



Environmental assessment of mercury pollution in urban tailings from gold mining

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ARTICLE INFO

Article history:

Received 28 March 2012

Received in revised form

24 December 2012

Accepted 26 December 2012

Available online 26 January 2013

Keywords:

Mercury contamination

Gold mining

Soil

Standard assessment

ABSTRACT

It is well-known that small-scale artisanal mining is a source of mercury emissions into the environment, mainly from the use of rudimentary technologies that use mercury amalgamation in the extraction process. Mines near Andacollo, which is located in the Coquimbo region of Chile, use primitive methods to mine gold and copper. In this study, we determined the mercury content of gold mining wastes from Andacollo. At each site, we randomly sampled the soil at the surface and at a depth of 2 m following the ISO 10381 guidelines. Mercury analysis was performed with a direct mercury analyzer. At least one site was contaminated at a mercury concentration of $13.6 \pm 1.4 \text{ mg kg}^{-1}$, which was above the international recommendations that were set by the Canadian Council of Ministers of the Environment's soil quality guidelines (CA-SQG) and the Dutch guidelines (NL-RIVM). At least four of the fourteen sites in this study were within the control and tolerance levels of these recommendations. Better characterization of these sites is required to establish whether they represent a risk to the local community. Based on the US-EPA recommendations, which have a higher tolerance limit, none of the fourteen sites should pose a risk to humans.

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1. Introduction

Heavy metals, such as mercury (Hg), are a growing cause of environmental pollution worldwide (Clifton, 2007; Spiegel and Veiga, 2010). Hg can occur in soil naturally or as a result of human activity, such as gold mining (Bose-O'Reilly et al., 2010; Veiga et al., 2006). Small-scale or artisanal gold mining often uses rudimentary technologies that involve amalgamation with Hg in the extraction processes. Although other extraction methods are available, these extraction methods, which date back to the time of Nero (54–68 B.C.), are widely used because they require a small initial investment and minimal technical knowledge (Spiegel and Veiga, 2010; UNIDO, 2004; Veiga et al., 2006). The amalgamation process is inefficient for extracting gold and inevitably introduces Hg into the environment (air, water, and soil). To date, 1000 t of Hg have been lost into the environment from the amalgamation process (Swain et al., 2007).

Hg is widely known for its toxic properties (UNEP, 2007). The health effects of Hg exposure depend on the dose and duration of the exposure. Acute exposures can be fatal or cause permanent damage to the central nervous system, whereas chronic exposures are characterized by less pronounced symptoms, such as

fatigue, irritability, memory loss, vivid dreams, and depression. The use of Hg for small-scale, industrial, and artisanal gold extraction has resulted in thousands of contaminated sites. Although localized ecological degradation and negative health impacts result from these sites, their total impacts are more widespread. Often, the inhabitants of the mining regions suffer long-term health effects (Bose-O'Reilly et al., 2010).

According to the International Labor Organization (ILO), the mining sector employs between ten and fifteen million artisanal gold miners worldwide. Furthermore, an additional 80–100 million people are directly or indirectly connected to or economically dependent on mining activities (UNIDO, 2004). Approximately one million miners use Hg to extract gold in Latin America (Veiga et al., 2006). Artisanal and small-scale mining accounts for at least 25 percent of the world's total gold production (Veiga et al., 2006).

In Chile, the production and extraction of gold dates back to the pre-Columbian era. Gold extraction increased after the arrival of the Spanish and grew from the production of over 2 metric tons per year to 40.8 metric tons in 2009 (Lagos and Peters, 2010). The currently exploited deposits are primarily located in northern Chile. This mining activity has resulted in abandoned mining sites that contain Hg. For example, the city of Andacollo was identified as a city with abandoned mine piles in the "Cadaster update of abandoned or paralyzed mines: Preliminary analysis of risks" study (SERNAGEOMIN, 2007). These abandoned mine piles resulted from small-scale gold mining activities that were located

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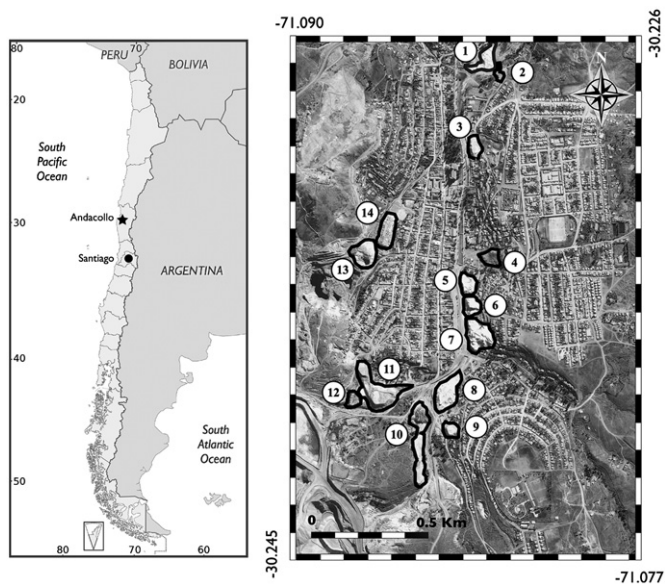


