The tailings pond failure at the Aznalcóllar mine, Spain[1,2]

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ABSTRACT: The tailings pond failure at the Boliden Apirsa mining operations in southern Spain in April 1998 captured the attention from the media, indudestry and the public. Both the immediate effects and the potential long-term effects of the accident were severe. This paper summarises almost 2 years of the work done by Boliden Apirsa after the accident including the clean up, the environmental impact assessment, the closure of the failed tailings pond, the re-start of the operations, as well as the human aspects related to this work.

1. INTRODUCTION

Boliden Apirsa is located 35 km west of Seville in the region of Andalucía in the south of Spain, Figure 1. The mineralisation forms part of the Iberian Pyrite Belt (Leistel et al. 1998) with more than 80 known mineral deposits.

Mining has been active in Aznalcóllar for thousands of years. Intensive mining was carried out already by the Romans. Large-scale mining started in 1976 when the Aznalcóllar open pit was developed. Boliden Apirsa purchased the property in 1987. The Aznalcóllar open pit was mined out in 1996 at which time the production began in the closely located Los Frailes open pit. The mine and the concentrator are designed for an annual production of 4.1 Mton of ore, containing zinc, lead and copper. The operations employ 500 persons. Until the accident in April 1998 the tailings were deposited in the 160 ha tailings pond, located on the riverbank of the Rio Agrio. The pond was designed and built in 1977-78 with a design capacity of 33 Mm^3. The pond contained 15 Mm^3 of tailings in April 1998. In 1996 the tailings pond was subject to a full-scale stability study conducted by independent experts and the Spanish authorities, whereby no signs of instability were detected. In addition, it was subject to regular third-party inspections, the last one on April 14, less than two weeks before the accident, without detecting any signs of instability.

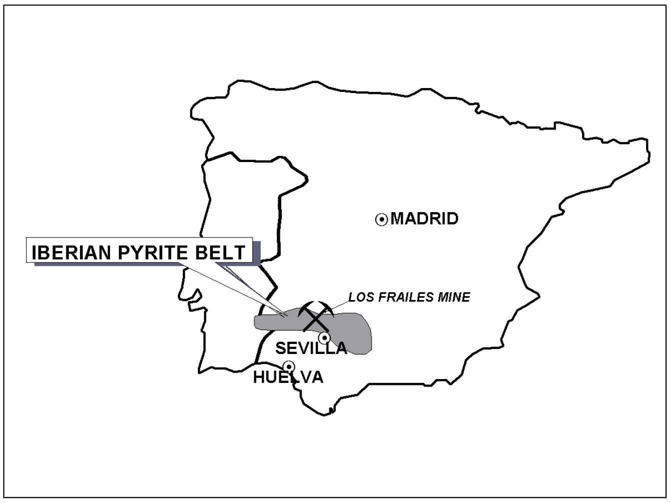

Figure 1. Map of Spain, location of the site and the Iberian Pyrite Belt.

The general geological sequence at the site is composed of Quaternary deposits on top of Miocene and Palaeozoic deposits. The Quaternary deposits consist of alluvial material of varying thickness, typically in the area of the tailings pond between 5 and 10 m. The alluvial is overlying a layer of marls (mud, lime and clay). The thickness of the marls increases towards the south and is around 50 m in the area of the tailings pond. Below the marls there is a thin layer, around 10 m, of bioclastic limestone, which forms the regional aquifer Niebla-Posadas. Further below this Miocene sequence there are

[1] Paper originally prepared for the Sixth International Symposium in Environmental Issues and Waste Management in Energy and Mineral Production, Calgary, Alberta, Canada, 30 May – 2 June 2000.
[2] Revised December 2016 for 23rd Annual British Columbia-MEND ML/ARD Workshop.

Paleozoic shales, Volcanic sedimentary complexes and Devonian or Carboniferous slates.

The climate in the region is subtropical Mediterranean with warm and dry summers and mild winters, when most of the annual rainfall occurs. The annual average temperature is 18 °C, the average rainfall is 650 mm/year.

