HYDROGEOLOGICAL AND GEOCHEMICAL ASSESSMENT OF HISTORIC TAILINGS IN MINAS GERAIS, BRAZIL[1]

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Abstract. Hydrogeological and geochemical studies were conducted on historic tailings located along the Cardoso Creek near the municipality of Nova Lima, in the state of Minas Gerais, Brazil. These tailings, which contain elevated arsenic levels, date from the first half of the twentieth century and are currently owned by AngloGold Ashanti Ltd. The investigations had three principal components: a) environmental, hydrogeological and geochemical assessment, including monitoring wells installation, field and laboratory tests and dynamic modeling; b) preliminary risk analysis; and c) development of conceptual remediation solutions and management practices to prevent adverse impacts to human health and the environment.

Additional Key Words: arsenic, environmental risk, human health, groundwater, surface water

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Introduction

Mineração Morro Velho Ltda. (MMV) has been tasked by the Minas Gerais environmental agency to study six historic mining tailings areas located in the municipality of Nova Lima, Brazil (Fig. 1) and develop appropriate remediation procedures. The tailings were deposited near Cardoso Creek, a tributary to the Rio das Velhas, from 1930 until the mine closed in early 1940. The tailings are presently owned by AngloGold Ashanti.

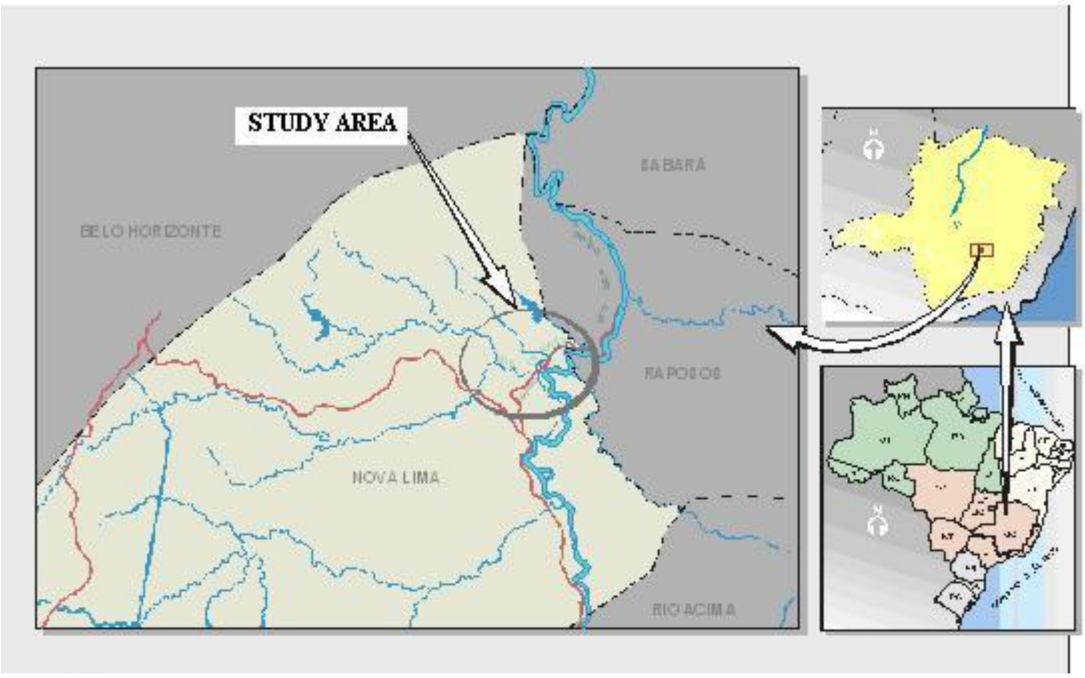

Figure 1 Location of the study area

Most of the tailings were placed along the creek valley to minimize transportation costs. At the time of disposal, they were situated in rural areas, far from the populated center of the town. Today, a large proportion of the tailings are located in the Nova Lima urban area. A chronology of the tailings deposition and the remediation efforts is shown on Table 1. It is interesting to note that the comparison between historical data on MMV's Au production and volumetric measurement of the six piles is quite consistent, indicating that most of the tailings generated during operation are located in these six areas (Fig. 2).

