased in specific health conditions reported by medical professionals in Kolwezi and surrounding areas over the past 5–10 years. Instead, they hint to possible synergistic effects arising from continued exposure to a cocktail of pollutants through water, food, and air, compounded by episodic, large-scale pollution event that placed additional stress on both communities and ecosystems. In specific areas and for specific metals (e.g., cobalt), the consumption of local fish or vegetables may represent an important exposure pathway for the adult population. Although insightful, these observations underscore **the urgent need for a formal epidemiological study to directly link mine-related pollution to adverse health outcomes in Lualaba’s frontline communities**.

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Introduction

The context

The city of Kolwezi and its surrounding communities lie at the heart of the Copper–Cobalt Belt in the southern Democratic Republic of Congo (DRC). This region has gained significant international attention in recent years due to its vast mineral reserves, which are strategic for the global green and digital transition. Indeed, **the DRC is currently the world's largest producer of cobalt**, a critical component of lithium-ion batteries used in electric vehicles and electronic devices.[1] **In 2024, the country supplied 76% of the cobalt extracted worldwide**, primarily through large industrial mines located in and around Kolwezi.[1,2]

While the international community increasingly recognizes the urgency of phasing out fossil fuels, **the environmental and human rights impact of this green transition remain largely overlooked**. Several strategic minerals required for this transition are sourced from countries where basic human rights are frequently violated and environmental regulations are weak, absent, or poorly enforced. Cobalt is one of these cases. A recent study conducted by RAID and Afrewatch documented **severe human health and environmental consequences of cobalt extraction in the DRC's Copper-Cobalt Belt**.[3] Through more than 140 interviews with residents, the study identified widespread health issues, including gynecological and reproductive health and recurring skin diseases, alongside a general deterioration of living standards associated with the recent cobalt boom.[3] Scientific studies and civil society reports have similarly reported extensive environmental damage, particularly heavy metal contamination in water bodies. Although the Chinese and

Figure 1. View of the stockpile near the COMMUS processing area in Kolwezi.

European multinationals included in the study acknowledged these risks in their Environmental and Social Impact Assessment, pollution remains pervasive in the area.[3]

This report

In 2025, Source International joined RAID, Afrewatch, and the University of Lubumbashi to strengthen the evidence base on environmental pollution and human rights abuses in the DRC's Copper-Cobalt Belt region. The first sampling campaign took place in October 2025, at the end of the dry season, with the objective of assessing air pollution and supporting ongoing scientific investigations into water and sediment contamination led by the University of Lubumbashi.

This report describes our assessment of water and sediment quality in Kolwezi, near Lake Kando, and in Fungurume, complementing and integrating the work done by Prof. Kaniki (2025) and Prof. Banza (2024). Our air quality assessment is thoroughly described in a dedicated report.[4]

Previous studies

We primarily compared our findings with those from Prof. Banza[5] and Prof. Kaniki[6], which were collected within the same project framework. Between January and February 2024, Prof. Banza and his team sampled water and sediments from 3 lakes and 5 rivers in the broad area of Kolwezi and Fungurume. Their results showed elevated concentrations of copper, cobalt, manganese, and uranium in both water and sediments, while arsenic, cadmium, lead, nickel, and zinc were generally less prominent. In October 2025, Prof. Kaniki's team collected surface water, underground water, and sediments at sites overlapping those investigated by Source International, plus other locations. Their results highlighted clear signs of industrial contamination around Fungurume – as evident, e.g., from the increase in sulfate and conductivity[a] in surface and underground water in comparison with historical data. Among heavy metals, copper, cobalt, and manganese were the most concerning, especially in sediments. Contamination was less evident in Kolwezi and almost absent in and near Lake Kando. Given the relevance of these studies, we incorporated all relevant data into the report and discussed them thoroughly in the text.

We identified only two additional investigations directly relevant to the study area, both conducted by Atibu and collaborators.[7,8] In 2011,[8] the team sampled water and sediments from the Liulu and Musonoïe rivers in Kolwezi (exact locations unspecified), reporting elevated concentrations[b] of cobalt (0.1–27 µg/L, with an outlier at 3160 µg/L), copper (0.3–103 µg/L, with an outlier of 5920 µg/L), manganese (0.1–16.2 µg/L, with an outlier of 117 µg/L), iron, and zinc, along with consistently high sediment concentrations of copper (42–47470 mg/kg), cobalt (59–13200 mg/kg), manganese (19–

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[a] Conductivity quantifies the total amount of dissolved ions without providing information on the chemical composition. Because it can be measured quickly and inexpensively, it provides a useful "snapshot" of the contamination potential of a water body. In general, the higher the conductivity, the higher the concentration of dissolved ions – thus, the higher the probability of anthropogenic contamination. In Prof. Kaniki's study, conductivity and sulfate followed the same trends, suggesting that sulfate was the predominant ion driving water conductivity values at these sites.

[b] We assumed the correct units are those in Figure 2 (ppb, thus µg/L) not in Table 2 (mg/L).

1040 mg/kg), and iron. In contrast, arsenic, cadmium, chromium, nickel, molybdenum, and tin in water were generally close to or below detection limits.

In a follow-up study conducted in 2016, Atibu et al.[7] sampled sediments, soils, and local plants collected along the Dilala, Liulu, and Mpigiri rivers in Kolwezi. The team found exceptionally high copper concentrations (115–209000 mg/kg), consistently exceeding the Canadian guidelines for the protection of aquatic life. Cobalt and lead were also present, but their levels were less concerning (19–18430 mg/kg and 11–899 mg/kg, respectively). The authors attributed these high values to the combined effect of a naturally elevated background and mining activities. They further showed that natural vegetation accumulates metals, highlighting both a potential exposure pathway for nearby communities (as, e.g., seen in urban gardens in Lubumbashi[9]) and a possible mechanism for natural attenuation and phytoremediation.

Other studies on water and sediment quality in the Cobalt-Copper Belt region have mainly focused on the area around Likasi and Lubumbashi,[9–13] where mining activities have also targeted metals other than copper and cobalt – including uranium, zinc, and lead.[14] Most of these studies were conducted more than a decade ago (sampling between 2008 and 2012), further limiting their comparability to our findings.

Reference: guidelines, standards, and background values

To contextualize our results, we referred to guidelines from the World Health Organization (WHO), environmental quality standards, guidelines, and other legislation from selected countries, and background values from international databases.[c] Given the different availability of reference parameters and norms, we cover separately surface waters, sediments, and domestic waters.

Regarding legislation, we included countries with active mining activities in Lualaba (e.g., Switzerland and China), with automotive and energy industries that are likely to use elements mined in this area (e.g., European Union and the United States), and South Africa, whose environmental legislation is often taken as reference by mining industry operating in the DRC. Whenever available, we also included legislation from the DRC.

Surface water

Due to a lack of internationally recognized guidelines for aquatic ecosystems, we used regulatory frameworks from selected countries (Table 1). These include the European Union (Water Environmental Quality Standards Directive),[15] the United States (Clean Water Act),[16] Switzerland (Water Protection Ordinance),[17] and China (Environmental Quality Standards for Surface water).[18] These jurisdictions set legally binding standards for several heavy metals considered priority pollutants, including cadmium, mercury, and lead (Table 1).

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[c] Guidelines are health-based recommendations aimed at protecting human health or ecosystems, and are typically not legally binding. Environmental Quality Standards are legally enforceable limits that compromise health or ecosystem protection with economic considerations.

Table 1. Overview of the reference legislation for surface water. For the European Union, we report the Maximum Allowable Concentration for inland waters.[15] For the United States, we show the Criterion Maximum Concentration for aquatic life in freshwaters from the National Recommended Aquatic Life Criteria Table.[16] For Switzerland, we show data from the Annex 2, both total ([b]) and dissolved ([c], in parenthesis).[17] For China, we reported the Environmental Quality Standards for surface waters (5 classes).[18] For South Africa, we show the Acute Effect Values from the 1st guidelines edition.[19] For the DRC, we report Maximum Allowable Concentrations from the mining regulations.[20] In this table, the median European background from the FOREGS Geochemical Atlas[21] is *not* multiplied by 10. [†] Units of measure: pH → arbitrary units; conductivity → µS/cm; metals → µg/L. [a] Depends on water hardness. [b] Total. [c] Dissolved. [d] Depends on pH. [e] Tentative.

Parameter[†]	**European Union**[15]	**United States**[16]	**Switzerland**[17]	**China**[18]	**South Africa**[19]	**DRC**[20]	**EU median background**[22]
pH				6–9		6–9	
Conductivity							30
Aluminum					100–150[d,e]		18
Antimony							0.11
Arsenic		340		50–100	130[b]	400	0.63
Barium							25
Beryllium							0.009
Boron							16
Cadmium	0.45–1.5[a]	1.8[a]	0.2[b] (0.05[c])	1–10	3–13[a,b]		0.01
Cobalt							0.16
Chromium			5				0.38
Chromium VI		16		10–100	200[c]		
Iron						6000	268
Manganese					1300[c]		20
Mercury	0.07	1.4	0.03[b] (0.01[c])	0.5–1	1.7[b]	2	
Molybdenum							0.22
Nickel	34	450[a]	10[b] (5[c])			1000	1.9
Lead	14	65[a]	10[b] (1[c])	10–100	4–16[a,c]	500	0.093
Copper			5[b] (2[c])	10–1000	1.6–12[a,c]	1500	0.88
Selenium				10–20	30[b]		0.34
Thallium							0.005
Uranium							0.32
Vanadium							0.46
Zinc		120[a]	20[b] (5[c])	50–2000	36[c]	10000	2.7

Most regulatory frameworks define both yearly and maximum allowable limits – e.g., as in Europe[15] and the US[16] – and in some cases different values based on water classes (e.g., as in China[18]). Since we collected only point samples, we considered standards referring to maximum concentrations or acute values whenever possible – thus, we adopted a worst-case scenario approach. We note the complete lack of reference values for cobalt, a direct results of the paucity of scientific studies on its ecotoxicity and rare occurrence in surface waters worldwide.[23] For South Africa, we identified only surface water *guidelines*.[19] To the best of our knowledge, the DRC has not yet established a regulatory framework for surface waters. For this reason, we referred to the national mining regulations, which sets maximum allowable concentrations in a point sample inside mining areas.[20] These values, available only for 7 metals, are substantially higher than typical environmental quality standards and guidelines (Table 1).

In addition to legal norms, we considered the median background values in European freshwaters from the FOREGS geochemical atlas.[21] This database was established in the context of a large-scale program that aimed at determining baseline concentrations in soils, stream waters, sediments, and floodplains across Europe. To account for the possibility of a naturally high background, we adopted a conservative approach by multiplying by 10 these background values.

Sediments

Due to the lack of established sediment legislation in the countries of interest, we primarily referred to the Canadian Sediment Quality Guidelines[24] and European background values derived from the FOREGS Geochemical Atlas[21] (Table 2). Canada defines two benchmarks: 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.

Parameter†	**Canada[24]**	**Switzerland[25]**	**EU median background[22]**
Arsenic	(5.9) 17		6
Barium			386
Cadmium	(0.6) 3.5		0.28
Cobalt			8
Chromium	(37.3) 90		63
Manganese			612††
Mercury	(0.17) 0.49	0.102	0.081
Lead	(35) 91.3	50.3	20.5
Copper	(35.7) 197	9.9	17
Uranium			2
Zinc	(123) 315	99.7	71

Table 2. Overview of available guidelines for freshwater sediments. For Canada, we report the Interim Sediment Quality Guideline (ISQG; in parenthesis) and the Probable Effect Level (PEL).[24] For Switzerland, we show the Sediment Quality Criteria proposed by the Ecotox center.[25] Median sediment levels in the European Union are shown only for selected elements (full list in Table 6; values in this table were *not* multiplied by 10). † Units of measure: metals → mg/kg. †† To convert % of manganese oxide (MnO) into mg/kg of manganese, we multiplied the MnO percentage by 7744. This factor corresponds to the ratio of the molecular weight of manganese to that of MnO multiplied by 10000 (0.079% * 7744 = 612 mg/kg).

Table 3. Overview of the reference legislation for drinking and domestic water. For the WHO, we refer to the 4th edition of its drinking water standards (2022).[26] For the EU, we report indicator (c) and chemical (d) parameters.[27] For the United States, we show Maximum Contaminant Levels from Primary (e) and Secondary (f) Drinking Water Quality Regulations.[28] For Switzerland, we report chemical parameters (d).[29] For South Africa, we show physical and aesthetical (g) and macro (h) determinants.[30] For China, we report toxicological (i; extended index k), sensory and chemical (j), and reference (l) indicators.[31] [†] Units of measure: pH → arbitrary units; conductivity → µS/cm; metals → µg/L. [a] Provisional value. [b] Inorganic mercury. [c] Indicator parameter. [d] Chemical parameter. [e] National Primary Drinking Water Regulations. [f] National Secondary Drinking Water Regulations. [g] Physical and aesthetical determinant. [h] Macro determinant. [i] Toxicological indicator. [j] Sensory and chemical indicator. [k] Toxicological indicator, extended index. [l] Reference indicator.

Parameter[†]	**WHO[26]**	**European Union[27]**	**United States[32]**	**Switzerland[29]**	**South Africa[30]**	**China[31]**	**DRC**
pH		6.5–9.5[c]	6.5–8.5[f]	6.8–8.2	5–9.7[g]	6.5–8.5[j]	
Conductivity		2500[c]					
Aluminum		200[c]	50–200[f]	200[d]	300[g]	200[j]	
Antimony	20	10[d]	6[e]	5[d]	20[h]	5[k]	
Arsenic	10[a]	10[d]	10[e]	10[d]	10[h]	10[i]	
Barium	1300		2000[e]		700[h]	700[k]	
Beryllium			4[e]			2[k]	
Boron	2400	1500[d]		1000[d]	2400[h]	1000[k]	
Cadmium	3	5[d]	5[e]	3[d]	3[h]	5[i]	
Chromium	50	25[d]	100[e]	50[d]	50[h]		
Chromium VI				20[d]		50[i]	
Iron		200[c]	300[f]	200[d]	2000[h] 300[g]	300[j]	
Manganese	80[a]	50[c]	50[f]	50[d]	400[h] 100[g]	100[j]	
Mercury	6[b]	1[d]	2[e]	1[d]	6[h]	1[i]	
Molybdenum						70[k]	
Nickel	70	20[d]		20[d]	70[h]	20[k]	
Lead	10[a]	5[d]	10[e]	10[d]	10[h]	10[i]	
Copper	2000	2000[d]	1000[f]	1000[d]	2000[h]	1000[j]	
Selenium	40[a]	20[d]	50[e]		40[h]	10[k]	
Thallium			2[e]			0.1[k]	
Uranium	30[a]	30[d]	30[e]	30[d]	30[h]	30[l]	
Vanadium						10[l]	
Zinc			5000[f]	5000[d]	5000[jg]	1000[j]	

As for surface waters, we used as background reference the European median stream concentrations in sediments from the FOREGS geochemical atlas multiplied by 10.