2. THE ACCIDENT

On the night between April 24 and 25 1998 a 600 m section of the downstream dike of the tailings pond suddenly slid up to 60 m. The slide created a breach in the dam through which water and tailings were flushed out. In a few hours, 5.5 Mm^3 of acid and metal rich water flowed out of the dam, Table 1. The amount of tailings that was spilled has been estimated to be between 1.3 and 1.9 Mton. Due to the fine particle size of the tailings ($k_{80} < 45$ μm) they were easily transported in suspension with the flood wave. At the flow gauging station El Guijo, 7 km downstream of the tailings pond, the water level increased 3.6 m in 30 minutes. Moreover, 12 hours later, the increase in water level was less than 0.2 m at El Guigo.

Table 1. Composition of spilled water and tailings.

	Tailings (%)	Tailings Water (mg/l)
Zn	1	450
Fe	45	80
Cu	0.2	17
Pb	1	3.5
As	0.6	0.2
S	45	1200
pH	n.a.	2.9

2.1 The cause of the accident

The causes of the accident were assessed by three independent investigations. One commissioned by Boliden Apirsa and conducted by the consulting company EPTISA. This investigation was continuously reviewed and supervised by an independent international expert panel. The regional authorities initiated an investigation that was conducted by the governmental research organisation CEDEX. The third investigation was initiated by the judge leading the legal procedures around the accident and carried out by professors from the University of Barcelona (not completed at the time of writing this paper).

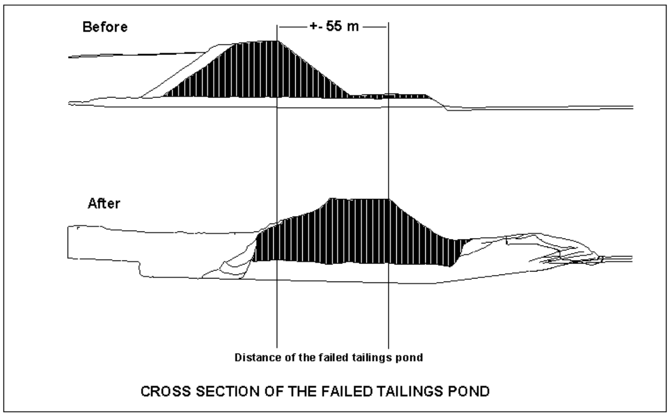

Figure 2. Cross section of the tailings pond.

EPTISA and CEDEX arrived at similar conclusions regarding the cause of the accident. The direct cause of the accident was a fault in the marls 14 m below the ground surface, Figure 2. This fault was the result of surplus pressure in the interstitial water of the clay due to the weight of the dam and the tailings deposit (EPTISA 1998).

2.2 Immediate effects

The spill flooded the riverbanks along the rivers Los Frailes, Agrio and Guadiamar, from a point located 300 m upstream the tailings pond in the river Los Frailes, down to Entremuros, 40 km south of the mine, Figure 3. In total 4634 ha of land were affected, of which 2600 ha were covered by tailings. When the water had withdrawn the thickness of the deposited tailings ranged between 4 m close to the tailings pond to a few millimetres near Entremuros. The flood wave was contained in the 2000 ha Entremuros area by an emergency containment wall built between the banks. The contaminated water did not reach the Doñana National Park.

The aquatic life in the affected section of the river was depleted. No deaths or injuries were caused by the accident, nor was any livestock reported missing. Damages to constructions was very limited and no major bridges open for public access were damaged. Acid water and tailings flooded more than 50 irrigation wells, built in the alluvium. The affected land was riverbanks, grazing fields, agricultural land and fruit plantations. Entremuros, which was affected by the acid and metal rich water, is part of the pre-park to Doñana and was before the accident an important resting site for migrating birds.

