Post-Mining Water-Soil Interaction in Au-Mine Area: Piedmont Region (NW Italy) Case Studies

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Abstract

Mining activities can affect water quality long after the mines have closed. This study focuses on the current status of water in two abandoned gold mines - Crocette and Pestarena - in the Western Alps (Piedmont, Italy). Surface and groundwater samples were collected in three monitoring campaigns in 2024. The results showed arsenic contamination in 75% of the samples. Contamination by aluminium, iron, lead, manganese and nickel was also found in groundwater close to the tailings. These results highlight the long-term impact of abandoned mining activities and the need for continuous monitoring to assess environmental and human health risks.

Keywords: Abandoned Au-mines, PTE mobility, soil, water, Italy

Introduction

Mining activities can have a substantial effect on soil and water quality both surface (SW) and groundwater (GW). Environmental problems often persist long after operations have ceased, especially when processing plants are not properly managed and mining waste is not effectively disposed (Antunes *et al*. 2014; ISPRA 2023).

The most substantial effect of Au mines are related to acid mine drainage (AMD), which is generated by the erosion and leaching of mining waste and by water drainage from mining tunnels (Karaca *et al*. 2018). AMD in Au mines is caused by the oxidation of sulfide minerals (e.g. pyrite and arsenopyrite) and it promotes the mobility of potentially toxic elements (PTEs) in the environment. The most commonly occurring PTEs include arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), manganese (Mn), iron (Fe) and zinc (Zn)(Hou *et al*. 2023). Added to this are the pollutants generated by Au mining process, such as mercury and cyanide (Ritcey 2005; Hou *et al*. 2023). These persistent pollutants pose a serious threat to ecosystems and human health due to their toxicity and their non-degradable nature (BRGM 2001).

These long-term environmental impacts need to be thoroughly assessed through effective monitoring. The aim of the study is to investigate the current status of soil, SW and GW affected by past Au mining activities in northern Italy, more than 60 years after closure. The obtained results will allow assessing the environmental and human health risk associated with the abandoned Au mines.

Study area

The Monte Rosa mining district (Piedmont, Western Italy) represents one of the most important Au mining districts in the Western Alps, with a history of exploitation since Roman times. This study focuses on two abandoned Au mines located in the municipalities of Crocette and Pestarena in the Anzasca Valley. The Valley is mainly drained by the Anza River; Pestarena is located on the left bank of the river, while Crocette is situated on the left bank of the Quarazza stream, a tributary of the Anza River (Fig. 1a).

Au mineralisation is hosted by the Monte Rosa Unit comprising a basement of paragneiss and micaschist intruded by orthogneiss (Dal Piaz 2001) (Fig. 1b). Veins mineralogy is dominated by quartz; carbonates are ubiquitous but always less abundant. Au is associated with sulfides, typically pyrite and arsenopyrite and subordinate galena, sphalerite, pyrrhotite, chalcopyrite (Stella 1943; Lattanzi *et al.* 1989). From a hydrogeological point of view, Pestarena and Crocette fall within the Crystalline Complex of the Alpine Chain; the metamorphic rocks of this complex are essentially impermeable or weakly permeable to fracturing (De Luca *et al.* 2020). The metamorphic rocks at the valley floor are covered by fluvial and debris flow deposits that host a phreatic aquifer connected to surface water bodies. GW circulation in the area occurs in fractured rocks, deposits and mining tunnels.

Mining in the Anzasca Valley began at the end of the 13th century with the exploitation of underground Au deposits. Over the centuries, Au production gradually increased, reaching a peak between 1938 and 1961, when about 5.4 tonnes of Au were mined. In the early years of this period the Au ore had a grade of 11 g/t, but there was a significant decline during the Second World War, culminating in the final closure of the mines in 1961 (Bruck 1985; Preite *et al.* 2007).

