C.1-Fate, transport and risks

ENVIRONMENTAL RISK ASSESSMENT OF RED MUD CONTAMINATED SOIL IN HUNGARY

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Abstract

The red mud catastrophe of 2010 in Hungary has caused a hardly manageable environmental problem, due to the lack of published information and of the general knowledge on red mud, especially regarding the hazards and risks posed by it to humans and environment.

Even a seemingly simple situation, – such as agricultural soil flooded by suspended solid in alkalic liquor –becomes extremely complex, due to the interactions with the environment and the ecosystem. The difficulties in its management comprise the lack of experience and the non-availability of case studies which would support the decision making of the professionals, mainly in the first catastrophe-response. This is the main reason why the authors consider that dissemination of such a case study is very important, so that the professionals obtain first-hand information on the fate, behavior and the adverse effects of red mud on soil.

This paper introduces the results of a tiered risk assessment and some of its analytical and experimental basis. The work has planned to support managing priority risks and decision making on the selection of the most efficient risk reduction measures for remediation of the agricultural soil in the impacted area. The risk assessment aims to assess and determine the following practical parameters: concentration and mobility of the Na^+ and OH^- ions at the site; the acceptable Na^+ and alkalinity levels in soil and groundwater; losses in habitat function and other ecological services in NaOH flooded soils; changes in the water and air balances of the soil; the influence on soil characteristics of the incorporated red mud; maximum percentage of red mud to be mixed into the soil; plant growth and production on red mud contaminated soil; risk posed on residents and farmers on the short and long term; the most risky exposure pathways; the short term and long term deteriorations of the soil and the site specific quality targets. There are many more problems and question in connection with other environmental compartments, such as surface waters, sediments, wetlands, or the cost efficiency of the clean-up and remedial activities, as well as people's and food-industries' response to products (vegetables, grains etc) grown on red mud contaminated soils, – but these questions are not discussed and answered in this study. Changes in the bauxite processing and storing technology, implemented in between – are also not evaluated. For further information see also: Gruiz, 2010; Reeves et al, 2011; Mayes et al, 2011 and Gruiz et al, 2012.

1. INTRODUCTION

On the 4th October 2010, the corner of the No. 10 red mud storage pond at the alumina production facility MAL, in Ajka, Hungary broke. 800 000 m^3 red mud of high alkalinity (pH 13) streamed with high velocity, has swept bridges, cars and unfortunately led to human casualties; 10 people died, 60 injured.

Figure 1 Red indications on houses and soil; 2. Clean-up works in the villages; 3. A former home; 4. In memory of the victims

It flooded three villages, thousands of hectares of agricultural land and caused intense environmental damage in a 10 km long section of the Torna valley, which is the upper watershed area of Marcal River, ending into the Rába River, which reaches the Danube (Gruiz, 2010; Reeves *et al*., 2011; Gruiz, 2012).

In spite of the fact that ten people were killed due to the corrosivity of the alkalic mud flow, most of the professionals intended to deal with the “heavy metals” in the environment. The inhabitants were afraid and tried to remove or just hide the red color. Hundreds of soil samples were analyzed for contaminants, but the Na-ion has not been measured and its fate has not been followed in the soil for many months after the accident. . Much effort was devoted to the removal of the thin red mud layer from soil surfaces during the springtime, 4–5 months after the accident, when the alkalinity has been already washed out by snowmelt and rain from the red mud covering the soil surfaces. All these facts show very clearly that the risk based management has still not been put into practice, the risk based judgment is still missing from the thinking of the practical professionals.

Figure 2 1. Breach of the dam (October 2010); 2. Construction works shown from the inside of the dam (November 2010); 3. Closure of the reservoir with a new, low dyke (December 2010), in the foreground of the cross section of the broken dyke.

Most of the red mud flooded area is covered by silty sand loess, fluvial and run off residual. The topsoil has a typical light mechanical composition (gravelly coarse sand, sand, loamy sand) with 30% gravel in the depth of 0–30 cm. The thickness of the humus layer is more than 30 cm and organic matter content is around 2%. The depth of the groundwater level is generally 0.5–1.5 m meters with seasonal changes. The extent of the flooded area is more than 1000 hectares.

2. RISK MANAGEMENT CONCEPT FOR RED MUD FLOODED SOIL

The urgent actions were aimed to protect human life, animals and other values, such as water. The decisions were based mainly on human health and socio economic aspects in this phase and the measures were protection of human life and exclusion of life threatening hazards, displacement of people from endangered or deteriorated parts of the villages, isolation of the dyke, neutralizing the alkaline flux (gypsum was added in large quantities to adjust pH to 9.5) to protect aquatic ecosystem of the rivers downstream (Mayes *et al.*, 2011), cleaning residential areas, open surfaces, removing deteriorated buildings, debris and cleaning river bed.

