Remediation strategies overview – Remediation of metal contaminated sites

L. Diels
Flemish Institute for Technological Research, Vito, Mol, Belgium

NATO – CCMS meeting
Prevention and Remediation Issues
Non-ferrous mining sector

September 7 - 11, 2003
Baia Mare, Romania
Problems related to metals mining, metals processing or surface treatment

- Acid mine drainage
- Air emissions: heavy metals contaminated land
- Landfills containing jarosite, goethite, gypsum, slags, fines:
  Anaerobic or aerobic leaching especially in the presence of organics
  - Solubilisation of metals and metalloids
  - Contamination of surface water
  - Disasters
  - Leaching into groundwater

- Diffuse pollution
- Huge groundwater plumes (sometimes very deep)
- Surface water pollution
Integrated Management System (IMS) for Megasites

1. Megasite
   1. Definition of the site as a megasite
   2. Regulations and boundary conditions
   3. Definition of the organisatorial role and management of the megasite

2. Risks and risk reduction
   1. Megasite conceptual model
   2. Regional risk approach by clustering
   3. Risk reducing measures per risk cluster

3. Management scenarios or conceptual model
   1. Risk reduction scenarios at megasite scale
   2. Effects and uncertainties of the risk scenarios
   3. Cost effective calculation of the selected scenarios
   4. Priorities of the scenarios

4. Long term planning and management of a megasite
   1. Technical implementation- en monitoringplan
   2. Long term audit of the IMS
1. Megasite

1. Definition of the site as megasite
   • Large contaminated area, different pollutants
   • Many proprietaries or concession holders
   • Many stakeholders
   • Many end-users
   • Non-acceptable costs for the remediation

2. Regulatory directives and boundary conditions
   • EU - Framework directive Water
   • EU - Groundwater directive
   • Local legislation

3. Definition of the organisatorial role and management of the megasite
   • Future use of the site? (tourism, continuity of industrial activities?)
2. Risks and risk reduction

1. Megasite conceptual model

1.1. Potential sources and contaminants

- Open pit or underground mines
- Waste heaps, lagunes, settling ponds, landfills
  - Solubilisation
  - Biological oxidation, reduction reactions
  - Metals, acids, cyanides

1.2. Dominant fate and transport characteristics

- Permeability
- Impermeable clay or bedrocks
- Fractures?
- Retardation: ion-exchange, sorption, binding,….
- Hydrogeological flows and flow rates
2. Risks and risk reduction

1. Megasite conceptual model

1.3. Potential receptors
   - Soil: residential, natural areas
   - Groundwater
   - Surface water, rivers
   - Deeper aquifers, drinking water wells

1.4. Final conceptual model
   - Flux to receptors
   - Interplanes related to measures
   - Source versus plume management
2. Risks and risk reduction

2. Regional risk approach by clustering

2.1. Integration in the risk evaluation of:
   - Transport modelling
   - NA en immobilisation potential of the site
   - Spatial planning issues

2.2. Definition of the basic elements for the IMS
   - Use GIS source-path-receptor analysis
   - Definition of risk-clusters
   - Understand the links between the clusters
   - Confirm the risk clusters with the stakeholders

2.3. Risk-reduction measures per risk cluster
   - Mobility: bioavailability methods
   - NA/MNA/INA
   - Intervention technologies
Conceptual model of the Risk Management Zone (= mining site)

E1. Spreading via the air to soil
E2. Run off to surface water
E4. Leaching in quaternary aquifer
E3. Transport via windows in clay layer to deeper aquifer
E5. Threatening drinking water wells
3. Management scenarios

3.1. Risk reduction scenarios at megasite scale

Source management versus plume management:
- Source is very large and diffuse
- Source management is too expensive (unless economical interest)
  ➔ Plume management

3.2. Effects and uncertainties of the risk scenarios

3.3. Cost effective calculation of the selected scenarios

3.4. Prioritisation of the scenarios
4. Long term planning and management of a megasite

1. Building of a technical implementation- and monitoring plan
2. Long term audit of the IMS
Measures at Interplanes of Risk Management Zones

- Unsaturated zone
  - Transport to soil (e.g. dust) and to groundwater (by rain) in residential areas and natural areas
    ➔ (Phyto)stabilisation (short term)
    ➔ Phytoextraction (long term)
Immobilisation unsaturated zone

- Immobilisation
- Leaching
- Phytostabilisation
- Additives mixing
- Unsaturated zone
- HM contaminated
- HM leaching
- No HM leaching
- Groundwater
- Rocks
Evaluation of immobilisation tests

Mixing of contaminated soil with selected additives to reduce the bioavailability

