Environmental Geochemical Impact Of Tailings Spills In Natural Streams In Chile (Mapocho River Case)

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Abstract

This study investigates abandoned tailings deposit from 1978, located near Santiago, Chile, posing environmental and public health risks. The tailings dam, situated on the banks of the Mapocho River and near a residential area, discharges effluents directly into the river. A partial collapse of the collapse of tailings impoundment in 1987 released approximately 400,000 m^3 of material, containing potentially toxic elements and identified as a source of acid drainage.

The primary objective of this study was to assess the downstream dispersion and geochemical stability of the collapsed tailings. To achieve this, a photogeomorphological map and a digital elevation model (DEM) were developed to locate potential tailings accumulation sites. Trial pits were excavated at several points along the river (0 to 2 meters depth), where tailings and sediment samples were collected for granulometric, geochemical, and mineralogical analyses. Excavations revealed two distinct tailings layers: one 5 cm thick and the other exceeding 1 metre.

These findings suggest that the tailings have been transported and deposited in unmonitored and unremediated fluvial bars and floodplains. However, geochemical analysis indicates that this material does not exhibit the high metal or sulfur concentrations characteristic of the tailings. Additionally, neutral paste pH values suggest a low potential for acid generation. The presence of reducing redox conditions in the buried material further supports its geochemical stability.

The integration of geological, geochemical and hydraulic methods proves effective for assessing the transport and fate of collapsed tailings, offering valuable tools for similar environmental assessments in Chile.

Keywords: Abandoned tailings, Acid drainage, Potentially toxic elements, Sediment geochemistry, Mine closure planning.

Introduction

In Chile, numerous tailings storage facilities built using the upstream method throughout the 20th century are at potential risk for physical instability due to natural events such as extreme precipitation, floods, and earthquakes. Several failures have been recorded in Chile, including the collapse of 200,000 m^3 of tailings at the Las Palmas facility after the 2010 earthquake (Pizarro *et al.*, 2010), the 1985 failure of the Cerro Negro dam releasing 500,000 m^3 (WISE Uranium Project, 2025), and the 1987 collapse of the Pudahuel dam due to extreme rainfall, discharging 400,000 m^3 of tailings into the Mapocho River (Nueva Pudahuel S.A, 2009).

Despite these significant environmental events, there is a lack of geochemical records of affected soils and fluvial sediments in Chile, hindering the assessment of long-term geochemical stability and potential environmental impacts. This issue is particularly complex for tailings spills from decades ago, where materials may have been buried or transported downstream without a detailed geochemical characterization of original materials.

This study focuses on an abandoned tailings dam impoundment, active from 1978 to 1987, located near Santiago, Chile. The tailings originate primarily from an epigenetic hydrothermal vein-type copper deposit. The site, which lacks adequate mitigation measures, poses significant risks to the environment and public health. The facility extends along the Mapocho River on a gentle hillside that drains directly into the river, contributing to contamination of fluvial sediments, particularly through the release of potentially toxic elements (PTEs) and acid mine drainage (AMD), as identified in prior evaluations (CIMMT & S, 2006). A residential area housing approximately 2,000 people is situated nearby, while agricultural fields covering an estimated 68 hectares extend 1.5 km downstream along the river. Therefore identifying and characterizing the accumulation zones of these tailings is crucial for understanding the associated risks.

Methods

A sampling campaign was conducted on August 16-17, 2024, collecting 40 sediment samples from seven points—two upstream control points and five downstream. Upstream points were sampled to establish a chemical baseline for fluvial sediments unaffected by tailings. Downstream points were selected within sediment depositional areas based on photogeomorphological mapping (Fig. 1) and high-resolution Digital Elevation Models (DEMs) from ALOS PALSAR (12.5 m resolution) and drone-based photogrammetry (4.73 cm resolution, Appendix A, Supplementary Material).

