Analysis of the impact of the March 2015 flood on the tailings deposits in the *Copiapo* valley

María Francisca Falcón Hernández[1], Leandro Herrera[1] and Stephen Edwards[2]

1. *Tailings Department; SERNAGEOMIN; Chile*
2. *UCL Hazard Centre, University College London, England, U.K.*

ABSTRACT

The March 25th, 2015 flood geochemical environmental impact, was studied and analysed to look into the impact of the Tailings Impoundments during the event, in the Copiapo basin. SERNAGEOMIN had a geochemical record of sediments, prior to the flood. As the SERNAGEOMIN went to assist the population during the emergency, a new sampling programs was launched, to study the same points as the previous study. The quantitative comparison against a base line was therefore available, an uncommon result in Chile, where baselines do not abound. In addition, the tailings Department had determined the geochemical composition of the tailings basins surface, the dams and the downstream soils of most of the tailings deposits. A methodology was devised to determine if the contents of a tailings deposit, had significantly contributed materials to downstream, nearby soils or sediments. The study concluded that the flood had actually improved the quality of the sediments in several points of the baseline, due to either a washing effect, or to erosion and / or to change of the old soils –soils that were the result of mining contributions during an extensive historical period- by materials with a lower content of pollutants, contributed by the alluvium. In addition, the geochemical comparison of soils against basins and dams, showed that, contrary to the common belief, the tailings deposits of the Copiapo basin did not contribute to the debris in the sediments observed after the flood. The revision of satellite images support these very same conclusions.

INTRODUCTION

On March 25, 2015, Chile's Atacama Region III, suffered a flood which strongly affected the towns of *Copiapo*, *Paipote*, *Tierra Amarilla* and *Chañaral* (see Figure 1, for the case of *Copiapo*)

Chile is, and has been, a mining country, and specifically the *Copiapo* region has historically focused its economic development on the mining of various metals (silver, gold, copper, etc.). The documentary evidence shows, for example, that when the Spanish *Conquistadores* arrived, they found gold and copper mining already installed in the *Copiapo* sector; the historian Sagayo (1894) states that: "General Hernando de Aguirre was the first miner of *Copiapo* and its first *trapichero* (stone minerals grinder operator)"; that is, it was around the 1550s.

[1] **Corresponding autor**: Jefa Departamento de Depósito de Relaves; Servicio Nacional de Geología y Minería; Santa Lucía 360; Santiago, Chile; francisca.falcon@sernageomin.cl

