Evaluation of soil intervention values in mine tailings in northern Chile

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The aim of this work is to show a methodological proposal for the analysis of soil intervention values in mine tailings in order to determine the intervention requirements in the commune of Andacollo in northern Chile. The purpose of this analysis is to guide the intervention policies of both private and public organizations. The evaluation method is based on the Dutch legislation. The usability of the proposed methods depends on the available geochemical data from soil samples, in particular, we tackle the case when information regarding clay percentage in the soil is not available. We use the concepts of a threshold factor and an adjusted threshold factor to calculate a weighted intervention ranking. In order to illustrate the utility of this methodological proposal, a case study is carried out with the prescribed approach. In particular, this work presents an analysis of the elements of environmental significance related to the mining activity (Hg, Cd, Pb, As, Cu, Ni, Zn, Cr) in the Commune of Andacollo, Coquimbo Region, Chile. The analyzed samples are used to determine where the intervention of tailing deposits is necessary and where a solution to these environmental liabilities is required as soon as possible. Out of the 81 samples evaluated, it was found that 18 require a potential intervention, and of these samples, 7 of them are associated with abandoned tailings that, in some cases, are located close to the town center itself, 1 sample is associated with active tailings and the other 10 with inactive tailings.

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33 **Abstract**

34 The aim of this work is to show a methodological proposal for the analysis of soil intervention

35 values in mine tailings in order to determine the intervention requirements in the commune of

36 Andacollo in northern Chile. The purpose of this analysis is to guide the intervention policies of

37 both private and public organizations. The evaluation method is based on the Dutch legislation.

38 The usability of the proposed methods depends on the available geochemical data from soil

39 samples, in particular, we tackle the case when information regarding clay percentage in the soil

40 is not available. We use the concepts of a threshold factor and an adjusted threshold factor to

41 calculate a weighted intervention ranking. In order to illustrate the utility of this methodological

42 proposal, a case study is carried out with the prescribed approach. In particular, this work presents

43 an analysis of the elements of environmental significance related to the mining activity (Hg, Cd,

44 Pb, As, Cu, Ni, Zn, Cr) in the Commune of Andacollo, Coquimbo Region, Chile. The analyzed

45 samples are used to determine where the intervention of tailing deposits is necessary and where a

46 solution to these environmental liabilities is required as soon as possible. Out of the 81 samples

47 evaluated, it was found that 18 require a potential intervention, and of these samples, 7 of them are

48 associated with abandoned tailings that, in some cases, are located close to the town center itself,

49 1 sample is associated with active tailings and the other 10 with inactive tailings.

51 1. Introduction

53 The Rio de Janeiro Summit of 1992 marked a historic milestone in the international commitment

54 to protecting the environment (Sequeiros, 1998). In this summit, the importance of soils was

55 recognized, as well as the need to protect them and their potential uses in the context of sustainable

56 development, in particular against the contamination caused by activities of anthropogenic origin.

57 This has led to the development of soil quality indicators with the purpose of preserving and

58 improving the productivity of soils (Doran & Parkin, 1996; Azapagic, 2014; Andrews et al., 2006;

59 Römbke et al., 2016; de Graaf et al., 2017; Turpin et al., 2017).

60 In Chile, as in many parts of the world, there is a great number of mining environmental liabilities,

61 mainly composed of tailings, which are potential risk sources for people and the environment. The

62 great number of tailings distributed throughout Chile, many of which are abandoned with no one

63 in charge of them, is a big problem for the State of Chile since the application of control measures

64 requires large amounts of money. Therefore, it is imperative to have an effective and economical

65 tool that allows determining whether a tailing requires intervention or not.

66

67 Mining is Chile's main economic activity and the fundamental pillar of its growth. Thanks to the

68 great geological diversity of its territory, large-scale deposits of different minerals can be found in

69 the country. In the case of copper, Chile has one of the largest reserves worldwide (Oyarzún &

70 Oyarzún, 2011), being the leading country in the production of this resource. The national

71 production of copper, which is concentrated mainly in the northern part of the country, reached

72 5,764,000 tons of fine copper in 2015 and is expected to grow at an annual rate of 1.19% by 2020

73 (COCHILCO, 2016).

74

75 An important point to consider is the strong increase in the production of copper concentrates that

76 is projected to rise by 32.1% within the next ten years, to the detriment of the production of

77 cathodes due to the depletion of oxidized resources and the lack of new hydrometallurgical projects

78 (Cifuentes, 2016). The strong growth of the production of concentrates, added to the low grades

79 of ores, has affected the generation of tailings from concentrator plants. For 10 years (2002-2011)

80 over 2,150 million tons of tailings have been produced that are generally not being treated. In

81 addition, the average generation of tailings by 2020 is projected to amount to more than 380 million

82 tons per year (Muñoz, 2017). Additionally, mining causes significant impact on the environment

83 such as air pollution associated with the movement of land in the case of open-pit mining and

84 emissions of toxic gases in smelters. Regarding water resources, this industry brings about their

85 depletion and pollution due to discharges of industrial liquid waste to superficial channels, or by

86 infiltration from tailings to underground layers. Also, ecosystems are affected by the mobilization

87 of leached metals from tailings deposits. In addition, there may be a potential archaeological

88 impact and an impact on the flora and fauna of the area.

89

90 Chile is a country that historically, besides copper, has focused on the mining of iron, gold, silver,

91 lithium, iodine and potassium, without giving space to the exploitation of new raw materials such

92 as cobalt, antimony, niobium and rare earth metals that have acquired increasingly important roles

93   in modern industry and whose future supply has become a concern for the industrialized countries

94   given the dominance of China in the market for these elements.

95

96   In the case of Chile, copper production schemes have considered the recovery of secondary

97   elements such as gold, silver, and molybdenum. However, the rest of the elements remain as part

98   of the waste, such as tailings, gravel or slag. On the other hand, there are the environmental

99   problems associated with mining tailings in Chile, totaling 696 deposits until 2016, of which 84%

100   correspond to non-active or abandoned tailings. Of the 584 non-active and abandoned tailings

101   deposits, 310 do not have an environmental rating resolution available for its project and 477 do

102   not have a closure plan because, due to their age, they have been closed and abandoned before the

103   change in regulations (SERNAGEOMIN, 2016). Added to the unknown state of regularization of

104   these tailings, an important growth of these deposits that would result in 81% more mass of tailings

105   is expected, according to the projections of COCHILCO (2016). This is explained by the growing

106   production of copper concentrates and the low-grade ores being exploited.

107

108   Despite the advances of the international community in this matter, Chile still has a pending debt

109   due to the lack of regulations for soil quality. This is particularly harmful to the population due to

110   the development of mining activities that bring about a series of negative impacts on the soil in

111   several regions of the country. These mining liabilities have been the result of a historical mining

112   that had very weak regulations regarding the closure stage. Fortunately, the Law 20,551 was

113   promulgated in 2012, which demands that all mining sites present a closure plan prior to starting

114   the mining project (SERNAGEOMIN, 2011; Neira, 2012).

115

116   In a mine site, the mineral of interest constitutes only a small fraction of the mined material (Wills

117   & Finch, 2015), because of this the mining process generates large volumes of waste, originating

118   a great amount of tailings and mine waste in general, which contain a high variety of heavy metals

119   and diversity of concentration levels (Burges et al., 2015; Pourret et al., 2016; Lam et al., 2016;

120   Lam et al., 2017). This renders many hectares of soil unsuitable for agriculture and generates

121   highly contaminated soils, in which substances will move depending on the physicochemical

122   properties of the substrate and on the climate conditions of the area in which the deposit is located

123 (Alloway., 2013; Chadwick et al., 2013; Li et al., 2014; Pandey et al., 2016; Antoniadis et al.,
124 2017).

125

126 Closing a mine using low technology and without having an adequate plan that would enable to
127 ensure the health and safety of the people and the environment brings about socio-environmental,
128 financial and economic liabilities, affecting mainly communities close to where the mining sites
129 are or have been, or where processes associated with extraction and processing of minerals are
130 carried out, including electric generation, mineral transportation, and waste disposal, among others
131 (González et al., 2014; Marnika et al., 2015; Ettler et al., 2016; Lechner et al., 2016; Schoenberger,
132 2016; Espinoza et al., 2017; García et al., 2017).

133

134 Abandoned and/or paralyzed mining sites that are distributed throughout the country constitute
135 potential sources of air, water and soil pollution; as well as potential harm to the population's
136 environment and health (Li et al., 2014; Diami et al., 2016; Mickus & Camacho, 2016; Pareja-
137 Carrera et al., 2014; Carkovic et al., 2016; Obiora et al., 2016; Antoniadis et al., 2017; Ghorbani
138 & Kuan, 2017; Christou et al., 2017; Espinoza & Morris, 2017; Unger, 2017). It is imperative to
139 face these issues, this requires identifying the potentially contaminated sites, the concentration,
140 and variability of contaminants present in them, and also identifying the potential "victims" of
141 these liabilities. In addition, it is necessary to consider the availability of technological and
142 financial resources to address this new challenge generated by a mining industry that did not have
143 the vision of a sustainable development, developing overexploitation and damage of resources,
144 applying poor management practices and inadequate technology (Oyarzún, & Oyarzún, 2011; Lam
145 et al., 2016; Christou et al., 2017; Espinoza & Morris, 2017; Unger, 2017).

146

147 The first regulations for estimating the degree of soil contamination were created in the
148 Netherlands (Boekhold, 2008). This legislation provides procedures and standards for the short-
149 term sanitation of contaminated soils. The law established limits depending on several factors: the
150 nature and concentration of the contaminants and the conditions of the place where the
151 contaminants are (e.g. soil characteristics).

152

153   In Chile, there have been several episodes of environmental impact on the marine environment
154   due to the presence of mine tailings deposits which hamper port activities, generate
155   geomorphological modifications on the coast and affect coastal ecosystems and recreational
156   activities (Castilla & Nealler, 1978; Castilla, 1983; Salamanca et al., 2004; Ramírez et al., 2005;
157   Besaury et al., 2013; Valladares et al., 2013; Dold, 2014; Contreras-Porcia et al., 2017; Monsalve
158   et al., 2017). It is necessary to give a solution to these liabilities as soon as possible, for they have
159   generated chronic problems for the population, posing an even more serious threat to future
160   generations.

161

162   Given the above, it would be very useful to have a tool that allowed evaluating whether a tailing
163   requires intervention or not. The aim of this study is to develop a methodology, based on the Dutch
164   regulations, that allows classifying the tailings according to their intervention requirements as: 1)
165   It does not require intervention 2) It requires intervention 3) Intervention is conditional on the
166   availability of more information.

167

168   The methodology developed can be applied by means of a graphical method, which is used in case
169   of having data on metal concentration and soil composition (in terms of its percentage of clay), or
170   through a method based on conditional and unconditional threshold values (intervention
171   thresholds) that only requires knowing the data of metal concentration in the soil. This allows
172   applying the method even in situations where all the information required is not available. The
173   methodology has been designed in such a way that future updates of the Dutch regulations are
174   easily applicable.