The measures addressing soil were planned to be carried out after the winter period, so that we had enough time to establish the conceptual risk model and quantitatively assess the current and future risks, taking into consideration natural attenuation and laboratory simulation test results.

The conceptual risk model illustrates clearly the primary and secondary sources, the transport pathways, the impacted environmental compartments and the users of the atmosphere, waters and soils, namely the ecosystem members and human receptors.

The main steps of the risk management of the red mud flooded soil are:

- Creating the conceptual risk model of the red mud flooded soils (Figure 3)
- Site assessment and monitoring;
- Laboratory analyses, ecotoxicological testing, simulation tests;
- Risk assessment and characterization based on field assessment and lab experimental data
- Risk reduction by removal or incorporation of red mud;
- Long term monitoring of the fate and transport of Na^+, alkalinity and sodification;
- Revegetation;
- Validation and verification of the applied clean-up and soil treatment technologies.

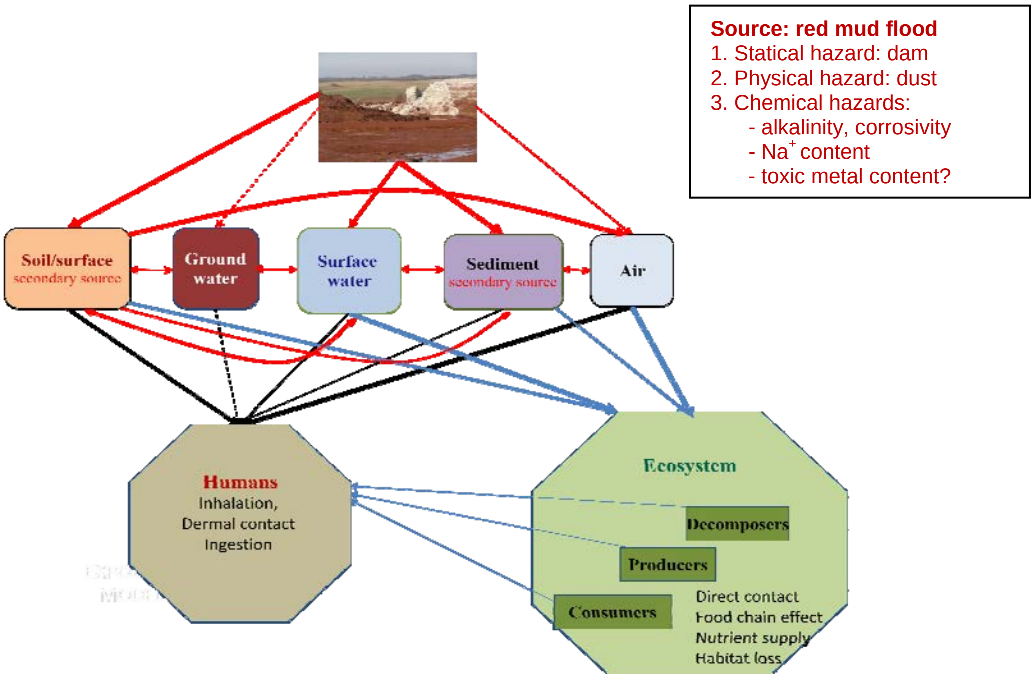

Figure 3 Conceptual risk model showing primary and secondary sources, transport routes and the exposure of the receptors

The targets of the problem-specific risk characterization methodology – developed by us – was to quantify the risk posed on human health and ecosystem, to estimate the maximum permissible red-mud proportion to be mixed into local agricultural soil and to enable the comparison of the candidate risk mitigation measures as well as long term soil quality deterioration.

For reducing the risk on more thousands of hectares of agricultural land, two alternatives have been evaluated: removal of the red mud layer and leaving it and mixing it into the soil. The removal of the alkalic liquor was not a realistic alternative, given that it has already infiltrated into the deeper soil layers.

The repeated sampling campaign and the results of the integrated monitoring (physico-chemical analyses and environmental toxicity testing including simulation microcosms) confirmed the prognosis of the risk assessment, providing additional information on the maximum incorporable red mud and its effect on soil ecosystem, sodification and plant production.