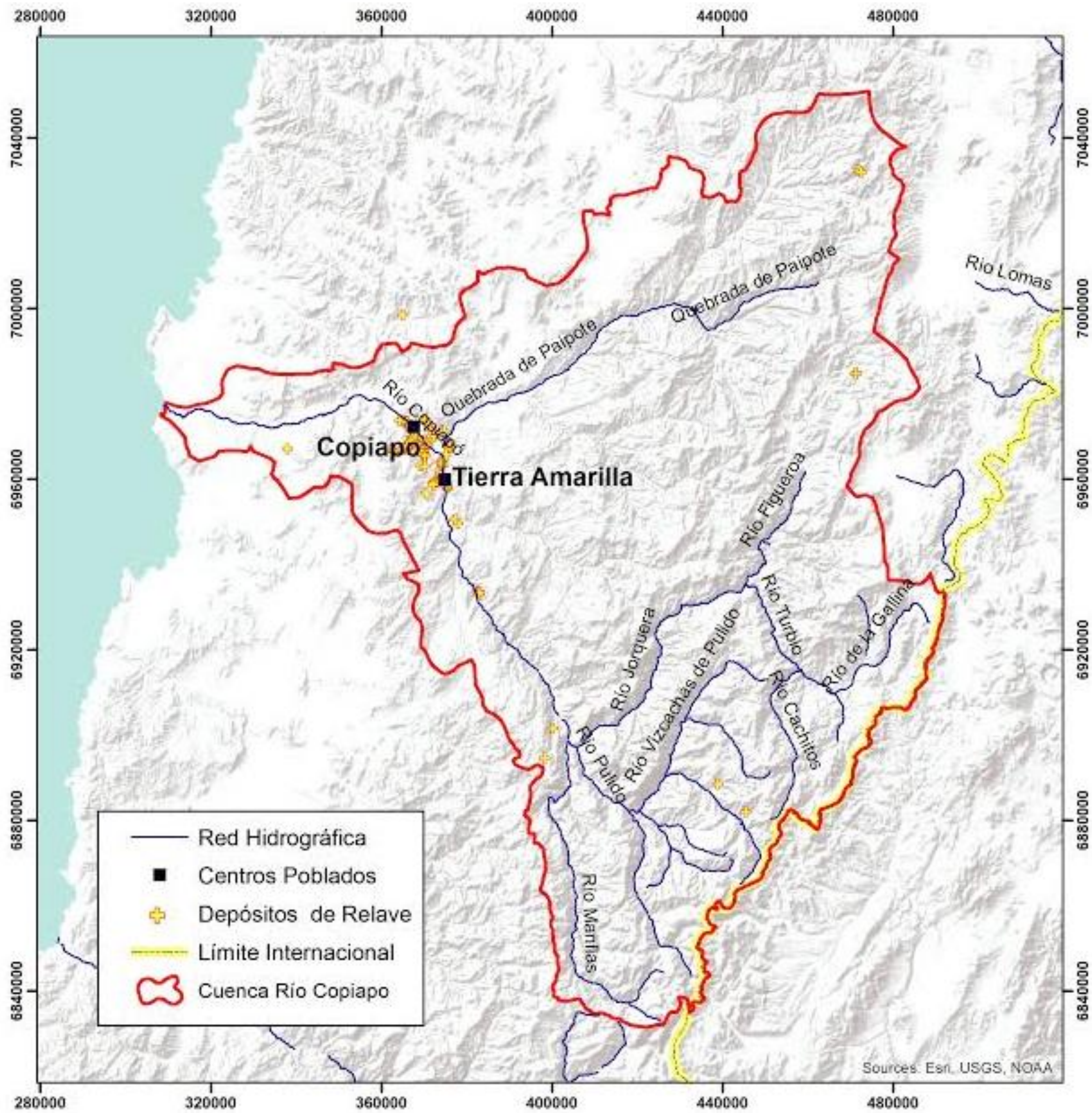

Figure 1: Copiapo region map, indicating the flood affected area.

The historical development of these early mining activities, resulted in the abandonment of wastes (as well as whole mining operations), in conditions far short of the technological solutions that we know today. A modern tailings deposit is the best environmental impact control and containment technique that we know. In ancient times, the spent minerals were abandoned anywhere, without much concern for chemical reactivity and many of these wastes are still piled up along the Copiapo Valley.

The citizens felt concerned about two risks: firstly, the physical instability (dam breaking) and; secondly, the chemical instability, where fine solids with high concentration of toxic metals might have over flowed or spilled from the basin of the deposits, into adjacent soil, where they would invade and intoxicate biomass (vegetables, animals, fish, people) and water (irrigation water, sources of drinking water). Concerns were important enough and the National Institute of Human Rights had a mission to receive all complaints from the citizens at the Valley, and compiled their important "Report of the Observation Mission to the Communes of Copiapo, *Tierra Amarilla* and *Chañaral*; 8 to 12 July 2015" (INDH, 2015).

The reported concerns of the citizens of Copiapo were related to chemical emergencies (overturned sulphuric acid trucks, for example) and their perception that the sediment carried into the populated areas consisted of tailings from collapsed deposits, rather than rain. The work presented here was inspired by that report and it might, hopefully, provide useful data to help to answer their concerns.

The flood was surprising, as it occurred in the driest desert in the world. Wilcox et al. (2016) estimated a flow of some 1000 m^3/s on the *Salado* River, leaving some 4.5 m depth sludge in *Chañaral* city.

Of the 696 tailings deposits in Chile, 368 of them are in this region (*Atacama* Region), making it the highest in deposits density. The Copiapo valley (as shown in figure 1) correspond to the Copiapo Province, which houses 114 deposits, of which 23 are active, 84 are not active and 7 are abandoned. While the active deposits are regulated by the rules in force (those that began operation after 2007, under the rule of DS 248/2007; and those built from 1970 to 2006, regulated by DS 86/1970), the vast majority of the tailings deposited in the Valley began their operation prior to 1970, under no explicit rules, further tan good engineering practices at the time. These old deposits were stablished without legal permissions, so there is no record of its activities. On the other hand, most of these contain small amounts of tailings, as compared to a modern tailings deposit.