175

176   A methodology as the one presented here will allow estimating if it is necessary to apply an
177   intervention on the tailings found throughout Chile, as well as prioritizing those that require a more
178   urgent intervention. Having a tool as the one presented in this work is vital for all those sites where
179   there are tailings and the soil quality regulations are weak, or worse still, non-existent. It is
180   important to note that the Dutch legislation, thanks to its rigorous foundation, is applied in Chile
181   by the National Service of Geology and Mining, SERNAGEOMIN, as well as in other countries
182   (Milenkovic et al., 2005; Swartjes et al., 2012).

183

184 **2. Materials and methods**

185 **2.1 Methodological proposal**

186 The proposal is based on the Dutch legislation for the regulation of soil quality. In particular, this

187 law provides intervention values for different metals. The intervention values are threshold

188 concentrations above which it is considered that the soil presents a serious case of contamination.

189 Above the intervention values, the functionality of the soil for human, animal or plant life is

190 seriously affected or complicated. In particular, the 2013 revised version of the Dutch standard

191 (Dutch Soil Remediation Circular, 2013) will be used for the base values.

192

193 The selection of this regulation was based on the following aspects: 1) Dutch legislation provides

194 a mathematical formula that allows adapting its use depending on the nature of the soil; 2) It is one

195 of the most stringent regulations for the evaluation of soils (Macklin et al., 2003) and 3) The Dutch

196 standard has been used for almost 4 decades, which makes it one of the longest-running standards

197 in this field.

198

199 Although the standard presents some limitations, it has been widely used in the literature since its

200 creation and it allows evaluating and filtering out the sites that do not require intervention. Some

201 recent examples of the application can be found in the study of metal concentration in agricultural

202 soils (Kelepertzis, 2014), urban soils (Darko et al. 2017) and mine soils (Bempah & Ewusi, 2016).

203 It should be noted that these applications have been carried out in different countries with soils of

204 diverse characteristics.

205

206 In general, to evaluate the soil quality according to the Dutch guidelines, the standard intervention

207 values must be converted to values that correspond to the characteristics of the soil to be evaluated.

208 The intervention values are then compared with the concentration found in the soil. The

209 characterization of the soil is done by measuring the percentage of clay and the organic matter

210 present in the soil. The Soil Intervention Value (SIV) is calculated through the formula shown in

211 Equation 1 (Dutch Soil Remediation Circular, 2013).

212

213 $$SIV = SSIV \cdot \frac{A + B \cdot x_A + C \cdot x_M}{A + 25 \cdot B + 10 \cdot C}$$ (Eq. 1)

214   Where each term of the equation is defined as follows:

- SSIV corresponds to the Standard Soils Intervention Value. SSIV is a value defined for a soil with 10% organic matter and 25% clay for each element. Table 1 presents the values for each element.

- Constants A, B and C correspond to parameters based on the characteristics of each element. Table 1 presents the values of these constants for some relevant metals.

- The variable x_A corresponds to the percentage of clay in the substrate that is being evaluated, expressed as a number between 0 and 100. In case that the clay content is less than a 2% then x_A is assigned the value 2 (that is, the lowest value it can take is 2%).

- The variable x_M corresponds to the percentage of organic matter in the substrate that is being evaluated, expressed as a number between 0 and 100. In case that the content of organic matter is less than a 2% then x_M is assigned the value 2 (that is, the lowest value it can take is 2%).

227   In the methodology proposed, two assumptions are made:

1. It is assumed that the data have been previously gathered, that the mineral concentration in the soil is available and, optionally, the percentage of clay in the soil.
2. It is assumed that the tailings do not have organic matter, or its percentage is equal to or less than 2%.

232   In case that both the concentration of metal in the soil and the percentage of clay are available, a graphical method can be directly applied to evaluate the necessity of intervention in a soil. On the contrary, if the clay percentage is not available, the methodology proposed allows using conditional and unconditional intervention thresholds defined in this work to determine the intervention requirements and prioritize the sites.

237   On the other hand, it must be mentioned that the proposal in this work can be generalized, since, although the methodology proposed has been developed for soils containing mine tailings, a similar strategy could be applied for soils of similar characteristics or that accept assumptions of similar nature.

241 2.2 Intervention values and graphical method

242 The lowest value that each percentage x_A and x_M can be assigned is 2. In particular, the

243 composition of tailing deposits guarantees that the percentage of organic matter is negligible (i.e.

244 close to 0), thus, according to the conditions of the method, it is assumed that for all the soils

245 considered in this work $x_M = 2$.

246

247 Bearing in mind all previous observations, in this work a referential table of the intervention values

248 has been built. These are presented in Table 2. Soil intervention values (SIV) have been calculated

249 using the method provided by the Dutch guidelines under the supposition that the organic matter

250 percentage in a tailing is negligible ($\leq 2\%$). If the concentration in mg/kg exceeds the values

251 indicated in this table for the composition of a given soil, then the tailings deposit must be

252 intervened.

253

254 In case that the clay percentage in the soil is not found in Table 2, a linear interpolation can be

255 used to obtain the result. This will produce the correct result (because the base calculation model

256 is linear). In case the clay percentage is less than 2%, it must be assumed that it takes the value of

257 2% (in accordance with the Dutch guidelines), so it must not be extrapolated.

258

259 The results of Table 2 are graphically represented for Arsenic in Figure 1 as an example. The clay

260 percentage is on the abscissa axis and the concentration of the corresponding element in mg kg^{-1}

261 is on the ordinate axis. These graphs show the straight line determined by the formula of

262 intervention value for tailings (intervention threshold). Two zones can be observed in the graph:

263 the zone above the intervention threshold that indicates the necessity of intervention and the zone

264 below that represents the safe zone that does not require immediate intervention.

265

266 It should be noted that the intervention threshold is given by a line of positive slope, this suggests

267 that for a given a value of the element concentration, then all the clay percentages above a certain

268 threshold will not require an intervention (i.e. they will be in the safe zone). The threshold for this

269 can be found graphically by tracing a horizontal line at the given concentration and finding the

270 point where it intersects with the intervention threshold inside the 0 to 100 range of clay

271 percentage. However, it is important to note that for some values of the concentration there will

272   be no intersection, in fact, if the horizontal line lies above the intervention threshold line, then it is

273   always necessary to intervene. On the other hand, if the horizontal line is below the intervention

274   threshold line it will always be in the safe zone. These observations provide the motivation for the

275   definition of the Threshold Factor and Adjusted Threshold Factor in the next sections, which can

276   be seen as a simpler quantitative alternative to the graphical methods.

277

278 **2.3 Threshold factor**

279   This work defines the concept of Threshold Factor C_F, corresponding to the minimum percentage

280   of clay acceptable in function of the concentration of the element measured (according to the

281   parameters of the Dutch standard). If the real percentage of clay in the soil exceeds this value, then

282   the intervention of the soil will not be required. In case the clay percentage is lower than the

283   threshold factor then the soil will require intervention.

284

285   The threshold factor is obtained by setting $x_M = 2$ (because it is assumed that the organic matter

286   content is negligible) and solving the SIV equation for x_A. From this procedure, the following

287   equation is obtained:

288

289    $$C_F = \frac{SIV}{SSIV} \cdot \left(\frac{A + 25 \cdot B + 10 \cdot C}{B} \right) - \frac{(A + 2C)}{B}$$ (Eq. 2)

290

291   Note that although this formula can deliver values lower than 0 or higher than 100, these have no

292   sense physically. In fact, these values are utilized as limits to determine if the tailings deposit does

293   not require intervention or if the intervention is strictly necessary, regardless of the real percentage

294   of clay in the soil. The threshold factor C_F facilitates the analysis of the tailings deposits by the

295   considerations shown in Table 3.

296

297   Thus, it is recommended that samples are obtained to evaluate the clay percentage of the soils in

298   the tailings deposits that have a threshold factor between 0 and 100 (conditional intervention).

299

300

300 **2.4 Adjusted Threshold Factor**

302   It should be noted that the threshold factor in its original definition brings about problems of scale

303   when converting the results obtained with real values into a graph. In order to simplify the

304   graphical analysis of the results, the Adjusted Threshold Factor (AC_F) is proposed in Equation 3.

305   This minimizes the problems of scale and facilitates interpretation.

306

307    $AC_F = \text{sign}(C_F) \cdot \log\left(1 + \text{abs}(C_F)\right)$ (Eq. 3)

308

309   It should be noted that this is similar to a logarithmic scale, but it admits negative values. The

310   evaluation by means of AC_F is carried out as follows:

311   • If $AC_F \leq 0$ then it is not necessary to intervene (it corresponds to the cases where $C_F \leq 0$).

312   • If $AC_F \geq 2$ then it is necessary to intervene (it corresponds to the cases where $C_F \geq 100$). It

313   must be noted that $AC_F = 2.004$ when $C_F = 100$, but for practical purposes the difference

314   is negligible, and the analysis is much simpler in this way. These sites should have the

315   highest priority of intervention.

316   • If $0 < AC_F \leq 1$ it corresponds to the cases in which the unadjusted threshold factor is

317   between 0 and 10 approximately. In this case the need of intervention is unlikely, however

318   it is, still considered as a conditional intervention. These sites should not be prioritized

319   above the next ones.

320   • If $1 < AC_F < 2$ it corresponds to the cases in which the unadjusted threshold factor is

321   between 10 and 100 approximately. In this case, the need of intervention is already more

322   likely, and it is considered as a conditional intervention. These sites should have the next

323   highest priority after unconditional interventions.

324

325   These cases are summarized in Table 4 which can be seen as the adjusted version of Table 3.

326   Based on a similar reasoning to the Unlikely Conditional Intervention case, high values of the

327   adjusted conditional factor (i.e. close to 2) could probably be taken as sites with a high probability

328   of requiring an intervention, thus it would be recommendable to act as if for every site with an AC_F

329    $\geq 2 - \varepsilon$ for some small value $\varepsilon > 0$ was actually an unconditional intervention. Note that this last

330 recommendation is more of a heuristic to reduce the extra resources that would be needed to take
331 another sample to determine the real clay percentage. This is especially important if there are more
332 sites in a conditional intervention state than available resources for sampling. In light of this, the
333 value of ε should be chosen carefully.

334 **2.5.   Andacollo mine tailings in Chile**

335 According to the survey carried out in December 2016 by the National Service of Geology and
336 Mining (SERNAGEOMIN), in Chile there are 696 tailings deposits, catalogued as active (16,1 %),
337 inactive (62,6 %) and abandoned (21,3 %), distributed from the Tarapacá region up to the
338 Metropolitan region. (Tarapacá 1,00 %, Antofagasta 6,18 %, Atacama 22,27 %, Coquimbo 52,87
339 %, Valparaíso 10,49 %, Bernardo O`Higgins 2,59 %, Maule 0,43 %, Aysén 0,72 % and
340 Metropolitan region 3,45 %).