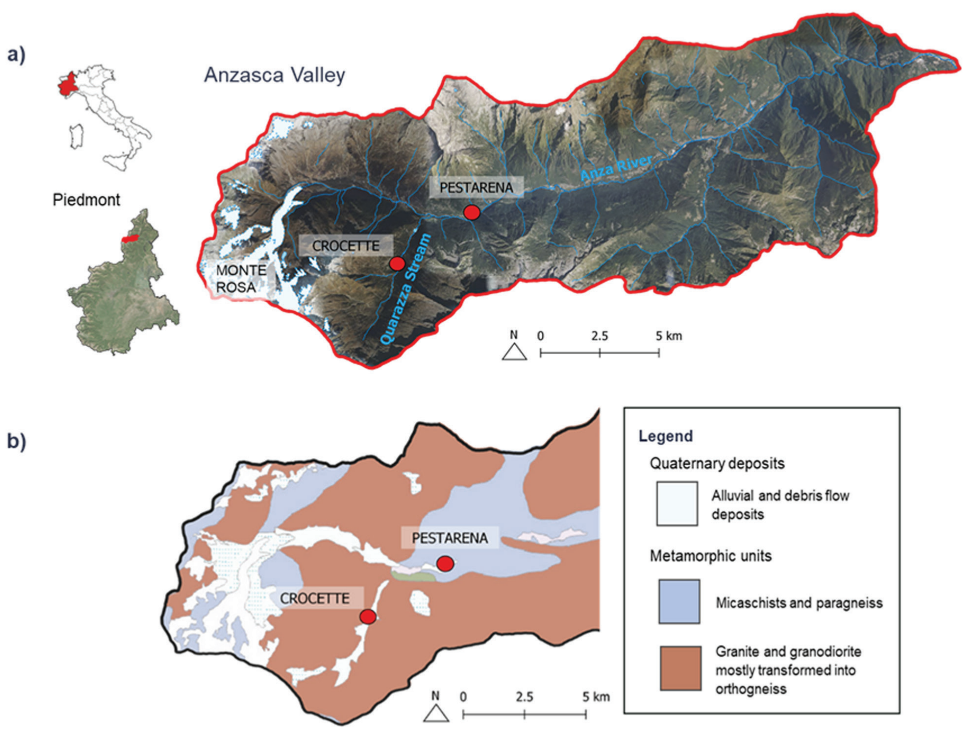

Figure 1 *Geographical, hydrographical (a) and geological (b) framework of the study area. Modified from Piana et al. 2017.*

Processing plants for the mined ore in the study area were located near the Pestarena and Crocette mines (Cerri and Fantoni 2017). Two main methods were used for Au extraction. Mercury amalgamation, a technique widely used since the Middle Ages, and cyanidation, which was introduced in the 1890s and became the dominant method until the mine's closure. The waste rock excavated and mined from the underground operations and the tailings from the processing of the ore were abandoned in the large area around the processing plants and deposited in waste dumps.

Previous studies

Previous studies (Bruno 2005; Nepote Valentin 2007; Rolando 2008) have shown that areas around mining processing plants have high levels of contamination due to the presence of abandoned processing waste (tailings), some of which is now covered by vegetation. The mine soil samples collected at Pestarena confirmed the presence of tailings with high concentrations of As, Hg, Pb and Sb, characterised by very acid pH values ranging between 4.0 and 6.85. Similarly, samples collected at Crocette showed high concentrations of arsenic and lead, with even more acidic pH values, ranging from 3.21 to 4.95 (Bruno 2005; Nepote Valentin 2007; Rolando 2008).

On a larger scale, soil samples collected in the Quarazza stream basin, where Crocette is located, and downstream along the Anza River near Pestarena, indicate arsenic concentrations higher than the threshold concentration set by Italian legislation (Legislative Decree 152/2006) for residential soils (20 mg/kg) (Caviglia *et al.* 2014; Allegretta *et al.* 2018). For these areas, the natural background value for soils was defined using the 95th percentile statistical method, resulting in a value of 414 mg/kg. This value is a fundamental reference point for distinguishing between natural geochemical enrichment and anthropogenic impacts. Many values founded in soils near the mining areas, were higher than the background of some order of magnitude. SW samples collected from the Quarazza Stream and the Anza River indicate that As concentrations in the most contaminated samples exceed the Italian threshold concentration for water (10 µg/L), reaching a maximum of 279 µg/L. The highest concentrations were found in areas close to mining activities. However, until now, no studies have evaluated the GW quality in these areas.

Materials and methods

In 2024, three monitoring campaigns were carried out in the areas of Pestarena (PE) and Crocette (CR) to analyse soil and water quality. The sampling, carried out in May (I), July (II) and September (III), was planned to study the temporal variability based on seasonal conditions and to ensure the accessibility of the sites, which is limited by the winter conditions of the alpine environment.