- Batch tests
  - SEM/AVS:
  - BIOMET®:
  - Plants:
- Accumulation of metals by plants
- Lysimeter tests

\[
y = -0.0037x + 1.41 \\
R^2 = 0.82
\]
Measures at Interplanes of Risk Management Zones

- **Saturated zone**
  - Transport to surface water or deeper groundwater layers (e.g. drinking water wells)
    - Pump & treat
    - Natural Attenuation
    - In situ bioprecipitation
    - Reactive zones (e.g. in situ redox manipulation)
    - Permeable Reactive Barriers
    - Wetlands
Plume management options

<table>
<thead>
<tr>
<th>Options</th>
<th>Technical Complexity</th>
<th>Investment Costs</th>
<th>O &amp; M Costs</th>
<th>Land Use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Contaminated Site: No measures
Future Situation: No NA
Heavy metals in groundwater

• Nature of heavy metals:
  – Can not be degraded,
  – Only immobilized or transferred

• Mechanisms:
  – Bioremediation
    • Biosorption
    • Bioprecipitation
  – Chemical technologies
    • reduction (zero valent Fe)
    • cementation (zero valent Fe)
    • oxidation (KMnO₄, Na₂S₂O₈)
  – Physical technologies
    • Electroreclamation
    • Adsorption
    • Precipitation

• Techniques:
“Pump & treat”:
SAND FILTER INOCULATION

Removal of heavy metals from:
- Non-ferrous waste water
- Mine water
- Groundwater

Removal of:
- Zn (100%)
- Cu (100%)
- Co (95%)
- Ni (90%)
- Ag, As, Se, Cr, Tl, Pb

Heavy metal conc. with 24-hour sampling [mg/l].

Sandcirc. speed [mm/min] and N-nutrients [mg/l].
Moving bed sand filter concept

SORPTION AND DESORPTION OF METALS BY INOCULATED SAND FILTERS

1. Inlet distributor
2. Outlet
3. Dirty sand
4. Air-lift pump
5. Sand washer
6. Washer labyrinth
7. Wash water outlet
8. Cleaned sand

SORPTION OF METALS BY INOCULATED SAND FILTERS

1. Inoculation with metal-sorbing bacteria
2. Contact with metal-bearing solution
3. Removal of metal-loaded biomass
4. Recycle biomass for treatment
Natural processes of metal removal in soil and aquifer

- Adsorption and complexation of metals by organic substrates
  - Binding to carboxylic, phenolic groups of humic acids
  - Fe = Cu >> Zn >> Mn
- Microbial sulphate reduction followed by precipitation of metal sulfides
- Precipitation of FeO3, MnO2
- Adsorption to Fe(OH)3
- Metals uptake by plants
- Filtration of suspended and colloidal materials
- Alkalinity generation
In situ bioprecipitation

Sulfate Reducing Bacteria (or iron reducing bacteria) must be available in the aquifer. Sulfate must be available sufficiently. An organic substrate as methanol, ethanol, molasse, acetate, lactate, HRC, compost leachate must be present or added. Not too extreme pH (5 – 9), minimal content of nutrients (N en P), no oxygen and a low ORP.

\[
\begin{align*}
\text{SO}_4^{2-} + 8 \text{ e} + 8 \text{ H}^+ & \rightarrow \text{ S}^2- + 4 \text{ H}_2\text{O} \\
\text{CH}_3\text{COOH} + 2\text{H}_2\text{O} & \rightarrow 2\text{CO}_2 + 8 \text{ H}^+ + 8 \text{ e} \\
\text{CH}_3\text{COOH} + \text{SO}_4^{2-} & \rightarrow 2\text{HCO}_3^- + \text{HS}^- + \text{H}^+
\end{align*}
\]

\[
\text{H}_2\text{S} + \text{Me}^{++} \rightarrow \text{MeS} + 2\text{H}^+
\]

Groundwater flow

Plume
Metal processing, site 1a: groundwater + low sulfate content

<table>
<thead>
<tr>
<th></th>
<th>T0</th>
<th>T4</th>
<th>T8</th>
<th>T12</th>
</tr>
</thead>
<tbody>
<tr>
<td>aquifer + groundwater</td>
<td>1870</td>
<td>1400</td>
<td>1510</td>
<td>644</td>
</tr>
<tr>
<td>aquifer + groundwater + 0.5 mM HgCl₂</td>
<td>1840</td>
<td>1630</td>
<td>1940</td>
<td>2270</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%)</td>
<td>1350</td>
<td>922</td>
<td>1200</td>
<td>1500</td>
</tr>
<tr>
<td>aquifer + groundwater + 5 ml K-acetate (25%)</td>
<td>1570</td>
<td>884</td>
<td>1160</td>
<td>434</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%) + Dd8301</td>
<td>38</td>
<td>14</td>
<td>14</td>
<td>25</td>
</tr>
<tr>
<td>aquifer + groundwater + 5 ml K-acetate (25%) + Dd8301</td>
<td>16</td>
<td>144</td>
<td>118</td>
<td>14</td>
</tr>
<tr>
<td>aquifer + groundwater + Postgate C medium + Dd8301</td>
<td>1170</td>
<td>51</td>
<td>20</td>
<td>26</td>
</tr>
</tbody>
</table>