MMV contracted with Golder Associates Brasil Ltda. (Golder) to conduct hydrogeological and environmental studies in support of selection of conceptual solutions for closure of the various tailings deposits and mitigate their environmental impact. As part of the selection process, risk assessments were conducted.

This article presents an overview of the 14-month hydrogeological and geochemical studies for the six tailings locations [*Galo*, *Matadouro*, *Isolamento*, *Rezende*, *Fabrica de Balas*, and *Madeira* (Fig. 2) and the recommendations for closure that were developed based on the risk assessments.

Scope and Methodology

The investigation was conducted in three phases. The first step was to asses available hydrogeology and geochemistry data, including background water quality, and to characterize the enviromental impact of each tailings pile. This involved:

- collection and analysis of available data (topography, climate, geology, hydrology, geomorphology, hydrogeology, water quality and tailings analyses)
- field inspections by a specialized crew (geologists, hydrogeologists, engineers, hydrologists, and a geographer);
- identification of potential environmental impacts;
- conceptual hydrogeological modeling.

Table 1. Evolution of mining in the Nova Lima region

Year	Owner of Mining Rights	Type of Mining	Waste Disposal	Notes
1725		Primitive, open pit	Cardoso Creek	Start of first gold mining explorations
1810	Family of priest Antônio de Freitas	Primitive	Cardoso Creek	Purchase by Captain George Francis Lyon
1834	St. John Del Rey Mining Co.	Underground mine	Cardoso Creek	Morro Velho effectively begins as a mining company
1910	St. John Del Rey Mining Co.	Underground mine	Small tailings pile first placed near the industrial plant; with their silting, the tailings were then conducted to Cardoso Creek	Implementation of the first metallurgical plant
1911	St. John Del Rey Mining Co.	Underground mine	Start of construction of tri-oxide arsenic plant in *Morro do Galo*, which would generate calcined waste	Construction of tri-oxide arsenic plant
1930	St. John Del Rey Mining Co.	Underground mine	Tailings piles "constructed" along Cardoso Creek, using the best technology available at that time	To construct the tailings, "advanced engineering techniques" were applied
1940	St. John Del Rey Mining Co.	Underground mine	Pumping to Raposos Dam (Queiroz). First Brazilian tailings dam	Mine deposit exhausted
1950	St. John Del Rey Mining Co.	Underground mine	Tailing discharged to Cardoso Creek	Raposos Dam capacity exhausted. Cardoso Creek renamed *Água Preta* (Black Water)
1975	MMV	Underground mine	Cardoso Creek	*Morro do Galo* arsenic plant closed
1980 a 1983	MMV	Underground mine	Construction of two tailings dams in Queiroz Valley	Disposal of tailings in Cardoso Creek ceased
2000	MMV/AngloGold	Underground mine	Cardoso Creek valley tailings made less permeable (see text)	
2001	MMV/AngloGold	Underground mine	Hydrogeological studies and risk analyses of Cardoso Creek tailings	
2002	MMV/AngloGold		Preparation of rehabilitation projects based on recommendations included in hydrogeological study.	
2004	MMV/AngloGold		Environmental rehabilitation of *Galo* tailings	

The second step involved activities related to risk analysis, which included:

- definition of acceptable risk criteria, according to existing environmental risk analysis methodologies (WHO 1981, 1987, 1993 and 1996);
- identification of plausible risk assessment scenarios;

- human health risk assessments using hypothetical exposure and land use scenarios to establish rehabilitation criteria for the tailing areas, through RESRAD – Chem methodology (USDOE 1993a, 1993b).

The third and final step was the presentation of suitable closure alternatives to the regulatory authorities.