341

342 Of particular interest is the Coquimbo region for its great number of tailing deposits compared to
343 the other regions of the country. The Coquimbo region has been an almost continuous exploited
344 source of Cu, Au, and Hg in Chile for centuries. In spite of this, the communities living in this
345 zone are still underdeveloped and suffer from the extended contamination produced by the
346 inefficient treatment of mine tailings and wastes (Higueras et al. 2004). It must be noted that
347 bioremediation plans exist for the commune, however, there is a number of problems, such as a
348 lack of a regulatory legal framework and operational issues, which prevent their implementation
349 (Leiva & Morales, 2013).

350

351 This case study focuses on the Commune of Andacollo, in particular, the utilized data corresponds
352 to the geochemical characterization of tailings deposits carried out by SERNAGEOMIN in the
353 Commune of Andacollo in the Coquimbo Region, Chile. In particular, 81 samples have been
354 analyzed corresponding to 22 tailings deposits. There have been previous studies to assess the
355 contamination and risks in the commune of Andacollo, such as Higueras et al. 2004 where a
356 general environmental analysis was carried out, detecting significant contamination of the
357 surrounding landscape due to decades of inefficient treatment of waste-rock stockpiles and
358 flotation tailings.

359

360   The present work focuses on the elements considered critical for the environment, presenting the

361   analysis carried out to the following elements of environmental relevance related to mining

362   activity: Hg, Cd, Pb, As, Cu, Ni, Zn, Cr. Andacollo is located in the Coquimbo region of Chile and

363   is about 57 km to the southeast of La Serena. It is situated at latitude 30°12'00" south and longitude

364   71°05'00" east. It covers an area of about 310 km² and is bounded on the south by Ovalle, northeast

365   by the Commune of Vicuña, and southeast by the Commune of Río Hurtado and, west by the

366   Commune of Coquimbo, and north by the Commune of La Serena. It is also home to several

367   mining activities (Higueras et al., 2004).

368

369   To use the graphical method described in Section 2.2 it is necessary to have data about the

370   percentage of clay and the concentration of the element of interest. Using this information, the

371   sample must be located in the corresponding graph to see in which zone it lies. However, since

372   this method requires the value of clay percentage, it is not possible to apply it directly to the data

373   provided by SERNAGEOMIN. Thus, the threshold values approach is used for this data set. The

374   results obtained for the different elements studied are presented and discussed. Specifically, the

375   state of each tailing is analyzed based on the criterion defined by the threshold factor.

376

377   The results obtained for the different elements studied are presented and discussed. The samples

378   have been identified following the identification number of the tailing deposit and its origin that

379   can be from the tailings pond (TP), the sediments (S) or the wall (W). The concentration values

380   reported as lower than a certain number n (in mg/kg) were assigned the value n mg/kg to obtain

381   an estimate corresponding to the worst case. Subsequently, the same scheme is applied if the data

382   have that format. Specifically, the state of each tailing is analyzed based on the criterion defined

383   by the threshold factor.

384 **3. Results**

385

386 **3.1.   Arsenic**

387

388   The results obtained for each sample available in the SERNAGEOMIN data are summarized in

389   Table 5. It is noted that for most samples, arsenic levels are low enough to guarantee that

390   intervention is not necessary at the moment. On the other hand, there are four samples that suggest

391   an unconditional intervention, regardless of the percentage of clay in the soil, while there is only

392   one sample that indicates a conditional need of intervention in a tailings deposit. Only in the latter

393   case, it would be necessary to obtain the real value of the clay percentage of the soil. It must be

394   noted that the elements that are shown in pairs with similar values come from the same deposit,

395   but from different samples, due to which they exhibit a similar behavior. This same pattern is

396   repeated in the subsequent analyses.

397

398   In particular, the samples 191-W, 191-W-2, 190-TP, and 190-TP-2 require unconditional

399   intervention. These samples are associated with the ARIZONA 1 and ARIZONA 2 tailing deposits.

400   Sample 152-TP suggests that the deposit SANTA TERESITA 2 requires conditional intervention.

401

402 3.2.   Cadmium

403   The threshold factors obtained for each sample are shown in Figure 2. The results obtained for

404   each sample available in the SERNAGEOMIN data are summarized in Table 5. In this case, it

405   should be noted that none of the samples suggests an unconditional intervention. Nevertheless, a

406   considerable number of samples suggests a conditional intervention, due to which it is important

407   to determine the corresponding percentage of clay to evaluate the course of actions needed in those

408   deposits.

409

410 3.3.   Lead

411   The results obtained for each sample available in the SERNAGEOMIN data are summarized in

412   Table 5. In this case, there are four samples that indicate that a conditional intervention is required,

413   hence it is necessary to obtain the corresponding percentage of clay. Regarding the other cases, it

414   can be seen that the analysis of most samples indicates that the deposits do not require any

415   intervention.

416

417   In particular, the samples 191-W, 191-W-2, 190-TP, and 190-TP-2 require conditional

418   intervention. These samples are associated with the ARIZONA 1 and ARIZONA 2 tailing deposits,

419   the same deposits that required unconditional intervention for Arsenic.

420

421

422 3.4.   Nickel

423   The threshold factors obtained for each sample are shown in Figure 3. The results obtained for
424   each sample available in the SERNAGEOMIN data are summarized in Table 5. The particular
425   case of Nickel is different from the previous ones since none of the extreme values observed above
426   are present here. For this criterion, all the tailings are classified as requiring conditional
427   intervention, due to which it is necessary to determine the percentage of clay to decide whether
428   there should be intervention or not.

429

430 3.5.   Mercury

431   The threshold factors obtained for each sample are shown in Figure 4. The results obtained for
432   each sample available in the SERNAGEOMIN data are summarized in Table 5. Regarding the
433   results obtained for Mercury, it is necessary to note that a great majority is below intervention
434   values, due to which in the short term it is not necessary to carry out interventions on them.
435   Nevertheless, there is a sample that indicates the need for unconditional intervention
436   (corresponding to an abandoned deposit) and some that indicate conditional intervention with the
437   available data.

438

439 3.6.   Copper

440   The threshold factors obtained for each sample are shown in Figure 5. The results obtained for
441   each sample available in the SERNAGEOMIN data are summarized in Table 5. The analysis of
442   the data shows the necessity of intervention of the tailings deposits regarding copper concentration.
443   There is only one sample that indicates that intervention is not needed, and it corresponds to an
444   abandoned deposit, all the other cases require intervention to some degree, be it conditional or
445   unconditional.

446

447 3.7.   Zinc

448   The results obtained for each sample available in the SERNAGEOMIN data are summarized in
449   Table 5. In this case, there are no samples that suggest an unconditional intervention. There are
450   five samples that indicate that conditional intervention is required, which correspond mainly to
451   inactive deposits. The other samples correspond in its majority to deposits that do not require

452   intervention. Regarding the five that require conditional intervention, it is necessary to obtain the

453   real values of the percentage of clay to define whether intervention is needed.

454

455   In particular, the samples 191-W, 191-W-2, 190-TP, 190-TP-2, and 154-S require conditional

456   intervention. These samples are associated with the ARIZONA 1, ARIZONA 2 and SANTA

457   TERESITA 2 tailing deposits.

458

459 **3.8.   Chromium**

460   The threshold factors obtained for each sample are shown in Figure 6. The results obtained for

461   each sample available in the SERNAGEOMIN data are summarized in Table 5. For Chromium, it

462   can be observed that there are six samples of inactive deposits that indicate the necessity of

463   unconditional intervention. Most samples suggest only a conditional intervention, while the rest

464   would not require intervention in the short term.

465

466 **4. Discussion**

467

468   **4.1.   General evaluation**

469   Out of the 696 deposits surveyed by SERNAGEOMIN (2016), 368 are found in the Coquimbo

470   region, distributed in 13 communes, one of them being the commune of Andacollo, which

471   concentrates the highest number of tailing deposits in the region. According to the survey by

472   SERNAGEOMIN (2016), out of the 368 deposits in the region, 118 are found in the commune of

473   Andacollo, which are then classified according to their status as abandoned (35), active (8) and

474   inactive (75).

475

476   9 tailing deposits are found in urban areas in the commune of Andacollo, which were abandoned

477   in the 1950's. That is to say, they have coexisted with the population for 70 years, constituting a

478   potential risk for them and the environment. Given the high costs associated with the required

479   interventions, it is necessary to rank the tailings to intervene according to priority. The information

480   regarding the current tonnage of the tailings is scarce, however, the information available

481   corresponds to the tonnages of tailings authorized for each deposit, which fluctuate between

482   500,000 and 416,000,000 tons.

483

484 The deposits that constitute major problems correspond to those that are abandoned, since they do

485 not have a responsible organization or person to take charge of them, being the State of Chile the

486 one that must have the necessary resources to face this great challenge. The authorized values for

487 the abandoned tailings in the commune of Andacollo are between 500 and 227,850 tons.

488

489 Having carried out the corresponding analysis for each element, the summary of results obtained

490 for each tailings deposit status (Active, Inactive and Abandoned) is shown. Table 6 presents a

491 summary of the results obtained for each sample of the SERNAGEOMIN data for active and

492 inactive deposits. It should be noted that in almost all cases of active deposits it is necessary to

493 carry out an unconditional intervention in each deposit due to copper concentrations. If the

494 particular case of copper is not considered, conditional intervention is required in all tailings. It

495 should be noted that in almost all cases an unconditional intervention in the deposit is needed due

496 to copper concentrations, although in contrast to the previous case, there are also cases that show

497 a potentially problematic concentration of chromium or arsenic. At any rate, if the particular case

498 of copper is not considered, conditional intervention is required in all tailings.

499

500 Table 7 shows a summary of results obtained for each sample of the SERNAGEOMIN data for

501 abandoned deposits. It should be noted that in almost all cases it is necessary to carry out an

502 unconditional intervention in each deposit due to the high concentrations of copper. If the

503 particular case of copper which requires unconditional intervention in all tailings is not considered,

504 it can be observed that, although the reasons for conditional intervention might be different in each

505 case, the element nickel in all cases suggests a conditional intervention.

506

507 **4.2.   Weighted Intervention Ranking**

508

509 The results show that in the vast majority of the tailings it is necessary to carry out an intervention

510 due to the high concentration of copper. Although there is a great variability between the Adjusted

511 Threshold Factors for the different deposits, the fact that the vast majority of them are above the

512 unconditional intervention limit makes prioritization difficult, even if they were ordered by AC_F

513 results. Given this situation, copper concentration in each tailing and their respective Adjusted

514   Threshold Factor is not a good indicator to provide a prioritization to interventions, due to which

515   it is necessary to be guided by the results of the other elements in this case.

516

517   According to the above, it can be seen that for all the other elements analyzed (Cd, Pb, Zn, Cr, As,

518   Ni and Hg) a significant number of the evaluated sites are in the category of conditional

519   intervention or unconditional intervention. A simple alternative to prioritize the sites that require

520   an expeditious intervention is starting with the sites that have the highest number of elements that

521   require intervention (conditional or unconditional). Nevertheless, a method based on a linear

522   model of weighted costs according to the health and environmental risk represented by each

523   element is proposed.