During the campaigns 19 SW samples and 13 GW samples were collected mainly at the same monitoring points during each campaign (Fig. 2). At Crocette, the GW sampling points were: the existing piezometer near the mining facilities and tailings dump (CR_1) and a spring (CR_2). The SW sampling points were: surface runoff (CR_4, CR_6); the Quarazza stream (CR_3 upstream of the mining facilities, CR_5 in correspondence, and CR_7 downstream); The lake that receives the waters of the Quarazza stream before the confluence with the Anza River (CR_8). At Pestarena, the GW sampling points were: three existing piezometers situated near the mining facilities, one upstream of the tailings dump (PE_1) and two downstream of the tailings dump (PE_2, PE_3); and a mine tunnel effluent (PE_4). The SW sampling points were: the Anza River (PE_5 upstream of the mining facilities, PE_6 in correspondence, and PE_7 downstream).

A total of 26 soil samples (Fig. 2) were collected during the second and third campaigns to assess the extent of potential contamination and its evolution over the years. Sampling points were selected in the area affected by mining activities, identified in previous studies and characterised by the presence of both dumps and scattered deposits of mining waste. Additional samples were taken up to 2.5 km upstream and downstream of the mining facilities.

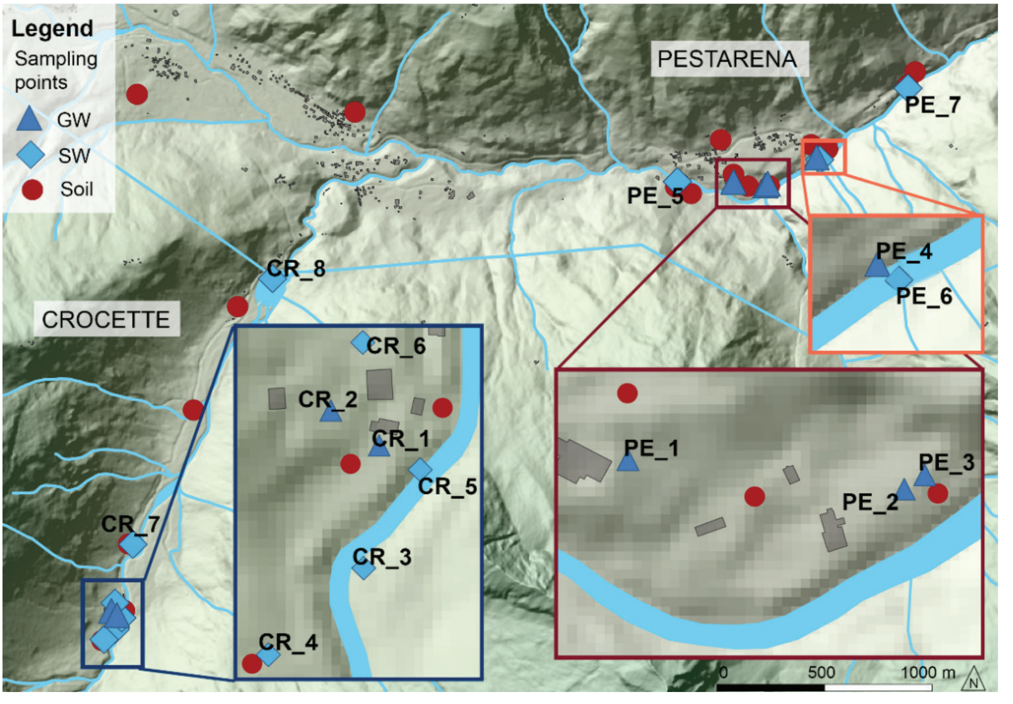

Figure 2 *Location of the sampling points of the three monitoring campaigns in 2024.*

The pH, total dissolved solids (TDS), electrical conductivity (EC) and temperature were measured in situ. Anions and cations were determined on non-acidified samples by ion chromatography. Metals and metalloids (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Sb, Zn) were analysed by ICP-MS on filtered (membranes with 0.45 µm porosity) and acidified with HNO_3 samples. The analyses were performed at the Department of Earth Sciences, University of Turin. Analyses for mercury and cyanide concentrations in water, as well as concentrations of PTEs in soils, are currently underway.

Results and discussion

Most water samples show a low mineralisation (EC = 8–58 µS/cm), which is also supported by the TDS ranging from 5 to 45 mg/L; except for GW in Pestarena close to the tailings dump (PE_2, PE_3) with high values (EC = 484–1190 µS/cm and TDS = 245–596 mg/L). The pH is neutral or acidic in most of the samples ranging from 3.2 to 7.8, with more acidic values during May campaign in the GW samples (CR_1, PE_3, PE_4). The acidic waters were usually due to oxidation of sulfides from the mineralised veins and consequently from the tailings.