The scarcity of sediment guidelines and standards reflects the difficulty in defining thresholds that are broadly applicable across different environmental contexts. In Europe and the United States, sediment guidelines are typically derived at the national level. The Swiss Ecotox Center has also recently proposed Sediment Quality Criteria for a handful of metals (Table 2).[25] Based on available information, these values do not appear to be legally binding yet.

Domestic water

For domestic water, we considered primarily the last WHO Guideline for Drinking Water Quality,[26] which are also adopted in the DRC due to the absence of national standards.[5] In addition to guidelines, 5 of the selected countries established legally binding drinking water standards (Table 3). Most regulatory frameworks distinguish between substances that pose a direct health risk (called, e.g., “chemical parameters” in the EU[27] or “toxicological indicators” in China[31]) and chemicals that primarily affect the aesthetic and organoleptic properties of water (e.g., “indicator parameters” in the EU[27] or “sensory and chemical indicators” in China[31]). All relevant values are summarized in Table 3.

Sampling sites and methods

Sampling sites

Between October 10 and 20, 2025, we sampled surface water, domestic water, and sediments in Kolwezi and surrounding areas (Figure 2; air quality measurements are described in a dedicated report[4]). In total, we obtained 12 surface water samples, of which 4 in Kolwezi, 4 from Lake Kando and surrounding areas, and 4 in Fungurume. At 9 of these sites, we also collected surface sediments; the only exceptions were 3 points on the shores of Lake Kando, where sediments primarily consisted of rocks or decomposing organic matter. We also collected 5 domestic water samples from wells and fountains used by local communities, of which 3 in Pierre Muteba II, and 2 in villages near Lake Kando. For ease of reference, the renamed each location to include information on sample type (W = surface water, WS = surface water + sediment, D = domestic water) and area (K = Kolwezi; P = Pierre Muteba II; L = Lake Kando and surrounding areas; F = Fungurume; Table A1).

Sites were selected based on their proximity to expected pollution sources and hydrological connectivity. In Kolwezi and Pierre Muteba II, we targeted locations primarily impacted by mining operations from the Compagnie Minière de Musonoie Global SAS (COMMUS) (Figure 2A).[3] For surface waters and sediments, we sampled 4 hydrologically connected sites: one upstream reference (SWK1) and 3 downstream locations (SWK2, SWK3, and SWK4) expected to suffer from mine-related contamination (Figure 2B). Site WSK2 was a small stream actively used by artisanal miners for mineral washing, downstream of COMMUS drainage canal. The stream emerged from beneath the waste rock dump, and flowed into the Musonoïe River (SWK3) and subsequently Lake Golf (SWK4). The wells sampled in Pierre Muteba II were close to a large tailing storage facility owned by COMMUS (Figure 2A). Further east in the Mutshatsha Territory, we collected surface water samples from Lake Kando (WL2), at its confluence with the Lualaba River (WL3), and further downstream near the bridge in Kisenda (WSL4; Figure 2C–D). We took sediments only at this last site. We also sampled the Lwakutsha River (WL1), a stream that drains from the MUMI concession and discharges into Lake Kando. This stream was interested by a large acid spill in 2017.[3] In the two villages, we collected domestic water from a fountain in Mibanze (DL1) and from a well in Rianda (DL2). In Fungurume, we sampled 3 sites along the Kelangile River, including an upstream site (WSF1), the effluent from the TFM 30k industrial plant (WSF2) – which was built in 2023 to process mixed ore[33] –, and a downstream location (WSF3; Figure 2E–F).[3] A fourth sample was collected in the city, before the Dipeta River merged into the Kelangile (WSF4; Figure 2E–F). Overall, these sites were at close distance to some of the sites sampled by Prof. Kaniki and his group (Figure A1) and were broadly overlapping with some locations from Prof. Banza's study.

We conducted most sampling activities after two intense rain events on the afternoons and nights of October 11 and 12, 2025, which may have worsened water quality. From October 13 until the end of the campaign, weather conditions were sunny or partially sunny, with absent to moderate winds.

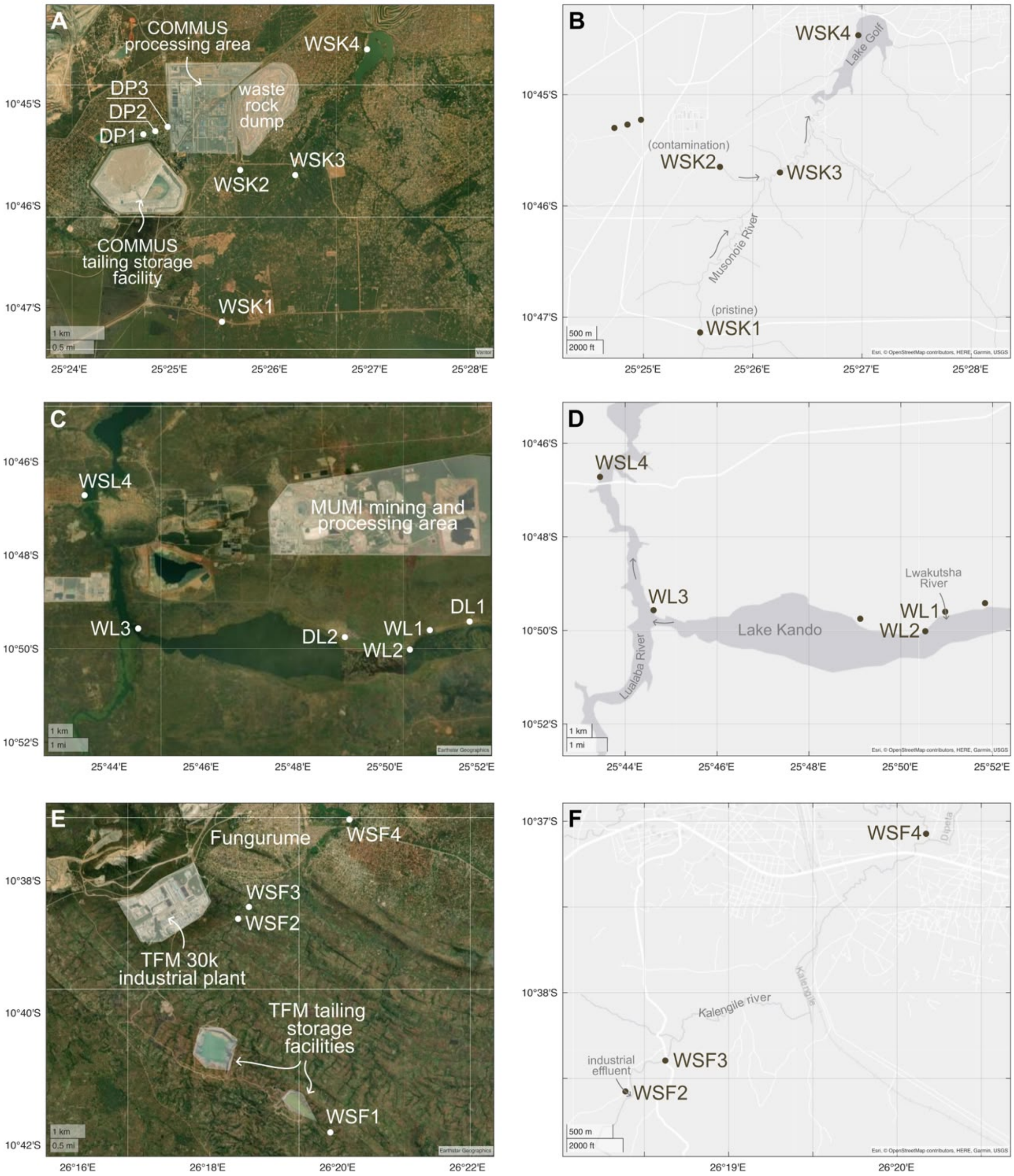

Figure 2. Overview of the sampling locations in Kolwezi and Pierre Muteba II (A–B), Lake Kando and surrounding areas (C–D), and Fungurume (D–E). The satellite maps on the left side were plotted with Matlab and do not necessarily reflect the ground situation at the time of sampling. The maps on the right side clarify the hydrological connections of sites where we collected surface water (W) and sediment (S) samples. The attribution of mining areas and facilities is primarily based on data from OpenStreetMap[34] and the DRC Mining Cadastre Map Portal[35].

General site characterization

At each site, we recorded general field data with ODK Collect,[36] which we used to fill up a questionnaire previously set up in KoboToolbox.[37] The questionnaire included date and time of sampling, sample ID, GPS location and altitude, types of parameters measured at the site, instruments ID, known or potential pollution sources, weather conditions, and photographic

Figure 3. Water and sediment sampling in Kolwezi and surrounding areas. For surface waters, we always collected samples away from river banks (A) in well-rinsed containers (B). For domestic waters, we first took them out from the well with the same containers used by the population, then we rinsed our vial, and filled it up with water (C). Sediments were homogenized and quartered (D); in Lake Kando, sediments only consisted of organic matter and were not analyzed (E).

evidence. Due to security constraints, we initially recorded our observations in a field notebook; GPS locations were obtained with a Garmin Fenix 7 watch and/or an iPhone 12 Compass tool. During sample preparation, which we conducted off-site within a few hours of collection, we digitalized all notes into KoboToolbox.

Sampling and pre-treatment

At each site, we collected at least 250 mL of water in a well-rinsed plastic bottle or Falcon tube (Figure 3A-C). At the end of each sampling day, we filtered an aliquot of each sample into a new 50 mL Falcon tube with a 0.45 µm syringe filter. This aliquot was acidified with 3 drops of concentrated nitric acid (70%), mixed, labeled, and stored in the dark for subsequent heavy metal analyses. A second aliquot was transferred unfiltered into a new 50 mL Falcon tube, amended with 1 mL of ammonium sulfate buffer, mixed, labeled, and stored in the dark for the later determination of chromium VI. We used the remainder of each sample for pH and conductivity measurements (details in General water chemistry analysis).

For sediments, we filled a new sampling bag with surface material (0–10 cm)[d] collected within a radius of 1-2 meters with a metal scoop. In general, sediments and surface waters were taken from approximately the same GPS location. At the end of each sampling day, sediment samples were transferred into a large container, homogenized, quartered, and 100–150 g of the remaining material placed into a clean sampling bag. In one case (WSK4), we performed homogenization and quartering directly onsite (Figure 3D). We did not collect sediments where the riverbed was too rocky (WL1) or where accessible material consisted primarily of decomposing organic matter (WL2 and WL3; Figure 3E).

After collection and pre-processing, all samples were stored away from direct sunlight at room temperature. During national and international transports, samples stayed at room temperature in the dark.

General water chemistry analysis

We measured water pH and conductivity using a multiparametric field probe (Hanna, HI 991300). The instrument was calibrated daily with commercial buffers at pH 4 and 7 and a 1413 µS/cm standard solution. For measurements, we used the remaining volumes after aliquoting waters for laboratory analyses (see Sampling and pre-treatment). First, we rinsed the probe thoroughly with the sample to be analyzed. We then transferred 25-35 mL of water into a well-rinsed falcon tube, immersed the probe, waited for stabilization, and recorded the resulting values. The probe was rinsed with bottled water, wiped gently, and prepared for the next sample. In one case where we suspected contamination from the calibrant solutions (WSK1), we remeasured the parameters onsite by placing the probe in running water.

Heavy metal analyses

For heavy metal analyses, we sent water and sediment samples to an Italian laboratory accredited by ACCREDIA, which completed all analyses within 2 months of collection. Filtered and acidified water samples were analyzed for 22 heavy metals according to UNI EN ISO 17294-2:2023 (inductively coupled plasma mass spectrometry, ICP-MS). Unfiltered water samples were used for the determination of chromium VI via the EPA 7199 1996 method (ion chromatography with post-column derivatization and spectrophotometric detection). Sediments were analyzed for heavy metals using the combined methods EPA 3051 A 2007 (microwave digestion) + EPA 6020 B 2014 (ICP-MS), while chromium VI was analyzed via EPA 3060 A 1996 (basic extraction) + EPA 7196 A 1992 (colorimetric method via spectrophotometric detection). Sediment concentrations were reported on a dry weight basis, which were determined via ISO 11465:1993/Cor 1:1994. Table A2 shows the limits of detection and average measurement uncertainties for the 23 analytes as extrapolated from the laboratory's test reports.

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[d] Surface sediments generally display the "average pollution story" of the last years to decades. Typical sediment deposition rates are approximately 1–3 cm/years,[38,39] corresponding to 10–30 years at 10 cm depth.

Data analysis

We analyzed all data in Excel and Matlab (R2021b). All maps were obtained from Matlab and did not necessarily reflect the ground situation at the time of sampling.

Comparison with previous campaigns

We compared our results with previous sampling campaigns run by the University of Lubumbashi.[5,6] Prof. Kaniki and his team sampled water and superficial sediments in October 2025, during our same deployment time and at comparable locations.[6] Prof. Banza worked in a wider geographical area between January and February 2024.[5] All teams investigated water and sediment pollution focusing primarily on heavy metals, though the actual parameters and the analytical details differ (Appendix, Table A3). Though the overall area is the same, only a few locations were included in all 3 studies (Figure A1).

To perform a thorough comparison, we selected only common analytical parameters and sampling sites. From Prof. Kaniki's study, we considered only cobalt, iron, manganese, nickel, lead, copper, and zinc in water and sediments, plus pH and conductivity in water. We converted relevant concentrations in water from mg/L to µg/L by multiplying them by 1000 (1 mg/L = 1000 µg/L). Values in sediments were already in mg/kg – except for iron, which we converted from % to mg/kg by multiplying it by 10000 (1% = 1000 mg/kg). To select relevant sampling sites, we first converted Prof. Kaniki's GPS coordinates into decimal units, then overlayed these points to our sampling map (Figure A1). In some cases, we also considered points that were near but not directly comparable to our sampling points (marked with "~" in the overview tables in the Appendix; Table A4, Table A5, and Table A6; see also Figure A1).

From Prof. Banza's report, we used water and sediment concentrations of arsenic, cadmium, cobalt, manganese, nickel, lead, copper, uranium, and zinc, plus pH in water. Although not explicitly reported, we assumed Prof. Banza's concentrations in Table 1 and Table 2 were in µg/L for water and µg/kg for sediments; thus, we only divided the latter by 1000 to obtain values in mg/kg, directly comparable the others (1 µg/kg = 0.001 mg/kg). Prof. Banza reported several coordinates per sampling point, which led us to assume that the data in their report refer to composite samples. Using this information, we identified sites that could be included in our discussion although not directly comparable to ours (Figure A1).