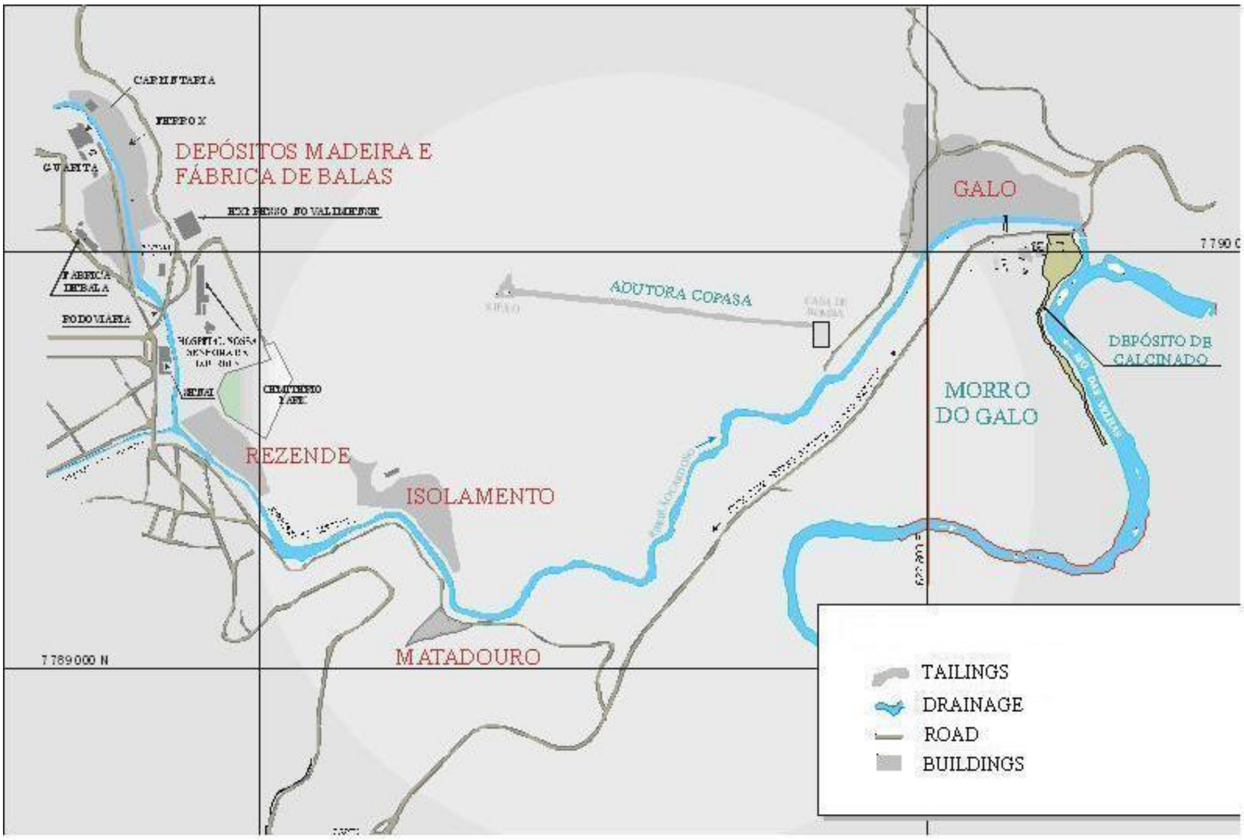

Figure 2: Location of the historic tailings along Cardoso Creek valley

Physiography , Geology, and Land Use

Physiography

The site is located in a mountainous region with irregular features at an average altitude of approximately 1,000 m. The climate is mild, with average temperatures are always over 20ºC. The hotter months (December to March) average about 24.5ºC and colder months (June to August) around 22.4ºC.

The rainfall system is tropical. Yearly average precipitation is high, typically ranging from approximately 1400 mm to 2300 mm. Eighty four percent of the rainfall occurs from October to March, peaking from November through January (approximately 58% of the total rainfall).

Throughout the Nova Lima region, winds originate predominantly from the east, and are generally minor, with annual average velocities of 0.98% m/s.

Geology

The study area lay over a sequence of volcanic-sedimentary rocks with calc-alkaline affinity, varying from basaltic-andesite to rhyolite with intercalation of komatiites and tholeiitic basalts in the base. These rocks were affected by four deformation events and two events of metamorphism from low to middle grade. The Au occurs in sulfidic ore bodies hosted in chemical sediments (BIF) or in quartz veins. Among the sulfidic minerals arsenopyrite is one of the predominant. Carbonate minerals such as dolomite, calcite, and siderite are associated with the hydrothermal veins mineralized with Au.

Land Use

Most of the tailings deposits are located in a partially urbanized area (e.g., the *Galo* tailing site on Fig. 3). Some are fenced, but others are easily accessible to the public, and are used for recreation, agriculture, grazing, or as transportation corridors. Trespassers are commonly encountered on the fenced properties.