524

525   For these reasons, this work proposes the use of a Weighted Intervention Ranking (WIR_j) of the

526   j-th site ($1 \leq j \leq m$, where m is the number of sites of the study) and is defined according to

527   Equation 4.

528    $$WIR_j = \sum_{i=1}^{n} w_i \cdot x_{ij} \qquad \text{(Eq. 4)}$$

529   Where n stands for the number of elements of interest in the analysis of the tailings (in the case of

530   this article $n = 8$), $1 \leq w_i \leq 5$ is an integer that represents the influence of the i-th element on the

531   WIR and x_{ij} corresponds to the Adjusted Threshold Factor for the i-th element in the j-th site of

532   interest.

533

534   The definition of the weights can be controlled by the user of the methodology, who can assign

535   different values to the weights according to environmental, economic and legal criteria. In Table

536   8 the weighting used in this work is shown. Note that the values can be modified according to the

537   needs of each analysis. Our values are based on the work of Adriano (2001), in particular, we use

538   the toxicity information for plants, animals, and humans through the following criteria: if a metal

539   is potentially toxic to plants, animals, and humans, it is given a weight of 3; if it is only toxic to

540   two of these three, then it is given a weight of 2; similarly, if it is only potentially toxic to one of

541   them, a score of 1 is given. Since it would not make sense to analyze the case of a zero-weight

542   metal in this study, the actual weights range from 1 to 3.

543

544   According to the values provided in Table 8, Weighted Intervention Rankings can be obtained.

545   The results obtained for the six sites with the highest Weighted Intervention Rankings are shown

546   in Table 9. The average *WIR* for all sites is -4.53, while the median is -5,71 and the standard

547   deviation is 7.53. The highest value of *WIR* is 19.88 and the lowest value is -16.28. Figure 7 shows

548   the distribution of the Weighted Intervention Rankings.

549

550   On the other hand, the difference between the fourth and the fifth sites of highest WIR in Table 9

551   should be noted. It should also be highlighted that the top four values are more than two standard

552   deviations above average. Considering the above, this point lends itself as a natural limit to define

553   a threshold regarding intervention priority, at least in a first stage.

554

555   Based on these results, it is estimated that the first priority of intervention corresponds to the

556   deposits ARIZONA 1 and ARIZONA 2, due to their high *WIR* value. In a subsequent stage,

557   SANTA TERESITA 2 and ARENILLAS 2 should be intervened. It is thus necessary to design an

558   intervention plan for these deposits. On the other hand, if we consider a value of zero WIR as the

559   cut-off for priority intervention, then 18 out of the 81 (22.22%) samples suggest requirements of

560   intervention according to this metric.

561

562   The proposed methodology was applied on 81 samples of available geochemical data (22 tailings

563   deposits), obtaining that 18 samples indicate a critical intervention requirement (with 10 coming

564   from inactive deposits, 1 from an active deposit and 7 from abandoned deposits). Of these samples,

565   11 come from tailings associated with Cu-Au extraction processes and 7 come from tailings

566   associated with Au extraction processes. Of the corresponding tailings, the one with greater

567   tonnage corresponds to "Punta Caletones 4", which is in a state of abandonment with an admitted

568   capacity of 227,850 tons.

569   Of course, the exact intervention plan and their feasibility depend on an analysis of environmental

570   impact and economic and legal aspects out of the scope of this work, since the aim of the

571   methodology is to indicate the sites that should be prioritized according to the defined criteria.

572   Having shown the calculation and application of the *WIR*, the exposition of the evaluation

573   methodology proposed in this work is concluded.

574

575   As a further analysis of our results, we perform a one-way ANOVA with the different deposit

576   states (Active, Inactive and Abandoned) as the main factor. Our null hypothesis is that the state of

577   the deposit has no influence on the WIR values, while our alternative hypothesis is that the state

578   of the deposit does have an effect on the WIR values. Our results indicate that there is a significant

579   difference between the value of the WIR depending on the state of the deposit (p-value = 0.005).

580   In particular, Tukey's test suggests that there are no significant differences between Active and

581   Abandoned deposits (p-value > 0.10), but Inactive deposits are different, showing a higher mean

582   WIR than Active (p-value = 0.045) and Abandoned deposits (p-value = 0.006).

583

584 **4.3.   Analysis of results**

585   Out of the abandoned tailings in the commune of Andacollo, 9 of them are located inside the urban

586   area, in daily coexistence with the population, constituting a potential risk to the health of people

587   (Morales, 2013). These are found in the open and can be destabilized both physically and

588   chemically, as a result of the interaction with external factors. For example, it is known that Chile

589   is a highly seismic country, which means that in the face of a large-scale earthquake, houses and

590   road structures could collapse and be wiped out, causing the death of people. This occurred in

591   Concepción (Chile) during the 2010 earthquake, as liquefied mine tailings hit a farmer's house,

592   burying people alive under the tailing mass (Verdugo et al., 2010).

593

594   On the other hand, the interaction of sulphide with air and rainfall generates acid mine drainage,

595   which tends to have a great impact on ecosystems, water resources and soils (Kefeni et al., 2017).

596   The lost spaces occupied by these tailings should also be taken into account because they cannot

597   be used for other activities such as agriculture, residential development, or others.

598

599   Since the tailings in Andacollo are located in the heart of the city, the handling of the toxic metal

600   for any type of intervention becomes very difficult and dangerous, so it requires a special

601   treatment. However, there are not many precedents on how to perform this task, since in general,

602   the tailings are in remote places of the communities.

603

604   The following two aspects must be taken into account when performing tailings intervention. On
605   the one hand, the potential environmental impact, which puts people and the environment at risk;
606   and on the other, an economic one, since current technology was not available when they were
607   exploited, it is possible that they contain high-grade ore according to current standards; this
608   represents a potential for the recovery of metals with a commercial interest.

609

610   When we speak of intervention, we refer to it as an action that avoids the direct contact of the
611   tailings with people, with water systems (surface and groundwater) or with ecosystems. The main
612   objective of the measures is to stabilize the tailings, both physically and chemically, in order to
613   protect the health and safety of people and the environment.

614

615   Finally, it is important to point out that although the methodology applied allows ranking the
616   tailings of Andacollo, this would be the first phase in the tailings' assessment, which would allow
617   assigning intervention priorities. The results should be corroborated with a risk assessment, which
618   should consider the size of the tailings, the proximity to potentially impacted receptors (human
619   and ecological receptors) and any other factor considered important.

620

621   According to the obtained results, of the 81 samples evaluated, it was found that 18 require a
622   potential intervention, of these samples 7 are associated to abandoned tailings, 1 to active tailings
623   and 10 to inactive tailings. While the assets and liabilities belong to the responsible companies that
624   according to the new Chilean legislation (Law 20,551 on mine closure plans) must take charge of
625   them, ensuring physical and chemical stability in perpetuity, this does not occur with abandoned
626   tailings, on which it is urgent to carry out a more thorough study that allows prioritizing the
627   intervention requirements. The accepted tonnages of the critical abandoned tailings found in this
628   work fluctuate between 5,872 and 227,850 tons. For the purposes of a subsequent study, these data
629   are of great importance, either to solve the problem with compounds of environmental connotation
630   or to recover metals of commercial interest.

631

632   In an international context, this work complements the Dutch regulations, exhaustively detailing
633   the definition and application of the method. In addition, an example of its application is given in
634   an area considered critical in the Chilean national environment. The latter is especially important

635   because Chile does not have specialized regulations and the availability of experimental data is

636   deficient, so this methodology is highly appropriate for this context. Given the above, this proposal

637   could be applied in countries with similar conditions, that is, countries that do not have specialized

638   national regulations or high availability of the required data.

639

640   At a global level, there are many tailings that are abandoned, many of these are historical tailings

641   and therefore there is a lack of information regarding their characterization. Since some of these

642   tailings might occupy high volumes in addition to their high heterogeneity, their characterization

643   involves high costs and could require extensive financing. Furthermore, given their age, no

644   organization or person can be held responsible for them, as occurs with the abandoned tailings in

645   Chile. Thus, it is the state that must take charge of the situation, but this requires adequate

646   financing. The high costs render the amount of interventions required unfeasible, so it is highly

647   necessary to have a cost-effective tool to rank these tailings, which in turn will lead to

648   prioritization. Based on this, characterizations can be made with an appropriate sampling design,

649   in order to perform the corresponding risk assessment.

650

651   **5. Conclusions**

652

653   This article has exposed a detailed methodology to analyze the requirements of soil intervention.

654   This methodology is based on the stringent and thoroughly tested Dutch regulation for soil

655   remediation (2013 version). The main contribution of this work is the definition of the conditional

656   and unconditional intervention thresholds and the simple graphical method. A case study in the

657   Commune of Andacollo in Chile has been detailed, the methodology has been applied successfully,

658   revealing several sites that require both unconditional and conditional intervention.

659

660   For the threshold values used by this methodology, the classic intervention value formula provided

661   by the Dutch normative has been modified and adapted to provide a simpler calculation approach

662   for mine tailings, where it can safely be assumed that organic matter is negligible. This approach

663   can be adapted to other kinds of soil provided that a similar assumption can be made about their

664   characterization. In particular, the values and formulas provided in this article can be applied to

665   any soil where organic matter can be assumed to be insignificant. Finally, the results obtained in

666 the case study indicate the necessity of intervention of the tailings. Unconditional interventions
667 being more severe and requiring a more immediate attention. On the other hand, conditional
668 intervention might not be necessary depending on the clay percentage of the soil. Thus, for these
669 tailings, a more detailed analysis is required.

670

671 One of the potential limitations of the proposed methodology and the performed analysis is that
672 the Andacollo background soil values have not been explicitly considered. Adding this information
673 could improve the accuracy of the results. On the other hand, in the case of samples associated
674 with a conditional intervention, it would also be necessary to have the clay percentage in order to
675 obtain a more accurate estimate. However, in the case of unconditional intervention, the
676 methodology would not need this information. Nevertheless, as an initial estimate of the potential
677 environmental risk of these tailings, the methodology delivers appropriate results.

678

679 If the deposit concentration delivers an Adjusted Threshold Value greater than zero and lower than
680 the threshold value for unconditional intervention, then it could be considered as slightly
681 contaminated (requiring conditional intervention). If it exceeds the threshold value, it will be
682 necessary to proceed with an intervention strategy. However, this intervention must be carried out
683 case by case, in particular, this analysis must consider all the metals present in the deposit, and this
684 is why the calculation of the WIR is important since it allows assigning weights to the importance
685 of each element with respect to its associated risks. The results obtained with this methodology are
686 only the first step to guide the study. The final decision on an intervention, if it is required, will
687 depend on the evaluation of the risks and environmental conditions of the site.

688

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Figure 1

Graphs of intervention regions for Arsenic source: own elaboration).

Each graph represents the intervention zones according to the parameters of each element.