Results

General overview

Surface water quality

Across the area, water pH ranged from 6.3 to 8.4, with a median of 7.8 (Table 4). These values were within the range established by the available Chinese[18] and Congolese[20] legislation (pH between 6–9; Table 1). Conductivity was 28–2940 µS/cm (median of 835 µS/cm), with highest values observed at sites associated to known pollution sources – i.e., WSK2 in Kolwezi and WSF2/WSF3 in Fungurume (Table 4 and discussion below).

Of the 22 heavy metals analyzed, beryllium, cadmium, chromium, mercury, lead, and tin were consistently below detection limits. Aluminum, antimony, arsenic, boron, chromium VI, molybdenum, nickel, selenium, thallium, and zinc were above detection only occasionally (2–4 samples of 12; 16–33%). Cobalt, iron, copper, uranium, and vanadium were detected more frequently (50–67% of samples), while only barium and manganese were present in all samples (Table 4).

Across the dataset, **only copper exceeded at least one regulatory threshold** (Table 4). Copper concentrations were 25–100 µg/L in Kolwezi and 1.9–200 µg/L in Fungurume, exceeding in nearly all cases the Swiss (2–5 µg/L)[17] and Chinese (category 1, 10 µg/L)[18] Environmental Quality Standards, as well as the South African guidelines (1.6–12 µg/L, depending on water hardness)[19]. In contrast, copper concentrations near and in Lake Kando were 0–2.1 µg/L, constantly below all international standards and only above the South African guidelines. Copper is also regulated under the DRC's mining legislation (1500 µg/L),[20] but all values were well below this threshold.

When compared with European baseline concentrations, **cobalt, manganese, and copper frequently exceeded 10 times the median levels reported for European surface waters** (Table 4). These exceedances were most pronounced in Kolwezi and Fungurume, while concentrations were substantially lower in the Lake Kando area (Table 4). This analysis also allowed us to identify hotspots of water pollution. The most evident was site WSK2, where we detected boron, copper, cobalt, manganese, molybdenum, thallium, uranium, and vanadium at concentrations at least 10 times higher than the European baseline (Table 4). This site was a stream emerging from under the COMMUS waste rock dump and was heavily used by artisanal miners for mineral washing.

Table 4. General characterization and metal content of surface waters in comparison with legislation and baseline values. pH is in arbitrary units, conductivity is in µS/cm, metal concentrations are in in µg/L. Cells highlighted in dark red exceed at least one environmental quality standard or guideline (Table 1); cells highlighted in grey exceed by more than 10-fold the median EU baseline. Values in grey were either not detected ("n.d.", reported as zeros by the laboratory) or below their limits of detection (Table A2). At the bottom, we report the range of values from selected legislation (Table 1) and the number of countries where that parameter is regulated (in italics and parenthesis).

Report ID	pH	Conductivity	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium VI	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
SWK1	6.34	50	29	n.d.	0.24	13	n.d.	5.2	n.d.	5.4	n.d.	n.d.	310	33	n.d.	n.d.	0.26	0.1	**49**	n.d.	n.d.	n.d.	0	0.4	3
WSK2	8.05	2940	1.4	0.41	4.0	48	n.d.	260	n.d.	14	0.66	1.1	2.1	570	0.22	14	1.1	n.d.	**64**	2.3	n.d.	0.17	16	6.0	0.31
WSK3	6.97	560	12	0.10	0.85	30	n.d.	51	n.d.	19	n.d.	0.55	8.2	400	n.d.	1.5	0.58	n.d.	**100**	n.d.	n.d.	n.d.	1.3	1.4	3.2
SWK4	7.38	346	30	0.15	0.53	45	n.d.	20	n.d.	23	0.1	n.d.	17	340	n.d.	0.63	0.4	n.d.	**25**	n.d.	n.d.	n.d.	1.5	1.4	1
WL1	7.84	664	28	n.d.	n.d.	11	n.d.	5.7	n.d.	0.19	n.d.	n.d.	6.9	35	n.d.	0.32	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.77	0.3	0.73
WL2	7.45	1276	1.2	n.d.	0.27	26	n.d.	9.3	n.d.	0.78	n.d.	n.d.	55	130	n.d.	0.18	n.d.	n.d.	0.34	n.d.	n.d.	n.d.	1.9	0.5	0.35
WL3	8.40	1217	1.4	n.d.	0.5	41	n.d.	9.3	n.d.	0.35	n.d.	n.d.	16	80	n.d.	0.3	n.d.	n.d.	0.33	n.d.	n.d.	n.d.	2.0	1.1	n.d.
WSL4	8.16	670	4.6	n.d.	0.51	29	n.d.	12	n.d.	0.70	n.d.	n.d.	17	50	n.d.	0.29	n.d.	n.d.	**2.1**	n.d.	n.d.	n.d.	0.94	1.1	0.17
WSF1	7.72	569	20	n.d.	0.72	1300	n.d.	11	n.d.	1.4	n.d.	n.d.	160	320	n.d.	0.38	0.57	n.d.	**1.9**	0.17	n.d.	n.d.	0.64	1.1	1.7
WSF2	8.09	1604	15	n.d.	0.72	30	n.d.	14	n.d.	1.0	0.36	n.d.	74	47	n.d.	0.53	0.78	0.31	**11**	n.d.	n.d.	n.d.	0.84	0.6	6.4
WSF3	8.23	2225	0.8	n.d.	1.4	95	n.d.	16	n.d.	330	0.13	n.d.	40	1200	n.d.	1.5	2.7	0.21	**200**	n.d.	n.d.	n.d.	1.7	0.8	5.6
WSF4	7.45	1001	62	0.12	0.75	87	n.d.	21	n.d.	47	1.6	n.d.	120	43	n.d.	0.92	0.44	n.d.	**95**	4.2	0.69	n.d.	2.9	1.2	3.6
Legislation range *(# of countries)*	6–9 *(2)*		100–150 *(1)*		50–400 *(4)*				0.2–13 *(5)*		5 *(1)*	10–200 *(3)*	6000 *(1)*	1300 *(1)*	0.03–2 *(6)*		10–1000 *(4)*	10–500 *(6)*	1.6–1500 *(4)*	10–30 *(2)*					20–10000 *(5)*
EU baseline x 10			180	1.1	6.3	250	0.09	160	0.1	1.6	3.8		2680	195		2.2	19	0.93	8.8	3.4		0.05	3.2	4.6	27

Table 5. Sediments metal content and comparison with legislation and baseline values. All concentrations are in mg/kg. Cells in dark red exceed the Canadian Probably Effect Level (PEL; reported at the bottom of the tale); cells in orange exceed the Canadian Interim Sediment Quality Guideline (ISQG; reported in *italics* at the bottom of the table); cells in grey are at least 10 times above the median EU baseline (Table 2). Values in grey are either not detected ("n.d.", reported as zeros by the laboratory) or below their limits of detection (Table A1).

Report ID	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium VI	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
WSK1	1300	0.041	1.0	74	0.082	0.62	n.d.	47	3.7	n.d.	5400	210	0.049	0.061	2.0	10	34	n.d.	0.61	0.053	0.79	41	6.6
WSK2	780	0.05	3.0	91	0.45	1.1	0.18	490	2.3	n.d.	6000	1700	0.095	0.46	8.2	5.7	**2100**	0.33	0.32	0.055	3.1	25	31
WSK3	790	n.d.	2.4	80	0.39	0.77	0.13	450	2	n.d.	4800	1500	0.082	0.35	7.1	4.8	**2000**	0.057	0.35	0.049	2.8	22	21
WSK4	1300	0.047	0.8	65	0.095	0.7	n.d.	340	3.5	n.d.	3600	640	0.033	0.061	1.6	12	**240**	n.d.	0.76	0.085	2.9	41	7.7
WSL6	1100	0.11	1.5	30	0.035	0.94	0.053	58	8	n.d.	6100	100	n.d.	0.18	1.6	16	**310**	n.d.	0.52	0.021	0.54	24	24
WSF1	2400	n.d.	0.72	860	0.24	1.3	0.062	28	5.3	n.d.	5800	760	n.d.	0.077	5.9	6.0	47	n.d.	0.27	0.038	0.72	18	15
WSF2	1400	0.094	1.3	83	0.23	0.65	n.d.	16	3.9	n.d.	3300	270	n.d.	0.098	2.9	5.6	33	n.d.	0.29	0.028	0.44	12	70
WSF3	2000	0.095	2.3	120	0.24	0.85	0.047	780	7.2	n.d.	6200	760	n.d.	0.15	5.9	8.0	43	n.d.	0.38	0.066	0.34	20	130
WSF4	1500	n.d.	1.6	110	0.25	0.86	n.d.	780	5	n.d.	4800	1400	0.056	0.076	3.1	8.2	**490**	0.26	0.57	0.05	0.60	28	14
Canada			*5.9*				*0.6*		*37.3*				*0.17*			*35*	*35.7*						*123*
(*ISQG* – PEL)			17				3.5		90				0.49			91.3	197						315
EU baseline x 10		10.7	60	3860	14.4		2.8	80	630		47000	7900	0.81	6.3	210	205	170		22.5	3.9	20	620	710

Table 6. General characterization and metal content of domestic water and comparison with legislation and guidelines. pH is unitless, conductivity is in units of µS/cm, metal concentrations are in in µg/L. Cells highlighted in red exceed at least one standard or guideline (Table 1); cells in grey exceed (see pH) or are close to (see uranium) their reference values. Values in grey are either not detected ("n.d.", reported as zeros by the laboratory) or below their limits of detection (Table A1); when 100% of the samples fulfills this criterion, the element's name is greyed. At the bottom, we report the range of values from selected legislation (Table 1) and the number of countries where that parameter is regulated (in italics and parenthesis). ^{a} Most norms set a pH range of 6.5–8.5 (Table 1 and text).

Report ID	pH	Conductivity	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium VI	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
DP1	**4.60**	605	**780**	n.d.	2.9	48	n.d.	71	n.d.	2.6	n.d.	n.d.	n.d.	**1100**	2.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	27	n.d.	84
DP2	**4.90**	30	13	n.d.	n.d.	11	n.d.	5	n.d.	2.0	n.d.	n.d.	0.53	24	n.d.	n.d.	n.d.	0.62	4.8	n.d.	n.d.	n.d.	n.d.	n.d.	1.2
DP3	**4.76**	48	27	n.d.	n.d.	6.9	n.d.	3.8	n.d.	2.3	n.d.	n.d.	n.d.	13	n.d.	n.d.	n.d.	n.d.	53	n.d.	n.d.	n.d.	0.19	0.1	6.1
DL1	5.10	30	17	n.d.	n.d.	20	0.14	4.1	n.d.	4.1	0.13	n.d.	n.d.	23	n.d.	n.d.	5.7	0.2	4.0	n.d.	n.d.	n.d.	n.d.	0.1	11
DL2	**4.74**	55	24	n.d.	n.d.	16	n.d.	19	n.d.	0.96	n.d.	n.d.	6.1	6.5	n.d.	n.d.	0.69	n.d.	0.93	n.d.	n.d.	n.d.	n.d.	0.1	2.4
WHO guidelines				20	10	1300		2400	3		50			80	6		70	10	2000	40			30		
Legislation range *(# of countries)*	5–9.7^a *(5)*	2500 *(1)*	50–300 *(5)*	5–20 *(5)*	10 *(5)*	700–2000 *(3)*	2–4 *(2)*	1000–2400 *(4)*	3–5 *(5)*		25–100 *(4)*	20–50 *(2)*	200–300 *(4)*	50–400 *(4)*	1–6 *(5)*	70 *(1)*	20–70 *(4)*	5–10 *(5)*	1000–2000 *(5)*	10–50 *(4)*		0.1–2 *(2)*	30 *(5)*	10 *(1)*	1000–5000 *(4)*

Sediment quality

In surface sediments, we detected aluminum, barium, boron, cobalt, iron, manganese, copper, vanadium, and zinc in all samples. Arsenic, beryllium, thallium, and uranium were present in 6–8 samples (of 9; 66–88%), whereas antimony, cadmium, and lead were detected only occasionally (in 1–3 samples of 9; 11–33%). Chromium, chromium VI, mercury, molybdenum, nickel, selenium, and tin were consistently below detection limits (Table 5).

Copper was the most concerning metal in sediments, with concentrations ranging from 33 to 2100 mg/kg (Table 5). In more than 50% of the samples, these values exceeded the Canadian Probable Effect Level (PEL; 197 mg/kg vs. a measured value of 240–2100 mg/kg). At the remaining sites, copper concentrations were 33–47 mg/kg, thus close to or slightly above the Canadian Interim Sediment Quality Guideline (ISQG; 35.7 mg/kg),[40] above the proposed Swiss Sediment Quality Criteria (9.9 mg/kg),[25] and at least 2 times above the EU baseline (17 mg/kg; Table 2).[21] The only other exceedance concerned zinc at site WSF3, whose concentrations were above the Canadian ISQG but below its PEL. While not included in the Canadian guidelines, we noticed that **cobalt was 40–60 times higher than the European baseline at the 3 sites showing the highest copper values** (Table 5). While this comparison should be interpreted with caution due to differences in local geology, we note that *only* sites downstream of known mine-related contamination showed high levels of cobalt in their sediments: a control site upstream of contamination had 47 mg/kg of cobalt, still 6 times higher than the EU baseline but 7–10 lower than the contaminated sites.

Domestic water quality

All domestic water sources exhibited a markedly acidic pH, with values from 4.6 to 5.1 – thus, outside the range recommended by most drinking water regulations (Table 6). While acidic water is not inherently harmful, most countries recommend a minimum pH of 6.5; only South Africa sets as lower limit a pH of 5 (Table 3). Acidic water can facilitate metal corrosion in pipes, containers, and cookware, which can indirectly lead to adverse health effects due to metal exposure.[41,42] We note that *all samples* were acidic, suggesting that underground water in the area may have a naturally low pH. In a recent study, Tshanga et al.[43] measured the pH of groundwater near the Mutoshi mine, northeast of Kolwezi, finding an average neutral pH of 7.0 ± 0.5 across 20 samples (range from 6.6 to 8.2). Unfortunately, the complex underground hydrology of the area[44] makes it hard to establish whether Tshanga et al. represents a reasonable control for our dataset or not.

Most waters showed low conductivity and low concentration of dissolved metals (Table 6). Conductivity was typically between 30 and 50 µS/cm; only one sample had a significantly higher value of 605 µS/cm (DP1). Consistent with this low conductivity, only 5 metals were above their limits of detection in more than 50% of the samples – i.e., barium (100%), cobalt (80%), manganese (100%), copper (60%), and zinc (60%). Antimony, cadmium, chromium, chromium VI, iron, mercury, molybdenum, lead, selenium, tin, thallium, and vanadium were never above detection, while the remaining metals were detected only sporadically.