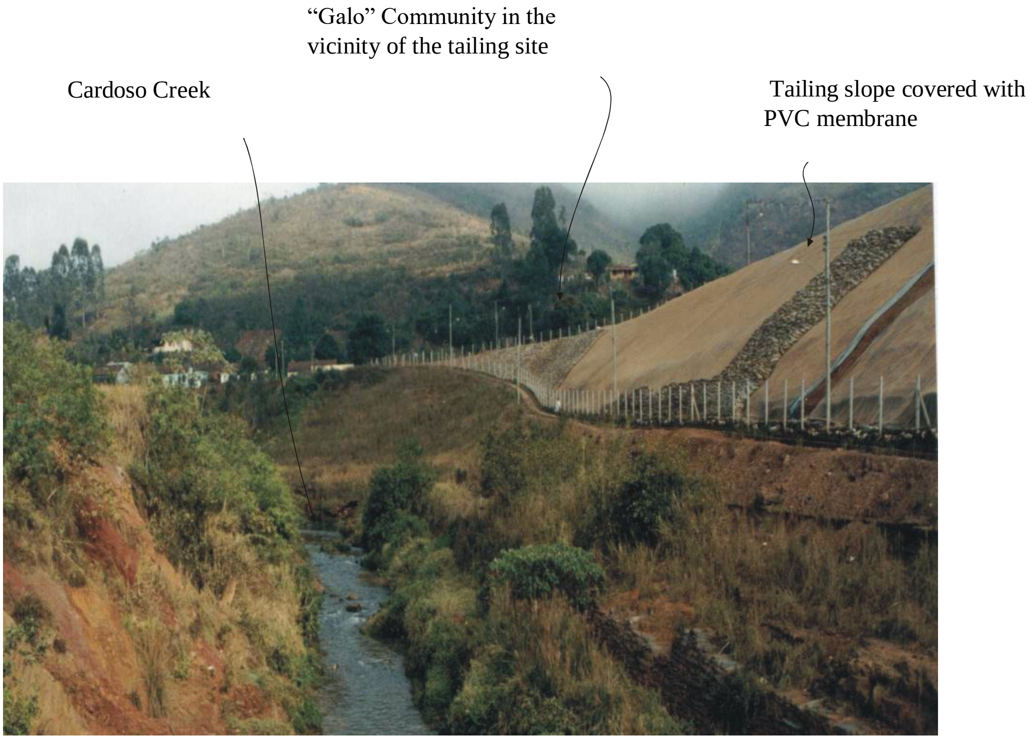

Figure 3: Galo tailing near Cardoso Creek

The *Matadouro* tailings site is fully urbanized and occupied by a small neighborhood called *Areião do Matadouro*, consisting of a residential area surrounding a public plaza (Fig. 4).

The *Isolamento* tailings site is located in part of an area owned by MMV (Fig. 5). Despite its location in the Nova Lima urban area, the site is rural in nature, since it is fenced and has no residences. However, people and domestic animals frequent the tailings area.

The *Rezende* tailing site is also located in a Nova Lima urban area but contains no residences (Fig. 6). The site is paved and used as a transportation corridor.

The *Fábrica de Balas* tailings site (Fig. 7) is fenced and contains no residences. It is occupied in part by MMV buildings and installations and is paved. People circulate through the area.

The *Madeira* tailings site is located in the Nova Lima Industrial Area and contains installations and buildings owned by MMV and a municipal transportation system serving the Nova Lima urban area, thus experiencing considerable pedestrian and other traffic. Due to the presence of sewage, it is uncommon to see people use Cardoso Creek for recreational purposes (e.g., swimming or fishing) in the area where the mine tailings are situated.