Before the 1970s, as tailings management did not have to meet particular standards, it was common to even discharge them to the rivers that finally reached the ocean, generating some of the best known and most painful environmental impacts. Since pre-1970 mining did not require specific regulations or permits, the tailings generated did not need to meet requirements vis-à-vis the State and constitute, in good faith, an environmental liability that must be resolved with new laws, rules and / or regulations yet to come. To this date, only one operation remains, from times prior to 1970s that discharges to the ocean, instead of properly depositing tailings in a regulated installation.

Thus, in the affected sector, there are several small damping of mining waste material that did not meet any standard, many of them historically originated by small-scale mining activities, during the last centuries.

This type of historical Chilean accumulation of mining wastes is not particularly original; on the contrary, it is fairly common in Latin American countries that have based part of their economic development on mining since past times, as for example in Colombia (Güiza, 2013) or Ecuador (Peña-Carpio), tailings that have become a centre of concern and attention of citizenship that is more aware of the necessary care of the ecosystems of their countries.

SERNAGEOMIN had information in three sources. First, Carrasco *et al.* (2015) showed that they had characterised the sediment baseline along the Copiapo River prior to the 2015 flood and had taken samples at the exact same locations after the flood. Second, the National Register of tailings deposits

(SNGM 2015) gave information of the location of all known deposits and pilings of tailings in the affected valley. Third, the Geochemical Composition Register of tailings deposits in Chile (SNGM 2017) had geochemical information for the deposits in the Valley, in terms of 46 elements (Au, Ag, As , Ba, Be, Bi, Cd, Co, Ce, Cu, Ga, Hf, Hg; Mo, Nb, Ni, Pb, Rb, Sb, Sc, Se, Sn, Sr, Ta, Th, Tl, U, V, W, Y, Zn, Zr, La, Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu, in ppm) and 10 rock forming elements, expressed as major and minor oxides in mass percentage (SiO_2; Al_2O_3; Fe_2O_3; CaO; MgO; Na_2O; MnO; TiO_2; P_2O_5; and Cr_2O_3). The discussion on "contamination", however, focused on the 8 compounds of environmental concern (abbreviated ECC), made up of copper (Cu), arsenic (As), total chromium (Cr), cadmium (Cd), mercury Hg), lead (Pb), zinc (Zn) and nickel (Ni). The specific analytical methods were those used by the SERNAGEOMIN Laboratory, standardized and specified on its website.