Across all parameters and sites, **we observed only 2 relevant exceedances, both at site DP1** (Table 6). This well, which was the nearest to the COMMUS tailing storage facility in Pierre Muteba II, had the dataset's lowest pH, highest conductivity, and highest concentrations of aluminum, arsenic, barium, boron, manganese, uranium, and zinc (Table 6). Aluminum and manganese were, respectively, 780 µg/L and 1100 µg/L, above all applicable standards (50–300 µg/L and 50–400 µg/L; Table 1). At this site, uranium was 27 µg/L, near but below the widely adopted standard of 30 µg/L (Table 1).

Although well water quality appears overall acceptable from a chemical standpoint, the actual health risks for local communities may be higher than our data suggests. Indeed, we analyzed water directly from the wells and fountains, therefore prior to its use in cooking or other household activities. However, when this water gets in contact with metallic containers or utensils, its acidic pH may trigger the release of metals – particularly under conditions of prolonged contact, elevated temperatures, or in the presence of low quality or damaged cookware.[42,45,46] While these effects are more pronounced at pH values of 3–4, certain cookware can still leach metals at the pH of our well waters.[46]

Comparison with previous campaigns

Overall, **we found a relatively good agreement between Prof. Kaniki's results and ours** – although individual values vary sometimes more than an order of magnitude, trends and conclusions remain overall comparable. In water, we found a good agreement for pH, conductivity, manganese, and elements present only in trace amounts – i.e., nickel and lead (Figure A2). Zinc in water appeared consistently higher in Prof. Kaniki's dataset than ours, which may be indicative of a measurement artifact. Cobalt, iron, and copper were in some cases higher and in others lower, which possibly reflects day-to-day changes in water quality and sampling locations. For well water, we noticed a small discrepancy in pH values (0.5–1.5 pH units) that may be the result of a measurement artifact relevant only in low conductivity samples (details in Domestic water quality in Lake Kando's villages).

Heavy metals in sediments were overall less variable than in water, reflecting their role as contaminants' reservoirs and lower sensitivity to day-to-day changes in environmental conditions. Despite some scatter, we observed good agreement for cobalt, manganese, copper, and zinc (Figure A3). At 2 mine-impacted sites in Fungurume, nickel was consistently higher in Prof. Kaniki's dataset than in ours, likely reflecting the spatial heterogeneity of sediments often seen in polluted environments. We observed a clear, systematic difference only for iron, which may stem from a conversion error: after converting % into mg/kg, *all* values appeared to include an extra "0". Iron is a naturally occurring element, so this discrepancy does not impact the overall conclusions.

In contrast, **we found greater variability between Prof. Banza's results and the two datasets collected in 2025**. This difference likely reflects natural temporal and spatial variation – Prof. Banza sampled in early 2024, nearly 2 years prior to the other campaigns, and in locations that are only broadly comparable to those sampled in 2025 (Figure A1). Despite the differences, **the overarching trends were coherent to our findings**. In surface waters, arsenic, cadmium, iron, nickel, lead, uranium, and zinc were consistently below legal thresholds and generally remained below 10 times the European baseline, while cobalt, manganese, and copper exceeded both reference frameworks in several instances (Table A4). In some cases, Prof. Banza's water measurements were markedly higher than those from 2025. For instance, manganese concentrations in Lake Kando were 32905 µg/L, compared to <1–130 µg/L in 2025 (Table A4). Cobalt and copper showed similar trends. While analytical artifacts cannot be excluded, this pattern is consistent with a localized pollution event preceding Prof. Banza's campaign, whose effects may have been naturally mitigated by 2025. In contrast, sediment results were overall comparable across datasets (Table A5).

Although conducted more than a decade earlier, **previous studies conducted in Kolwezi broadly agreed with our results**. In 2011, Atibu et al.[8] reported elevated concentrations of cobalt, copper, and manganese in the Musonoïe and Liulu rivers (Kolwezi), but arsenic, cadmium, chromium, nickel, molybdenum, and tin below detection limits. Excluding a clear outlier, concentrations ranged 0.1–27 µg/L for cobalt, 0.3–103 µg/L for copper, and 0.1–16.2 µg/L for manganese,[8] values that are within the lower range of what we measured in this area (cobalt: 1–330 µg/L; copper: 1.9–200 µg/L; manganese: 43–1200 µg/L; Table 4, range for Kolwezi). The same study also identified copper as particularly elevated in sediments (43–47470 mg/kg), alongside cobalt (60–13200 mg/kg), manganese (19–1040 mg/kg), and iron. Although the highest values exceed our 2025 observations, the key metals of concern and their median values are broadly consistent with our findings (Table 4). A follow-up study[7] focused on sediments from other mine-impacted rivers in Kolwezi similarly reported elevated levels of cobalt (19–18430 mg/kg) and copper (115–209000 mg/kg); lead was also high (11–899 mg/kg), possibly reflecting local geological differences or specific pollution sources.

Kolwezi and Pierre Muteba II

Water and sediment quality in the Musonoïe River

In Kolwezi, we sampled 4 hydrologically connected sites along the Musonoïe River (Figure 4A): a pristine site upstream of known contamination (WSK1; Figure 4C); a stream emerging from a large waste rock dump near the COMMUS processing plant and heavily used by artisanal miners to wash minerals (WSK2; Figure 4D); a site along the Musonoïe River downstream of WSK1 (WSK3; Figure 4E); and Lake Golf (WSK4; Figure 4F). Prof. Kaniki sampled a puddle in the contaminated stream approximately at WSK2; an upstream site roughly equivalent to WSK1; and Lake Golf near our sampling location (Figure A1A). Prof. Banza reported data only for Lake Golf (sediments only) and the Musonoïe River without specifying the exact sampling location.

The results clearly highlighted the influence of mining activities on local water quality. **At site WSK2, we observed a pronounced increase in conductivity and several heavy metals**, including manganese, thallium, uranium, and vanadium (Figure 5, green bar). Additional elements with this pattern included arsenic and boron (Table 4; only elements above detection). For most parameters, concentrations declined downstream, approaching values only moderately higher than the reference site by the time water reached Lake Golf. We note that the overall neutral to basic pH of this river (7–8.1 at downstream sites; Table 4) helps limit the dissolution of metals in suspended sediments, which were substantial at WSK2 and WSK3 (Figure 4D and Figure 4E).

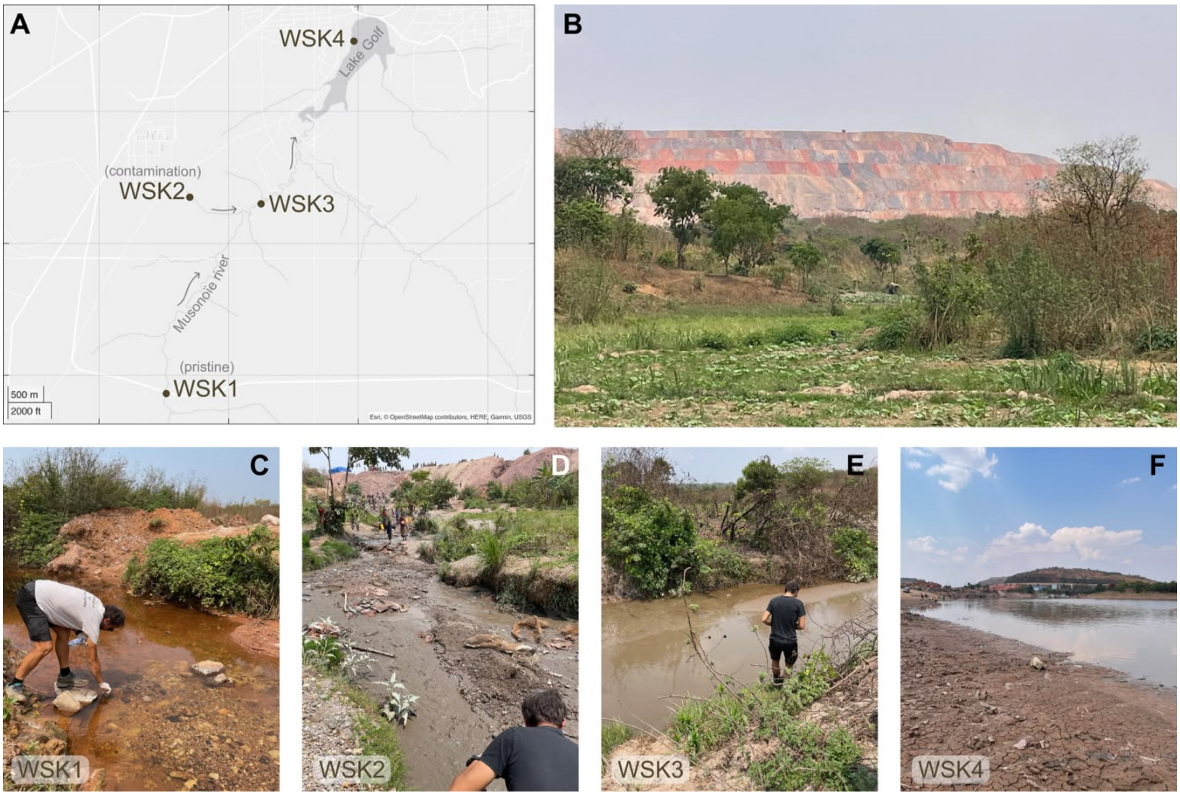

Figure 4. Surface water and sediment sampling in Kolwezi. In Kolwezi, we sampled 4 hydrologically connected sites along the Musonoïe River (A), including a pristine upstream site (C), a stream emerging from under the COMMUS' waste rock dump in panel B and used for mineral washing (D), a downstream site always along the river (E), and Lake Golf (F).

Although this behavior suggests that contamination is significant only at specific (and predictable) points, some metals deviated from this trend. **Manganese remained elevated downstream of contamination**: at Lake Golf (WSK4), it was 340 µg/L, more than 10 times the concentration

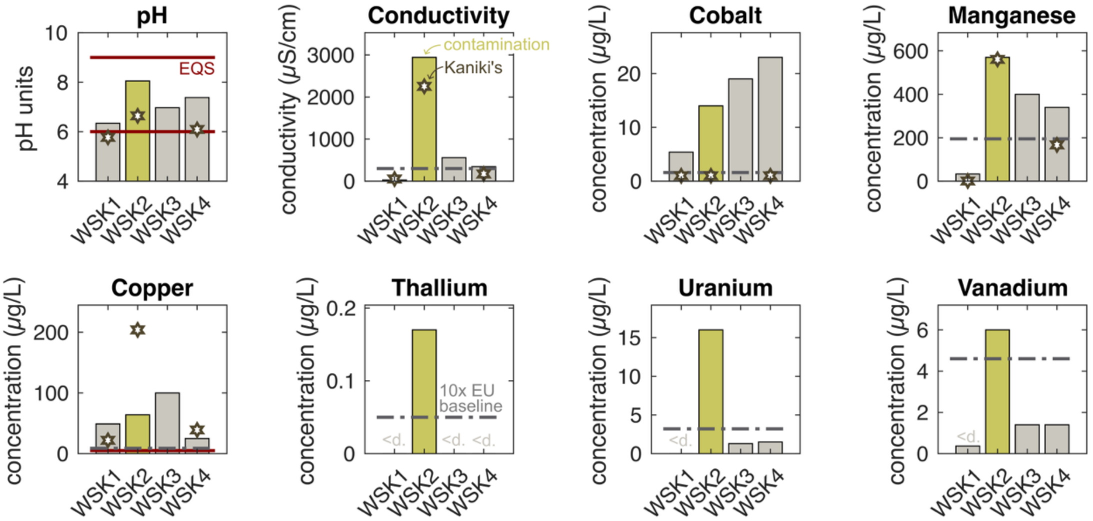

Figure 5. Overview of selected surface water parameters in Kolwezi. The red lines are ranges of Environmental Quality Standards (EQS; Table 1); grey dashed-dot lines are 10-fold the EU baseline from the FOREGS database[21]; the stars are relevant results from Prof. Kaniki's report[6] (thallium, uranium, and vanadium were not measured). Values not detected or below detection limits are marked with "<d.".

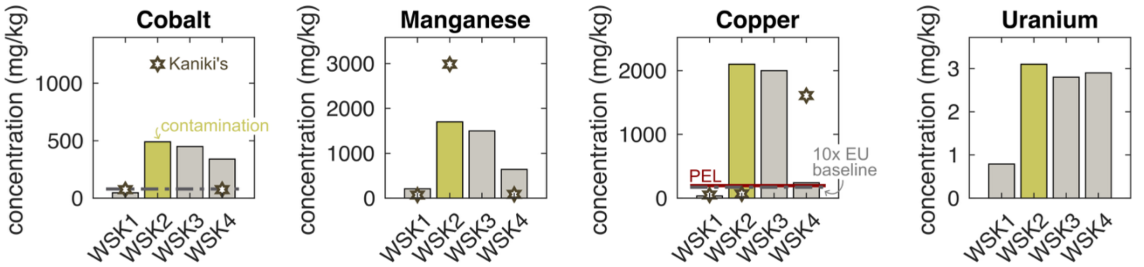

Figure 6. Overview of selected metals in sediments in Kolwezi. The red line is the Canadian Probable Effect Level (PEL); grey dashed-dot lines are 10-times the EU baseline from the FOREGS database[21] (above the upper limit when not visible); the datapoints are Prof. Kaniki's results[6].

observed at the pristine site (33 µg/L; Table 4). Despite the differences in absolute values, Prof. Kaniki observed the same trend for this metal (Figure 5 and Table A4). **Cobalt** exceeded more than 10-fold the European baseline at the reference site (WSK1, 5.4 µg/L vs. a baseline of 0.16 µg/L) and **increased steadily downstream** to a maximum of 23 µg/L at Lake Golf (Figure 5 and Table 4). **Copper showed a similar behavior**, with concentrations exceeding both 10 times the European baseline and several international references already at WSK1 – though concentrations at Lake Golf were comparable to those at the pristine site (Figure 5 and Table 4). These observations reinforce previous hypotheses (see Atibu et al.[7]) that background water concentrations of copper and cobalt in the Musonoïe River may be naturally high. However, **anthropogenic inputs related to mining activities add to this naturally elevated background**, contributing to localized deterioration of water quality, particularly near discharge or contamination points.

Prof. Kaniki observed comparable trends in pH, conductivity, and concentrations of manganese, copper, iron, nickel, and lead (Figure 5 and Table A4). On the other hand, they consistently reported lower cobalt (always < 1 µg/L vs. 14–23 µg/L) and higher zinc (63–110 µg/L vs. always < 5 µg/L) than our team (Table A4).

Heavy metal concentrations in sediments further strengthen the evidence of mining impacts along the Musonoïe River. Cobalt, manganese, copper, and uranium showed a pronounced increase at site WSK2, followed by a gentle decline downstream (Figure 6). Several other metals displayed a similar pattern, including arsenic, barium, beryllium, boron, cadmium, iron, thallium, and zinc (Table 5; only elements above detection). Notably, **the elements most characteristic of local geology** – cobalt, manganese, copper, and uranium – **had their lowest concentration at the pristine reference site**. For cobalt and copper, these values were well below 10 times the European baseline and the Canadian PEL at the reference site, while they exceeded both references at WSK2 and all downstream sites (Figure 6). Together, these results indicate a pattern of recent accumulation of cobalt, copper, manganese, and uranium across the watershed, pointing to a **clear legacy of mine-related contamination.**[e] At the same time, the comparison with surface water results suggests the presence of day-to-day variations in mining inputs, especially for copper and cobalt.