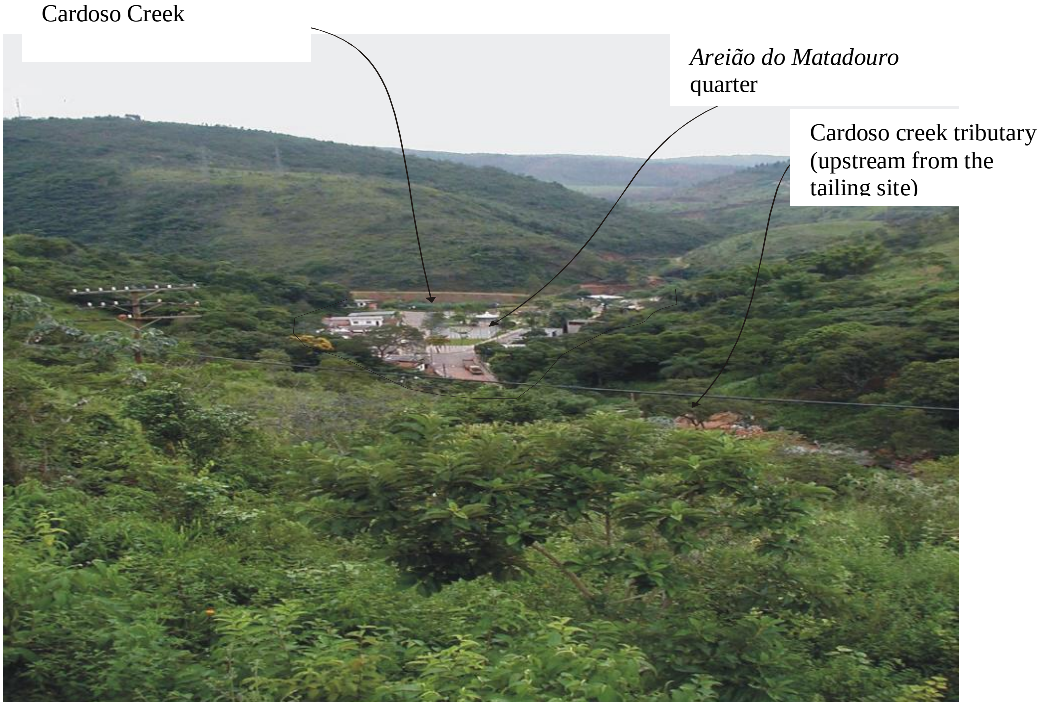

Figure 4: The *Matadouro* tailing site

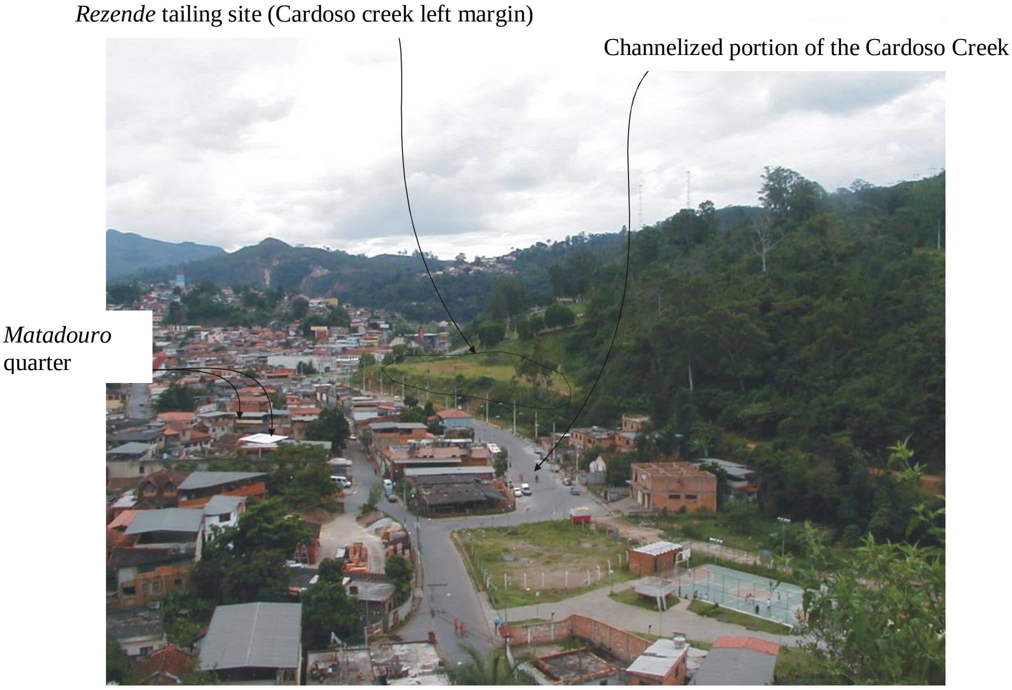

Figure 6. Overview of the urban area surrounding *Rezende* tailing.