Fig. 1. The study area in the city of Andacollo, Chile. The sampled sites within the urban area are indicated.

in the urban area (see Fig. 1). Based on historical accounts, the Incas founded this city and began to exploit its natural riches in 1420 by transforming it into a mining colony. Finally, in the late 1990s, two large-scale mining companies begin operating in Andacollo: Carmen de Andacollo (the Pacific-Rim Mining Corporation and National Mining Corporation) and the Dayton Mining Corporation (a subsidiary of the Dayton Xining Corporation) (Lagos and Peters, 2010; Reyes, 1991).

Tailing piles are immediately noticeable in Andacollo. These waste deposits from gold and copper extraction processes have become part of the landscape because of their urban setting. Although these deposits have different origins, volumes, and owners, the 12,000 inhabitants of this community must live with the climate and behavior changes that result from these deposits. These changes negatively impact human health in various population sectors. The problem of Hg contamination in these tailings was identified by Andacollo (CONAMA, 2009). This study focused on a single tailing pile with a Hg concentration of 1.1 mg kg^{-1} (CONAMA, 2009). However, it is important to consider that Chile has not established any laws that limit soil metal concentrations. However, current Chilean legislation may mandate regulations that are similar to the current international guidelines or standards of other countries, such as Holland (NL-RIVM, 2001), Canada (CA-SQG, 2010), and the United States (US-EPA, 2004a).

This study evaluates the Hg contamination in the waste piles of artisanal mining sites that result from the amalgamation of gold in urban areas of Andacollo, Chile. Because industrial mining, passive mining, and artisanal extraction of gold occurs near population centers, gold extraction is related to environmental pollution and health problems of the general population.

2. Materials and methods

2.1. Site description and gold mining in Andacollo

Andacollo ($30^{\circ}14'S$, $71^{\circ}06'W$) is a Chilean commune located in Elqui province in the Coquimbo IV region and is 56 km southeast of La Serena, the capital of the IV region (Higuera et al., 2004; Reyes, 1991). This commune is located at an elevation of 1100 m above sea level and is between two hills in one of the last branches of the Andes mountain range (see Fig. 1). Andacollo is bordered by

La Serena to the north, Rio Hurtado and Ovalle to the south, Vicuña to the east, and Coquimbo to the west. The commune has a population of 10,288 inhabitants, which corresponds to 1.71 percent of the inhabitants in the region, and a surface area of 310.3 km^2 (Higuera et al., 2004).

The Pacific anticyclone impacts the regional climate, which is an arid or dry desert that receives notably little precipitation in the winter. During the summer, the mean temperature is between 26°C and 30°C . The winter is short, lasting from the end of June to the end of August, and has a mean temperature of 15°C .

From a geological point of view, Andacollo is a complicated district that includes porphyry Cu, epithermal Au, Cu, and Hg deposits. The porphyry Cu occurs in the central portion of the district, and the Au and Hg occur to the west and east, respectively. The epithermal Au deposits consist of Au-bearing pyrite, native Au and minor chalcopyrite (Higuera et al., 2004; Reyes, 1991).

2.2. Sample collection and preparation

Samples were collected in October 2010 following the ISO 10381 guidelines "Soil Quality Sampling—Part 1 and Part 8" (ISO10381-1, 2002; ISO10381-8, 2006). These samples were collected to determine the Hg and organic matter concentrations and the clay content of the urban Andacollo tailings. A total of 80 samples were collected from fourteen different urban tailing piles in Andacollo. Table 1 contains the number of samples collected by tailing location and depth. Soil samples were collected from the surface and at two depths with a plastic scoop and an auger, respectively. Each sample weighed approximately 1 kg and was stored in a glass container at less than 6°C . To establish the baseline value, a sample was collected from the road leading out of the city, which was outside of the areas that were affected by the tailings.

The sample sites were piles of gold and copper mining wastes that were located in urban areas. A total of fourteen sampling sites were selected, as shown in Fig. 1. In addition, we selected a background site that was located 40 km from Andacollo. A total of 80 samples were analyzed, of which 45 were from the surface and 35 were from a depth of two meters.

2.3. Analytical procedures and methods

In the laboratory, the samples were air-dried, ground, and sieved through a minus 150 mesh sieve. A DMA-80 (Milestone Inc., Sorisole, Italy) attached to an auto-sampler and with nickel sample boats (US-EPA, 2004b) was used for direct Hg analysis. Bottled oxygen was delivered to the instrument at 65 psi at a flow rate of 200 mL min^{-1} . The instrument had two working ranges for Hg detection, 0–40 ng and 40–600 ng. Each range was independently calibrated to optimize the response over the entire dynamic range.