The separating line corresponds with the intervention threshold.

Intervention Zones for As

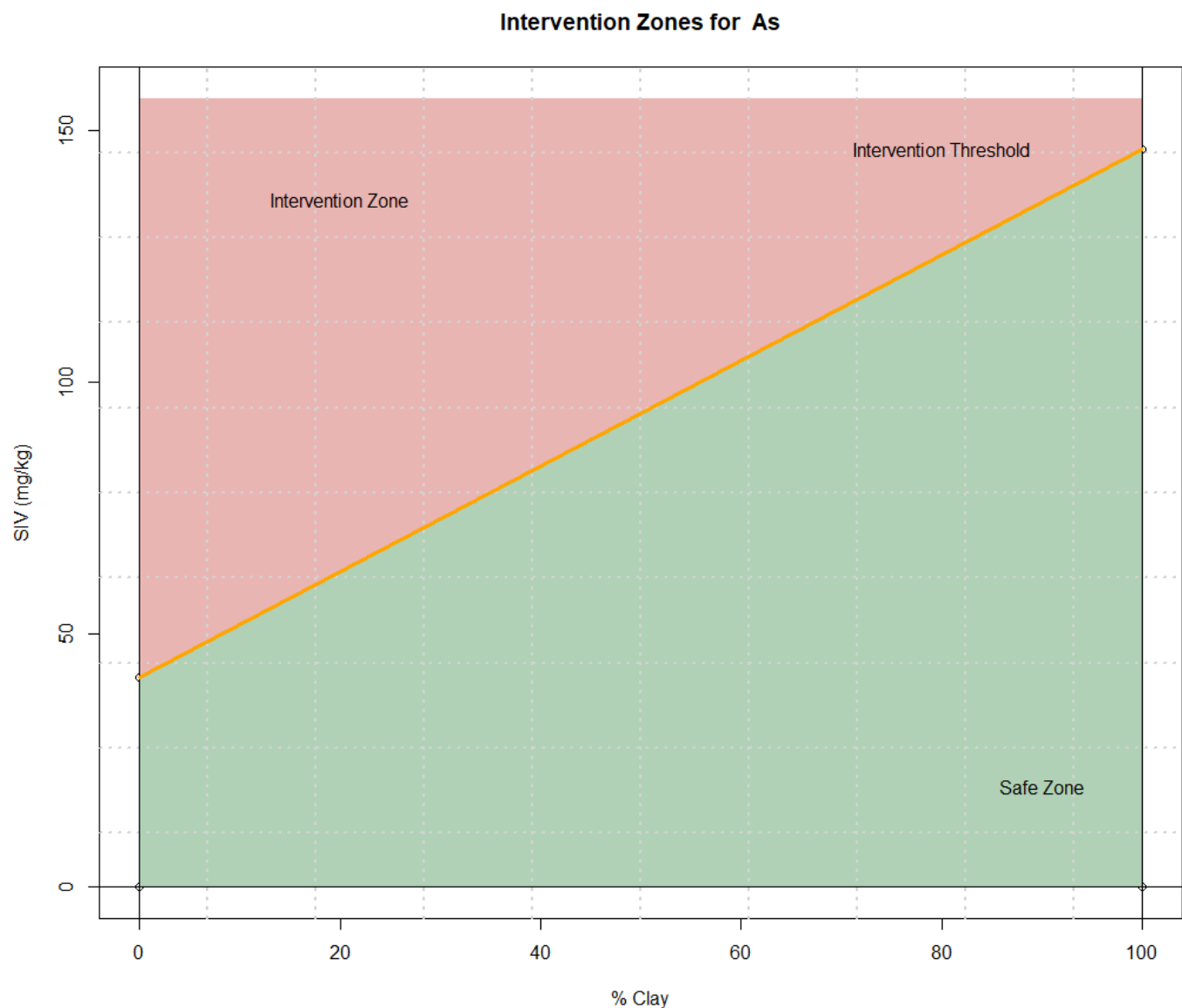



Figure 2

Adjusted threshold factor for Cadmium.

Each data point indicates the value of the Adjusted Threshold Factor of a tailing sample for Cadmium. The red line indicates the unconditional intervention threshold and the green line indicates the conditional intervention threshold. The data points between these lines are considered for a Conditional Intervention, while the points above the red line are considered for an Unconditional Intervention.

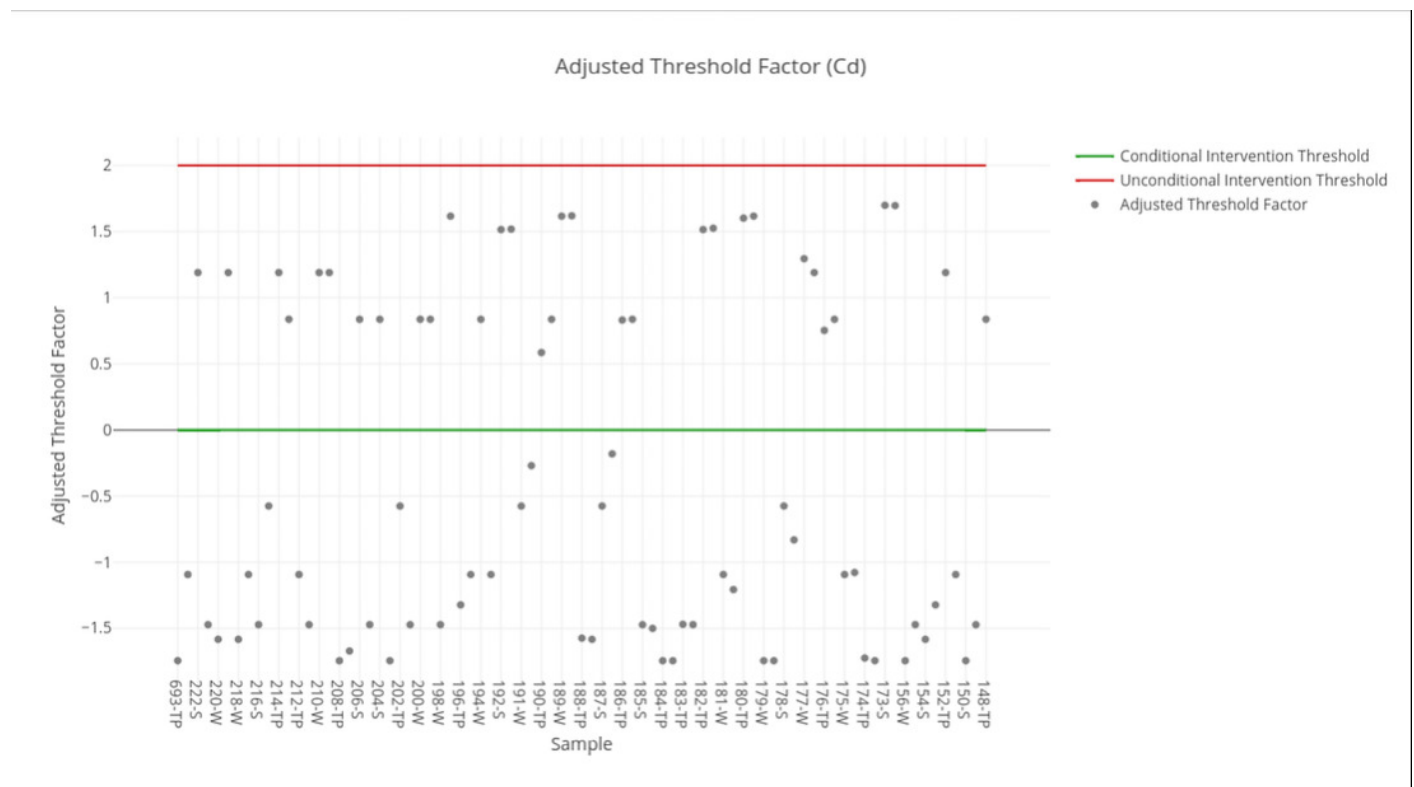



Figure 3

Adjusted threshold factor for Nickel.

Each data point indicates the value of the Adjusted Threshold Factor of a tailing sample for Nickel. The red line indicates the unconditional intervention threshold and the green line indicates the conditional intervention threshold. The data points between these lines are considered for a Conditional Intervention, while the points above the red line are considered for an Unconditional Intervention.

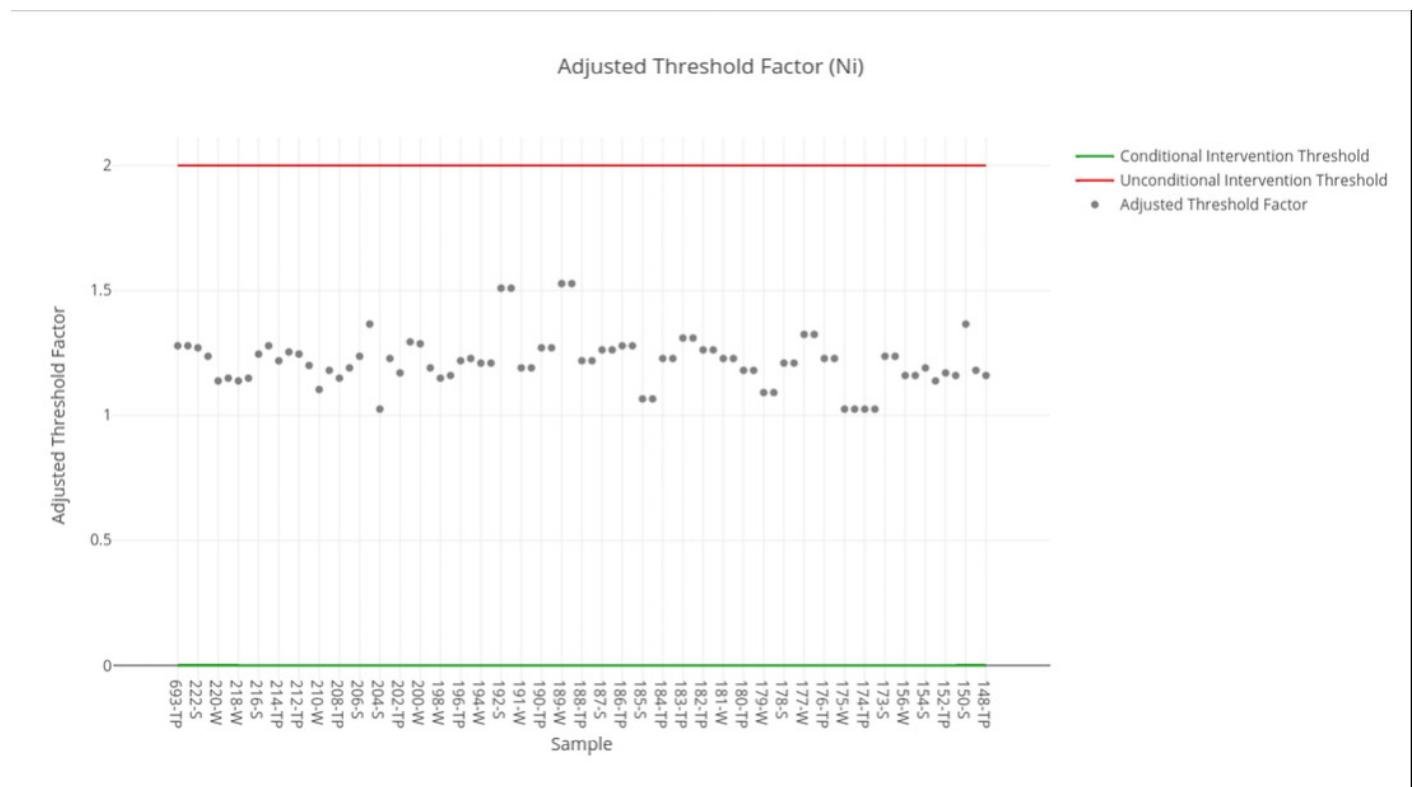



Figure 4

Adjusted threshold factor for Mercury.