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[e] At a first approximation, surface sediments show the "average pollution history" of the past years to decades. The exact time span depends on local hydrology and occurrence of natural and anthropogenic perturbation events (see footnote *d* for more details).

This conclusion is overall consistent with previous sampling campaigns. Prof. Kaniki reported the lowest sediment concentrations of cobalt, manganese, copper, and zinc at the upstream reference site (Figure 6 and Table A5). Downstream locations were typically more contaminated than the upstream site, though to a different extent compared to our dataset (Figure 6). Nickel and lead were always below detection, in analogy to what we observed (Table 5). Prof. Banza's results for the Musonoïe River and Lake Golf highlighted an exceedance in the Canadian PEL for copper at both sites; results for other metals were overall comparable across the 3 datasets (Table A5).

Domestic water quality in Pierre Muteba II

In Pierre Muteba II, we sampled 3 wells for domestic use located close to COMMUS tailing storage facility and processing area (Figure 7). Based on community reports, these wells have an approximate depth of 5–6 m (DP1), 10 m (DP2), and 60 m (DP3).

Water pH was by far the most concerning parameter, with values of 4.6–4.9 (Table 6). These values are typically 1.5 to 2 units lower than recommended by the international normative (Table 1). As pH is expressed in a logarithmic scale, a difference of 2 units denotes water 100 times more acidic than recommended. We note that underground water becomes more acidic as the wells approach the tailing storage facility and become shallower.

In addition to having the lowest pH of the dataset, **the well closest to the COMMUS tailing storage facility** (DP1) **was also a hotspot for selected heavy metals**. This site had the highest conductivity and highest concentrations of aluminum, arsenic, barium, boron, cobalt, manganese, uranium, and

Figure 7. Domestic water sampling in Pierre Muteba II. We sampled 3 domestic water wells near COMMUS' tailing storage facility and processing area (A), including site DP1 (B-C), DP2 (C), and DP3 (E).

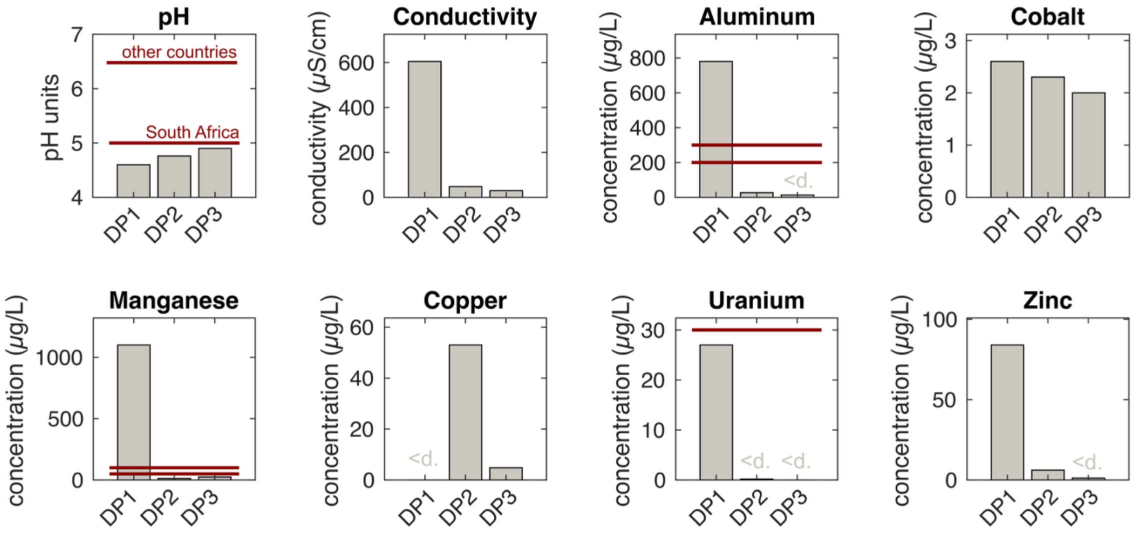

Figure 8. Overview of selected metals in domestic water wells in Pierre Muteba II. Red lines denote the range of available standards and guidelines for drinking water (Table 3); when not visible, they are above the reported values or not defined. Values below detection limits are denoted with the symbol "<d.".

zinc (Figure 8 and Table 6). **Aluminum and manganese exceeded by several folds all available standards and guidelines**. Aluminum was 780 µg/L, 3–15 times above any normative limit included in our analysis (50–300 µg/L; Table 1); likewise, manganese was 1100 µg/L, also exceeding 3–20 times the available standards (50–400 µg/L; Table 1) and almost 14 times the WHO guideline of 80 µg/L.[26] While the health impacts of aluminum are less established,[26,41] **manganese above the recommended values has toxic effects on the central nervous system**, especially on infants.[26]

Prof. Kaniki did not sample these wells, so a direct comparison was not possible. However, 2 domestic water samples collected in Tshizuza, southeast of the tailing storage facility, were overall comparable to DP2 and DP3. In particular, water pH was acidic (5.4–6.2), conductivity was low (9–18 µg/L), and most metals were below detection, with no exceedances in standards and guidelines (Table A6).[6] Prof. Banza did not sample well waters.

Lake Kando and nearby areas

Water and sediment quality in the Lualaba River watershed

Near Lake Kando, we sampled 4 hydrologically connected sites around the MUMI concession (Figure 9). Locations included the Lwakutsha River, a small stream that passed into the MUMI concession and flowed into Lake Kando (WL1; Figure 9A); Lake Kando near the Kaindu village (WL2; Figure 9B) and at the confluence with the Lualaba River[f] (WL3; Figure 9C); and the Lualaba River near Kisenda, approximately 7 km downstream of the lake outflow (WSL4; Figure 9D). We took sediments only at WSL4; at the other locations, sediments primarily consisted of decomposing organic matter or rocks, which we deemed inappropriate for heavy metal analyses (Figure 3E). Two of our sampling locations

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[f] Lualaba is the name of the Congo River upstream of the Boyoma Falls.[47]

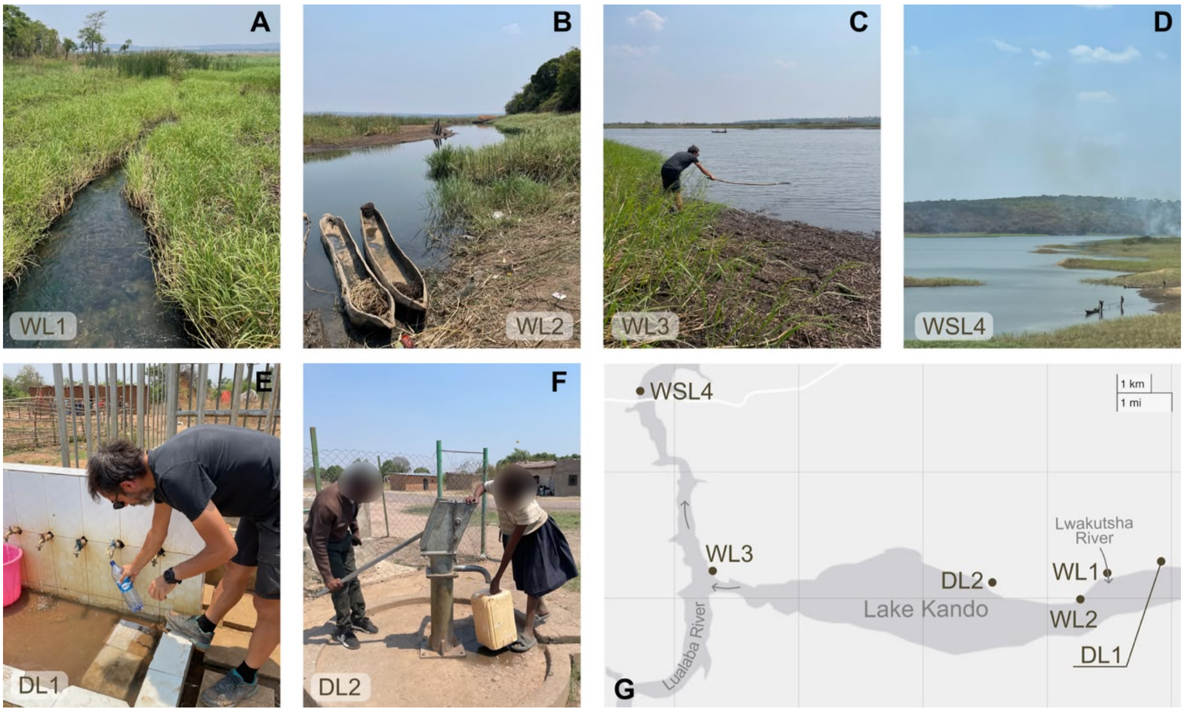

Figure 9. Sampling sites at Lake Kando and surrounding areas. We sampled 4 hydrologically connected sites in the Lualaba River watershed (A–D) and 2 domestic water sources: one in Mibanze (E) and one in Rianda (F).

were also included in Prof. Kaniki's campaign, allowing for direct comparisons: site WL1 (PM12 in Prof. Kaniki's report) and a point on the shores of Lake Kando approximately 500 m west of WL2 (PM10; Figure A1B). The following discussion includes 2 additional sites Prof. Kaniki's team sampled on the northern shores Lake Kando and Prof. Banza's data for the same lake (Table A3).

Overall, **this area emerged as the least polluted of our campaign, particularly regarding surface waters.** Barium and manganese were the only metals detected in all samples (Table 4). Of the remaining elements, only aluminum, iron, copper, uranium, and vanadium were above their detection limit in at least 2 of the 4 sites; when detected, they typically occurred at low concentrations. We identified only one exceedance in the South African guidelines at the most downstream site (WSL4) and all concentrations remained well below 10 times the European baseline values. Although possibly not relevant, we noticed that **manganese in Lake Kando exceeded the WHO drinking water guideline** (80–130 µg/L vs. a guideline of 80 µg/L; Table 3 and Table 4) and other international standards. This represents a potentially overlooked exposure pathway in local communities that rely on surface, not underground, water for domestic purposes.

The results obtained by Prof. Kaniki broadly align with our findings (Table A3). All metals were below detection in the Luwakutsha River (ML12/WL1), and most were also below detection in Lake Kando; likewise, conductivity and pH were fully comparable across datasets. We observed discrepancies only in cobalt and manganese. Prof. Kaniki detected 111 µg/L of cobalt near Kaindo (ML10), but concentrations were below detection at our nearby site (WL2) and at the 2 other sampling locations (ML9 and ML14). Likewise, we measured 130 µg/L of manganese at WL2 but Prof. Kaniki reported < 1 µg/L of this metal at all sites in Lake Kando (Table A3). In contrast, **Prof. Banza's 2024 data showed water concentrations of cobalt, manganese, copper, and zinc up to 3 orders**

of magnitude higher than either 2025 campaigns, with 3 elements exceeding international standards and guidelines (Table A3). Although direct evidence is lacking, these elevated concentrations may reflect a transient pollution event that occurred shortly before Prof. Banza's campaign. We note that the area is also rich in natural vegetation that may have helped absorbing excess metals from the water – a process that has already been hypothesized in the area.[7,9]

The sediments collected at WSL4 also had overall low metal content: of the 22 elements analyzed, we detected only 13, most of which near their detection limits (Table 5). **The only notable exception was copper**, which was as high as 310 mg/kg. This value was comparable to Lake Golf (240 mg/kg; WSK4) but almost 10-fold higher than the most pristine locations of our dataset (34–47 mg/kg); it also exceeded the Canadian PEL and was more than 10 times higher than the European baseline (Table 5). Prof. Kaniki and Prof. Banza both measured comparable copper concentrations in the sediments of Lake Kando (118–461 mg/kg; Table A4). This result strongly indicates that **copper is consistently high in the Lualaba River watershed**, which may be due to legacy copper contamination over the past years to decades, a naturally high background (compared, e.g., to the Musonoïe River watershed), or a combination of both.

Domestic water quality in Lake Kando's villages

Well water quality in Mibanze and Rianda was overall acceptable. **The only parameter outside recommended limits was pH**, which was 4.7–5.1 (Table 6) – well below the 6.5–6.8 lower limit recommended in most drinking water legislation (Table 3). Both samples had low conductivity (30-50 µS/cm) and low concentration of dissolved metals (Table 6). In Rianda, only barium and manganese were above their limits of detection, while in Mibanze we also detected small amounts of beryllium, cobalt, nickel, copper, and zinc. None of the metals exceeded international standards nor guidelines.

Prof. Kaniki's results at these villages were broadly consistent with our observations, with relevant differences only in iron and pH (Table A5) Iron concentrations were significantly higher in Prof. Kaniki's dataset (46–623 µg/L) compared to ours (below detection). In most drinking water legislations, iron is considered an organoleptic parameter with no known health effects in the observed concentration range.[26] Likewise, pH values were consistently 0.5–1.5 units higher (5.1–6.6) than we observed (4.7–5.1; Table A5). Prof. Kaniki's team also found acidic well water in Moloka 1 (pH of 5.1) and one of the sampling points in Kisenda (pH of 6.3), while in other 2 villages pH values were 6.7–6.8 (Table A5).

We note that part of the discrepancy in pH values between our and Prof. Kaniki's results may be attributed to technical artifacts. While Prof. Kaniki measured pH *onsite*, we measured it *offsite* up to a few hours after collection due to security constraints. Although this small delay is generally not problematic, it can affect pH values in waters with low conductivity (i.e., < 100 µS/cm), as gas exchanges with the atmosphere may lower the water's natural pH. This effect may be further compounded by the reduced reliability of pH measurements in low conductivity waters.[48] Despite these potential artifacts, all wells consistently showed pH values below 7, with 6 of 9 measurements falling outside recommended limits (Table A5). The consistency of this pattern across datasets strengthens our confidence in the overall results.

Water and sediment quality in Fungurume

Water and sediment quality in the Kelangile River watershed

Near Fungurume, we sampled 3 hydrologically connected sites along the Kelangile River (Figure 11): a site upstream of known contamination (WSF1); the effluent from the TFM 30k industrial plant (WSF2); and a downstream location (WSF3). We also collected a sample from the Dipeta River shortly before its confluence with the Kelangile (WSF4). Most of these locations were also included in Prof. Kaniki's campaign, while Prof. Banza sampled the Kelangile River at different points close to WSF2 and WSF3, and the Dipeta River significantly upstream of our sampling site (Figure A1C).