3. RISK ASSESSMENT STRATEGY

The focus of risk assessment is the soil, and its users, the human and ecosystem receptors,.The following risk compartments were considered:

- Air pollution by particulate matter and its human health risk;
- Human health risk of alkaline soil inhalation, ingestion and dermal contact;
- The effect of the alkaline/caustic slurry seeping into the soil;
- The effect of red mud mixing spontaneously or in a planned way into soil;
- Groundwater and soil toxicity;
- The risk of toxic metals in red mud flooded soil.

Environmental risk was assessed and characterized in three tiers.

1. Inventory of the hazards and risks and priority setting of the main risks of red mud to soil;
2. Qualitative evaluation of the risk scenarios, determined by the planned risk reduction alternatives (removal or mixing into soil);
3. Quantitative evaluation of the main risk components.

A detailed inventory is shown below with red-mud caused potential changes which may affect adversely the agricultural soil.

- Infiltration of the alkaline liquid phase into soil and groundwater
    - Soil and groundwater alkalinization;
    - Increase of soil and groundwater Na content;
    - Modification of the chemical forms and mobility of plant nutrients and toxic metals;
    - Changes in soil nutrient quality / quantity and water cycling;

  - Increased risk of sodification;
  - Soil and groundwater toxicity;
  - Plant growth inhibition, limited nutrient supply, deteriorated nutrient household;
  - Caustic/corrosive effect of the contaminated soil on humans;
  - Detrimental effect of contaminated soil and ground water on humans.
- Fine grained red mud on the soil surface and in the soil
  - Red mud plugs the soil pores resulting anoxic conditions in the soil;
  - Meanwhile the micro-plug hinders penetration of further contaminants;
  - Damaging effect of the (temporary) anoxic conditions on soil living organism;
  - Detrimental effect of (temporary) anoxic conditions on plant growth.
- Hazards subsequent to drying of the fine grained red mud
  - Dusting, dust deposition on remotely located surfaces and threat to humans by dust inhalation, hazard of the PM10 and PM2.5;
  - Hazard due to caustic effect, threat to humans by ingestion;
  - Supposed toxic element content.
- Plowing the red mud into soil means the incorporation of the residual red mud into deeper soil layers to prevent dusting. The hazards are:
  - Increased alkalinity, Na and Fe content;
  - Increased sodification potential;
  - Toxicity to soil ecosystem and cultivars.
- Revegetation/planting
  - Successful planting may reduce dusting but might increase toxicants (if present) bioaccumulation;
  - Plant growth inhibition;
  - Secondary poisoning through plants grown for human consumption.

Risk reduction measures and their expected efficiency are evaluated by using the same tiered risk assessment tool for the following scenarios in accordance with the risk reduction options:

- No action;
- Removal of the red mud from the surfaces and its isolated storage;
- Mixing the red mud into soil by plowing;
- Revegetation of the soil after removal or mixing red mud into soil;
- Storage of the removed red mud or its mixture with soil, and isolation of the dumped red mud by vegetation cover or physical encapsulation.

4. DETAILED RISK ASSESSMENT

Risk assessment focused on soil, with special emphasis on:

- Air pollution by particulate matter and its human health risk;
- Human health risk of alkaline soil inhalation, ingestion, dermal contact;
- The effect of the alkaline/caustic slurry seeping into the soil;
- The effect of red mud mixing into soil;
- Groundwater and soil toxicity;
- The risk of toxic metals in soil.

4.1. HUMAN HEALTH RISK ASSESSMENT

Human health is endangered by particulate matter and by the caustic effect of red mud through inhalation, dermal contact, and ingestion by dust or food. Risk was characterized by using site specific exposure concentrations compared to generic screening values and epidemiological information.

Dust inhalation

Subsequent to the accident 12 additional (to the existing two) measurement points for continuous measurement of the PM_{10} fraction were placed in the Ajka and Torna valley area. After the accident the former average of PM_{10} values were exceeded at 4 measurement stations at a moderate scale: 43–55 compared to the required 40 µg/m^3. The number of exceedances is significantly higher in the first 5 months: 49–72 instead of the permitted maximum of 35. The forecasted reduction has been validated by data measured at the end of 2011, upon completion of the clean-up works: 25–30 µg/m^3 with 5–15 exceedances, which is not higher than the values of the previous years. Unfortunately the change of bauxite processing and storage from wet to dry technology in 2012, increased extremely the PM10 content of the air in the area.

Caustic effects on humans

NaOH is irritative and corrosive to the eye, skin and the respiratory system, causing mainly occupational health problems in the practice.
Human health risk of NaOH has been calculated as an RCR (Risk Characterization Ratio) comparing the exposure results to the occupational health quality criteria or to epidemiological data (OSHA 2011; NIOSH, NaOH; INCHEM 2002). The inhaled amount was calculated from a highly overestimated 10% NaOH content of the desiccated red mud and the measured PM_{10} concentrations. Irritation and corrosion were evaluated based on pH.