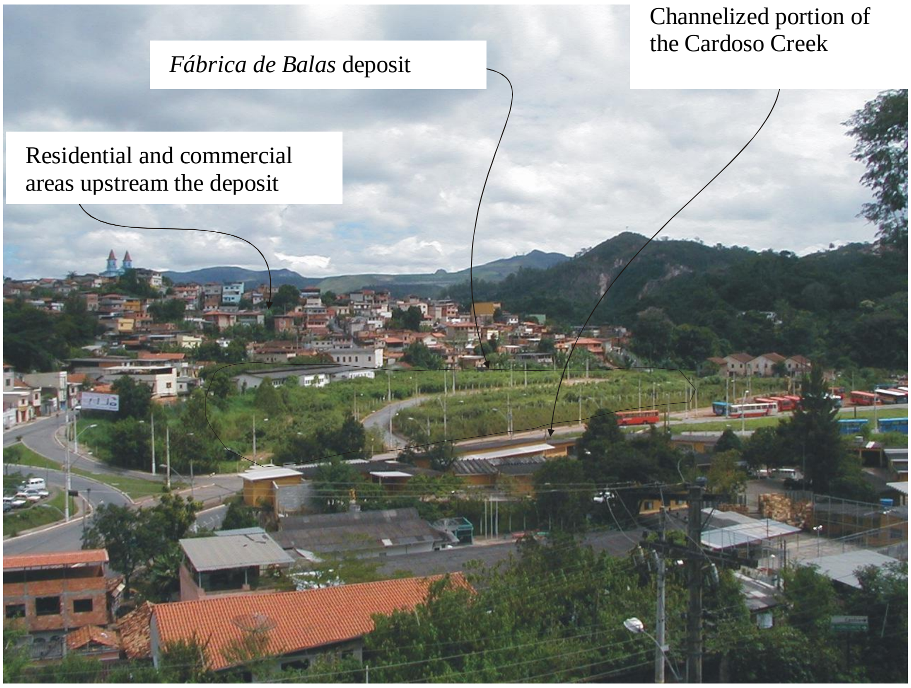

Figure 7. Overview of the urban area surrounding *Fábrica de Balas* tailing.

Hydrogeological and Geochemical Appraisal

Due to the extensive presence of mineralized areas and associated arsenopyrite, the soils and rocks of the Nova Lima area have a high background level of As (Matshullat et al., 2000). The natural AS concentrations found in soils of this area (between 50 and 200 mg/kg) are above the average concentrations found in most areas of the world (Ball et al., 1993; Smedley and Kinniburgh, 2002).

Toxicity Characteristic Leaching Procedure (TCLP) tests carried out on 11 samples from the area (6 tailings samples and 5 samples of material underneath the tailings) indicated that only one sample leached As at a concentration greater than 5 mg/L (toxicity criterion established by the Environmental Protection Agency (USEPA 1994). The samples taken down-gradient of the tailings generally produced leachates of better quality than the tailings. Moreover, the leachates of even the finest-grained tailings, which would enhance arsenic extraction, indicated that the amount of arsenic extracted during the TCLP test was below 1% of the total As present.

Modified acid-base accounting tests (USEPA 1994) indicated a very low probability of acid generation (NP/AP >> 3.0) in the tailings located along Cardoso Creek (Table 2). Therefore, release of arsenic through acid generation was not considered a feasible mechanism (Table 2). .

Elevated As concentrations in groundwater were found only in the tailings themselves, and only in the presence of reducing conditions (Fig. 8). This fact suggested that the mobility of the As in the surrounding areas, where a direct source for arsenic was absent and groundwater conditions were more oxidizing, was low. Other researchers found the same conclusion for the behavior of arsenic in relation to the Eh conditions (Nadakavuskaren *et al*., 1994).

Table 2. Modified Acid Base Accounting Results.