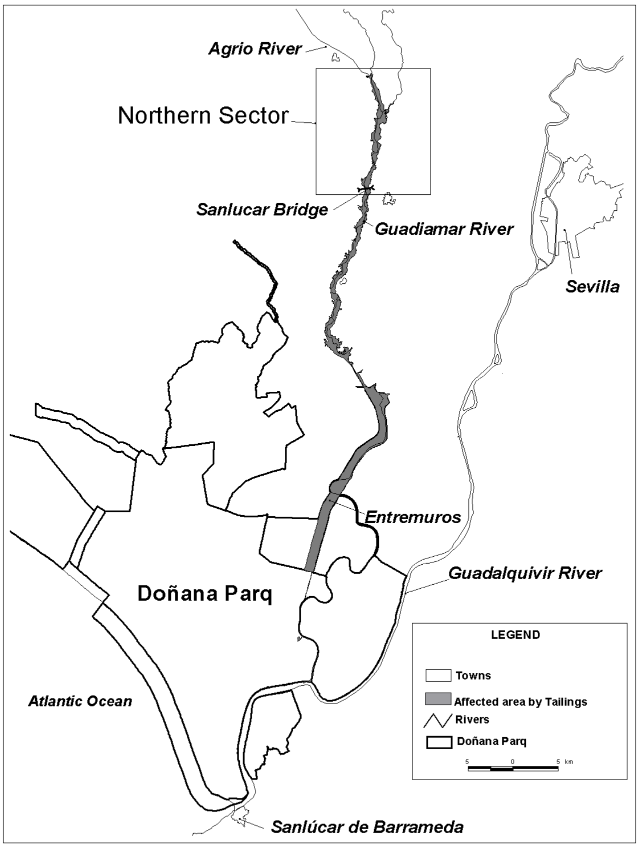

Figure 3. Map of the affected area with reference points and rivers.

2.3 Immediate actions

The plume of contaminated water was stopped in the Entremuros area by the wall built by the Spanish authorities, as described above. The authorities banned all form of land-use and the use of all wells for irrigation in the affected area.

Boliden Apirsa managed to seal the breach within 36 hours. This was required because there was still intensive rainfall expected for the end of the rainy season, which could mobilise more tailings and acid water. Mining and milling operations were stopped immediately and a large part of the working force was laid off (Lindvall et al. 1999).

Boliden Apirsa organised a number of working groups to address various issues such as: investigating the causes of the dam failure, environmental impact, clean-up of the spilled tailings, insurance and legal issues, information issues, restart of the mining operations and decommissioning of the failed dam (Lindahl 1999). The organisation at the mine was not dimensioned to handle this working load. Competent people were rought in from within the Boliden group and external help was seeked.

Being fully aware of the seriousness of the situation, Boliden Apirsa undertook the fastest possible actions to address the existing and potential effects of the accident. The immediate damage was a fact. The priority was then to avoid any secondary damage in the medium and long-term. Three days after the accident a plan for the clean-up work was presented to the authorities. Boliden Apirsa offered to make funding available, even though stating that the financial and legal responsibility for the accident was a separate issue and had to be determined in court at a later stage. Boliden Apirsa bought the entire harvest of fruit for 1998 from the affected area, to minimise the effects for the affected farmers and to calm down fears that crops from the affected area would reach the market (Lindahl 1999).

3. THE CLEAN-UP

Boliden Apirsa's plan for the clean-up led to intensive discussions and collaboration with the authorities. On May 2 the permit for the clean-up was issued. It was decided to divide the responsibility for the clean-up, Boliden Apirsa assumed the responsibility for cleaning the northern sector (from the mine and 14 km downstream to the Sanlúcar bridge) and the authorities became in charge of the southern sector. Although the northern sector was smaller, 780 ha, it contained approximately 80% of the spilled tailings.

Boliden Apirsa's objective with the clean-up was to return the land to a state in which the previous land-use could be resumed. The clean-up had to be finished before the onset of the autumn rains, which normally occurs in October. This meant that there were only 5-6 months available to clean the entire affected area.

The tailings were excavated together with as little underlying soil as possible and trucked to the Aznalcóllar open pit for final sub-aqueous disposal. If the method of removing the tailings was simple, the logistics around the operation were proportionally more complex. A total of more than 450 conventional highway trucks were used to transport the tailings together with 26 mining trucks. More than 250 excavators, motor graders and other machinery were used to collect and load the tailings on the trucks. Even though provisional roads were constructed on both sides of the river, some public roads had to be used for the transport of the tailings back to the Aznalcóllar open pit. All trucks had to cover their buckets, nonetheless there was increased generation of dust, mainly brought to the roads by mud sticking to the tires. There were five lethal accidents during the clean-up operation, all of them were traffic accidents.