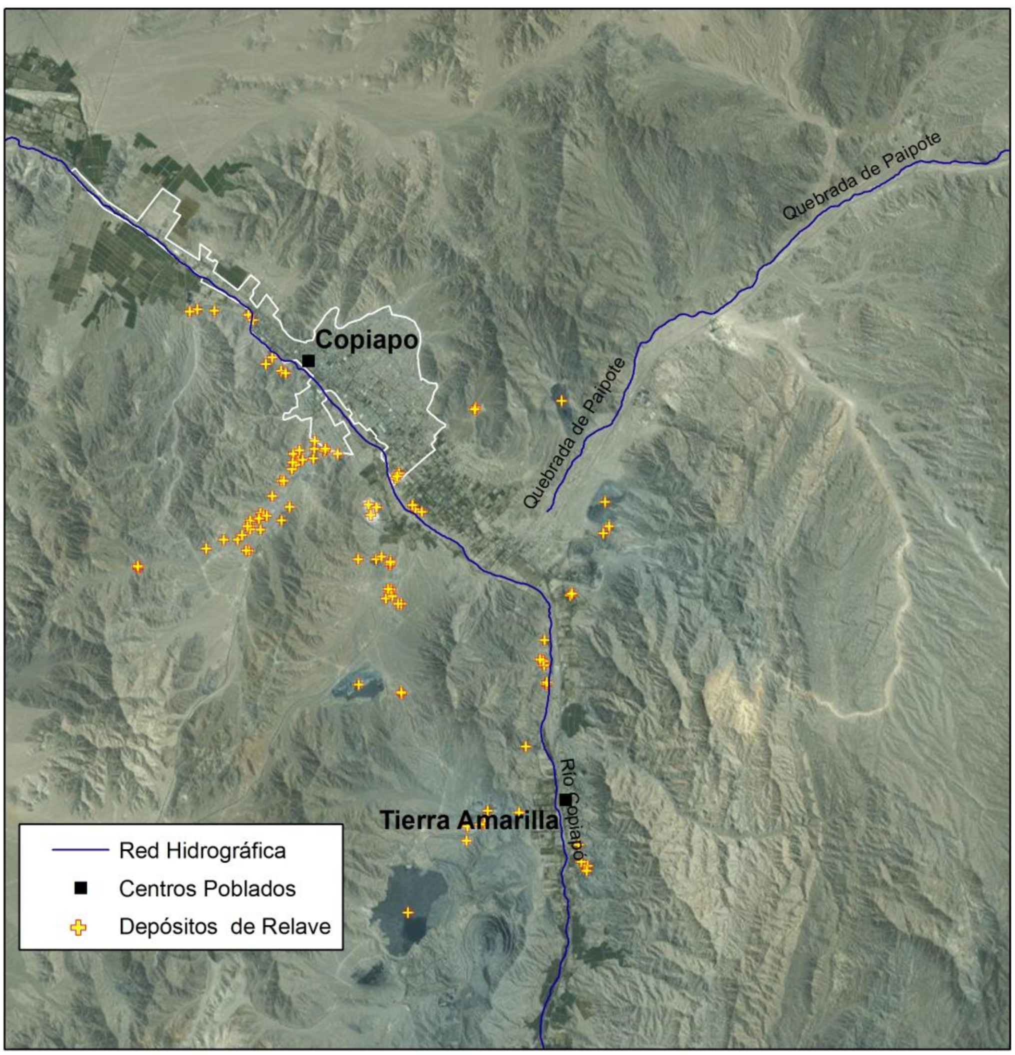

Figure 2: Tailings deposits near *Copiapo* city.

During the emergency, SERNAGEOMIN participated actively, generating abundant information for the authorities. Activities date since the second day of the flood, including overflight of active and inactive tailings deposits built since the 1970s (Falcón, M.F. April 2015, "Summary of Inspection to tailings deposits after Copiapo 2015 Flood" SERNAGEOMIN; Internal Report). The report concluded that in the days of the flood, all major deposits in the region (including *Embalse Pampa Austral, Tranque El Gato, ENAMI Planta Matta, Coemin, Tranque Las Cruces* and *Tranque Candelaria*) were not damaged in any way. Of the 101 deposits visited, 10 of them had minor damages, in which the alluviums dragged small parts the foot of the dam, and a case in which the deposit was partially buried. The 10 affected deposits were of small size, associated to smaller plants (*trapiches* i.e. stone wheel grinders); 4 are located in *Diego de Almagro* commune, along the course of the *Salado* River, 3 were non-active deposits and 1 was active. Of the remaining six, 3 are in *Tierra Amarilla* and are inactive, 1 abandoned in *Chañaral*, 1 abandoned in *Freirina* and 1 active in *Vallenar*.

The tailings deposits located in the environs of the city of Copiapo, which can be seen in Figure 2 (an enlargement of the city of Copiapo neighbourhood from figure 1), were feared to have failed during the first few hours of the flood, but appeared not affected at all.

This article examines the problem of the feared physical and chemical impact of the tailings deposits, after the flood of March 2015. This work aims to find methods to prove deposits stability after this type of events, which might become common

METHODOLOGY

Carrasco *et al.* (2015) analysed the geochemical composition at the same locations that had previously been characterized (pre-existing baseline), and compare them to extract a view of the impact of alluvium in the composition of the sediments along the Copiapo River.

A first method of analysis will be to compare the geochemical composition of the points for which alluvial data were available and in which samples were taken after the flood. This analysis was presented by SERNAGEOMIN in the aforementioned study by Carrasco *et al* (1975).

In order to analyse the possible contributions of materials contained in the tailings deposits, to the nearby ecosystem, an indicator of the relationships between compounds was built for both, the tailings deposits surface geochemistry and the sediments of soils adjacent to the deposit. The comparison of the ECC relations in each case should help to determine whether or not a sediment was caused by spillage or rupture of the dam of a nearby tailings deposit.

The specific values in the sediments can be compared with standards or guidelines of acceptable composition of soils for different intended use, to assist subsequent decision making of the national planning authorities.