Prior to analysis, the instrument was programmed with an appropriate heating cycle. The required drying and decomposition times are matrix-dependent and should be determined experimentally. However, guidelines do exist (US-EPA, 2004b). For solid samples, 0.05–0.5 g were weighed in a tarred nickel sample boat and later processed. For aqueous samples (calibration standards and digested samples), 10–500 μL was dispensed into the sample boat and was processed. The calibration standards were freshly prepared from a traceable NIST stock solution consisting of $1000 \mu\text{g L}^{-1}$ of Hg in 10 percent HNO_3 . Solutions with both 1 and 10 ppm of Hg were prepared by the quantitative transfer and dilution of stock solution aliquots in 10 percent HNO_3 .

This method was validated using a certified reference material (CRM) for commercial soil (RTC Corp., Number: SQC001, lot: 13214). This method had a recovery and repeatability of 98 percent and 4 percent, respectively, for duplicated measurements that were conducted on the same or on different days. The expanded uncertainty was 9.7 percent with a coverage factor of 2. The limits of detection and quantification were 0.08 and 0.27 mg kg^{-1} , respectively.

The percent organic matter (percent OM) was obtained with the loss by ignition method, which subjects a 5 g sample to a temperature of 430°C in a muffle furnace for 4 h or until a constant weight is obtained (Byers et al., 1978). Complete oxidation of the OM occurs at this temperature. The limit of detection was 0.17 percent, and the reproducibility was less than 6 percent.

The Bouyoucos method was used to determine the percent clay (percent CLAY) (Bouyoucos, 1936). First, 50 g of the sample was added to 5 mL of a dispersing agent (150 g of sodium tripolyphosphate and 30 g of sodium carbonate (Na_2CO_3) in 4 L of distilled water). Next, 60 mL of water was added, and the mixture was allowed to equilibrate for 24 h. Following equilibration, the solution was stirred for between 5 and 10 min in a blender. Next, 250 mL of this mixture was placed in a cylinder and was mixed with a rod to suspend the particles. Amylic alcohol was added to remove any foam. To determine the correction factor, the temperature of the suspension was measured with each Bouyoucos densimeter reading. The first reading for the percent sand calculations was obtained after 40 s, and the second reading was obtained after 5 h. The estimated repeatability of the method between duplicate samples was less than 6 percent. The Hg concentration, percent OM and percent CLAY were measured in duplicate.

Table 1

Mercury concentration (Hg, mg kg⁻¹), organic matter (percent OM), and clay content (percent CLAY) results for the study sites (see Fig. 1) with their respective standard deviations (SD_i) and expanded uncertainties (U_i).

Site code	n	Hg (mg kg ⁻¹)	SD _{Hg} (mg kg ⁻¹)	U _{Hg} (mg kg ⁻¹)	OM (percent)	SD _{OM} (percent)	U _{OM} (percent)	CLAY (percent)	SD _{CLAY} (percent)	U _{CLAY} (percent)
0-0 m	2	0.4	0.6	0.8	2.7	1.3	1.9	16	10	14
0-2 m	2	0.4	0.1	0.1	5.2	0.2	0.7	14	2	4
1-0 m	2	1.5	1.1	1.6	1.8	0.6	0.8	16	9	13
1-2 m	3	0.9	0.5	0.5	2.0	1.1	1.3	22	9	11
2-0 m	3	13	1.7	2.4	2.2	0.6	0.8	17	7	9
2-2 m	3	14	1.0	1.8	2.7	0.8	1.0	15	5	6
3-0 m	6	0.4	0.2	0.1	0.2	0.2	0.2	11	1	2
4-0 m	3	13	5.0	5.9	2.8	0.5	0.7	12	1	3
4-2 m	3	9.5	5.5	6.4	4.2	0.3	0.6	10	1	2
5-0 m	3	3.7	4.4	5.1	3.2	1.5	1.7	26	7	9
5-2 m	3	8.0	13	15	2.1	1.8	2.1	25	3	6
6-0 m	2	0.4	0.3	0.4	1.5	1.2	1.7	21	1	4
6-2 m	2	0.9	1.0	1.5	2.7	1.6	2.3	28	6	10
7-0 m	2	4.1	4.3	6.1	1.7	0.8	1.2	15	1	3
7-2 m	2	4.1	4.6	6.5	3.4	1.0	1.5	34	30	43
8-0 m	3	3.0	1.0	1.7	4.4	1.0	1.3	21	0	4
8-2 m	3	2.0	1.0	0.8	3.7	1.8	2.1	14	8	9
9-0 m	3	0.5	0.2	0.2	1.5	0.4	0.5	15	1	3
9-2 m	3	0.4	0.1	0.2	3.4	1.0	1.3	14	2	4
10-0 m	3	3.1	2.0	2.4	2.2	1.1	1.3	36	23	27
10-2 m	2	2.5	2.6	3.7	2.3	0.3	0.5	10	7	10
11-0 m	3	10	6.0	6.7	1.9	0.4	0.5	42	1	8
11-2 m	3	4.0	3.8	4.4	1.5	0.2	0.3	17	12	14
12-0 m	2	0.4	0.1	0.1	2.5	1.0	1.4	25	1	5
12-2 m	2	0.6	0.2	0.3	1.8	1.5	2.1	18	7	10
13-0 m	3	1.5	1.4	1.5	1.7	0.4	0.5	11	1	2
13-2 m	3	2.6	3.1	3.6	2.4	2.6	3.0	23	11	14
14-0 m	3	3.0	3.8	4.4	2.0	0.9	1.1	17	1	4
14-2 m	3	0.9	0.5	0.6	1.8	0.3	0.4	20	9	12