Sampling was carried out through trial pits along channels in lateral bars of the Mapocho River, with depths ranging from 0 to 190 cm, using an Edelman auger for more compact substrates. Samples weighed around 2 kg for trial pits and 80-500 grams for auger samples. Depth sampling was based on textural and

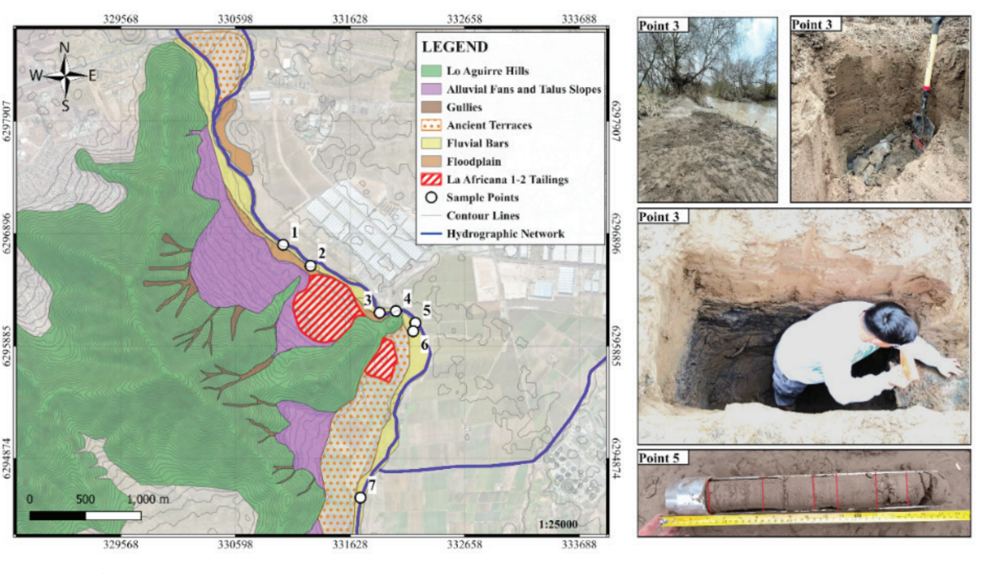

Figure 1 *The geomorphological map of the western slope of the Mapocho River highlights sampling points (1 to 7), key geomorphological units (fluvial bars, terraces, and alluvial fans), and the Pudahuel tailings deposit. Photographs show trial pit examples, with an edited image of sampling point 3 to enhance the paste-like tailings material at depths below 47 cm, and sampling point 5 demonstrating the use of an Edelman auger for sediment separation.*

color variations, compaction, and moisture. All samples, except for point 6, were collected within 2 meters of the river channel.

Sample preparation was conducted at the HEMERA Center and the CNAP Center at Universidad Mayor in Chile, following standard methods (Smodis *et al.*, 2003). The process involved quartering, drying at 40°C, and sieving with a Ro-Tap W.S. Tyler RX-29 shaker to separate gravel, sand, and silt/clay fractions. Geochemical analysis of the sand and fine silt/clay fractions was performed using X-ray fluorescence (XRF) with a SciAps X-200 portable analyzer. Instrument calibration was performed using fundamental parameters with Compton normalisation. Prior to each use, calibration was verified using a 316 stainless steel plate as a reference standard Descriptive statistics were applied to elements with over 90% data above the detection limit, calculating the minimum, maximum, median, mean, and standard deviation.

The paste pH measurement was conducted using 20 g of dried sample mixed with 20 mL of deionized water in a Falcon tube, ensuring homogenization. Once the solid material settled, the pH of the solution was measured with a Hanna HI 98194 multiparameter device, after verifying calibration with pH 4.01 and 7.00 buffer solutions.

X-ray diffraction (XRD) analysis was performed on the silt/clay fraction (#230 mesh) of dried samples using a Bruker D2 PHASER powder diffractometer at the VREMAS laboratory, Universidad de La Frontera. The analysis employed Cu Kα radiation (λ = 1.5418 Å) over a 2θ range of 5°–70° with a step size of 0.02° for high-resolution diffraction patterns. The XRD results helped identify crystalline mineral phases in four sediment samples, focusing on sulfide minerals, oxidation products, and silicate gangue minerals. One sample was collected upstream, and three separated samples from a deep trial pit near the tailings.