Surface water quality in Fungurume was worse than in the Lake Kando area but better than in Kolwezi. At all sites, we detected only barium, cobalt, iron, manganese, and copper. Aluminum, antimony, arsenic, molybdenum, nickel, selenium, uranium, vanadium, and zinc were present only at 1 or 2 sites (of 4), often in concentrations close to their limit of detection; all other elements were consistently below their limit of detection (Table 4).

In surface water, **copper emerged as the most concerning metal**, displaying a behavior compatible with anthropogenic disturbance. Concentrations at the control site (WSF1) were 1.9 µg/L, but they

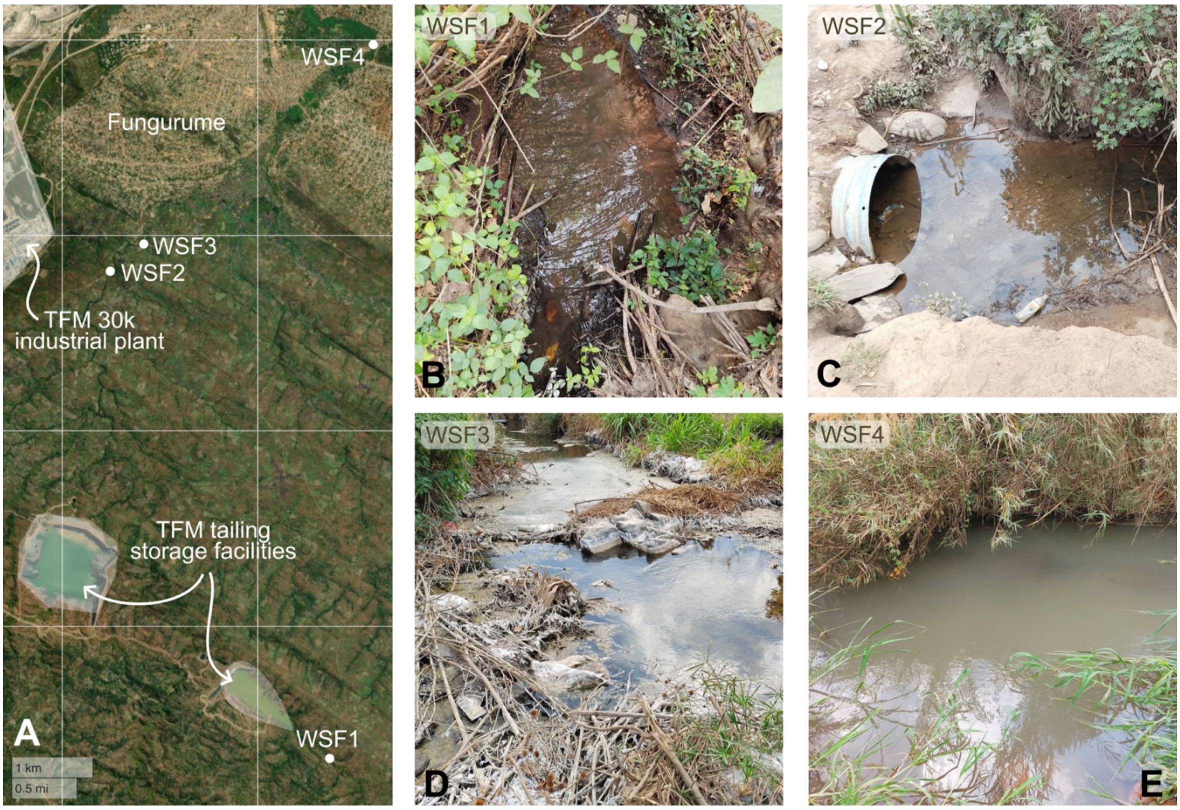

Figure 11. Sampling sites in and around Fungurume. We sampled 3 hydrologically connected sites along the Kelangile River (B, C, and D), and one site along the Dipeta River shortly before its confluence with the Kelangile (E).

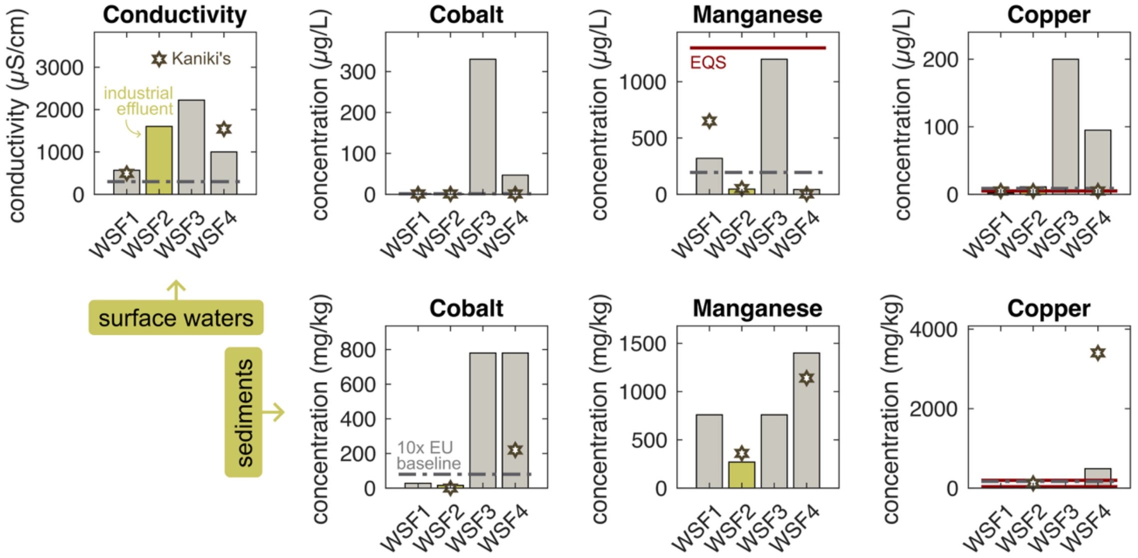

Figure 12. Overview of selected surface water (top) **and sediment** (bottom) **results in Fungurume.** Red lines are ranges of Environmental Quality Standards (EQS; Table 1); grey dashed-dot lines are 10-fold the EU baseline from the FOREGS database;[21] the stars are relevant results from Prof. Kaniki's report.[6]

increased 10–100 times as they approached known contamination sources (11–200 µg/L; Figure 12 and Table 4). These values exceeded 10 times the European baseline and were also above the Swiss, Chinese, and South African regulations (Table 1). We note that WSF2, the industrial effluent from the TFM 30k processing plant, was not a contamination hotspot (Figure 12). **The most concerning site was instead WSF3**, approximately 0.5 km downstream, where we detected concentrations of cobalt, manganese, and copper at least 2 orders of magnitude higher than at the control site (Figure 12). Arsenic, molybdenum, nickel, and uranium were also above detection, although their concentration was overall low (Table 4). A hypothesis compatible with these observations is that the Kelangile River gathers several sources of contamination as it approaches the city and its ore processing plants (e.g., tailing storage facilities): thus, the industrial effluent is only one of these inputs, not the major one. In support of this interpretation, Prof. Kaniki found significantly higher conductivity and manganese, copper, and cobalt concentrations at a site immediately upstream of the industrial effluent (FL2) compared to the effluent itself (FL1; see also Table A4). We also noted that the control site showed the highest concentrations of barium (1300 µg/L) and manganese (320 µg/L; Table 4). Barium forms insoluble salts in the presence of sulfate, a compound whose concentration increased markedly from the control site (below detection) to the contaminated locations (152–1490 mg/L; see Prof. Kaniki's report[6]). Thus, our hypothesis is that the *decrease* in barium at downstream locations is also an effect of mine-related pollution. On the other hand, we do not have good explanations for the high levels of manganese at WSF1. In conclusion, **Fungurume showed an overall more complex pollution scenario than Kolwezi**.

Sediments showed a trend comparable to surface waters, with cobalt, manganese, and copper – among others – with increased concentrations at WSF3 and WSF4, the most downstream sites (Figure 12). At WSF4, in the Dipeta River, copper exceeded the Canadian PEL.

While a few data differ, **our trends match relatively well observations from Prof. Kaniki and Prof. Banza**. The agreement is better for sediments than surface waters, possibly due to their lower susceptibility to day-to-day changes in water regimes and individual pollution events. For surface waters, we observed the same discrepancies found in the rest of the dataset. For instance, Prof. Banza's concentrations were markedly higher than the other two datasets (especially for cobalt and manganese), while Prof. Kaniki's zinc and cobalt concentrations were, respectively, higher and lower than ours (Table A5). Prof. Kaniki observed a significant increase in sulfate (a parameter that we did not measure) in the Kelangile River, highlighting a clear impact of TFM mining and processing activities on water quality. This increase was evident both in space – i.e., in 2025, sulfate was 2 mg/L at the river source vs. 1490–755 mg/L at downstream locations – and in time – i.e., historic mean of 13 mg/L vs. 1040 mg/L in 2025.[6] The team observed comparable increase in sulfate also in underground waters.

Key findings

Aquatic environments

Metals of highest concern

Copper emerged as the most concerning metal in water and sediments across all sites. In surface water, it exceeded several regulatory thresholds and was above 10 times the European baseline at most sites (Table 4). In sediments, copper was also above the Canadian PEL and ISQG in 55% and 78% of the samples, respectively (Table 5), with the highest values observed downstream of known pollution sources (Figure 5, Figure 6, and Figure 12). These findings are consistent with the results from Prof. Kaniki and Prof. Banza's, as well as with previous studies conducted in Kolwezi.[7,8] Overall, comparison across polluted and control sites suggests that elevated **copper levels likely result from the combined effect of mine-related inputs that add to naturally high background concentrations**.

This result is particularly relevant given copper's effects on aquatic organisms. Although it is an essential nutrient, copper becomes toxic to aquatic biota at concentrations above ~ 1–10 µg/L (values vary depending on water hardness).[19,49] Among other effects, **elevated concentrations of copper can impair fish behavior and growth**.[49] Although we do not have evidence of a casual nexus, nearly all communities interviewed by RAID in 2023 in the Lualaba province lamented a substantial decrease in fish yields and size over the past decade.[3] In this area of likely high natural background, we expect aquatic fauna to be overall more resistant to elevated levels of copper than the average. Still, individual pollution events (e.g., as the 2017 acid spill in Lake Kando[3]) represent acute stressors that may have contributed to the biodiversity loss local communities have experienced in the past years. In contrast, drinking water standards allow much higher copper concentrations (1000–2000 µg/L; Table 3) than those measured in our study (0–200 µg/L; Table 4), suggesting that direct risks to human health due to copper exposure via drinking water are unlikely.

Cobalt in water and sediments and manganese in sediments also frequently exceeded 10 times the European baseline at several sites in Kolwezi and Fungurume. While a naturally high background cannot be excluded, multiple lines of evidence point to direct contributions from mine-related activities. Above all, copper, cobalt, and manganese are ore-specific elements[50] that were ubiquitously detected in the area in previous studies focused in water and sediments[7,8] and in inhalable dust[51]. Furthermore, these elements generally increased downstream of known contamination sources (e.g., Figure 6). Like copper, also cobalt and manganese are essential elements that become toxic to aquatic life at elevated concentrations.[19,23,52] Cobalt is significantly understudied but recent work has estimated a chronic toxicity reference value for aquatic life of 5–7 µg/L,[23] which is up to 60 times *lower* than what we observed at the most polluted locations (Table 4). Likewise, all manganese concentrations were below the South African guidelines for *acute* effects (Table 1) but 5 were close to or above those for *chronic* effects (320–1200 µg/L vs. 370 µg/L; Table 4).[19] While aquatic plants appeared to be more sensitive to cobalt than fauna,[23] **manganese impacts**

on fish resemble those of copper – including behavioral change and mortality.[53] Although we did not use this reference in the text, **at 7 sites manganese in surface waters also exceeded up to 15-fold the WHO guideline for drinking water quality** (80–1200 µg/L vs. 80 µg/L[26]; Table 4). This finding may be especially relevant for communities that still use Lake Kando's surface water for domestic purposes. Dietary exposure to manganese damages the nervous system, causing behavioral changes (e.g., slow movements) and decreased ability to learn and remember – effects that are more pronounced in children than adults.[54] Reproductive effects have also been observed.[54]

In addition to direct exposure through contaminated water, **consumption of locally caught fish may represent a significant pathway for metal exposure in local communities**. Squadrone et al.[55] reported elevated levels of cobalt, copper, manganese, and other metals in fish from Lake Tshangalele, near Likasi; for cobalt and copper, concentrations consistently exceeded recommended daily intake levels. A biomonitoring study conducted in the same area further identified diet as the main pathway of cobalt exposure in the general adult population, with fish representing a non-negligible contributor in lakeside communities.[56]

Geographic distribution

Kolwezi was the most impacted area in 2025. WSK2, a stream emerging from under the COMMUS waste rock dump, was the most contaminated location in the dataset, receiving inputs from both industrial and artisanal mining. Although the overall contamination decreased downstream, the concentration of several metals remained elevated (Figure 5 and Figure 6). The area near WSK2 and WSK3 has been used for vegetable production – and, despite its lower productivity, is still cultivated. Previous work by Mununga Katebe et al.[9] documented the transfer of heavy metals from irrigation water to soil and from soil to crops in urban gardens in Lubumbashi – this process, called bioaccumulation, is well-established in the literature.[57] While we did not investigate this exposure pathway, **using unprocessed water from the Musonoïe River for irrigation raises concerns on potential heavy metal accumulation in locally produced food** – and, in turn, exposure through food consumption. This concern is well justified: Cheyns et al.[56] showed that consumption of locally grown vegetables was the primary cobalt exposure pathway in adults living near mining and smelting activities in Lubumbashi, Likasi, and surrounding areas.

In Fungurume, the situation appeared more complex. Although we detected elevated levels of ore-specific metals at downstream sites, we were unable to unequivocally identify the single sources of this contamination. In contrast, we found no clear evidence of recent contamination near and in Lake Kando, especially in surface waters. Copper in sediments was consistently high across datasets and higher than at control locations (Table A5). This pattern may reflect a naturally high background, legacy contamination (over the past years to decades; e.g., in 2017[3]), or a combination of both. In some areas, **natural attenuation processes mediated by local vegetation may have contributed to the removal of heavy metals from surface waters**, potentially explaining the mismatch between water and sediment results. We note that **the use of Lake Kando's surface waters for domestic purposes poses significant health concerns due the considerable levels of manganese** observed in our and Prof. Banza's datasets.

Domestic water

With a notable exception, **groundwater quality was overall acceptable**, having overall low conductivity and low concentration of dissolved metals (Table 6). **The only parameter consistently outside the recommended limits was pH**, which ranged 4.6–5.1 vs. typical guideline values of 6.5–8.5 (Table 3 and Table 6). While these pH values do not necessarily pose direct health risks, **they may have indirect effects by facilitating the dissolution of toxic metals**.[42] Indeed, our results refer to water samples taken directly from wells (Figure 3C). Subsequent domestic use, particularly with metal containers or tools, may promote the leaching of toxic metals.[46] Suspended particles – which we excluded from our analysis by filtration – could also release metals when this acidic water is heated. Thus, **a comprehensive risk assessment would require analysis of water samples *after* typical household processing**, not only at the point of collection.