2.4. Statistical analyses

The differences between the Hg concentrations, percent OM, and percent CLAY at different locations and at different sampling depths were statistically analyzed using a one-way ANOVA model in MS Excel[®] Version 2010 (Microsoft Corporation, Redmond, CA, USA). It was important to determine if the Hg concentrations, percent OM, and percent CLAY significantly differed between sample sites and depths. Thus, pairwise differences between specific sample sites and depths were examined using a least significant difference test with a Tukey–Kramer adjustment. A confidence interval of 95 percent ($\alpha=0.05$) was used for the significant difference analysis.

2.5. Estimating uncertainty

Two important aspects of analyzing regulation compliance are the uncertainty and tolerance control limits and the measurement traceability (Ellison and Williams, 2012; Ridler et al., 2007). The standard uncertainty (u_i) can be estimated over successive measurements from the standard deviation of the source i (s_i) over the square root of the number of measurements (n_i) (Weckenmann et al., 2006) according to the following equation:

$$u_i = \frac{s_i}{\sqrt{n_i}} \quad (1)$$

From this value, it is possible to obtain the standard relative uncertainty (u_{qi}), which is calculated from the uncertainty (u_q) and the magnitude (q) of the corresponding source, i , based on the following equation:

$$u_{qi} = \frac{u_i}{q_i} \quad (2)$$

Next, the combined relative uncertainty of the method (u_c) was estimated, which can be calculated for non-correlated sources of uncertainty (Ellison and Williams, 2012) from the geometric sum of their standard relative uncertainties (u_{qi}) according to the following equation:

$$u_c = \sqrt{\sum_{i=1}^n u_{qi}^2} \quad (3)$$

Finally, these results must be reported along with the expanded uncertainty (U), which is calculated by using a coverage factor of $k=2$ (as shown in Eq. (4)) (Ellison and Williams, 2012). This equation provides a confidence level of

approximately 95 percent.

$$U_q = k u_{qi} \quad (4)$$

The estimation of uncertainty for the repeatability studies (ten measurements on the same day and ten measurements on successive days) and recovery studies (ten measurements on the same day) were performed (Leiva et al., 2012). In addition, the dependency of the results on the measurement procedure was considered to estimate the combined uncertainty of the volumetric uncertainty, uncertainty scales, and calibration curve contributions (Leiva et al., 2012). The expanded uncertainties associated with the Hg, percent OM, and percent CLAY measurements were 9.7 percent, 6 percent, and 6 percent, respectively.

A detailed description of the procedure for estimating uncertainty is not a goal of this study. However, it is possible to find procedures for estimating uncertainty in the literature (Ellison and Williams, 2012; Leiva et al., 2012).

2.6. Comparison of the results with international guidelines

The Hg concentration results were directly compared with the recommendations of the US-EPA and CA-SQG for residential areas (such as Andacollo), which are 23 mg kg⁻¹ and 6.6 mg kg⁻¹, respectively. In addition, the obtained results were compared to the Dutch guidelines (NL-RIVM, 2001). The Dutch guidelines establish two values for standard soils, a target value (TV) of 0.3 mg kg⁻¹ and an intervention value (IV) of 10 mg kg⁻¹. These values require adjustments based on the percent OM and percent CLAY of the soil, which are defined by the following empirical relationship in the guidelines (NL-RIVM, 2001):

$$TV_s \text{ or } IV_s = (TV_{std} \text{ or } IV_{std}) \left(\frac{0.2 + 0.0034 \text{ percent CLAY} + 0.0017 \text{ percent OM}}{0.302} \right) \quad (5)$$

where TV_s and IV_s are conversion factors for TV_{std} (target value, 0.3 mg kg⁻¹) or IV_{std} (intervention value, 10 mg kg⁻¹). The resulting converted values can be compared to the measured soil concentrations.

3. Results and discussion

3.1. General soil properties (percent OM and percent CLAY)

Table 1 contains the percent OM and percent CLAY of the samples (n) and their respective standard deviations (SD) for each depth (0 and 2 m). Likewise, we present the expanded uncertainty

results for the obtained values, which were used to determine their adherence to the international soil Hg standards (see Section 3.3).