The environmental quality of the sediments was evaluated using two reference guidelines: the Consensus-Based Sediment Quality Guidelines (MacDonald *et al.*, 2000), which assess the potential effects of sediment chemical composition on aquatic ecosystems, and the Canadian Sediment Quality Guidelines, designed to evaluate potential risks to human health in residential and industrial areas.

This study used a two-dimensional model of an incompressible Newtonian fluid for hydraulic modeling, solving the Saint-Venant equations with Manning's resistance law using HEC-RAS software. The digital elevation model (DEM) was obtained from the ALOS PALSAR satellite product with a spatial resolution of 12.5 m × 12.5 m, and a channel incision was applied to address vegetation-related issues. Bedload sediment transport was analyzed using the Meyer-Peter and Müller equation. A structured mesh with 22 m cell size was used in areas away from the Mapocho River channel, while a non-structured mesh with refined cells down to 12 m was used within the channel. Monthly mean discharge time series from March 2004 to May 2016 were used as the upstream boundary condition, and normal depth was set as the downstream boundary condition. The hydraulic model was calibrated considering Manning's roughness and the depth correction of the digital elevation model, through the validation of flow levels during high and low flow periods. Additionally, different mesh sizes were evaluated to optimize computational time and the quality of the hydraulic modeling.

Results

The sediment distribution was 60% sand and 40% silt/clay. The paste pH of tailings samples was acidic (1.5–2.7), while sediment samples were near-neutral to slightly alkaline (6.7–8, average 7.2). Samples with paste pH below 5 can be considered evidence of immediate acidity. The major elements in river sediment samples were Si (average 15.5%), Al (average 4.6%), Fe (average 3.8%), and Ca (average 2.3%), while the most abundant potentially toxic elements (PTEs) had mean concentrations of Mn (874.6 mg/kg), S(433.8 mg/kg), Cu (199.2 mg/kg), V (140.8 mg/kg), Zn (96.0 mg/kg), and Pb (13.7 mg/kg), mainly found in the silt/clay fraction. A detailed breakdown of sediment chemistry is available in the supplementary material (Appendix B, Table 1).

XRD analysis showed river sediments predominantly composed of quartz, followed by iron oxides and minor calcite, while tailings consisted mainly of iron oxides with quartz and trace sulfides, as bornite. Tailings samples had higher sulfur content, with average concentrations of Fe (13.2%), S (8.4%), Si (6.3%), Al (1.9%), and Ca (0.9%). Among PTEs, Cu (3950.3 mg/kg), Zn (56.7 mg/kg), and As (42.6 mg/kg) were most abundant.

Bedload sediment transport estimated using the Meyer-Peter and Müller equation, shows sediment transport downstream of the tailings dam, with a sedimentation area identified upstream. The modeled area in HEC-RAS 2D is shown in brown in Fig. 2, with purple points representing sediment sampling locations. A raster in Fig. 2 illustrates sediment transport rates, with red indicating high transport and green low transport. Transparent pixels highlight sedimentation zones, particularly between sampling points 2 and 3, where tailings deposition is expected after dam failure or spills.

Sediment transport occurs in both the river channel and floodplain, with tailings particles not remaining long due to flow-driven transport. Further downstream, additional sediment accumulation zones may exist, requiring an expanded model area and higher DEM resolution for more detailed assessment.