The clean-up was relatively easy in the agricultural fields and other flat areas where the thickness of the tailings was comparatively limited. There, motor graders could be used to scrape the tailings into rows. On the riverbanks and other uneven areas the vegetation was removed to facilitate the clean-up and large areas had to be drained before the tailings removal. Especially complicated was the cleaning of gravel pits, which could not be drained completely.

The clean-up left a completely barren landscape without ground vegetation, except for some large trees that could be saved. All vegetation in the river was also removed together with the tailings as the river was drained and cleaned in sections. By October 15, the original deadline for the clean-up, 90% of the area had been cleaned. The clean-up was finally completed on December 1. By that date 10 Mton of tailings and soil had been recovered in approximately 500,000 truckloads.

The clean-up was conducted without any criteria for the residual metal concentrations. The Guadiamar intervention criteria (Table 2) were set on December 18, 1998. In order to direct the clean-up in the northern sector Boliden Apirsa implemented a soil sampling program, described in section 6.2, which provided fast feedback on the success of the clean-up. It resulted in the immediate re-cleaning of approximately 65 ha.

The clean-up also included 45 irrigation wells in the northern sector. This was carried out through liming the wells in-situ and pumping out water and tailings with large pumps.

During the summer of 1999 a second clean-up was undertaken targeting areas where the residual metal concentration exceeded the intervention criteria, mainly in the river channel. In this second clean-up, approximately 200 ha were re-cleaned and 1 Mm^3 of material taken to the Aznalcóllar open pit for deposition.

4. THE RE-START OF THE MINE

Re-starting the mining and milling operations at the site was the second highest priority for Boliden Apirsa, besides from cleaning up the spill. The operations were intact, with the important exception of the tailings pond. The possibility to resume tailings disposal in the failed tailings pond was soon ruled out. Instead, the efforts were concentrated on finding a new tailings disposal facility. The preferred alternative showed to be the mined out Aznalcóllar open pit.

Investigations were conducted addressing mainly the permeability and the water balance of the pit. In November 1998 an application was submitted to the authorities demonstrating the suitability of the Aznalcóllar open pit as tailings disposal facility. After an extended round of questions and additional investigations, Boliden Apirsa received a provisional permit in March 1999. Production in the mine was resumed by the end of March and milling started in June.

The drawbacks of using the Aznalcóllar open pit exclusively for tailings disposal were that a large volume allocated to waste rock disposal was lost and that process water needed to be pumped out of the mine to assure that the water level would not reach above the permitted level, i.e. 0 masl. An application for raising the water level in the open pit to +34 masl and the subsequent extension of the dumps was submitted to the authorities in February 2000.

5. CLOSURE OF THE TAILINGS POND

After the accident, the pond had been drained but still contained more than 13 Mm^3 of tailings, causing concerns about the stability of the dam. A program for emergency works was therefore implemented, including building a stabilising berm around the perimeter of the dike, filling the erosion channels created by the outflow of tailings, covering the tailings surface closest to the breach in the dike and installing a system for pumping the surface run-off from the pond. Practical problems arose, incurring significant costs due to the fact that the work had to be carried out on water-saturated tailings.

The emergency program evolved into a complete decommissioning of the failed dam that, in addition to the above mentioned procedures, has the following main components: diversion of the Rio Agrio; building an impermeable seepage cut-off wall around the north and east sides of the dam; installation of a hydraulic barrier including a back-pumping system on the inside of the cut-off wall; cutting and re-sloping the dike to 3:1 and covering it; remodelling of the tailings surface to minimise the infiltration and to control the surface run-off; and constructing a vegetated composite cover over the remodelled tailings surface. Starting from the tailings, the cover consists of a geo-textile, 0.5 m waste rock, 0.1 m blinding layer, 0.5 m compacted clay, 0.5 m protective soil layer and vegetation.

The final closure plan for the tailings pond was submitted to the authorities in December 1999, for their approval. The decommissioning is scheduled to be finished in September 2000. A comprehensive control system is being established including inclinometers, piezometers and fix-points to control the stability of the dike and the cover, as well as monitoring wells to control the performance of the cut-off wall and the hydraulic barrier.