Our dataset contained a clear outlier – DP1, a shallow well located less than 200 m from COMMUS tailing storage facility in Pierre Muteba II (Figure 7). This site, which appeared to be actively used by the community at the time of sampling, exhibited the most acidic pH, the highest conductivity, and the highest concentration of heavy metals among all sampled wells (Table 6). Aluminum and manganese were several folds above all available drinking water standards and guidelines, and uranium was also close to its international reference values. **Manganese was particularly concerning, exceeding 3–20 times all available standards and almost 14 times the WHO guideline**. Given the established effects of this metal on the nervous system,[26,54] **water from this well is unlikely to be safe for human consumption**.

The available information did not allow us to establish the origin of this consistently acidic pH. The exceptional contamination observed at DP1 combined with its closeness to the COMMUS tailing storage facility hints to a possible leach of acidic water into the local aquifer. Despite displaying an overall good quality in 2025, Lake Kando and surrounding areas experienced a severe sulfuric acid spill in 2017;[3] thus, some of this acid may have likewise reached the local aquifer. However, given the limited availability of data, these remain working hypotheses requiring more in-depth investigations. A second possibility is that underground water in the area is naturally acidic – though a recent study investigating groundwater in another area of Kolwezi disproves this interpretation.[43]

Comparison across studies

Despite the heterogeneity in parameters, analytical approaches, sampling sites, and timing (Table A3 and Figure A1), **the 3 datasets converged towards comparable conclusions when interpreted within a common reference framework**. We observed a clear agreement in the most critical metals (i.e., cobalt, copper, and manganese) vs. metals present in lower amounts (e.g., arsenic, cadmium, nickel, lead) – though individual concentrations often differed by an order of magnitude or more (Table A4, Table A5, and Table A6). Notably, **copper and cobalt were also identified as key contaminants** in rivers near and in Kolwezi in studies conducted between 2011 and 2016.[7,58] The agreement was stronger for sediments than for water, likely reflecting the fact that sediments accumulate metals over time, while water concentrations are more sensitive to short-term environmental variability and episodic pollution events. Consistency was also higher between our dataset and Prof. Kaniki's – both collected in October 2025, at comparable locations, and using similar methodologies – than with Prof. Banza's, which differed more significatively in sampling period and site selection (Figure A1).

Water quality and human health in Lualaba's frontline communities

The data presented in this report provide important evidence to help establish a link between mine-related pollution and human health impacts in Lualaba's frontline communities.

The grey literature has documented worsening health conditions in the area following the recent mining boom. In 2024, RAID and Afrewatch interviewed healthcare professionals in Kolwezi, who reported a **marked increase in specific diseases over the last 5–10 years, coinciding with an intensification in mining activity in the region**.[3] The most reported conditions included skin problems (e.g., itchiness, rashes, chronic dermatoses), eye irritation, respiratory issues, impaired digestion, and, among women, gynecological and reproductive problems. Based on their daily experience, **local communities pointed to contaminated water as the primary cause of these health conditions**. In addition to children – who often play in water – women appeared particularly affected due to their reliance on water for domestic tasks, like laundry, food preparation, and water collection.

Unfortunately, **our results do not point to a single causal factor**, hinting to the likely occurrence of **synergic effects caused by continued exposure to a cocktail of pollutants through water, food, and air**. Within our dataset, manganese emerged as the most concerning metal for human health, although dietary exposure may be more relevant than direct contact with contaminated water.

There is strong evidence that **communities within kilometers of mining or smelting operations** in Lubumbashi, Likasi, and surrounding areas **have higher concentrations of heavy metals in their urine** than control populations.[56,59] Cheyns et al.[56] showed that food was the predominant exposure pathway for cobalt in adults, whereas contaminated dust dominated in children. The findings presented in this report hint that **consumption of local fish and vegetables may represent an important exposure pathway for adults also in Kolwezi and surrounding areas**, especially for cobalt (see above); on the other hand, dust ingestion and inhalation may be more prevalent for children and miners (see our report on air quality[4]).

At present, the lack of a formal epidemiological study directly linking exposure to heavy metals in water and sediments to specific health outcomes in Lualaba represents a critical gap that this report alone cannot fill. An urgent, independent health assessment is thus warranted.

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Appendix

Table A1. **Overview of sampling sites for surface water, domestic water, and sediments.** For domestic waters, the area is the actual village where the sample was collected; for surface waters and sediments, it refers to the broad area. The report ID contains information on sample type (W = surface water, WS = surface water + sediments, D = domestic water) broad sampling area (K = Kolwezi, P = Pierre Muteba II, L = Lake Kando, F = Fungurume), and, when relevant, hydrological connectivity (increasing sample number).

Report ID	Field ID	Sampling date	Sampling time	Area	Closest relevant concession	Site type	Surface water (* domestic)	Sediments	Latitude	Longitude
WSK2	CK05	12/10/25	11:15	Kolwezi	COMMUS	Stream	Yes	Yes	-10.76083	25.42833
WSK3	CK06	12/10/25	11:40	Kolwezi	COMMUS	Stream	Yes	Yes	-10.76167	25.43750
DP1	CK07	12/10/25	12:50	Pierre Muteba II	COMMUS	Well	Yes*	No	-10.75500	25.41222
WSK4	CK08	12/10/25	13:50	Kolwezi	COMMUS	Lake	Yes	Yes	-10.74111	25.44944
DP2	CK09	13/10/25	11:30	Pierre Muteba II	COMMUS	Well	Yes*	No	-10.75377	25.41628
WSK1	CK10	17/10/25	10:15	Kolwezi	COMMUS	Stream	Yes	Yes	-10.78564	25.42530
DP3	CK11	17/10/25	14:40	Pierre Muteba II	COMMUS	Well	Yes*	No	-10.75449	25.41422
DL1	CK12	18/10/25	12:15	Lake Kando	MUMI	Fountain	Yes*	No	-10.82361	25.86389
WL1	CK13	18/10/25	12:30	Lake Kando	MUMI	Stream	Yes	No	-10.82667	25.84944
WL2	CK14	18/10/25	12:50	Lake Kando	MUMI	Lake	Yes	No	-10.83361	25.84222
WL3	CK15	18/10/25	14:05	Lake Kando	MUMI	River	Yes	No	-10.82611	25.74361
DL2	CK17	19/10/25	13:40	Lake Kando	MUMI	Well	Yes*	No	-10.82917	25.81861
WSL4	CK18	19/10/25	14:50	Lake Lando	MUMI	River	Yes	Yes	-10.77861	25.72417
WSF4	CK01	10/10/25	14:45	Fungurume	TFM	River	Yes	Yes	-10.61789	26.33620
WSF2	CK02	10/10/25	15:10	Fungurume	TFM	Industrial effluent	Yes	Yes	-10.64293	26.30763
WSF3	CK03	10/10/25	15:20	Fungurume	TFM	River	Yes	Yes	-10.63993	26.31040
WSF1	CK04	10/10/25	16:00	Fungurume	TFM	River	Yes	Yes	-10.69677	26.33130

Table A2. Overview of limits of detection and average measurement uncertainty. When the limit of detection was not available (n.a.), analytes were either always above their limits of detection. [a] Sampling and analyses not accredited by ACCREDIA.

	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium VI	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
Waters																							
Limit of detection (µg/L)	25	0.1	1	n.a.	0.1	25	0.1	1	5	0.5	20	n.a.	0.5[a]	1	1	1	1	1	1	0.1	1	1	5
Average relative error (%)	26%	27%	30%	27%	29%	26%	n.a.	27%	n.a.	16%	28%	25%	n.a.[a]	16%	21%	n.a.	24%	25%	n.a.	24%	30%	21%	27%
Sediments																							
Limit of detection (mg/kg)	n.a.	0.1	n.a.	n.a.	0.1	n.a.	0.1	n.a.	10	1	n.a.	n.a.	0.1	0.5	10	10	n.a.	0.5	1	0.025	0.5	n.a.	n.a.
Average relative error (%)	24%	64%	41%	25%	29%	50%	29%	25%	n.a.	n.a.	24%	24%	n.a.	n.a.	n.a.	23%	25%	n.a.	n.a.	25%	46%	30%	28%

Table A3. Comparison of measurement parameters across studies. A = MES, TDS, calcium, manganese, sulfate; B = pH in water, pH in KCl, MO.

	pH	Conductivity	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Chromium VI	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc	Other
Surface waters																										
Source International (2025)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Prof. Kaniki (2025)	X	X								X			X	X			X	X	X						X	A
Prof. Banza (2024)	X				X				X	X				X			X	X	X				X		X	
Sediments																										
Source International (2025)			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Prof. Kaniki (2025)	X									X			X	X			X	X	X						X	B
Prof. Banza (2024)	X				X				X	X				X			X	X	X				X		X	
Domestic waters																										
Source International (2025)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Prof. Kaniki (2025)	X	X								X			X	X			X	X	X						X	A
Prof. Banza (2024)																										

Table A4. Comparison of surface water results across studies (color code: black = Source International (2025); blue = Prof. Kaniki (2025); blue and italic = Prof. Banza (2024)). Locations near but not comparable 1-to-1 to ours are marked with a "~" symbol (Figure A1). The sample IDs are taken directly from each report. Cells highlighted in grey include values above 10 times the EU baseline; cells highlighted in dark red exceed at least one international standard or guideline. Values below detection limit are greyed. n.r. = not reported.

Sample ID	pH	Conductivity	Arsenic	Cadmium	Cobalt	Iron	Manganese	Nickel	Lead	Copper	Uranium	Zinc
WSK1	6.34	50	0.24	0	5.4	310	33	0.26	0.1	**49**	0	3
~ KL7	5.77	51			< 1	267	< 1	< 1	< 1	**22**		**63**
WSK2	8.05	2940	4.0	0	14	2.1	570	1.1	0	**64**	16	0.31
KL8	6.64	2253			< 1	< 1	561	< 1	< 1	**204**		**110**
WSK3	6.97	560	0.85	0	19	8.2	400	0.58	0	**100**	1.3	3.2
~ *Musonoïe River*	*7.1*		*1.1*		*176*		*129*	*2.2*	*5.1*	***722***	*5*	*57*
WSK4	7.38	346	0.53	0	23	17	340	0.4	0	**25**	1.5	1
KL2	6.09	172			< 1	157	167	< 1	< 1	**39**		**82**
~ *Lake Golf*	n.r.		n.r.		n.r.		n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
WL1	7.84	664	0	0	0.19	6.9	35	0	0	0	0.77	0.73
ML12	7.26	482			< 1	< 1	< 1	< 1	< 1	< 1		< 1
WL2	7.45	1276	0.27	0	0.78	55	130	0	0	0.34	1.9	0.35
ML10	7.21	913			111	3	< 1	< 1	< 1	< 1		< 1
~ ML9	6.97	1015			< 1	46	< 1	< 1	< 1	< 1		< 1
~ ML14	8.20	1072			< 1	< 1	< 1	< 1	< 1	< 1		< 1
~ *Lake Kando*	*7.2*		*1.6*		*1266*		***32905***	*9.9*	*0.6*	***52***	*0.3*	***45***
WSF1	7.72	569	0.72	0	1.4	160	320	0.57	0	1.9	0.64	1.7
FL0	6.61	495			< 1	< 1	651	2	< 1	< 1		< 1
FL2	8.39	6189			63	< 1	**2188**	< 1	< 1	**558**		**50**
WSF2	8.09	1604	0.72	0	1.0	74	47	0.78	0.31	**11**	0.84	6.4
FL1	8.22	3189			< 1	< 1	52	< 1	< 1	< 5		**43**
WSF3	8.23	2225	1.4	0	330	40	**1200**	2.7	0.21		1.7	5.6
Kelangile River	*6.1*		*1.1*	*0.2*	*1436*		***11352***	*8.3*	*0.4*	***31***	*0.4*	*12*
WSF4	7.45	1001	0.75	0	47	120	43	0.44	0	**95**	2.9	3.6
FL6	8.12	1542			< 1	< 1	4	< 1	< 1	< 5		**43**
~ *Dipeta River*	*6.4*		*0.8*	*n.d.*	*45*		*114*	*1.9*	*0.5*	***308***	*1.0*	*7.3*
Range legislation (# of countries)	6–9 (2)		50–400 (4)	0.2–13 (5)		6000 (1)	1300 (1)	10–1000 (4)	10–500 (6)	5–1500 (4)		20–2000 (5)
EU baseline x 10			6.3	0.1	1.6	2680	195	19	0.93	8.8	3.2	27

Table A5. Comparison of sediment results across studies (color code: black = Source International (2025); blue = Prof. Kaniki (2025); blue and italic = Prof. Banza (2024)). Locations near but not comparable 1-to-1 to ours are marked with a "~" symbol (Figure A1). The sample IDs are taken directly from each report. Cells highlighted in grey include values above 10 times the EU baseline; cells highlighted in dark red exceed the Canadian PEL; cells highlighted in pink exceed the Canadian ISQG. Values below detection limit are greyed. n.s. = not sampled

Sample ID	Arsenic	Cadmium	Cobalt	Iron	Manganese	Nickel	Lead	Copper	Uranium	Zinc
WSK2	3.0	0.18	490	6000	1700	8.2	5.7	**2100**	3.1	31
KB8			1166	42000	2985	<0.6	<0.6	66		9
WSK3	2.4	0.13	450	4800	1500	7.1	4.8	**2000**	2.8	21
~ Musonoïe River	*5.5*	*0.30*	*1413*		*479*	*12*	*11*	***6168***	*10*	*32*
WSK4	0.8	0	340	3600	640	1.6	12	**240**	2.9	7.7
KB2			74	33400	84	<0.6	<0.6	**1608**		38
~ Lake Golf	4.7	0.84	34		347	16	9.2	**201**	1.7	32
WSK1	1.0	0	47	5400	210	2.0	10	34	0.79	6.6
KB7			74	10390	69	<0.6	<0.6	49		25
WL1	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
MB12			42	15380	n.r.	52	<0.6	**281**		94
WL2	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
MB10			42	11900	25	<0.6	<0.6	118		213
~ MB9			265	10270	26	52	<0.6	**461**		144
~ MB14			42	84100	384	<0.6	<0.6	134		100
~ Lake Kando	*12*	*0.49*	*270*		*778*	*46*	*19*	***374***	*6.3*	*58*
WSF2	1.3	0	16	3300	270	2.9	5.6	33	0.44	70
FB1			<0.6	50400	360	130	<0.6	120		40
WSF3	2.3	0.047	780	6200	760	5.9	8.0	43	0.34	130
Kelangile River	*9.0*	*0.13*	*481*		*893*	*27*	*7.4*	***357***	*1.3*	*44*
WSF4	1.6	0	780	4800	1400	3.1	8.2	**490**	0.60	14
FB6			220	56300	1140	120	<0.6	**3400**		<2
~ Dipeta River	*12*	*0.13*	*425*		*828*	*30*	*11*	***2414***	*2.1*	*86*
Canada (*ISQG* – PEL)	*5.9* 17	*0.6* 3.5					*35* 91.3	*35.7* 197		*123* 315
EU baseline x 10	60	2.8	80	47000	6120	210	205	170	20	710

Table A6. Comparison of domestic water results across studies (color code: black = Source International (2025); blue = Prof. Kaniki (2025)). Locations near but not comparable 1-to-1 to ours are marked with a “~” symbol (Figure A1). The sample IDs are taken from each report. Cells highlighted in dark red exceed at least one international standard or guideline. Values below detection limit are greyed. Prof. Banza did not analyze domestic water samples.