- Inhaled NaOH, calculated for a worst case scenario resulted in an RCR value below 1/1000.
- Ingestion of NaOH calculated for an average ingestion rate for adults and children resulted 1.7 mg/kg/d and 8.5 mg/kg/d respectively. RCRdig values are 1/1300 and 1/6400 in the worst cases, the risk of contaminated soil ingestion is negligible.
- Dermal irritation / corrosion has been evaluated for six risk scenarios as shown in Table 1.

Table 1. Risk of dermal irritation of red mud for six risk scenarios

Risk Scenario	pH	Risk Characterization Ration	Verbal risk characterization
Freshly discharged red mud	pH >13	RCR>10	significant
Red mud on soil: after 5 months	pH 12.5	RCR=5	significant
Red mud on soil: after 10 months	pH 12.3	RCR=3	significant
Soil surface after red mud removal	pH 8.0	RCR~0	negligible
10% red mud in soil	pH 8.8–9.9	RCR=0.001–0.01	negligible
Disposal of removed red mud	pH 11–12.3	RCR=0.1–3	moderate–significant

4.2. RISK OF ALKALINITY AND SODIUM ON SOIL QUALITY AND FUNCTION

The two main risk-sources are alkalinity and socium ion concentration in soil not only for humans but also for the soil and its ecosystem.

Alkalinity

Based on reference soils' average pH (pH 8.15±1.1), local geological, hydrogeological and soil properties and on measured ecotoxicity data, the following risk classes were created:

- pH 8≥ negligible risk
- pH 8–8.5 small risk
- pH 8.5 threshold of moderate risk
- pH 8.5–9.0 moderate risk
- pH 9 threshold of significant risk
- pH 9< significant risk

Field samples after red mud removal gave an average of pH 8.00±1.0, representing negligible risk. Incorporating 10% red mud into a 50 cm deep soil layer resulted in a pH 8.8±0.5, representing moderate risk. Revegetation of the red mud contaminated soils further lowered the pH with a value of 1.7 in laboratory experiments, resulting in negligible pH-risk. Plant growth is inhibited by pH above 9.5.

Sodium ion

High Na-concentration in the soil increases the risk of sodification. Based on the typical Na-content of 200–300 mg/kg of the floodplain of the Torna Creek, the recommended site specific screening value is: 900 mg/kg with the notification, that whenever Na-concentration is above 900 mg/kg, the sodification potential should be evaluated and the Na-concentrations and forms are to be monitored.

Table 2. Soils Na-content, its predicted attenuation and the risk of sodification

Red mud / scenario	Na 7 months mg/kg soil	RCR 7 months	Verbal risk characterization	Risk reduction guidance
Red mud (RM) on the top of soil	**3100**	RCR_{Na}=3.4	High	Not acceptable, remove
Soil after RM removal	**200**	RCR_{Na}=0.1	Negligible	Unlimited use
Incorporation 5% RM	**420**	RCR_{Na}=0.2	Moderate	Unlimited use
Incorporation 10% RM	800	RCR_{Na}=0.8	Moderate	Usable
Incorporation 10% RM and low attenuation	1600	RCR_{Na}=1.6	Significant	Use specific plants, apply monitoring and control
Deposition of RM with soil	15 000	RCR_{Na}=15	Very high	Isolate by vegetation, if plants are able to grow
Deposition of only RM	38 600	RCR_{Na}=40	Very high	Encapsulate

measured value estimated value

Attenuation of Na-concentration is significant in the catchment, due to the intensive groundwater flow. Based on field data measured for three months, the attenuation factors are 0.8 for red mud (left on the soil surface); 3.5 for the upper and 2.0 for the deeper soil layer. As an outcome of these findings we estimated 3 months half-life time for Na^+ in the local contaminated soils. We used this attenuation factor to estimate the Na-exposure 7 months after the accident. The risk assessment results are summarized in Table 2. The reduction of Na-content in soil was confirmed by the laboratory microcosm experiments run for the simulation of the sodification process. Meanwhile these experiments draw our attention to the long term deterioration of the texture and structure of the soil, meaning that 800 mg/kg Na-content causes sodification in the local soil.