Several studies have explored the issue of soil impact, according to its composition. The aim has been to formally define chemical concentration values that would allow the healthy development of humanity. Solids composition has been a source of concern since the 90s, as their particular composition can be the base of damage to ecosystems and human health. Several studies have explored this issue, aimed at defining values that would allow the healthy development of humanity, studies that led to the "*Probable Effect Concentration*" (PEC). Current PEC values, after years of intense work by various international regulators (USEPA, Canada, Europe, etc.), reached the consensus proposed in the work of McDonald et al (2000), presented in table 1, column 2.

It is also important to discuss the quality of soils for diverse intended use, specifying concentration values for agriculture, residential, commercial or industrial use. There is no such definition in Chile, therefore a Canadian guideline was used in this study (CCME 2007).

Table 1: For the Environmental Concern Compounds (ECC), Probable Effect Concentration values and for soil reuse criteria (mg/kg)

ECC	USEPA	Canadian guidelines			
item	PEC	Agriculture	Residential	Commercial	Industrial
Arsenic (inorganic)	33	12	12	12	12
Cadmium	4,98	1,4	10	22	22
Chrome	111	64	64	87	87
Copper	149	63	63	91	91
Lead	128	70	140	260	600
Mercury (inorganic)	1,06	6,6	6,6	24	50
Nickel	48,6	50	50	50	50
Selenium	N.A.	1	1	2,9	2,9
Uranium	N.A.	23	23	33	300
Vanadium	N.A.	130	130	130	130
Zinc	459	200	200	360	360

These criteria values were compared with geochemical composition of the sediments and of the tailings deposits in Copiapo.