6. ENVIRONMENTAL IMPACT

Initially the work was focused on determining and quantifying the immediate impact of the accident. However, the focus shifted quickly towards predicting and preventing medium and long-term effects and monitoring the recovery. The fieldwork program was also designed to provide the best possible input data for a comprehensive risk assessment. Using initial monitoring data and a series of assumptions, a screening assessment of human health and ecological risks was conducted (O´Connors 1999). A list of 8 COCs was identified in this work (Ag, As, Cd, Cu, Hg, Pb, Tl and Zn). In the human health screening, 3 of these COCs (Pb, Tl and Zn) were identified as possibly exceeding the benchmark dose for a farmer in a worst case scenario. In addition, a possible increased risk for skin cancer was indicated for As. The ecological risk assessment identified As, Ag and Tl as metals for which exposure could exceed the benchmark dose for rabbits, which form an important part in the food chain in the area for lynx and imperial eagle.

Based on the results from the screening assessment, it was evident that further site characterisation was required in order to accurately quantify the potential exposure arising from the affected soils and sediments. In particular, more site-specific data on metal uptake in vegetation in the affected area, groundwater, along with data on food consumption habits, will improve the accuracy of the estimated exposures. The follow-up also includes ground and surface water monitoring, soil characterisation and monitoring of the recovery of the ecosystem after the clean-up. The results to-date are summarised below.

6.1 Surface and groundwater

The surface water monitoring program initially included 14 monitoring stations in the Rio Agrio, Rio Guadiamar, Rio Guadalquivir, with reference sampling in the upper Guadiamar, Guadalquivir and Doñana Natural Park. The monitoring frequency was, following the accident, daily and was reduced gradually.

Results showed a fast recovery of the water quality in the Guadiamar river system. At the Aznalcázar official flow gauging station located 20 km south of the mine, the zinc concentration was in the order of 400 mg/l immediately after the accident. It decreased rapidly and was two weeks after the accident below 10 mg/l. Since the end of August 1998, i.e. three months after the accident, the Zn concentration has been below 1 mg/l. The fast recovery was due to the carbonate-rich sediments in the Guadiamar riverbed that buffered the pH and caused precipitation and adsorption of metals.

Figure 4 shows the measured Zn concentration at El Guijo from 1980 to 1999, an official flow gauging station 7 km downstream of the tailings pond. In individual samples it was as high as 90 mg/l before the accident, and average quarterly Zn concentrations ranged up to 50 mg/l before 1993. The likely reason for the enhanced concentrations was probably the diffuse drainage of acid waters from the mining area, documented already for the period 1983- 1986 by González et al (1990). The annual Zn load in the river before the accident ranges between 300 and 1200 tonnes/year between 1980 and 1997. Two trends can be noted. Whilst the increasing trend can most likely be attributed to the accumulating amounts of acid-generating sulphuric waste coincident with the advance of the large-scale mining, the decreasing trend is likely to be the result of remedial measures taken by Boliden Apirsa at the site.

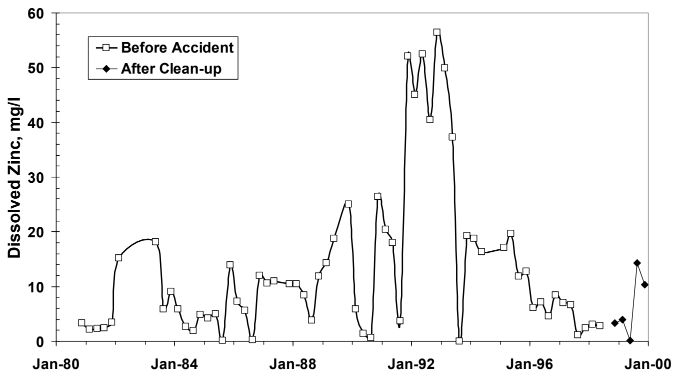

Figure 4. Quaterly average zinc concentrations in the Guadiamar river at El Guijo, 7 km downstream the mine, before and after the accident.

Following the clean-up, the Zn concentrations are not higher than before the accident. No concentration peaks have been detected in the river after rainfall events as was feared. In this perspective, the accident has had no significant lasting impact on the river water quality. However, it is obvious that the water quality in the river is objectionable. Therefore Boliden Apirsa is implementing a comprehensive program addressing this situation.