4.3. EVALUATION OF THE TOXIC METAL CONTENT OF RED MUD FLOODED SOILS

The toxic metal content of the overflown red mud is under the screening values for sewage sludge application on soil. On the other hand "alkalic digestion" of the soil (rather its long term soaking in NaOH solution) may mobilize from the soil some metallic anions such as arsenate, selenate, nickelate, chromate, vanadate or molibdenate.

The applied risk assessment approaches are: comparing the soils' measured metal content both to the Hungarian soil screening criteria and to the criteria for sewage sludge disposable on soil. The ratio of the measured concentration and the screening concentration is the RCR_{metal}. Summary results are shown in Table 3.

Metal-content of red mud

The average toxic metal concentrations of 11 red muid samples collected from the reservoirs and from the flooded surfaces is given in Table 3 in comparison to soil and sewage sludge screening concentrations.

Table 3. Average metal content (mg/kg ed mud) of red mud samples

Metal (mg/kg)	As	B	Ba	Cd	Co	Cr	Cu	Hg	Mo	Na	Ni	Pb	Se	Sn	Zn
Red mud average	36.5	22.6	80.1	1.3	47.2	419	38.5	0.5	0.2	38 600	182	84.8	kh	25.2	105
Sewage sludge SC*	75	-	-	10	-	1000	-	10	-	-	200	750	-	-	2500
Soil SC**	15	-	250	1.0	30	75	75	0.5	7	-	40	100	1	30	200

Regulations: *HU-50/2001 **HU-10/2000 SC = Screening Concentration

higher than soil SC but under sewage sludge SC | slightly higher than soil CS | under soil SC

Measured metal concentration in red mud flooded soils – field data

The average metal content of the reference and of the flooded soils, – except selenium (Se) – were under the soils' screening concentration (HU-10/2000). The deviations of As and Ni concentrations were high, but not in correlation with the red mud flood. A site specific limit value of 25 mg/kg was recommended for As. Selenium occurs in the area at concentrations higher than 1 mg/kg, (this is the Hungarian screening value), but it is under the European limit value of 3 mg/kg, which was recommended by the experts for the Torna creek area as a site specific limit value.
The risks of the four priority metals – As, Cr, Ni and Se – were evaluated for the contaminated soil and associated with the risk reduction scenarios.

Table 5 Summary of the risk posed by toxic metals to soil

Scenario	RCR_{As}	RCR_{Cr}	RCR_{Ni}	RCR_{Se}	Verbal characterization	Action required
Reference soil	0,44	0,39	0,45	0,6	Small	No action
RM on top of the soil*	**1,5**	**5,6**	**4,5**	0	Significant	Remove RM or mix in soil
Removal of RM	0,6	0,4	0,6	0,5	Moderate	Unlimited use
RM mixed into soil**	0,5	0,4	0,9	0	Moderate	Unlimited use
5% RM in soil	0,6	0,5	0,5	0,4	Moderate	Unlimited use
10% RM in soil	0,8	0,8	0,7	0,4	Moderate	Unlimited use
Soil:RM = 2:1	0,8	**2,1**	**1,6**	0,3	Significant	Limited plant use
Soil:RM = 1:1	1	**3**	**2,5**	0,2	Significant	Encapsulation

*considered as soil; **considered as sewage sludge; **above soil SC**

4.4. DIRECT TOXICITY TESTING OF FIELD SOIL SAMPLES

Red mud contaminated soil was sampled from several points of the flooded Torna valley and characterized for soil physic-chemical characteristics, contaminant concentrations and soil-ecotoxicity. The concept of sampling was that three samples were taken from the same locality: one soil sample (30 cm) together with the covering red mud, another 30 cm deep one after the removal of the red mud from the surface, and a third one from 30–60 cm depths. The plant growth and the springtail survival results are shown in Figure 4 and 5.