Fig. 2a demonstrates that the percent OM varied from 0.3 percent to 4.4 percent at the surface and from 1.5 percent to 5.2 percent at a depth of 2 m. The average percent OM for the surface and 2-meter depth samples were 2.3 (SD: 0.9 percent) and 2.8 (SD: 1.0 percent), respectively. In addition, as observed in Table 1 and Fig. 2b, the percent CLAY varied from 11 percent to 42 percent at the surface and from 10 percent to 34 percent at a depth of 2 m. The average percent CLAY at the surface and at a depth of two meters was 19 percent (SD: 8 percent) and 20 percent (SD: 7 percent), respectively.

The one-way ANOVA analysis demonstrated that no significant differences occurred between sampling sites or depths for percent OM and percent CLAY (percent OM, between sites: $F(F_{crit})=1.94$ (2.58); $P=0.12$ and between depths: $F(F_{crit})=3.68$ (4.67); $P=0.08$; percent CLAY, between sites: $F(F_{crit})=0.94$ (2.58); $P=0.54$ and between depths: $F(F_{crit})=0.14$ (4.67); $P=0.72$).

3.2. Mercury in the soil of the study area

Table 1 shows the Hg concentrations obtained at each of the sites and depth levels with the number of samples (n) and the corresponding standard deviations (SD_{Hg}). In addition, we present uncertainty values (U_{Hg}) that will be used below to evaluate the compliance with international standards (see Section 3.3). The expanded uncertainty is always larger than the SD because it accounts for both the sample variability and the measurement uncertainty.

Fig. 2c shows the distribution and the average results that were obtained at each depth level by site. The Hg concentrations varied between 0.18 and 16.7 $mg\ kg^{-1}$ at the surface and between 0.13 and 22.4 $mg\ kg^{-1}$ at a depth of 2 m. These differences reflected the heterogeneity of the sites that resulted from different processing techniques and the age of the tailings. The average concentrations at each depth level were 1.2 (SD: 4.9) and 1.3 (SD: 5.7) $mg\ kg^{-1}$, respectively (at 0 and 2 m). These values are normal for a region that was subjected to such intense and prolonged mining activities. For example, in some regions of Spain (Higuera et al., 2003), Slovenia (Loredo et al., 1999), and the USA (Biester et al., 1999), previous mining practices have resulted in abandoned Hg mine sites that have mercury concentrations between 1.5 and 8000 $mg\ kg^{-1}$. However, relative to 'normal soils' (i.e., not subjected to active contamination), the Andacollo Hg concentrations are high. Soil Hg concentrations are

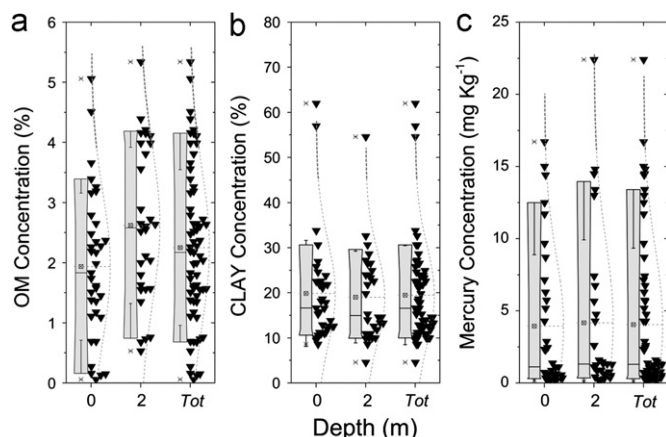


Fig. 2. Descriptive statistics for the (a) organic matter (percent OM), (b) clay content (percent CLAY), and (c) mercury concentration (Hg , $mg\ kg^{-1}$) at the surface and at a depth of 2 m and averaged over the two depths.

generally between 0.01 and 0.03 $\mu g\ g^{-1}$ (Senesi et al., 1999). The Andacollo background area had a Hg concentration between 0.02 and 0.9 $\mu g\ g^{-1}$ Hg. Thus, we can conclude that the studied urban tailings from Andacollo are enriched in mercury by a factor of 10–20.

The one-way ANOVA analysis indicated that significant differences occurred between the two depths ($F(F_{crit})=0.84$ (4.67); $P=0.37$). However, significant differences were observed between the different tailing piles ($F(F_{crit})=12.1$ (2.58); $P=0.00$). This result demonstrates that more detailed analyses of the Hg concentrations are needed for each tailing to determine their potential impacts on human health.

The highest concentrations were found at site 2 (13 and 14 $mg\ kg^{-1}$ at 0 and 2 m, respectively), site 4 (13 and 9.5 $mg\ kg^{-1}$ at 0 and 2 m, respectively), site 11 (10 and 4.0 $mg\ kg^{-1}$ at 0 and 2 m, respectively), site 5 (8.0 and 3.7 $mg\ kg^{-1}$ at 2 and 0 m, respectively), and site 7 (4.1 $mg\ kg^{-1}$ at 0 and 2 m). The lowest concentrations were found at the selected background sites as follows: site 0 (0.4 $mg\ kg^{-1}$ at both 0 and 2 m), site 3 (0.4 $mg\ kg^{-1}$ at 0 m), and site 9 (0.5 and 0.4 $mg\ kg^{-1}$ at 0 and 2 m, respectively).