A series of monitoring wells were drilled in 4 profiles in the alluvial aquifer in the northern sector. The profiles stretched from the river, through the affected area and into the unaffected land. The results show no signs of the accident having affected the alluvial aquifer. All these wells have background concentrations of metals and sulphate except the profile located closest to the mine. The reason for the elevated metal concentrations in this profile is, most likely, historical contamination of the aquifer. High Zn concentrations, up to 35 mg/l, in that area had been detected already in 1995 by the Spanish Geological Survey (ITGE).

6.2 Soils

In order to control the clean-up and to form a basis for the risk assessment, a comprehensive soil sampling program was implemented. The northern sector (780 ha) was divided into 159 sampling units (SU), approximately 5 ha each. In every SU 15 discrete soil cores were obtained to a depth of 0.3 m. In total, 3225 discrete samples were taken, 215 composites prepared and analysed. The whole sampling program and sample preparation was supervised and documented by an independent consultant. Sample preparation was done at the Boliden Apirsa assay lab, where a composite sample was produced for each SU and split into 3 parts. One was analysed at the Boliden Apirsa assay lab to provide immediate feedback to the clean-up operation, one was sent to a certified laboratory for analysis and the third was stored as a reference. In 32 SU´s all the discrete samples were analysed to provide the basis for a statistical evaluation. 27 SU´s were re-sampled after re-cleaning or for quality control purposes. The statistical analysis of the data shows that the results obtained are within ± 25-30% in 90% of the time. To obtain a meaningful improvement of the results, more than 50 samples in each SU would have been needed.

The results of the clean-up of the northern sector, completed in December 1998, are given in Table 2 in relation to the Guadiamar intervention criteria. According to these results, metal concentrations generally meet the established criteria, except for arsenic. The success was greater in former agricultural land than in the riverbed and in former waste land and gravel pits. The results imply that 97-98 % of the tailings were recovered in the first clean-up. For example, in the northern sector the total residual load of Zn was around 700 ton.

It has been difficult to obtain pre-accidental baseline concentrations for the affected area, (Ramos et al. 1994). In the study that was completed to set the official intervention criteria (González-Aurioles 1999) the baseline concentrations were concluded to be relatively high in the area, Table 2. It is worth mentioning that for arsenic, the criteria for sensitive land use are identical to the baseline values. This implies that large areas did not pass these criteria before the accident occurred.

6.3 Biota

The scope of the ecosystem monitoring program carried out by Boliden Apirsa includes the main trophic levels, individual organisms and specific population components of the aquatic and terrestrial ecosystems. The program includes monitoring of metal uptake in selected indicator species, and effects/succession monitoring of benthic invertebrates and periphyton communities, as well as vegetation and birds (Boliden Apirsa & Ekologigruppen AB, 2000).

The results of community monitoring of benthic macro-invertebrates in the Guadiamar river have shown that a relatively diverse community of macrofauna has been established already half a year after the accident. This macrofauna is affected by various anthropogenic impacts from discharges of municipal sewage and waste from olive oil processing which overshadow the residual impacts from the tailings spill. In fact, neither on the basis of calculated diversity indexes nor on the relative abundance of macro-benthic communities could the various impacts be clearly distinguished. A better indicator is provided by composition and structure of periphyton communities, as well as by the derived diatom indexes which demonstrate that water quality in the affected area is less favourable than at the reference sites. However, this sampling media also indicates a strong influence of anthropogenic effects other than mining.

Fish (mugils, gambusia and carp) have returned amazingly fast to the river and an otter family established permanently in the river during the winter 1998/1999.

Table 2. Guadiamar Baseline Concentrations, Intervention Criteria and Clean up Results.

		Criteria		**Clean up results**	
	Baseline*	**Sensitive land use***	**Less Sensitive land use***	**Sensitive land use**	**Less Sensitive land use**
	(mg/kg)	(mg/kg)	(mg/kg)	(% Passing criteria)	(% Passing criteria)
As	52	52	100	3	59
Cd	-	5	10	100	100
Cu	120	250	500	92	100
Pb	86	350	500	76	99
Zn	366	700	1200	86	100

*González-Aurioles 1999.

Also the presence of kingfisher birds indicates that a food source is available.