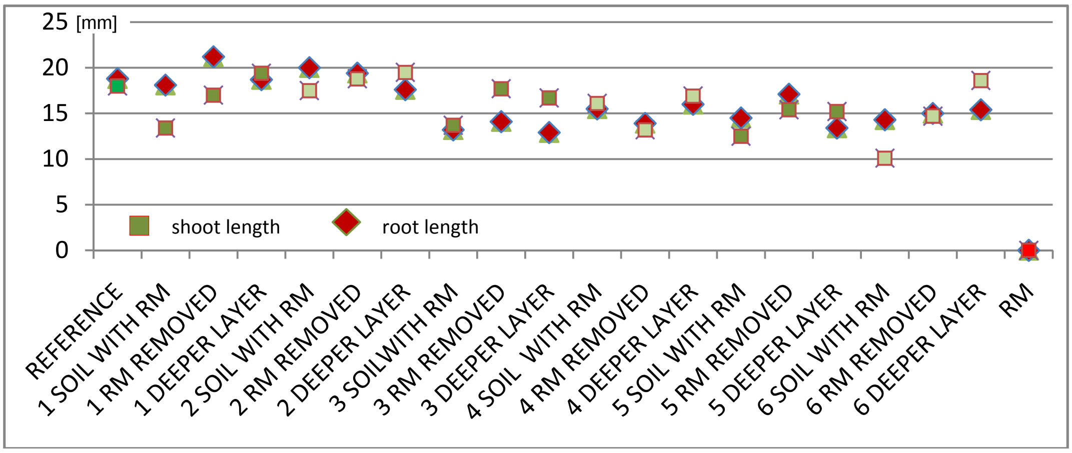

Figure 4 Plant shoot and root growth on 6 localities of the Torna valley

Root growth does not correlate with the red mud contamination, shoot growth is reduced in all of the red mud containing soil samples; it is an indirect effect of the pH, limiting plant nutrient availability.

The springtail *Folsomia candida* tolerates red mud and alkalinity well, the differences compared to the reference are not significant. It is considerable, that 5 animals (from 20) survived in red mud alone (Figure 5).

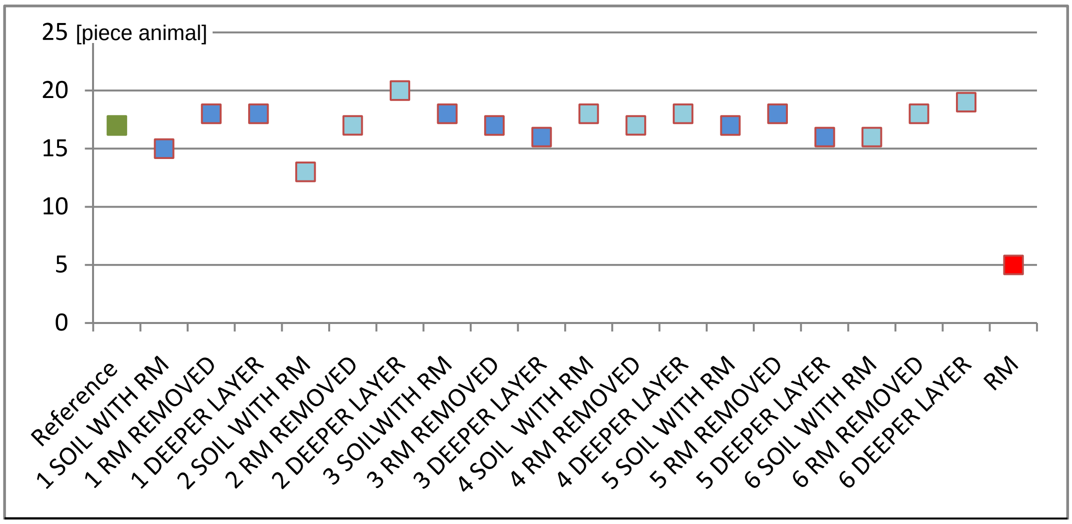

Figure 5 Survival of the *Folsomia candida* testorganism in field samples from the red mud flooded Torna valley soil

4.5. SIMULATION OF RED MUD CONTAMINATION IN SOIL MICROCOSMS

Risk assessment is partly based on field result, partly on the findings of the laboratory experiments. Microcosms were carried out for observing some of the field scenarios, such as covering soil with RM, infiltrating alkali liquor into soil, mixing red mud at different ratios into soil. The measured endpoints of the microcosm tests are physical and chemical characteristics and behavior of the soil, the indicators of sodification, some biological responses, such as microbial activity and the toxic effect of the red mud contaminated soil on soil living microorganisms, plants and animals. The integrated monitoring results of the microcosms have been utilized for risk assessment of the initial situation and for the evaluation of the effect of time and of the remediation technologies. Some of the monitoring-results of the microcosm tests are shownbelow .

Microbial cell-concentration in soil mixed with increasing proportion of red mud

We measured separately the cell concentration of the aerobe heterotrophic bacteria with two different methods (by plating and diluting), fungi and anoxic/anaerobic bacteria (Figure 6).