Each data point indicates the value of the Adjusted Threshold Factor of a tailing sample for Mercury. The red line indicates the unconditional intervention threshold and the green line indicates the conditional intervention threshold. The data points between these lines are considered for a Conditional Intervention, while the points above the red line are considered for an Unconditional Intervention.

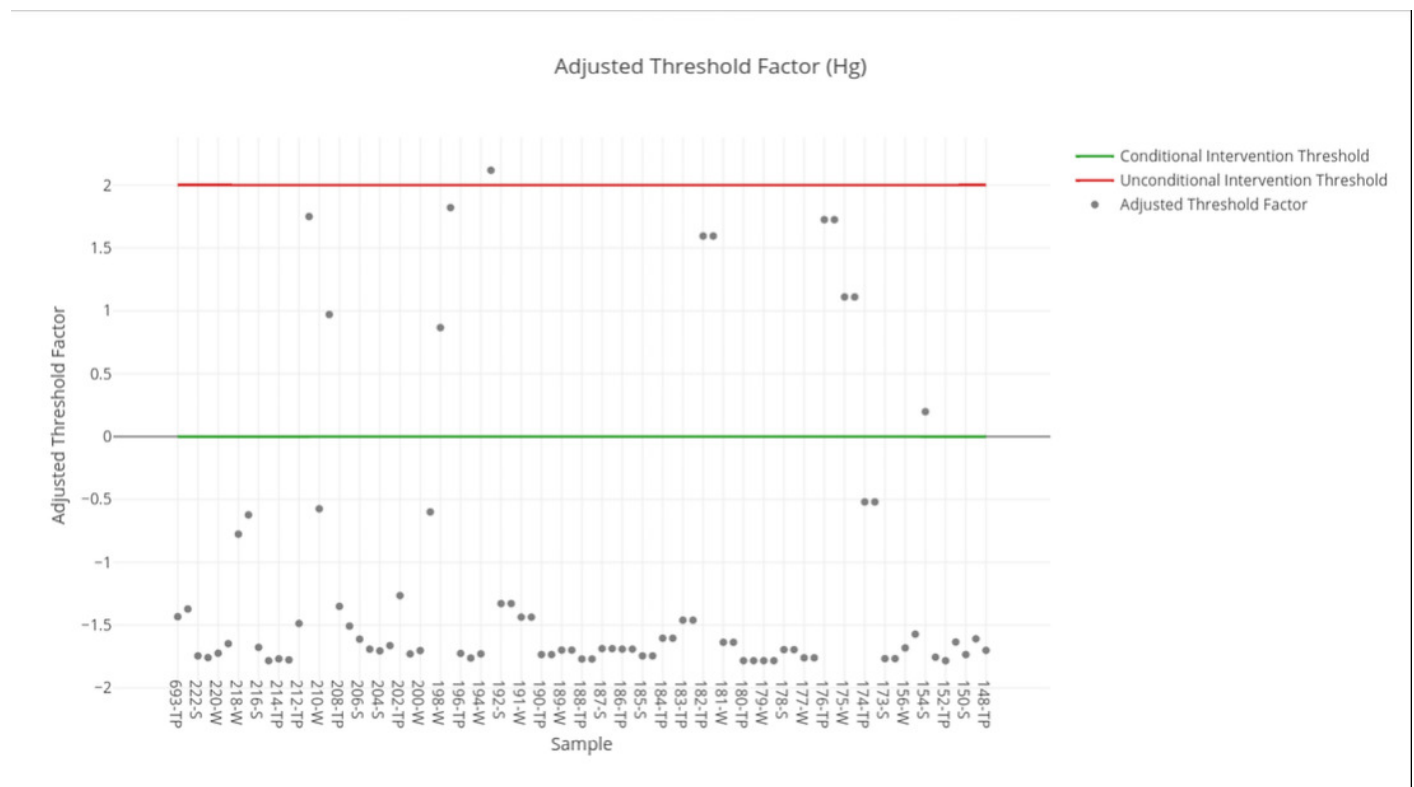



Figure 5

Adjusted threshold factor for Copper.

Each data point indicates the value of the Adjusted Threshold Factor of a tailing sample for Copper. The red line indicates the unconditional intervention threshold and the green line indicates the conditional intervention threshold. The data points between these lines are considered for a Conditional Intervention, while the points above the red line are considered for an Unconditional Intervention.

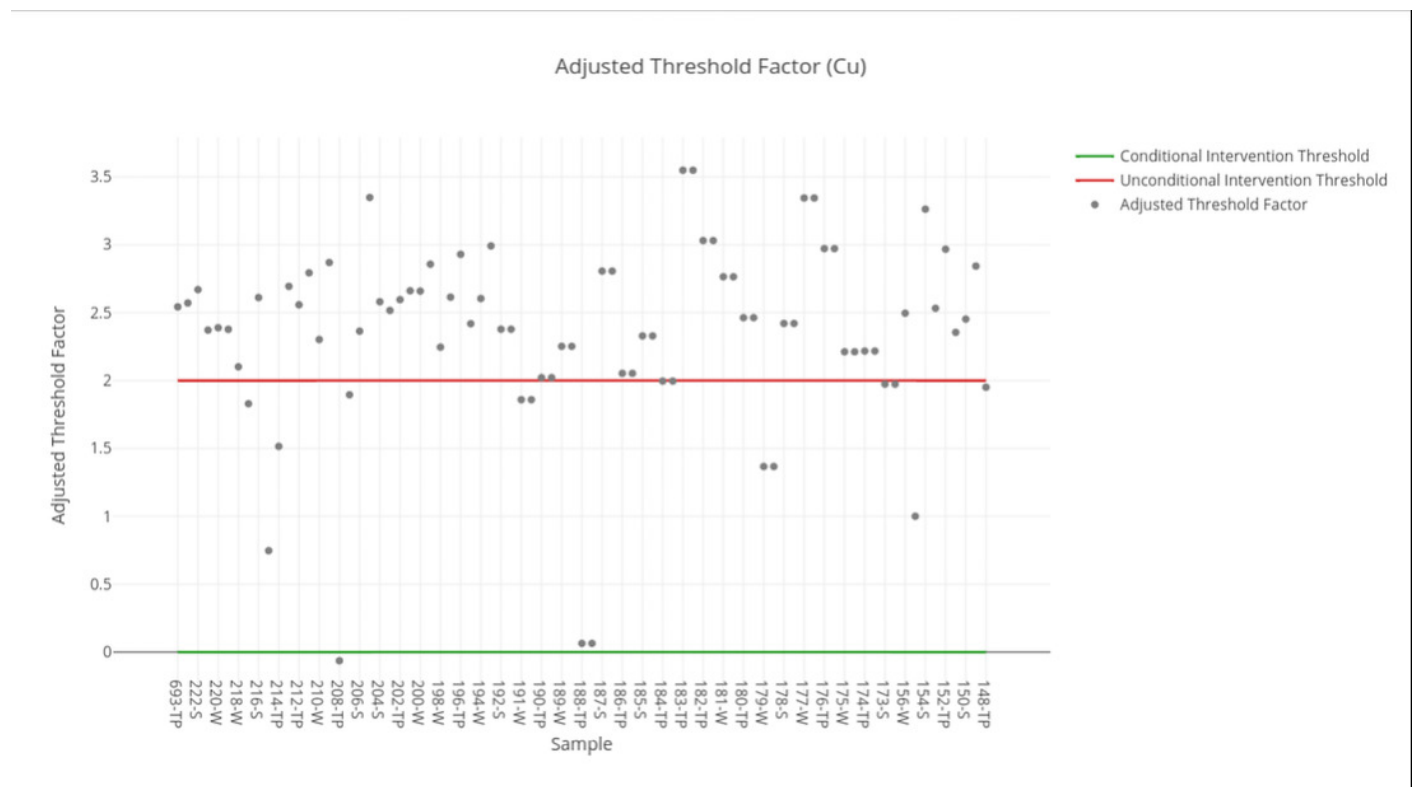



Figure 6

Adjusted threshold factor for Chromium.

Each data point indicates the value of the Adjusted Threshold Factor of a tailing sample for Chromium. The red line indicates the unconditional intervention threshold and the green line indicates the conditional intervention threshold. The data points between these lines are considered for a Conditional Intervention, while the points above the red line are considered for an Unconditional Intervention.