We focus on Cu and S as proxies for identifying mining-related sources, given the very high concentrations of residual Cu and S in the local tailings impoundment. Fig. 3 shows that Cu concentrations are higher

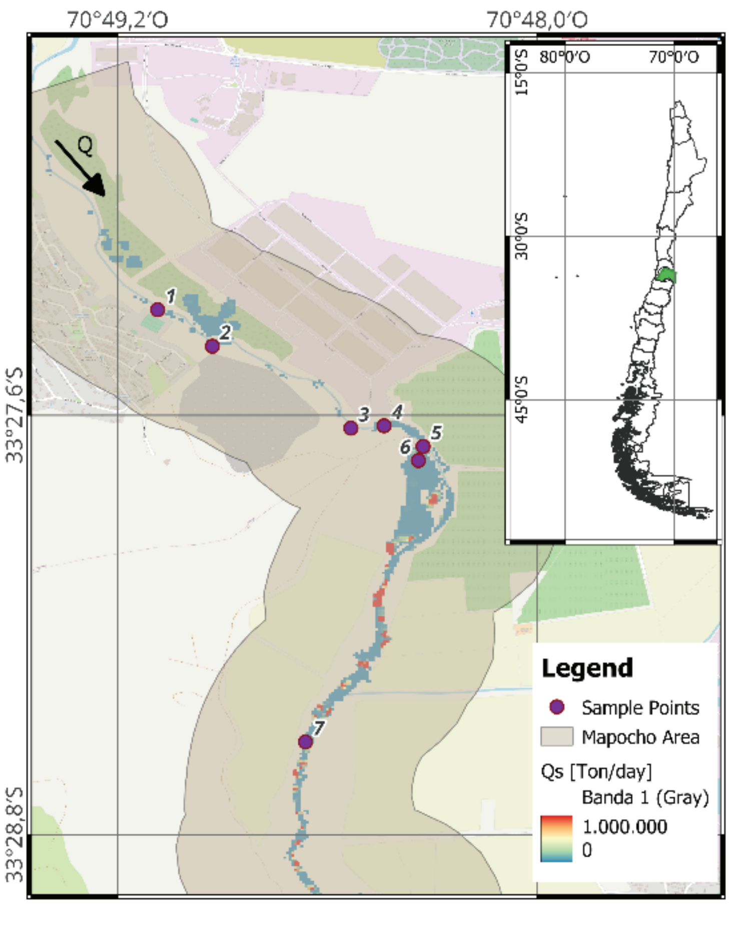

Figure 2 Bedload sediment transport in the Mapocho River was estimated using the Meyer-Peter and Müller equation, with sample point locations marked by purple points.

in the fine fraction than in the sand fraction. Three distinct patterns were observed:

- Sampling point 1 (upstream of the tailings site) shows higher Cu concentrations at 5–10 cm and below 30 cm, compared to other depths within the same sample point.
- Sampling point 5 exhibits increased Cu concentrations below 20 cm, particularly in the fine fraction.
- Sampling points 3 and 4 show elevated Cu concentrations near the surface, especially in the fine fraction (>350 mg/kg), with lower concentrations in buried tailings.

For S concentrations, Fig. 3 shows a similar pattern to Cu upstream, with higher surface values and below 20 cm, but S concentrations are similar in both fractions. Sampling point 3 shows peak S concentrations in the sand fraction at the surface and in buried paste-like tailings (~700 mg/kg), while the fine fraction has lower values (250–500 mg/kg), except at the surface.

The buried paste-like tailings, possibly from the 1987 spill, suggest minimal oxidation and preservation of sulfide minerals due to reduced redox conditions. This is supported by paste pH measurements, which showed no acidic conditions at depth. Oxidation could have occurred during droughts, mobilizing sulfates.

Sampling point 4 shows distinct Cu variations, with high concentrations (>750 mg/kg) at three depths, especially in the fine fraction. Sampling point 5 has lower Cu concentrations across all depths. Cu and S in the buried material at point 3 may originate from tailings but with differing geochemical patterns. The hydraulic model suggests tailings deposition between points 2 and 3, explaining the Cu variations at different depths.

Elevated Cu and S concentrations at point 1 suggest a potential upstream metal source, possibly linked to seasonal acid drainage in the Mapocho River (Correa-Burrows *et al.*, 2021) or nearby mining activities.