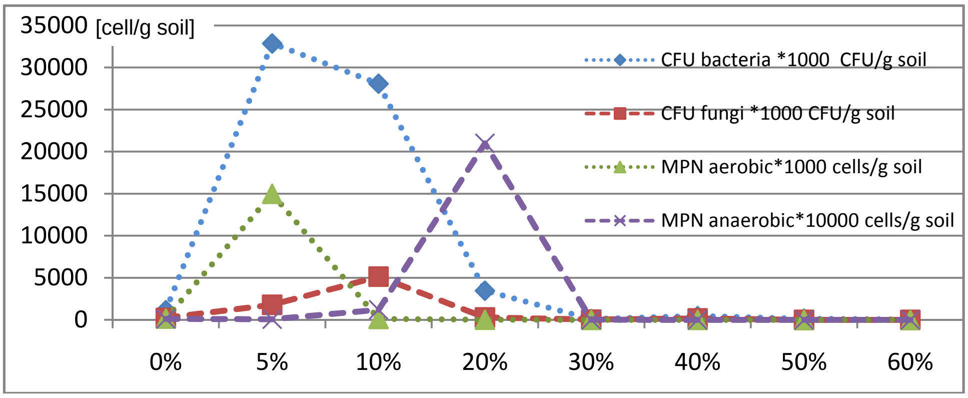

Figure 6 Microbiological cell concentration in soils with growing red mud content

The reference soil had low microbial concentration, which has increased upon addition of 5% and 10% red mud. 5% RM resulted 10^4 times more aerobic heterotrophic bacterial cells than the reference; 10% RM containing soil had still high aerobic bacterium concentration and maximum fungal cell concentration. The anoxic/anaerobic cell concentration increased by adding 20% RM into soil.

Toxicity of soil contaminated with increasing percentage of red mud

The same series of red mud containing soil was tested with *Sinapis alba* (white mustard) and the springtail *Folsomia candida* in order to find the acceptable limit of RM in soil. Seed germination, shoot and root growth can be seenion Figures 7 and 8.

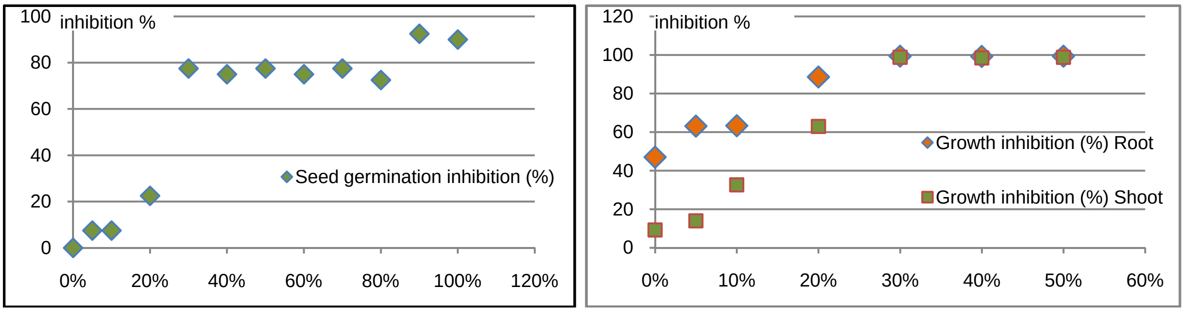

Figure 7 Seed germination and plant growth in soils with growing RM content

Seed germination is not significantly inhibited by 20% red mud, shoot and root growth is inhibited by 10% red mud in the soil. The 20% RM in soil is a limit value for the springtail too.

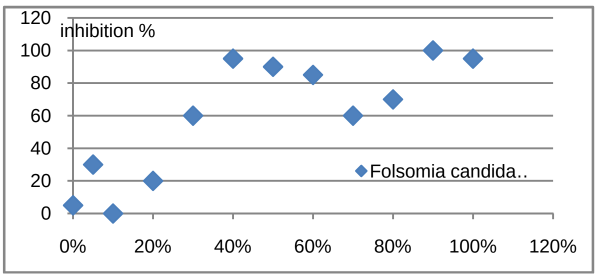

Figure 8 Survival of the springtail *Folsomia candida* in soils with growing RM content

From the biological and ecotoxicological results we defined the red mud concentrations, causing 10%, 20% and 50% inhibition in growth or survival of the testorganisms (Table 6). Considering all microbial, plant and animal testorganisms, the 10% adverse effect (inhibition) can be considered as the lower threshold of having an effect at all, and the 20% inhibition as significant.