In spite of very sparse rainfall during the autumn-winter 1998/1999, in the spring of 1999, a vegetation cover has been spontaneously re-established on about 20% of the northern sector (compared to reference areas where the mean vegetation cover is about 60%). Regarding species biodiversity, the mean value for the affected area was found to be 13 species per 100 m^2, compared to 37 species per 100 m^2 in the reference areas.

The selected wild plants sampled during autumn 1998 and spring 1999 have shown generally elevated metal content, 2 to 30 times, compared to values obtained at two reference stations outside the affected area.

Controlled field vegetation tests have been performed during the winter vegetation season of 1998/1999 as a supplement to ecosystems monitoring and in order to supply site-specific data for human health risk assessment (Departamento Agronomía, UCO, 1999). The tests utilised three edible crops, barley (*Hordeum distichum*), triticale (*Triticum aestivum* × *Secale cereale*) and rape (*Brassica napus*), and one supposedly bio-accumulating plant - Ethiopian mustard (*Brassica carinata*).

The results of the tests indicate that metal extraction from soils with representative residual metal concentrations, by physiologically mature plants, is approximately 2 to 8 times higher than metal up-take in a control area. An exception is the extraction of thallium by the rape plants which was found to be as much as 200 times higher. The concentration of metals in the edible parts of the plants, i.e. grains and seeds, is negligibly higher than the concentrations in the control area, with the exception of thallium concentration in seeds of rape and mustard which is approximately 30 times higher than in the control area. The mustard seeds also show 20 times higher concentration of arsenic. Nevertheless, metal concentrations in seeds and grains do not exceed MACs of foodstuff (note, criteria for thallium are not known).

7. HUMAN ASPECTS

The accidental dam failure posed a big challenge for the entire Boliden company. The working load was large and decisions had to be made under time pressure. It was unavoidable that many persons involved were often under heavy stress. In order to learn from the experience, Boliden decided to follow up on the personal experiences of those involved. 65 persons received detailed questionnaires, which were returned anonymously. Some of the conclusions were that (Englyst et al 1999): the needs for information, for both Boliden employees and hired consultants, were not fully met; the majority of the involved personnel noted crisis reactions in themselves; the supporting structure was strong both from the company and from families; one year after the accident, 9 persons still thought that their health was adversely affected by their involvement in the project. Naturally, the feeling that the information was not sufficient also made people feel that the responsibilities and the objectives of the work were not clearly defined. Fortunately, the prevailing opinion amongst the involved persons is that the involvement in the project has been personally and professionally developing and that the results of the clean-up are to be considered as a success.

8. COSTS

The cost of the clean-up of the northern sector finishing in December 1999 was 25 MUSD. According to the newspaper information, the authorities have spent 165 MUSD cleaning the southern sector but that also includes the cost for expropriating the area for the Green Corridor project (of which the affected area forms one part) in which the Doñana Park will be connected to the Sierra Morenã Park by a 40 km long green corridor. The objective is to reduce the isolation of the animal populations in Doñana. The estimated cost for the tailings pond closure is 37 MUSD, project management and quality control included. The cost for buying the fruit harvest for 1998 was 9.9 MUSD. Even though there was nothing wrong with the fruit, it was deposited in a hazardous-waste deposit.

9. DISCUSSION AND CONCLUSIONS

The need for internal and external information cannot be overestimated in this type of situations. Significant resources have to be allocated to dealing with the mass media.

It is unlikely that the accident will have any significant long-term effects on the river water quality. The affected soils contain elevated concentrations of metals and analyses of the vegetation from the affected area show increased accumulation of metals compared to the control areas. However, the metal concentrations in grains from cereals grown in the affected soils do not exceed MACs. Whether these concentrations imply any human health or ecological risk still needs to be evaluated. A good baseline study, conducted before the accident, would have significantly facilitated the evaluation of the effects of the accident.

Considering the starting point for the clean up operation and the limited time available before the rains, the clean up was a major challenge. However, although the situation was very much facilitated by the dry weather conditions, the job was done by the people. These people, who during the hard work went through many emotional stages, rightfully feel proud of their job and consider it a success.

ACKNOWLEDGEMENT

Concha Ortiz, Hugh Blair, Ismael Barbero, Manfred Lindvall and Lars-Åke Lindahl are gratefully acknowledged for their input to this paper.

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