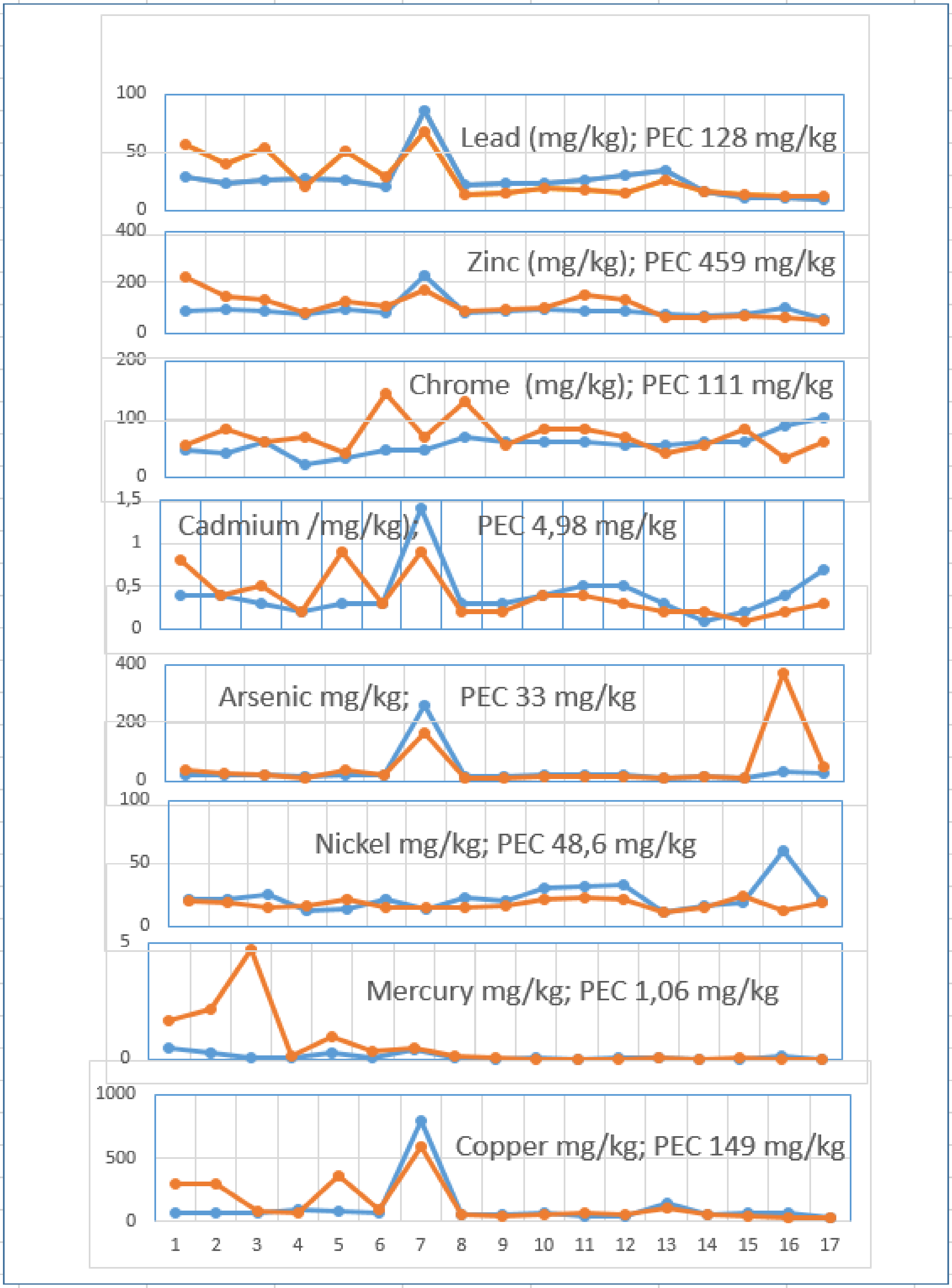

Figure 3 Environmental Concern Compounds Concentration (mg/kg) in sediments along Copiapo River, before (brown) and after (blue) the flood. PEC values are annotated by ECC.

RESULTS AND DISCUSSION

The data used for this study, already specified above, consists of measurements of compounds of environmental concern, extracted from the various sources available at SERNAGEOMIN.

As for the geochemical compositions observed in the 17 points that had baseline, it was observed that several compounds lowered their concentration, while some others increase it in certain points; this observation can be seen in the data of Figure 3.

The composition of the sediments in the Copiapo River has been a source of concern since the 90s, as their particularly high values can be the basis of the damage to ecosystems and human health. It is thought that biomass grown on these soils would incorporate toxics and be harmful to consumers along the food chain.

As for the eventual contribution of materials contained in the tailings deposits, to soils or sediments, a mass ratio index was first constructed for each ECC of the tailings deposits and the sediments, on average. The average values were calculated from Castillo et al. (2015).

Table 2 contains these average values (line 2), in addition to the averages of ECC readings in sediments before (line 3) and after (line 4) the alluvium. These values were used to calculate the ratio between concentrations in the tailings deposit basin, with respect to the values in the sediments; both before and after the flood.

Table 2: Average ECC concentrations in tailing deposits in the Copiapo Valley, along with values in sediments before and after the flood and calculated ratio.

	Cu ppm	Cr ppm	Ni ppm	Zn ppm	Pb ppm	As ppm	Cd ppm	Hg ppm
Tailings	2562,01	97,05	75,81	245	640,43	749,908	3,488	0,005
Sediments (Pre flood)	137,28	71,23	17,85	109,529	28,31	49,76	0,38	0,63
Sediments Post flood	108,94	57,55	23,44	91,23	26,24	33,92	0,41	0,12
	Tailings over sediment ratio							
PRE flood	18,7	1,4	4,2	2,2	22,6	15,1	9,2	0,008
POST flood	23,5	1,7	3,2	2,7	24,4	22,1	8,5	0,042

The highly variable relationship of the ratio values indicates that there is no similarity between compounds. Therefore, soils have a composition that seems independent of the composition of the tailings.

However, it is possible to argue that the average values of the geochemical composition of tailings is meaningless, as each deposit has a specific and particular bias, originated in the type of mining, the technology used and the origin of the mineral.

The same analysis was then applied on a case-by-case analysis, and generalized as a method to search for soil compositions that might have been the result of earlier tailings contamination, be it by overtopping or dam disruption during the alluvium.

The data from deposits was compared to data from sediments close to it, obtained from the current geochemical register, maintained by the Department (SNGM, 2017a). The method was to build ratios of each ECC in the tailings deposits surface (the basin surface) to the same value for the soil or sediment nearby. Table 4 shows the composition of: the basin surface (column 2); a first nearby site (column 3); a second nearby site (column 4); the composition of sediments after the flood (column 5), sampled at the exact same location as the sample prior to the flood (column 6). From this table, the comparison indices were built and can be seen in table 3, where each value was divided by the value at the basin surface. All these values correspond to the tailings deposit *Elisa de Bordos*, which was one of the main locations where contamination was thought to have happened.