Conclusions

The chemical analysis of Mapocho River sediments reveals that Cu concentrations are significantly elevated at surface levels or below 20 cm, surpassing the PEC parameter of consensus-based sediment quality guideline (SQG) (MacDonald *et al.*, 2000) for potentially toxic elements (PTEs). Mn follows with slightly elevated concentrations in some surface samples downstream of the tailings deposit, also exceeding the SQG.

The buried tailings layers show low PTE concentrations and lack reactivity in terms of acid release upon contact with water, likely due

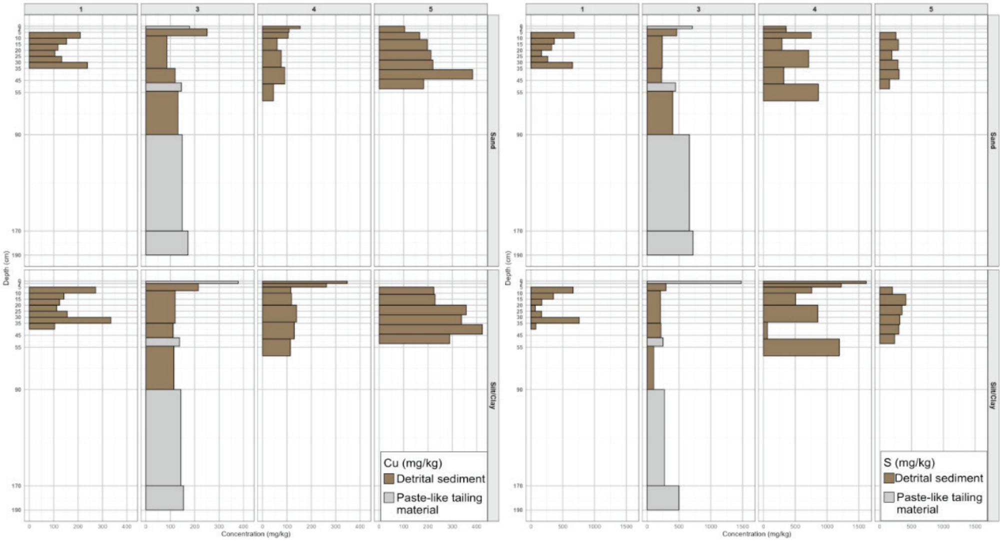

Figure 3 Depth profiles of Cu and S concentrations (mg/kg) in trial pits along the river, with each column representing a sampling point. The upper section shows the sand fraction, and the lower section shows the silt/clay fraction. Brown indicates detrital river sediment, and grey represents buried paste-like tailings.

to the reducing conditions from burial, which may stabilize sulfide minerals. However, further research is necessary to determine if the tailings-like material originates from the Pudahuel tailings deposit or another source. Isotopic analysis is recommended to confirm the source. If linked to the Pudahuel tailings, future studies will investigate the geochemical processes responsible for the mobilization and reduction of Cu and S concentrations in the buried material. A reanalysis of surface sediments before the next seasonal rains will help assess if concentrations stabilize or decrease naturally, aiding predictions of the buried material's seasonal behavior.

Geochemical data reveal high concentrations of Cu, Fe, Mn, and S in the upper centimeters of riverbed sediments, exceeding the PEC threshold for freshwater environments. Extreme precipitation accelerates tailings erosion and deposition in river sediments. Hydrodynamic modeling shows how these events transport sediments downstream and create hazards for the surrounding ecosystem and human health. Elevated Cu concentrations upstream of the tailings deposit suggest a potential alternative source and additional mobilization events. Future research will focus on examining Cu concentrations in the river upstream.

The hydraulic model successfully identified sediment accumulation and erosion zones. However, it did not fully align with transport patterns observed during the 1987 and 2001 flood events, and ongoing refinements are necessary. This study emphasizes the synergy between hydraulic modelling and geochemistry, highlighting its potential to investigate other historical tailings spills in Chile.

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