Table 6 Inhibitory effect of red mud on soil ecosystem members

Test	% red mud in soil causing 10% inhibition	% red mud in soil causing 20% inhibition	% red mud in soil causing 50% inhibition
Soil microorganisms	30	35	40
Seed germination	13	18	25
Plant shoot growth	5	8	18
Plant root growth	6	8	15
Collembolan lethality	15	20	25

The red mud percentages in soil, with significant direct effect on microorganisms, plant germination and soil living animals are 35%, 18% and 20%, respectively. Plant growth may be inhibited by 8% red mud in the soil, due to the accumulated direct inhibitory effect of alkalinity, soil texture changes, and to the reduced availability of cationic plant nutrients, such as K^{+}, Ca^{2+}, Mg^{2+}, etc due to high soil pH

5. RISK REDUCTION AT THE RED MUD FLOODED LAND

Risk reduction started after quantitative characterization of the risk associated with the most hazardous risk components. The main steps of risk mitigation and risk reduction were:

- Protection of human life and exclusion of life threatening hazards.
- Isolation of the dyke: it was finally closed 7 months after the accident.
- Neutralize alkaline flux gypsum was added in large quantities to adjust pH to 9.5 and protect aquatic ecosystem of the Torna Creek and the rivers downstream. (Mayes *et al.*, 2011).
- Cleaning residential areas, open surfaces, removing deteriorated buildings, debris.
- Gradual cleaning of the river bed.
- Removal of the secondary contaminant sources, including red mud inundated surfaces, wetlands and ponds.
- Risk reduction of agricultural land by removal or incorporation of red mud into soil
- Long term monitoring of the fate and transport of Na, alkalinity and sodification.
- Revegetation.
- Verification of the applied soil treatment technologies.

Table 7 Scoring based risk assessment and the assigned risk reduction measures

Evaluated risk scenario		Risk score max.100	Risk characterization	Action necessary?
1. Red mud layer on soil: infiltrated alkaline solution, desiccated red mud				
1.1.	Below5 cm thick red mud layer	63	High risk	Action required
1.2.	5–10 cm thick red mud layer	74	Very high risk	Action required
1.3.	10–20 cm thick red mud layer	85	Very high risk	Action required
1.4.	Above 20 cm red mud layer	91	Very high risk	Action required
2. Red mud removal: caustic solution infiltrated, solid red mud layer removed				
2.1.	Below5 cm thick red mud layer	14	No risk	No action required
2.2.	5–10 cm thick red mud layer	19	No risk	No action required
2.3.	10–20 cm thick red mud layer	38	Low risk	Not likely required
2.4.	Above 20 cm red mud layer	44	Medium risk	Likely required
3. Red mud incorporated into soil				
3.1.	Below5 cm thick red mud layer	16	No risk	No action required
3.2.	5–10 cm thick red mud layer	25	Low risk	Not likely required
3.3.	10–20 cm thick red mud layer	41	Medium risk	Likely required
3.4.	Above 20 cm red mud layer	49	Medium risk	Likely required
4. Soil with planted vegetation				
4.1.	Removed red mud layer >10 cm	21	No risk	No action required
4.2.	Mixed in red mud layer <5 cm	14,5	No risk	No action required
4.3.	Mixed in red mud layer 5–10 cm	20,5	Low risk	Not likely required
5. Disposal of the removed red mud		78	Very high risk	Action required

6. SUMMARY

The complex assessment/monitoring and evaluation of the detrimental effects of red mud on soil has been executed for six months after the accident. A tiered risk assessment was done based on the results of field sampling and physico-chemical and ecotoxicological testing, simulation tests and microcosm experiments. The risk reduction options were assigned to the different risk scenarios.

The most important findings focusing on the red mud contaminated agricultural land are the following:

- Air pollution by particulate matter and its human health risk became acceptable by the end of the clean-up activities. (The newly introduced dry red mud disposal increased dusting again!)
- Risk of alkaline soil inhalation, ingestion and dermal contact became negligible by the end of the clean-up activities.
- The alkaline infiltrate poses high risk to soil structure and vegetation, but the attenuation of alkalinity is significant.
- Fine particles of the red mud slurry plugged soil pores resulting anaerobic soil conditions and killing of soil dwelling animals. Tilling reinstalls aerobicity.
- The effect of mixing incremental amounts of red mud into the microcosms has forecasted a higher acceptable mixing dose (8–10%), than the calculated 5%, but sodification still remains a threat.
- Na-ion-concentration increased significantly, exceeding the site specific screening level. Significant Na-attenuation (half-life: three months) may reduce the risk on the long term.
- Directly measured toxicities were not significant, and were mainly associated with alkalinity (pH).
- The risk of toxic metals is not significant, some metals have been mobilized from the soil due to alkalic conditions (phosphate, arsenate, nickelate, chromate, molibdenate and selenate), but without causing ecotoxicity, plant growth inhibition or food chain effects.

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