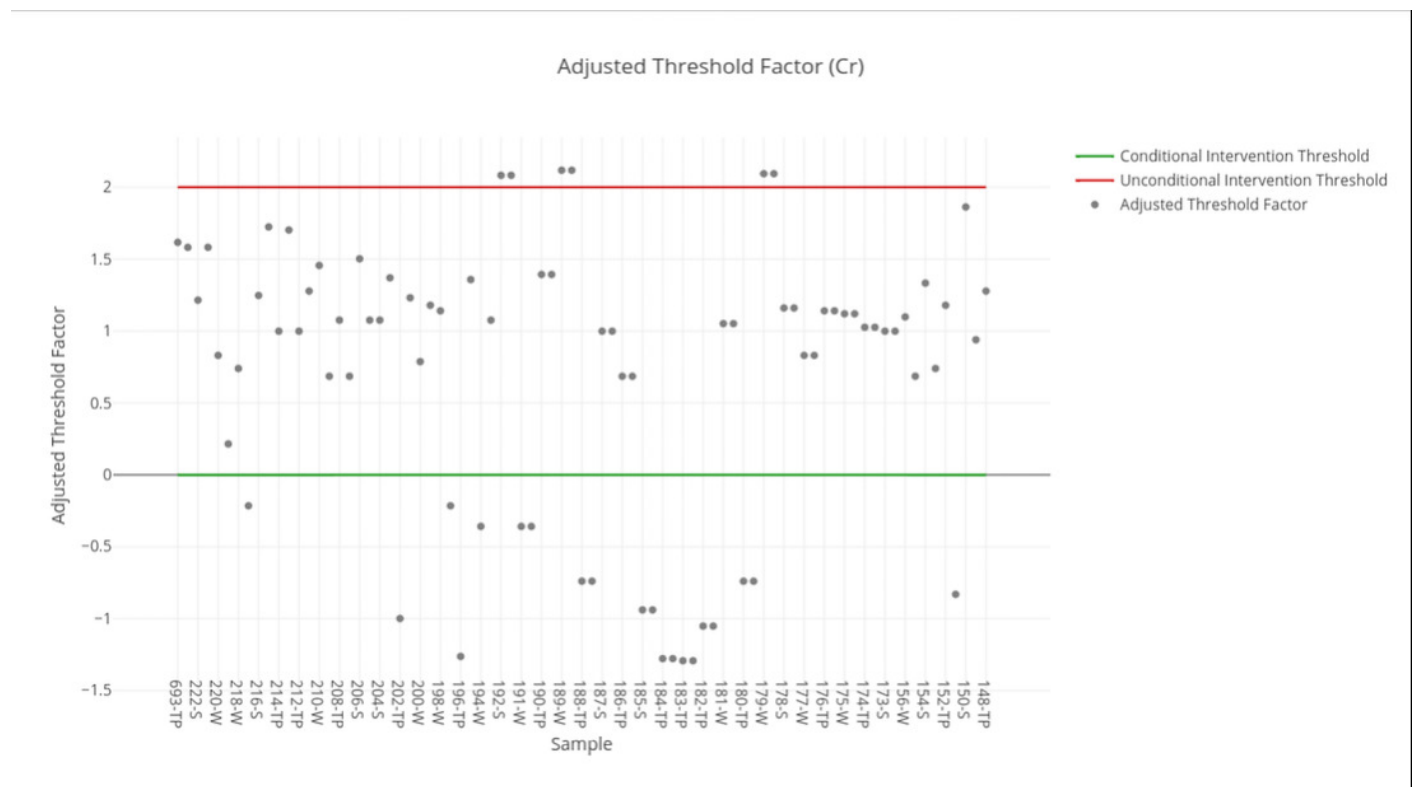
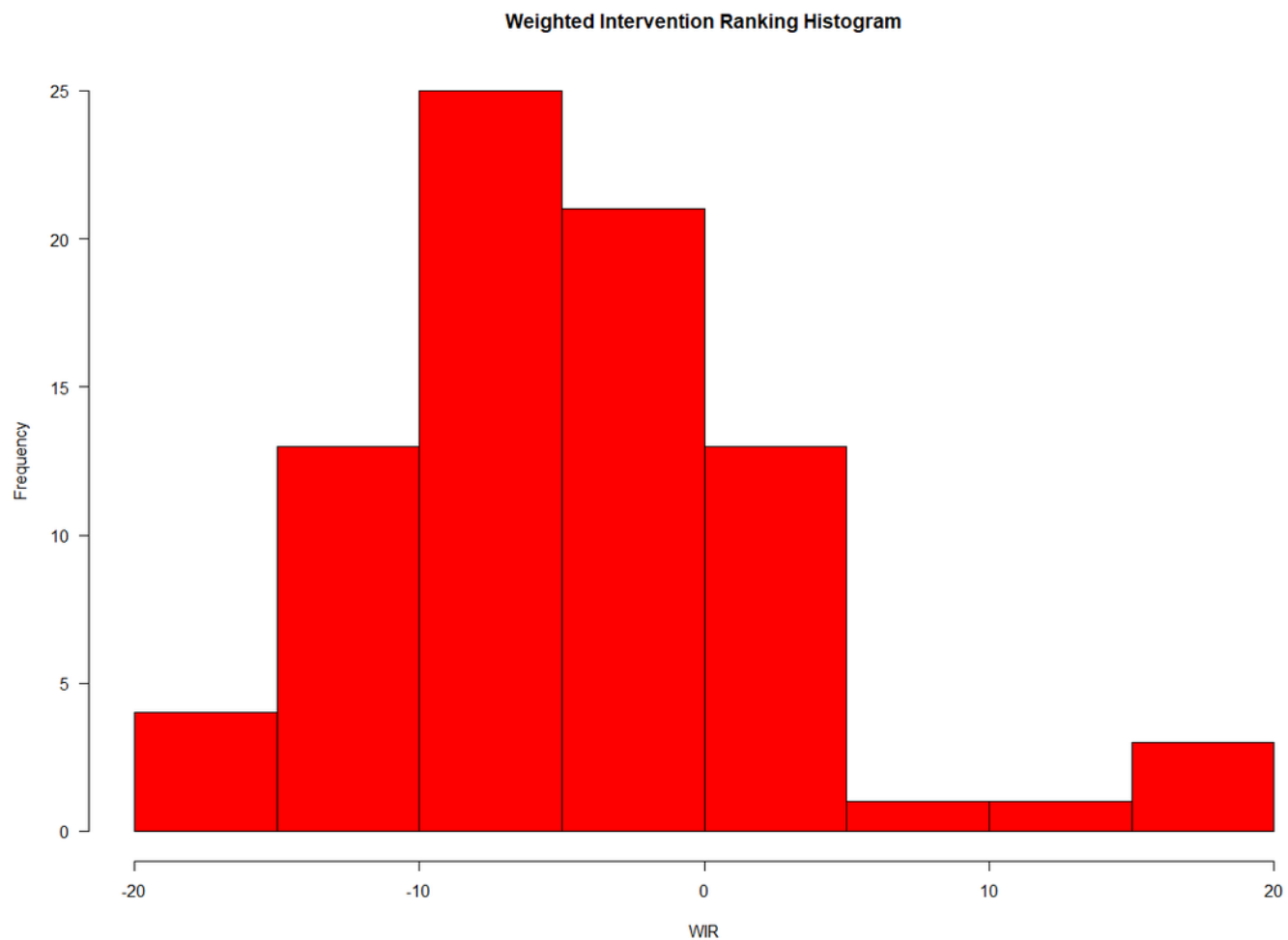



Figure 7

Histogram for the values of Weighted Intervention Ranking for all the 81 samples from the Commune of Andacollo.

This graph shows the distribution of the Weighted Intervention Ranking (*WIR*) for all the samples from the Commune of Andacollo. The average *WIR* for all sites is -4.53, while the median is -5,71 and the standard deviation is 7.53. The highest value of *WIR* is 19.88 and the lowest value is -16.28.

Weighted Intervention Ranking Histogram

Parameters of the equation for the calculation of SSIV for each element (source: Dutch soil quality regulations, 2013).

Each row shows the value of the corresponding parameter for each element.

1   *Table 1 - Parameters of the equation for the calculation of SSIV for each element (source: Dutch*
2   *soil quality regulations, 2013).*

Element	A	B	C	SSIV (mg kg⁻¹)
Arsenic	15	0.4	0.4	76
Cadmium	0.4	0.007	0.021	13
Mercury	0.2	0.0034	0.0017	4
Lead	50	1	1	530
Nickel	10	1	0	100
Zinc	50	3	1.5	720
Copper	15	0.6	0.6	190
Chromium	50	2	0	78

Manuscript to be reviewed

Referential table of intervention values (SIV) of each element for different soils according to clay percentage assuming organic matter is ≤ 2% (source: own elaboration).

Each row of this table presents the intervention values (SIV) of each element, depending on the percentage of Clay in the soil and assuming a negligible amount of organic matter.

1   *Table 2 – Referential table of intervention values (SIV) of each element for different soils*
2   *according to clay percentage assuming organic matter is ≤ 2% (source: own elaboration).*

SIV (mg/kg)		As	Cd	Hg	Pb	Ni	Zn	Cu	Cr
							Element		
Percentage of Clay	2	43.50	7.55	2.78	336.71	34.29	303.43	91.83	42.12
	5	46.65	7.90	2.92	355.41	42.86	349.71	101.33	46.80
	10	51.89	8.48	3.14	386.59	57.14	426.86	117.17	54.60
	15	57.13	9.06	3.37	417.76	71.43	504.00	133.00	62.40
	20	62.37	9.64	3.59	448.94	85.71	581.14	148.83	70.20
	25	67.61	10.22	3.82	480.12	100.00	658.29	164.67	78.00
	30	72.86	10.80	4.05	511.29	114.29	735.43	180.50	85.80
	35	78.10	11.38	4.27	542.47	128.57	812.57	196.33	93.60
	40	83.34	11.96	4.50	573.65	142.86	889.71	212.17	101.40
	45	88.58	12.54	4.72	604.82	157.14	966.86	228.00	109.20
	50	93.82	13.12	4.95	636.00	171.43	1044.00	243.83	117.00
	55	99.06	13.70	5.17	667.18	185.71	1121.14	259.67	124.80
	60	104.30	14.28	5.40	698.35	200.00	1198.29	275.50	132.60
	65	109.54	14.85	5.62	729.53	214.29	1275.43	291.33	140.40
	70	114.79	15.43	5.85	760.71	228.57	1352.57	307.17	148.20
	75	120.03	16.01	6.07	791.88	242.86	1429.71	323.00	156.00
	80	125.27	16.59	6.30	823.06	257.14	1506.86	338.83	163.80
	85	130.51	17.17	6.52	854.24	271.43	1584.00	354.67	171.60
	90	135.75	17.75	6.75	885.41	285.71	1661.14	370.50	179.40
	95	140.99	18.33	6.97	916.59	300.00	1738.29	386.33	187.20
	100	146.23	18.91	7.19	947.77	314.29	1815.44	402.16	195

4
5
6

Summary of intervention cases with respect to the threshold factor.

Each row describes a different case depending on the value of the threshold factor.

1   *Table 1 – Summary of intervention cases with respect to the threshold factor.*

Case	Condition	Description	Required Actions	Subcases	Additional Conditions
No Intervention	$C_F \leq 0$	The tailing deposit does not require intervention, regardless of the soil composition.	None	None	None
Conditional Intervention	$0 < C_F < 100$	The tailing deposit may or may not require intervention, this depends on the soil composition.	Determine the clay percentage x_A.	Intervention not required, it is not necessary to intervene the soil because it is under the intervention value specified for this type of soil.	$x_A > C_F$
				Intervention required, the soil must be intervened because it exceeds or equals the intervention value specified for this type of soil.	$x_A \leq C_F$
Unconditional Intervention	$C_F \geq 100$	The tailing deposit requires intervention, regardless of the soil composition.	Prepare an intervention plan for the site.	None	None

Summary of intervention cases with respect to the adjusted threshold factor.

Each row describes a different case depending on the value of the adjusted threshold factor.

1   *Table 4 – Summary of intervention cases with respect to the adjusted threshold factor.*

Case	Condition	Priority	Required Actions
No Intervention	$AC_F \leq 0$	None	None
Unlikely Conditional Intervention	$0 < AC_F \leq 1$	Low	If possible, determine the clay percentage x_A to find if intervention is required.
Conditional Intervention	$1 < AC_F < 2$	Medium	Determine the clay percentage x_A and find if intervention is required.
Unconditional Intervention	$AC_F \geq 2$	High	Prepare an intervention plan for the site.

Summary of results for all the studied metals.