Sample ID	Paste pH	Neutralization Potential	Acidification potential	Net Neutralization Potential	NP/AP Ratio
PZRZ01A-02	5,27	27930	362,5	27568	77
PZRZ01B-02	5,59	10626	368,8	10257	28,8
FRRZ01-02	5,07	9870	384,4	9486	25,7
FRRZ02-02	5,03	6400	122,8	6277	52,1
PZIS01-02	4,64	6479	176,3	6303	36,8
PZIS01-04	4,81	16541	279,1	16262	59,3
PZIS01A-02	4,57	7440	149,4	7291	49,8
PZIS01A-06	4,61	18603	212,5	18391	87,5
PZIS01B-02	4,45	6048	229,4	5818	26,4
PZIS01B-04	4,38	14280	208,1	14072	68,6
PZIS06-02	4,37	5528	90,3	5437	61,2
PZIS07-02	4,98	13916	280	13636	49,7
MNGA02-02	5,1	24360	273,4	24086	89,1
PZGA01-02	6,75	32744	177,8	32566	184,1
PZGA02-02	5,52	45510	331,3	45179	137,4
PZGA03-02	7,27	39146	292,2	38854	134
PZGA03A-02	6,88	53580	231,6	53348	231,4
PZGA03B-02	7,08	37843	231,6	37611	163,4
PZGA04-02	7,37	46608	165	46443	282,5
PZGA08-02	5,99	38663	266,3	38397	145,2
PZGA09-02	5,28	20290	215,3	20074	94,2

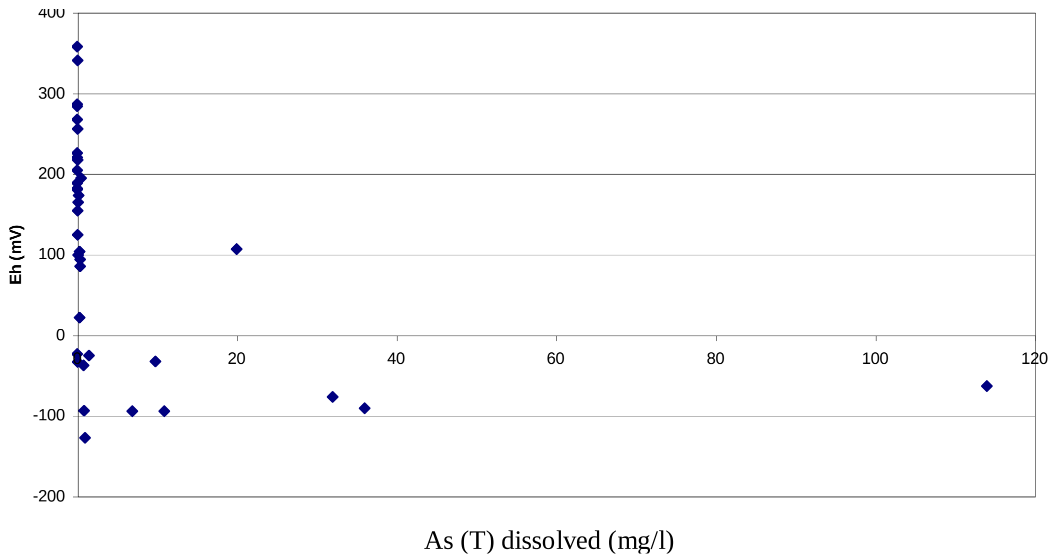

Figure 8. Dissolved As concentrations vs. redox conditions.

Cardoso Creek waters had only levels of trace metal contaminants (Cu, Zn, Pb, Cd, etc.) from centesimal to millinesimal mg/L, except for As, where the concentrations vary from 5 to 180 mg/L along the hydrological year. The geochemical data over time suggest that these As concentrations are not increasing, likely due to the limited As mobility from the tailings to the surrounding environment. Based on results obtained from other researchers it is well known that As has high affinity for Fe oxyhydroxides (Manning and Goldberg, 1997). Additional potential As sources for Cardoso Creek are the stream sediments and materials eroded from the tailings deposits.

Water samples from wells and fountains in the vicinity of the tailings did not indicate abnormal As concentrations, according to monitoring conducted by MMV since April 2001. This confirms the absence of elevated As concentrations in groundwater and surface water outside of the direct deposits. A likely mechanism for As attenuation is due to adsorption by Fe oxyhydroxides, a common mineral found in tropical areas (Reynolds *et al.,* 1999; Ladeira, 1999; Smedley and Kinniburgh, 2002). Abnormal As concentrations, when noted in wells in residual soils, saprolite and alluvial rocks, were clearly associated with the presence of tailings.