According to the Piper classification (Fig. 3), SW at Crocette is mainly of bicarbonate-calcium type while SW and GW at Pestarena is mainly of sulfate-calcium facies. The GW samples collected in piezometers downstream of the tailings (PE_2, PE_3) have a more pronounced tendency towards sulfates probably related to mining wastes. In fact, dissolved sulfate is remarkably persistent through mine water systems, and discharge waters commonly retain a strong dissolved sulfate signature (Craw *et al.* 2015).

The comparable composition of SW and GW suggests a relationship between these water bodies and also suggest that SW at Pestarena could be more influenced by the presence of highly mineralised and exploited areas than Crocette.

The analyses of metals and metalloids in the water samples are presented in Tab. 1. 75% of the water samples show arsenic contamination, with concentrations exceeding the limits set by Italian legislation (Legislative Decree 152/2006). Mining activities have increased the exposure of

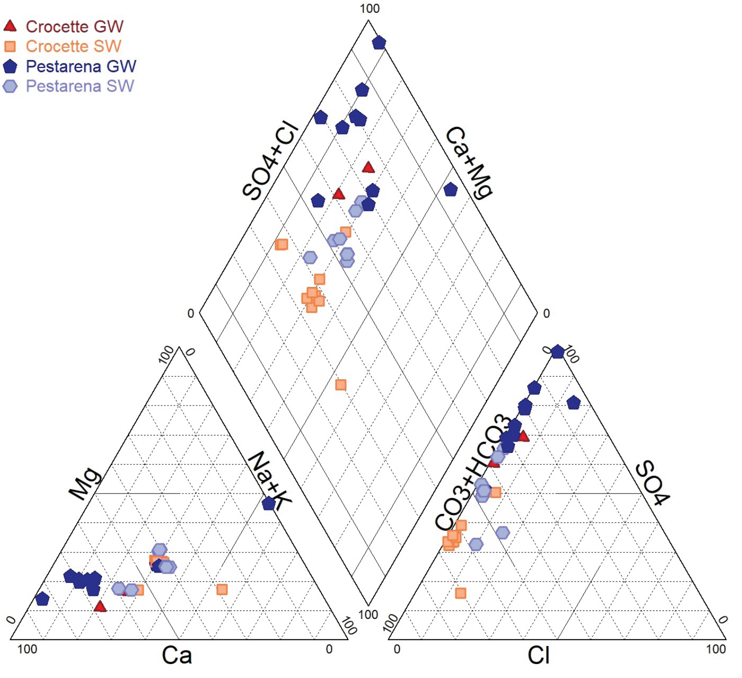

Figure 3 *Piper diagram of the samples collected during the three campaigns in 2024.*

arsenic-rich rocks, resulting in the presence of arsenic in the water. While the other metals remain at low concentrations in the SW, threshold values are exceeded in the Pestarena GW (PE_2, PE_3) downstream of the tailings, including aluminium (up to 7266 µg/L), iron (up to 1785 µg/L), lead (up to 25 µg/L), manganese (up to 276 µg/L) and nickel (up to 86 µg/L). These values highlight the impact on GW quality of abandoned mining activities and inadequate waste management.

Conclusions

This study highlights the long-term effects of two Au mines in the Alpine environment.

At Crocette and Pestarena, soil and water were found to be contaminated with arsenic more than 60 years after closure. The contamination of SW and GW with arsenic persists into the present day. Moreover, the presence of elevated arsenic and other metals concentrations in the Pestarena GW, along with acidic pH and high EC and TDS, underscores the persistent impact of mining waste.

This research provides insight into the environmental impacts of abandoned mining activities and highlights the need for continuous monitoring. Future studies will focus on assessing and mapping soil contamination and evaluating potential leaching into water bodies. By collecting this additional information, it will be possible to assess the ecological and human health risks associated with abandoned Au mining activities.

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Table 1 Concentration of metals and metalloids in water samples collected from sampling points during the three campaigns in 2004 (n: I-May; II-July; III-September).