Table 3: *Elisa de Bordos* tailings deposit data from Castillo et al. (2015)

	Basin surface	Site 1	Site 2	Post Flood	Before Flood
Cu (ppm)	3558	1717	1369	63	95
Cr (ppm)	14	21	41	48	144
Ni (ppm)	5	15	15	21	15
Zn (mg/kg)	445	506	374	81	106
Pb (mg/kg)	327	103	65	21	29
As (mg/kg)	144	168	113	19	19
Cd (mg/kg)	3,9	2,2	1,2	0,3	0,3
Hg (mg/kg)	8,21	11,03	9,14	0,03	0,35

Table 4: *Elisa de Bordos* tailings deposit composition dimensionless ratios, sites to tailings

	Basin surface	Site 1	Site 2	Post Flood	Before Flood
Cu	1	0,4826	0,3848	0,0177	0,0267
Cr	1	1,5000	2,9286	3,4286	10,2857
Ni	1	3,0000	3,0000	4,2000	3,0000
Zn	1	1,1371	0,8404	0,1820	0,2382
Pb	1	0,3150	0,1988	0,0642	0,0887
As	1	1,1667	0,7847	0,1319	0,1319
Cd	1	0,5641	0,3077	0,0769	0,0769
Hg	1	1,3435	1,1133	0,0037	0,0426

It can be seen that ratios vary significantly, whereby copper is diluted but nickel concentrated in the receiving sediments, at nearby sites. It is also noted that the flood diluted most of the compounds, but again, the tendency is not what it would be if sediments came from the tailings. This type of results occurred for all deposits examined in the area.

Finally. If there was an idea to install work or constructions on top of mine tailings, the Canada Guidelines criteria would clearly indicate that such a project would be forbidden, as shown in table 5, where the exceeded criteria have been painted orange. It is seen that more than one ECC is above the criteria; therefore, nothing can be built on this deposits (the same has been true for all examined deposits, with a couple of non-metal mines deposits).

	Cu ppm	Cr ppm	Ni ppm	Zn ppm	Pb ppm	As ppm	Cd ppm	Hg ppm
Cubeta	2562	97,05	75,81	245	640,43	749,91	3,49	0,005
USGS	149	111	48,6	459	128	33	4,98	1,06
Guía Canada suelo industrial	91	87	50	360	600	12	22	50

CONCLUSION

In general terms, the concentration of the environmental concern compounds used in this study decreased, in fluvial sediments along the Copiapo River. This conclusion is supported by the generally diminished concentrations before (base line) and after (new samples) the flood (figure 3). Thus, the flow of debris (flood) washed and/or replaced, in an important fraction, the contaminants that were historically present in the sediments. There are, also, points where such change was reversed (notably, the high valued sample point number 7 along the river).

In quantitative terms, the change in the sediments showed that after the flood, the average chemical composition evaluated at 10 control points decreased in chromium (-32%), copper (-42%), lead (-7%), zinc (-30%) and mercury (-83%), but increased in nickel (+ 37%) and arsenic (+ 9%). This effect is due to the already high concentration of metals in the Copiapo valley sediments and soils, directly related to the historical development of Copiapo, discussed in the introduction. The alluvium started high in the mountains and flowed downstream, washing metal containing solids from old, abandoned, tailings piles, which could sediment somewhere else, downstream. If the rain was heavy enough, most points would have been washed, but some horizontal lands might become more contaminated.

Figure 3 also contains the PEC value. These solids, in the soils wouldn't allow healthy ecosystems and humans, as for most sites at least one of the criteria (usually Zinc) was exceeded by measured data.

As for the reuse of these soils for industrial activities (the most permissive activity evaluated by the already quoted Canadian guidelines), in a few cases the sediments do not exceed the values, but it is clear that urban planning should look into each site in detail.

The tailings deposits, most definitively, could not be used for any activity. This means, in turn, that the Deposits do their job of containing materials which would, otherwise, render sites unusable for any activity, according to the guidelines adopted in this study. Simultaneously, this shows the need to properly isolate the deposits once finished their activity, to initiate their post closure life cycle.

The method devised to verify that tailings have been spilled on the soils, as stated before, was applied on a case by case analysis. The *Elisa de Bordos* case is summarized in tables 3 and 4. As seen, the ratio of each element in the soils and/or sediments nearby, vary by 1 order of magnitude for nearby soils and by 3 orders for the nearby sediments. Although there is not enough data points to certify the certainty of this conclusion, it strongly suggests that this deposit had not contributed to contamination of the sediments.