3.3. Comparing the results to the international guidelines

The Hg concentrations and their respective expanded uncertainty (see Table 1) were compared to the United States Environmental Protection Agency (US-EPA, 2004a), Canadian Council of Ministers of the Environment's soil quality (CA-SQG, 2010), and Dutch guidelines (NL-RIVM, 2001) for soils to determine their compliance.

In this analysis, we compared the TVs and IVs measurement results, which were established to eliminate any risk associated with exposure to certain contaminants, such as Hg (ICRCL, 1987). The reference values define three possible Hg concentration ranges (see Fig. 3). The concentration range, which includes the concentration of the contaminant at the site, will determine the actions required. Only relatively low contaminant concentrations are found in the first region. Thus, no significant risk occurs in the first region. As the concentration increases, it reaches a level at which the risk becomes significant. The concentration at which this occurs is defined as the threshold concentration, which may vary based on how the site is used. Below the threshold value, a site is considered uncontaminated for its intended use. Thus, no

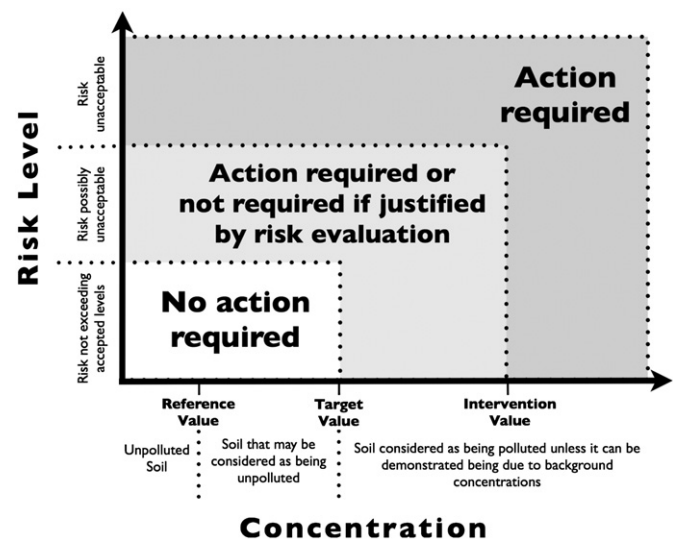


Fig. 3. Interpretations of the reference, target, and intervention values as a function of risk level.

corrective action is required, even when the concentrations are above the typical values for that zone.

In the second (intermediate) region, the contaminant concentration is between the threshold value and the upper limit of the threshold. This region does not imply significant risk. However, it must be determined if the level of the contaminant justifies adopting corrective measurements. In other words, an informed decision must be made.

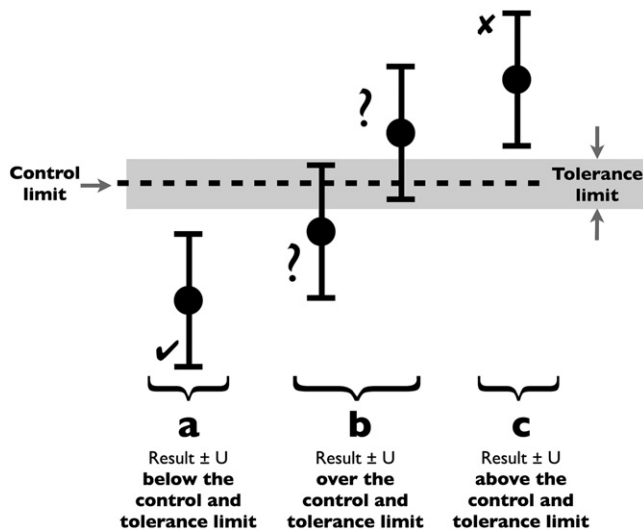


Fig. 4. Uncertainty and compliance limits.

Finally, if the concentration is greater than or equal to the IV in the third region, then the health risks are significant. Therefore, the presence of the contaminant must be considered undesirable or unacceptable. In this case, the site is considered contaminated. Thus, a decision must be made regarding the appropriate course of action, which can range from reclamation to changing the proposed land use of the site.

The results comparison accounted for the uncertainty in the Hg concentration measurements using the criteria shown in Fig. 3 (Ellison and Williams, 2007). Fig. 4 shows the hypothetical Hg concentration measurement results for the soil samples from different sites. The expanded uncertainty is superimposed over these results. These results clearly show that the measurements in region (a) are within the specified limits and that those in region (c) are above the limits, which occurs because the differences between the results and the control limits are greater than their uncertainties in both cases. However, the results in region (b) could be above or below the control limit. Therefore, it is not possible to evaluate whether these results meet the specifications. In addition, further studies are required to establish adherence to the control limits.