Hydrogeological studies carried out in the area, supported by computer modeling, indicated that the historic tailings deposits do affect hydrogeological areas in zones of low to average hydraulic conductivity (the Nova Lima Group schists and weathering products (residual soil and saprolite).

Hydrometric measurements and regional hydrologic information show that the average recharge of the Cardoso Creek basin is less than predicted by computer models. Therefore, for this study, measured stream flows were used to assess base flow, rather than computer modeling. The sum of the base stream flow from the six tailings areas reaches $8.0 \times 10^4\ m^3$/year, which is approximately 0.5% of the average Cardoso Creek water gain of $1.8 \times 10^7\ m^3$/year in that area. The remaining 99.5% of water inflow originates chiefly from Cristais Creek and the Nova Lima urban sewage outfall.

The annual As load from the tailings into Cardoso Creek waters, in the interval comprising the deposits area, is 1.8×10^9 mg/year. However, based on the water balance of the creek basin and applying the highest As concentration found in the tailing areas, the maximum As contribution from the tailings to the creek would be approximately 13% of this amount. Therefore, the remaining As (approximately 87% of the observed load in Cardoso Creek) is thought to mainly derive from other sources, such as creek bottom sediments, surface drainage and erosion developed along the creek. In relative terms, major contribution comes from the *Isolamento* tailing site (7.2%), followed by *Galo* (3.1%), *Fábrica de Balas* (1.4%), *Matadouro* (0.9%), *Madeira* (0.2%) and *Rezende* (0.003%) deposits.

Risk analysis based on hypothetical scenarios of land use indicated that for any tailings deposit, a full use of the site scenario would result in an unacceptable risk. In these cases, the major risk components would be related to direct consumption of groundwater, to soil ingestion and consumption of meat and vegetables derived from the site. Scenarios that include covering of the contaminated areas, and limited use of the site (i.e. no consumption of groundwater, meat and vegetables) present an acceptable risk.

Conclusions and Recommendations

Institutional Steps

The use of groundwater in the tailings deposits and adjacent areas should be restricted. Water use should be scrutinized by government environmental agencies. The impoundment of groundwater on the tailings should be forbidden unless it is associated with an approved water treatment project. In addition to this restriction, social and informational campaigns, with technical and operational support by MMV, should be undertaken so that the population understands the reasons to limit utilization of wells and cisterns (excavated wells) within the deposits areas.

Cisterns and fountains located in upstream areas or in areas not influenced by groundwater flow from the tailings may continue to be used by the population, provided that the water quality is monitored.

The planting of vegetables (orchards and vegetable gardens) and the raising of animals on the tailings or on soil placed directly on the tailings should also be forbidden, in view of the potential risks. At sites like Matadouro, for instance, it is recommended that the tailings be paved in the residential areas. Although paved yards are relatively common in large urban areas, it is not characteristic of the area under investigation; however, the benefits of such an action are considered higher than the social costs. Pavement would facilitate the cultivation of vegetable gardens and other ornamental trees using special elevated beds and soil imported from non-contaminated areas.

Rehabilitation Actions

The main rehabilitation approach for these historic tailings should be containment. Rehabilitation projects should focus on covering the tailings using engineering project specifications based on internationally accepted criteria (Bonaparte, 1990). Such covers typically consist of multiple layers.

The non-accumulation of water on the tailings is critical. The recommended containment strategy should therefore be accompanied by drainage facilities to minimize surface flow on the tailing and to allow efficient and rapid dissipation of rainfall from the covered tailings. Contour drainage system should be constructed on all of the tailings areas (except for *Matadouro* and *Madeira*, where urban occupation does not allow it), preferably not crossing the deposits, in order to divert water from the slopes and upstream creeks and thereby avoid uncontrolled discharge to Cardoso Creek. The engineering of these drainage facilities should be carefully checked with respect to choice of materials, quality control and quality assurance procedure, and facility design.

Environmental Monitoring Actions

It will be necessary to monitor surface water and groundwater quality in the vicinity and down-gradient of the Cardoso Creek valley tailings. Additional studies should be conducted on arsenic geochemical and hydrochemical mobility to augment the proposed water quality monitoring program and establish an appropriate monitoring program .

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