Although the concentration of ECC at contaminated sites need not be as high as in tailings, because water flow could have washed away or replaced sediments to some extent, it would expected that the mass ratio of ECC of sediments and tailings, at potentially affected or suspected sites should be similar to that stated for the original material, if the flow of water had washed all ECC to the same extent. Naturally, the flood was not pure water, but its composition should have been much diluted, compared to the tailings sludge, complicating this simple method of analysis. This comparison was made at various sediment measurement points, comparing them with the nearest tailings deposit upstream and no similarity was found. The mass ratios differed by 1 to 3 orders of magnitude. That is, not only the magnitude of the concentration values of species is much lower in the sediments than in the tailings deposited, but the relationships between compounds is dissimilar. This line of analysis can also be stated by saying that if there were a debris drag from the tailings deposit, it would be unlikely that some selectively dilution of compounds would be in place, so that the ratio between the affected soil and the tailings should be similar.

The argument may be questioned from various points of view, especially the unknown composition of the flooded materials, but all of them lead to conclude that the ratio should be maintained, at least in order of magnitude.

Mass balance studies have started, to fine tune a method to investigate whether soil composition might respond to tailings contamination. The problem in Copiapo is that the same metals found in tailings are already quite high is soils and sediments, making the method difficult to tune.

When the Elisa de Bordo data was compared with soils use criteria from the Canada Guidelines, it was clear that no activity should be allowed on top of it. Therefore, this serves to enhance the need for a proper closure of these deposits, for them to become isolated from the environment.

Similar studies were run across the whole data available (SNGM 2017a), comparing basin or dams composition to downstream soils. Results show that only in a few small deposits case, soils do have a similar composition ratio to the tailings, indicating earlier soil contamination from the tailings.

All evidence and data treatment seems to support a general conclusion: the tailings deposits designed, built and operated according to specifications (i.e. those built after 1970) have stand the floods, thus the deposits have accomplished their design purpose, which is to contain the materials deposited, even when subjected to serious events, such as the Copiapo 2015 alluvium.

REFERENCES

USEPA (2000) 'Prediction of sediment toxicity using consensus-based freshwater sediment quality guidelines' viewed 21st Jan 2017 https://www.cerc.usgs.gov/pubs/center/pdfdocs/91126.pdf

CCME (2007) 'Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health' viewed21st Jan 2017 http://ceqg-rcqe.ccme.ca/en/index.html#void

Güiza, L. (2013) 'La pequeña minería en Colombia: Una actividad no tan pequeña', *DYNA*, 181, 109-117.

Peña-Carpio, E. & Menéndez-Aguado, J. M. (2016) 'Environmental study of gold mining tailings in the Ponce Enriquez mining area (Ecuador)', *DYNA*, 195, 237-245.

MacDonald DD, Ingersoll CG, Berger T. (2000) 'Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems'. Arch Environ Contam Toxicol 39:20-31

Wilcox, A. C., C. Escauriaza, R. Agredano, E. Mignot, V. Zuazo, S. Otárola, L. Castro, J. Gironás, R. Cienfuegos, and L. Mao (2016) 'An integrated analysis of the March 2015 Atacama floods' Geophys. Res. Lett., 43, 8035–8043

Carrasco F., Lacassie J. P., Baeza L. Servicio Nacional de Geología y Minería (2015) 'Evaluación geoquímica del impacto de las inundaciones y aluviones de Marzo de 2015 en las zonas afectadas del Río Copiapo, II Región, Chile' (Report)

Sagayo, C.M (1874) 'Historia de Copiapo' p 292; viewed 24th August 2016, www.memoriachilena.cl/602/w3-article-9278.html

SNGM 2016, 'Atlas de Depósitos de Relaves de Chile' Sernageomin - Gobierno de Chile; viewed 2nd June 2016: http://relaves.sernageomin.cl/#/home

SNGM 2017a, Geochemical data from Tailings deposits in Chile, Sernageomin – Gobierno de Chile, 2nd January 2017: www.sernageomin.cl/pdf/mineria/relaves/Datos-GeoquimicaDepositosdeRelavesdeChile.xls

SNGM 2017b, Geochemical data description from Tailings deposits in Chile, Sernageomin – Gobierno de Chile, January 2017: www.sernageomin.cl/pdf/mineria/relaves/Geoquimica-de-Depositos-de-Relaves-de-Chile.pdf