Table 2 and Fig. 5 show the results of this comparison with respect to the standard deviation of the measurements. All of the sites met the US-EPA guidelines, and no remediation actions were required. Only the 2 m sample from site 2 had a value above the CA-SQG guidelines after the uncertainty was accounted for. When the average value of both depths at site 2 was used, the sample did not meet the guidelines. In addition, sites 4, 5, 7, 10, 11, and 14 all had values from at least one depth that were potentially above the control limit. Thus, it was impossible to evaluate whether these results were within the CA-SQG specifications.

Table 2

Mercury concentrations at the different sites relative to the guidelines established by the United States Environmental Protection Agency (US-EPA), Canadian Council of Ministers of the Environment-soil quality guidelines (CA-SQG) and the technical evaluation of the intervention values for soil/sediment and groundwater (NL-RIVM).

Guideline or standard	Standard (mg kg ⁻¹)	Depth (m)	Case ^b	N° Sites	Site code	
US-EPA	23	0	a	15	All	
		2	a	15	All	
		Tot	a	15	All	
CA-SQG	6.6	0	a	9	0, 1, 3, 6, 8, 9, 10, 12, 13	
			b	4	5, 7, 11, 14	
			c	2	2, 4	
		2	a	9	0, 1, 6, 8, 9, 10, 12, 13, 14	
			b	4	4, 5, 7, 11	
			c	1	2	
		Tot	a	9	0, 1, 2, 6, 8, 9, 12, 13, 14	
			b	5	4, 5, 7, 10, 11	
			c	1	2	
NL-RIVM	Target value 0.3 ^a	0	b	4	0, 3, 6, 12	
			c	11	1, 2, 4, 5, 7, 8, 9, 10, 11, 13, 14	
			b	2	6, 9	
		2	c	12	0, 1, 2, 4, 5, 7, 8, 10, 11, 12, 13, 14	
			Tot	b	5	0, 3, 6, 9, 12
			c	10	1, 2, 4, 5, 7, 8, 10, 11, 13, 14	
	Intervention value 10 ^a	0	a	11	0, 1, 3, 5, 6, 8, 9, 10, 12, 13, 14	
			b	3	4, 7, 11	
			c	1	2	
		2	a	11	0, 1, 6, 7, 8, 9, 10, 11, 12, 13, 14	
			b	2	4, 5	
			c	1	2	
Tot	a	10	0, 1, 3, 6, 8, 9, 10, 12, 13, 14			
	b	4	4, 5, 7, 11			
	c	1	2			

^a Reference values for standard soil the target value and intervention value are calculated according to Eq. (5).

^b See Fig. 4.