This table presents the information regarding to the necessity of intervention results for the tailings according to the adjusted threshold factor for the different metals grouped by tailing deposit status (active, inactive or abandoned).

1   *Table 5 - Summary of results for all the studied metals.*

Element	Deposit Status	$AC_F \leq 0$ (no intervention)	$0 < AC_F < 2$ (conditional intervention)	$AC_F \geq 2$ (unconditional intervention)	Total
As	Active	10	1	0	11
	Inactive	18	0	4	22
	Abandoned	48	0	0	48
Cd	Active	9	2	0	11
	Inactive	10	12	0	22
	Abandoned	30	18	0	48
Pb	Active	11	0	0	11
	Inactive	18	4	0	22
	Abandoned	48	0	0	48
Ni	Active	0	11	0	11
	Inactive	0	22	0	22
	Abandoned	0	48	0	48
Hg	Active	10	1	0	11
	Inactive	20	2	0	22
	Abandoned	39	8	1	48
Cu	Active	0	2	9	11
	Inactive	0	6	16	22
	Abandoned	1	8	39	48
Zn	Active	10	1	0	11
	Inactive	18	4	0	22
	Abandoned	48	0	0	48
Cr	Active	1	10	0	11
	Inactive	6	10	6	22
	Abandoned	13	35	0	48
Total					648

Summary of results by sample for ACTIVE deposits ("NO": no intervention, "YES": unconditional intervention and "CND": conditional intervention).

Each row corresponds to a tailing sample from active deposits, the columns show if this sampling suggests a conditional intervention, an unconditional intervention or no intervention according to the adjusted threshold factor.

1   *Table 6 – Summary of results by sample for ACTIVE and INACTIVE deposits ("NO": no*

2   *intervention, "YES": unconditional intervention and "CND": conditional intervention).*

Deposit status	ID	Cr	Zn	Ni	Pb	Hg	Cu	Cd	As
ACTIVE	148-TP	CND	NO	CND	NO	NO	CND	CND	NO
	149-W	CND	NO	CND	NO	NO	**YES**	NO	NO
	150-S	CND	NO	CND	NO	NO	**YES**	NO	NO
	151-W	NO	NO	CND	NO	NO	**YES**	NO	NO
	152-TP	CND	NO	CND	NO	NO	**YES**	CND	CND
	153-W	CND	NO	CND	NO	NO	**YES**	NO	NO
	154-S	CND	CND	CND	NO	CND	**YES**	NO	NO
	155-TP	CND	NO	CND	NO	NO	CND	NO	NO
	156-W	CND	NO	CND	NO	NO	**YES**	NO	NO
	692-TP	CND	NO	CND	NO	NO	**YES**	NO	NO
	693-TP	CND	NO	CND	NO	NO	**YES**	NO	NO
INACTIVE	176-TP	CND	NO	CND	NO	CND	**YES**	CND	NO
	176-TP-2	CND	NO	CND	NO	CND	**YES**	CND	NO
	177-W	CND	NO	CND	NO	NO	**YES**	CND	NO
	177-W-2	CND	NO	CND	NO	NO	**YES**	CND	NO
	178-S	CND	NO	CND	NO	NO	**YES**	NO	NO
	178-S-2	CND	NO	CND	NO	NO	**YES**	NO	NO
	179-W	**YES**	NO	CND	NO	NO	CND	NO	NO
	179-W-2	**YES**	NO	CND	NO	NO	CND	NO	NO
	180-TP	NO	NO	CND	NO	NO	**YES**	CND	NO
	180-TP-2	NO	NO	CND	NO	NO	**YES**	CND	NO
	181-W	CND	NO	CND	NO	NO	**YES**	NO	NO
	181-W-2	CND	NO	CND	NO	NO	**YES**	NO	NO
	188-TP	NO	NO	CND	NO	NO	CND	NO	NO
	188-TP-2	NO	NO	CND	NO	NO	CND	NO	NO
	189-W	**YES**	NO	CND	NO	NO	**YES**	CND	NO
	189-W-2	**YES**	NO	CND	NO	NO	**YES**	CND	NO
	190-TP	CND	CND	CND	CND	NO	**YES**	CND	**YES**
	190-TP-2	CND	CND	CND	CND	NO	**YES**	CND	**YES**
	191-W	NO	CND	CND	CND	NO	CND	NO	**YES**
	191-W-2	NO	CND	CND	CND	NO	CND	NO	**YES**
	192-S	**YES**	NO	CND	NO	NO	**YES**	CND	NO
	192-S-2	**YES**	NO	CND	NO	NO	**YES**	CND	NO

Summary of results by sample for ABANDONED deposits ("NO": no intervention, "YES": unconditional intervention and "CND": conditional intervention).

Each row corresponds to a tailing sample from abandoned deposits, the columns show if this sampling suggests a conditional intervention, an unconditional intervention or no intervention according to the adjusted threshold factor.

1   *Table 7 – Summary of results by sample for ABANDONED deposits (“NO”: no intervention,*

2   *“YES”: unconditional intervention and “CND”: conditional intervention).*

ID	Cr	Zn	Ni	Pb	Hg	Cu	Cd	As
173-S	CND	NO	CND	NO	NO	CND	CND	NO
173-S-2	CND	NO	CND	NO	NO	CND	CND	NO
174-TP	CND	NO	CND	NO	NO	**YES**	NO	NO
174-TP-2	CND	NO	CND	NO	NO	**YES**	NO	NO
175-W	CND	NO	CND	NO	CND	**YES**	NO	NO
175-W-2	CND	NO	CND	NO	CND	**YES**	NO	NO
182-TP	NO	NO	CND	NO	CND	**YES**	CND	NO
182-TP-2	NO	NO	CND	NO	CND	**YES**	CND	NO
183-TP	NO	NO	CND	NO	NO	**YES**	NO	NO
183-TP-2	NO	NO	CND	NO	NO	**YES**	NO	NO
184-TP	NO	NO	CND	NO	NO	CND	NO	NO
184-TP-2	NO	NO	CND	NO	NO	CND	NO	NO
185-S	NO	NO	CND	NO	NO	**YES**	NO	NO
185-S-2	NO	NO	CND	NO	NO	**YES**	NO	NO
186-TP	CND	NO	CND	NO	NO	**YES**	CND	NO
186-TP-2	CND	NO	CND	NO	NO	**YES**	CND	NO
187-S	CND	NO	CND	NO	NO	**YES**	NO	NO
187-S-2	CND	NO	CND	NO	NO	**YES**	NO	NO
193-TP	CND	NO	CND	NO	SÍ	**YES**	NO	NO
194-W	NO	NO	CND	NO	NO	**YES**	CND	NO
195-S	CND	NO	CND	NO	NO	**YES**	NO	NO
196-TP	NO	NO	CND	NO	NO	**YES**	NO	NO
197-W	NO	NO	CND	NO	CND	**YES**	CND	NO
198-W	CND	NO	CND	NO	CND	**YES**	NO	NO
199-TP	CND	NO	CND	NO	NO	**YES**	CND	NO
200-W	CND	NO	CND	NO	NO	**YES**	CND	NO
201-W	CND	NO	CND	NO	NO	**YES**	NO	NO
202-TP	NO	NO	CND	NO	NO	**YES**	NO	NO
203-S	CND	NO	CND	NO	NO	**YES**	NO	NO
204-S	CND	NO	CND	NO	NO	**YES**	CND	NO
205-S	CND	NO	CND	NO	NO	**YES**	NO	NO
206-S	CND	NO	CND	NO	NO	**YES**	CND	NO
207-W	CND	NO	CND	NO	NO	CND	NO	NO
208-TP	CND	NO	CND	NO	NO	NO	NO	NO
209-TP	CND	NO	CND	NO	CND	**YES**	CND	NO
210-W	CND	NO	CND	NO	NO	**YES**	CND	NO
211-W	CND	NO	CND	NO	CND	**YES**	NO	NO
212-TP	CND	NO	CND	NO	NO	**YES**	NO	NO
213-S	CND	NO	CND	NO	NO	**YES**	CND	NO
214-TP	CND	NO	CND	NO	NO	CND	CND	NO
215-W	CND	NO	CND	NO	NO	CND	NO	NO
216-S	CND	NO	CND	NO	NO	**YES**	NO	NO
217-TP	NO	NO	CND	NO	NO	CND	NO	NO
218-W	CND	NO	CND	NO	NO	**YES**	NO	NO
219-TP	CND	NO	CND	NO	NO	**YES**	CND	NO
220-W	CND	NO	CND	NO	NO	**YES**	NO	NO
221-S	CND	NO	CND	NO	NO	**YES**	NO	NO
222-S	CND	NO	CND	NO	NO	**YES**	CND	NO

Assigned weights to each element for the calculation of the Weighted Intervention Ranking.

Each row in this table shows an element with its respective weight for the calculation of the Weighted Intervention Ranking.

1   *Table 8 – Assigned weights to each element for the calculation of the Weighted Intervention*

2   *Ranking.*

Element	Assigned Weight
Cr	2.0
Zn	1.0
Ni	3.0
Pb	3.0
Hg	2.0
Cu	1.0
Cd	3.0
As	3.0

Summary of results for the top ten critical sites according to their WIR value.

Each row represents a tailing sample, this table details the values of the adjusted threshold factor for each element and the value of the WIR, it also includes the information about the deposit from where the sample was extracted.

1   *Table 9 – Summary of results for the top ten critical sites according to their WIR value.*

ID	Deposit	Status	As	Cd	Pb	Ni	Hg	Cu	Zn	Cr	WIR
190-TP-2	ARIZONA 1	INACTIVE	2.45	0.84	1.21	1.27	-1.73	2.02	1.26	1.39	19.88
190-TP	ARIZONA 1	INACTIVE	2.45	0.59	1.21	1.27	-1.73	2.02	1.26	1.39	19.13
191-W-2	ARIZONA 2	INACTIVE	2.74	-0.27	1.68	1.19	-1.44	1.86	1.56	-0.36	15.84
191-W	ARIZONA 2	INACTIVE	2.74	-0.57	1.68	1.19	-1.44	1.86	1.56	-0.36	14.93
152-TP	SANTA TERESITA 2	ACTVE	1.58	1.19	-1.12	1.17	-1.78	2.97	-0.94	1.18	9.27
176-TP-2	ARENILLAS 2	INACTIVE	-1.33	0.84	-1.67	1.23	1.73	2.97	-1.18	1.14	4.71
176-TP	ARENILLAS 2	INACTIVE	-1.33	0.75	-1.67	1.23	1.73	2.97	-1.18	1.14	4.45
197-W	PUNTA CALETONES 3	ABANDONED	-1.33	1.62	-1.62	1.16	1.82	2.61	-1.00	-0.22	4.30
209-TP	IRENE 2	ABANDONED	-1.33	1.19	-1.58	1.18	0.97	2.87	-0.97	0.69	3.57
189-W-2	ARIZONA 1	INACTIVE	-1.33	-1.09	-1.54	1.21	2.12	2.99	-0.99	1.08	3.14