Sampling point	n	Al µg/L	As µg/L	Cd µg/L	Co µg/L	Cr µg/L	Cu µg/L	Fe µg/L	Mn µg/L	Ni µg/L	Pb µg/L	Sb µg/L	Zn µg/L
Threshold		200	10	5	50	50	1000	200	50	20	10	5	3000
CR_1 GW	I	191.8	14.0	0.0	0.2	0.1	0.9	18.0	11.1	1.4	0.2	0.1	8.4
	III	215.9	10.6	0.0	0.1	0.2	15.3	49.4	6.3	1.2	2.0	0.1	27.5
CR_2 GW	I	54.4	51.6	0.0	0.1	0.1	0.5	9.1	7.7	0.2	0.0	0.6	2.5
CR_3 SW	I	32.9	5.6	0.0	0.0	0.0	0.5	4.6	0.5	0.1	0.0	0.0	0.8
	III	17.6	14.0	0.0	0.1	0.1	2.4	8.8	2.5	0.6	0.0	0.3	11.1
CR_4 SW	II	118.5	6.7	0.0	0.1	0.1	45.0	19.2	1.8	0.6	0.2	0.0	20.1
CR_5 SW	I	38.4	6.0	0.0	0.0	0.0	0.4	4.3	0.5	0.1	0.0	0.1	2.1
	II	24.1	13.8	0.0	0.1	0.1	2.9	42.6	4.0	1.1	0.1	0.4	23.7
	III	26.4	15.9	0.0	0.1	0.2	4.4	23.6	3.5	1.0	1.2	0.3	34.2
CR_6 SW	I	213.9	6.0	0.0	0.1	0.1	0.5	7.2	10.6	0.4	0.1	0.0	6.6
CR_7 SW	II	24.8	12.4	0.0	0.1	0.1	1.8	18.5	1.6	0.6	0.2	0.2	15.0
	III	25.6	12.9	0.0	0.3	0.1	3.4	13.7	2.5	1.1	0.7	0.2	38.5
CR_8 SW	II	31.7	16.3	0.0	0.2	0.3	3.5	23.6	15.3	1.4	0.1	0.3	25.8
	III	37.8	29.7	0.0	1.1	0.5	5.5	178.0	189.2	2.2	0.4	0.2	33.3
PE_1 GW	I	8.6	4.1	0.0	0.2	0.1	1.8	8.9	1.0	1.1	0.1	0.4	8.9
PE_2 GW	I	70.4	43.7	0.3	3.4	0.1	5.6	137.3	62.5	18.3	0.4	0.1	76.2
	II	2.8	45.6	0.0	1.2	0.0	2.0	270.5	15.1	15.7	0.0	0.1	14.3
	III	3.9	69.6	0.0	1.6	0.3	4.2	438.8	27.9	20.5	0.1	0.2	26.2
PE_3 GW	I	7265.4	11.9	1.5	13.5	1.8	78.7	1785.3	234.5	29.4	25.0	0.1	278.4
	II	94.5	20.3	0.4	11.3	1.2	8.8	310.8	151.1	61.3	0.5	0.5	235.9
	III	92.1	22.4	0.6	19.8	0.7	8.1	672.5	276.4	86.2	0.3	0.2	265.7
PE_4 GW	I	178.5	3.2	0.1	0.7	0.1	2.6	49.8	13.3	2.2	1.5	0.2	23.5
	II	98.0	44.1	0.0	0.6	0.1	2.0	163.2	19.6	2.9	0.6	0.2	12.1
	III	103.9	67.1	0.0	0.4	0.2	3.9	132.7	10.8	3.1	0.8	0.2	39.5
PE_5 SW	I	27.6	10.6	0.0	0.1	0.1	2.0	12.0	1.1	0.8	0.6	0.1	11.0
	II	14.7	4.4	0.0	0.4	0.1	2.2	24.4	12.5	3.6	0.1	0.1	9.5
	III	19.6	12.0	0.0	0.2	0.1	1.8	25.2	5.2	2.7	0.0	0.1	20.1
PE_6 SW	I	29.4	10.5	0.0	0.0	0.1	1.1	10.9	0.9	0.5	0.4	0.1	10.4
	II	37.7	21.2	0.0	0.4	0.1	1.9	57.6	12.3	3.9	0.8	0.1	13.6
	III	43.2	16.7	0.0	0.3	0.9	3.1	49.6	7.3	3.2	0.3	0.2	33.3
PE_7 SW	II	11.8	5.2	0.0	0.4	0.3	1.7	15.3	11.1	3.8	0.0	0.1	9.4
	III	25.0	18.5	0.0	0.3	0.2	2.5	34.4	6.6	3.0	0.1	0.2	14.0

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