Sample ID	pH	Conductivity	Cobalt	Iron	Manganese	Nickel	Lead	Copper	Zinc
DL1 (Mibanze)	**5.10**	30	4.1	0	23	5.7	0.2	4.0	11
ML13	6.56	11	< 1	167	< 1	< 1	< 1	< 1	< 1
DL2 (Rianda)	**4.74**	55	0.96	6.1	6.5	0.69	0	0.93	2.4
ML8	**5.10**	36	< 1	46	< 1	< 1	< 1	< 1	< 1
~ ML7	**5.27**	9	< 1	**623**	< 1	< 1	< 1	< 1	14
Other samples near Lake Kando									
ML11 (Kaindo)	6.82	30	< 1	< 1	< 1	< 1	< 1	< 1	17
ML4 (Moloka 1)	**5.08**	9	< 1	1	< 1	< 1	< 1	< 1	< 1
ML2 (Kinsenda)	6.68	98	< 1	2	< 1	< 1	< 1	< 1	< 1
ML1 (Kinsenda)	**6.25**	138	< 1	156	< 1	< 1	< 1	< 1	< 1
Other samples near Kolwezi									
KL4 (Tshizuza)	**6.17**	18	< 1	34	< 1	< 1	< 1	22	63
KL5 (Tshizuza)	**5.42**	9	< 1	< 1	< 1	< 1	< 1	< 1	116
KL9 (Pierre Muteba II)	6.92	27	< 1	90	55	< 1	< 1	< 1	52
WHO guideline					80	70	10	2000	
Range legislation (# of countries)	6.5–8.5 (5)	2500 (1)		200–300 (4)	50–400 (4)	20–70 (4)	5–10 (5)	1000–2000 (5)	1000–5000 (4)

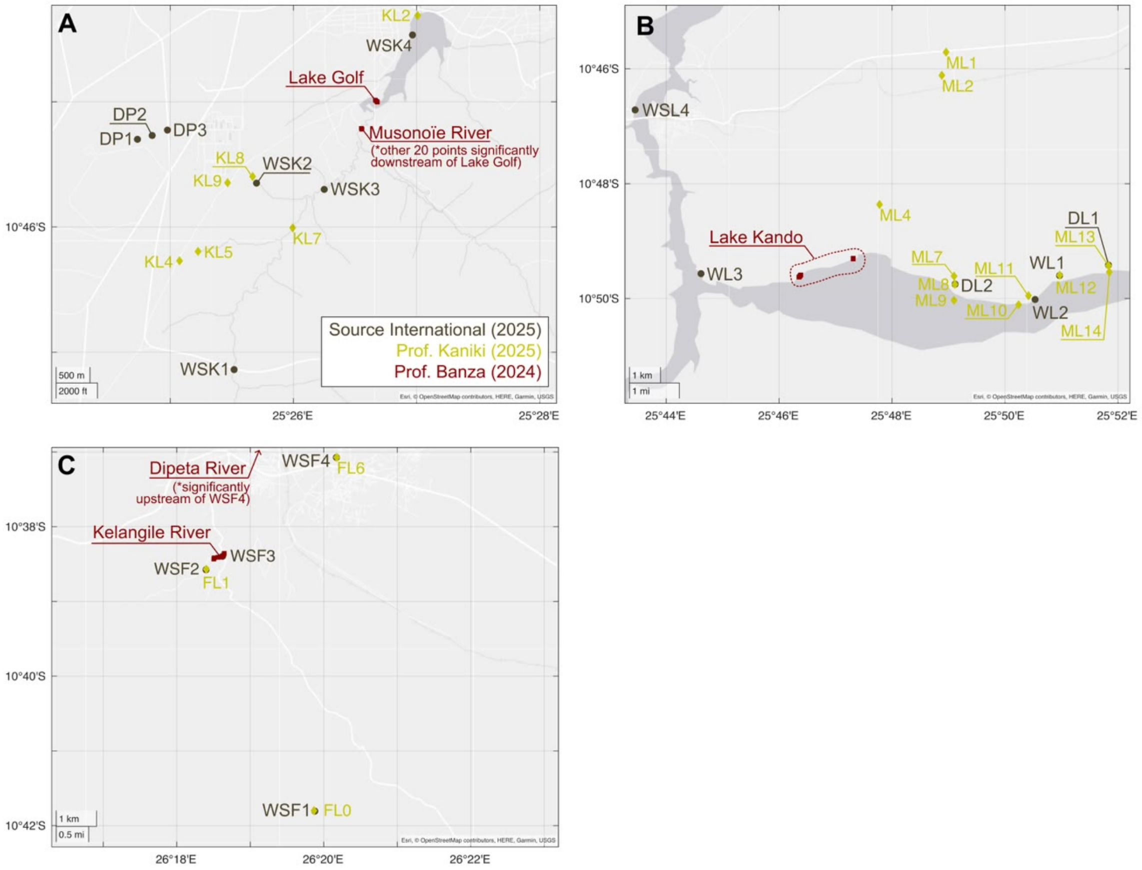

Figure A1. Comparison of sampling locations across studies in Kolwezi and Pierre Muteba II (A), Lake Kando and surrounding areas (B), and Fungurume (C). All available GPS locations were converted to decimal degrees and plotted with Matlab. Prof. Banza reported several GPS locations for each sampling site, which we collectively indicated with the name of the lake or river as done in the report.

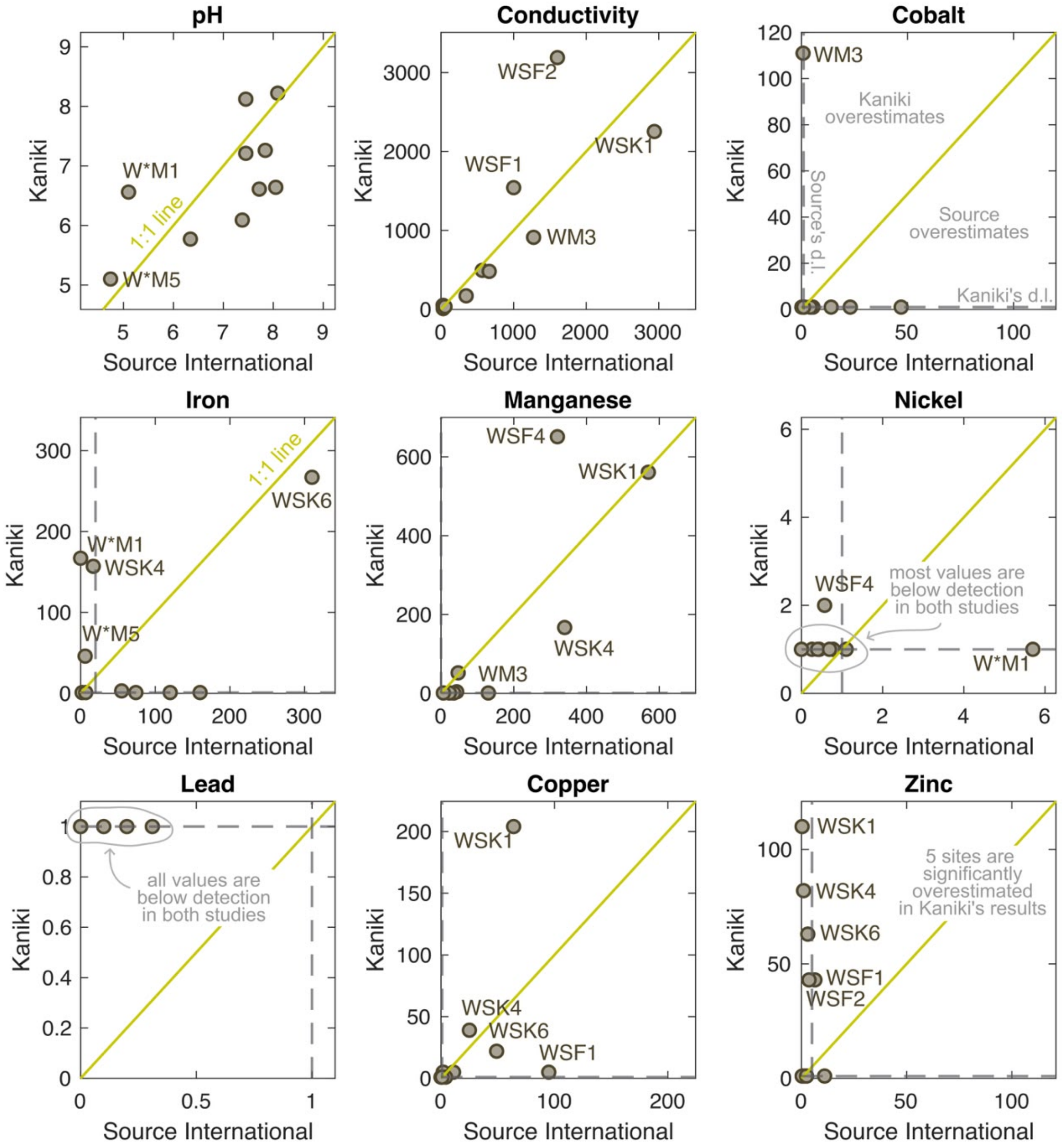

Figure A2. Pointwise comparison of surface and domestic water results (Source International vs. Prof. Kaniki). The green line is the 1:1 comparison; the grey dashed lines denote the detection limits (vertical: Source International's; horizontal: Kaniki's). Points that fall approximately onto the 1:1 line were equivalent in the two studies; points below the dashed lines were below detection; points markedly outside the 1:1 line (e.g., zinc) were significantly overestimated in Kaniki's study (above the line) or Source International's study (below the line). Given the variability of analytical methods and the not exact correspondence of sampling sites and days, we consider significant only variations in the order of magnitude.

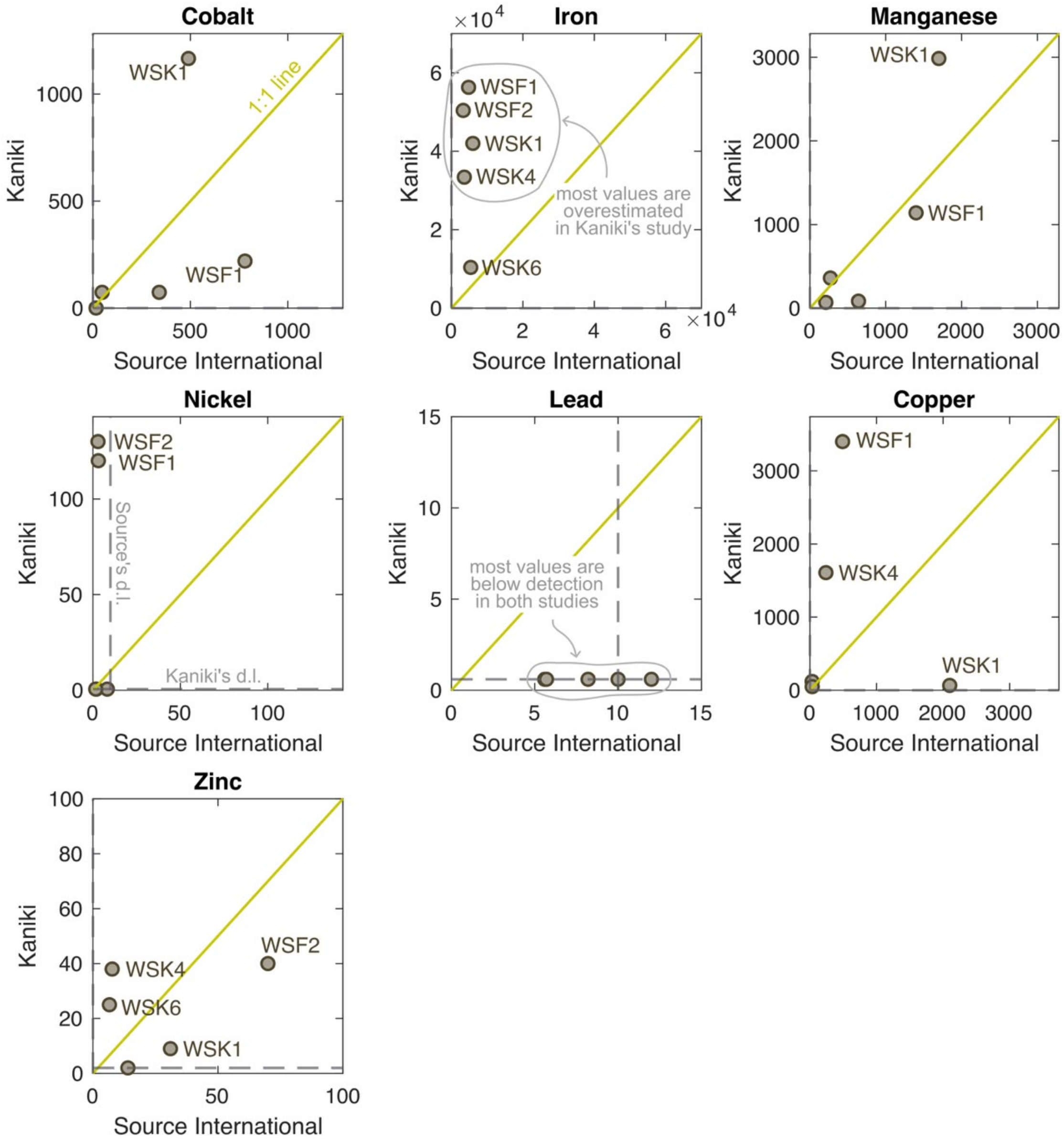

Figure A2. Pointwise comparison of sediment results (Source International vs. Prof. Kaniki). The green line is the 1:1 comparison; the grey dashed lines denote the detection limits (vertical: Source International’s; horizontal: Kaniki’s). Points that fall approximately onto the 1:1 line were equivalent in the two studies; points below the dashed lines were below detection; points markedly outside the 1:1 line (e.g., zinc) were significantly overestimated in Kaniki’s study (above the line) or Source International’s study (below the line). Given the variability of analytical methods and the not exact correspondence of sampling sites and days, we consider significant only variations in the order of magnitude.