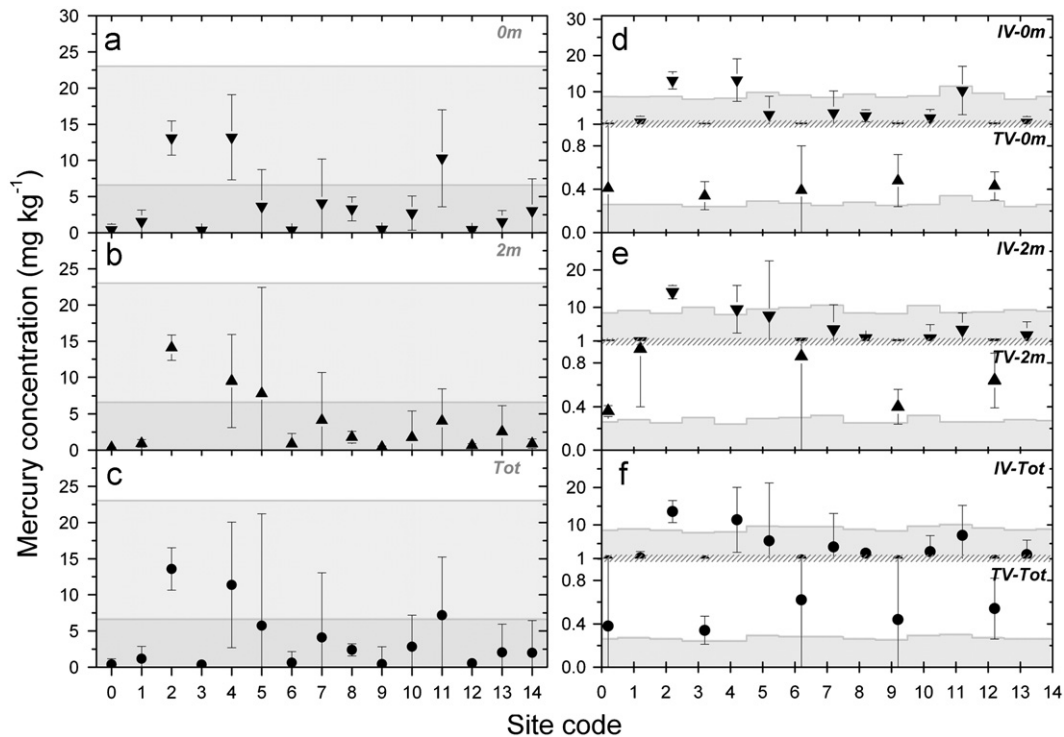


Fig. 5. Compliance of the results with the mercury concentration standards. A comparison of guidelines from the United States Environmental Protection Agency (US-EPA, 23 mg kg^{-1}) (for clear-colored lead), the Canadian Council of Ministers of the Environment-soil quality guidelines (CA-SQG, 6.6 mg kg^{-1}) (for dark-colored lead) and the sample Hg concentrations (a) at the surface, (b) at 2 m, and (c) for an average of both depths. Comparison between the intervention values (IV) and the target value (TV) of the Netherland guidelines (NL-RIVM). The IV and TV, which were calculated based on Eq. (5), are shown as gray bars (d) for the surface, (e) a depth of 2 m, and (f) for the average of both depths.

Table 2 shows the evaluation results that were obtained from the NL-RIVM guidelines. The limit values are calculated according to Eq. (5) and have an associated tolerance, even when they are subjected to the uncertainty spread.

This analysis, which uses Table 2 and Fig. 5d–f, demonstrated that sites 0, 3, and 6 are potentially below or above the control limit. All of the other sites were above the TV when the uncertainty was taken into account. In addition, no site was potentially below the TV specifications. Thus, careful consideration is required when evaluating the risks and when determining if any action must be taken. In addition, we found that sites 4, 5, 7, and 11 were potentially above the IV. Site 2 was clearly above the control limit, which is in keeping with the CA-SQG analysis guidelines and requires immediate action according to the NL-RIVM guidelines.

The mean Hg concentrations in this study were lower than those previously reported for other small- and medium-scale mining sites around the world, including Brazil, the Philippines, and Indonesia.

4. Conclusions

This study demonstrated that a certain degree of Hg contamination occurs in the trailing piles that are located in the urban areas of Andacollo city. Therefore, we have concluded the following:

The data analysis confirmed a high Hg contamination level in one of the fourteen study sites. This site had a Hg concentration of $13.6 \pm 1.4 \text{ mg kg}^{-1}$, which was above the Canadian Council of Ministers of the Environment's soil quality (CA-SQG) and Dutch guidelines (NL-RIVM).

Sites 4, 5, 7, and 11 were at the control and tolerance limits of the Canadian Council of Ministers of the Environment's soil quality (CA-SQG) and the Dutch guidelines (NL-RIVM). Therefore, these sites are potentially below or above the control limit. Thus, better characterization of these sites is required to establish whether they represent a health risk.

According to the recommendations established by the US-EPA, which have a higher control limit, none of the sites represented a health risk.

This study is important because it developed an integrative and efficient methodology for identifying and evaluating the Hg distribution within an urban environment.

In general, better Hg characterization of currently contaminated sites is required to prevent environmental effects from the release of Hg into the ecosystem. Thus, intensive studies of different environmental components are required to establish environmental Hg concentrations and to evaluate any potential health, economic, and human impacts. Scientific information is needed to design appropriate corrective measures for any areas that are affected by Hg.

It is important to emphasize that Hg and other heavy metals (such as arsenic and lead in concentrations of up to 49 and 89 mg kg^{-1} , respectively) were found. Therefore, further analyses should include other heavy metals, whose toxicities are just as important as Hg.

Plans for the bioremediation and confinement of these sites in Andacollo already exist. However, operational and legal problems, such as owner acceptance, still exist. These problems are associated with remediation and tailing removal because a number of these sites are still valuable sources of copper and gold.

Another aspect to consider in the regulatory framework is the competition between different government institutions and how these institutions can help coordinate efforts to develop solutions.

Therefore, any actions taken toward resolving the tailing contamination found in urban Andacollo should focus on innovation and on using low-pollution technologies. Thus, it is necessary to demonstrate the profitability of such techniques to expand education programs and training programs for small scale mines, to create micro-financing programs, to allocate community resources, and to develop programs that monitor and follow up on the waste deposits.

Finally, for these types of health risk studies on abandoned mine sites, the environmental authorities have developed plans and policies to obtain both scientific and technical information regarding the potential health risks that are associated with these abandoned mining sites. This type of monitoring allows for adequate decision-making. However, resources are still required to execute this task systematically and periodically, and a systematic approach will minimize information loss and maximize available resources.

Acknowledgments

The financial support of the Chilean Ministry of the Environment (Ministerio del Medio Ambiente, MMA) is gratefully acknowledged. This research was conducted under the Ministerio del Medio Ambiente—Centro Nacional del Medio Ambiente 2008–2010 and Centro de Ciencias Ambientales—Centro Nacional del Medio Ambiente agreements. The authors thank the anonymous EES journal referees for their useful comments regarding a previous draft.

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