74 mg sulfate/l
# Metal processing, site 1a: groundwater + low sulfate content

<table>
<thead>
<tr>
<th></th>
<th>T0</th>
<th>T1</th>
<th>T4</th>
<th>T8</th>
<th>T12</th>
<th>T20</th>
</tr>
</thead>
<tbody>
<tr>
<td>groundwater</td>
<td>-68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>aquifer + groundwater</td>
<td>156</td>
<td>57</td>
<td>161</td>
<td>-95</td>
<td>-32</td>
<td>86</td>
</tr>
<tr>
<td>aquifer + groundwater + 0.5 mM HgCl₂</td>
<td>393</td>
<td>389</td>
<td>418</td>
<td>345</td>
<td>358</td>
<td>361</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%)</td>
<td>129</td>
<td>93</td>
<td>191</td>
<td>-118</td>
<td>-149</td>
<td>141</td>
</tr>
<tr>
<td>aquifer + groundwater + 5 ml K-acetate (25%)</td>
<td>189</td>
<td>-140</td>
<td>280</td>
<td>211</td>
<td>191</td>
<td>259</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%) + Dd8301</td>
<td>-224</td>
<td>-60</td>
<td>-28</td>
<td>-295</td>
<td>-219</td>
<td>-152</td>
</tr>
<tr>
<td>aquifer + groundwater + 5 ml K-acetate (25%) + Dd8301</td>
<td>-173</td>
<td>-165</td>
<td>217</td>
<td>107</td>
<td>-102</td>
<td>-188</td>
</tr>
<tr>
<td>aquifer + groundwater + Postgate C medium + Dd8301</td>
<td>-276</td>
<td>-172</td>
<td>-287</td>
<td>-354</td>
<td>-331</td>
<td>-337</td>
</tr>
</tbody>
</table>

74 mg sulfate/l
### Metal processing, site 1b: high sulfate concentration

<table>
<thead>
<tr>
<th></th>
<th>T0</th>
<th>T8</th>
<th>T20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn (µg/l)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer + GW</td>
<td>101000</td>
<td>79200</td>
<td>49000</td>
</tr>
<tr>
<td>+ HgCl₂</td>
<td>109000</td>
<td>94200</td>
<td>62400</td>
</tr>
<tr>
<td>+ acetate</td>
<td>109000</td>
<td>82800</td>
<td>15</td>
</tr>
<tr>
<td>+ 5 x acetate</td>
<td>103000</td>
<td>109000</td>
<td>90000</td>
</tr>
<tr>
<td>+ acetate + Dd</td>
<td>93100</td>
<td>77200</td>
<td>12</td>
</tr>
<tr>
<td>+ 5x acetate + Dd</td>
<td>96100</td>
<td>91600</td>
<td>72800</td>
</tr>
<tr>
<td>ORP (mV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer + GW</td>
<td>-117</td>
<td>-60</td>
<td>-36</td>
</tr>
<tr>
<td>+ HgCl₂</td>
<td>232</td>
<td>-50</td>
<td>-104</td>
</tr>
<tr>
<td>+ acetate</td>
<td>-146</td>
<td>-70</td>
<td>-229</td>
</tr>
<tr>
<td>+ 5 x acetate</td>
<td>-65</td>
<td>-78</td>
<td>-90</td>
</tr>
<tr>
<td>+ acetate + Dd</td>
<td>-194</td>
<td>-78</td>
<td>-259</td>
</tr>
<tr>
<td>+ 5x acetate + Dd</td>
<td>-103</td>
<td>-96</td>
<td>-88</td>
</tr>
</tbody>
</table>

Initial sulfate concentration: 506 mg SO₄²⁻/l
Metal processing, site 1c: Toxic metals

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>+ Molasse</th>
<th>+ methanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.3</td>
<td>5.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Eh</td>
<td>-93</td>
<td>-185</td>
<td>-344</td>
</tr>
<tr>
<td>SO4</td>
<td>1260</td>
<td>430</td>
<td>67</td>
</tr>
<tr>
<td>Cd</td>
<td>22900</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Zn</td>
<td>131000</td>
<td>99</td>
<td>26</td>
</tr>
<tr>
<td>Ni</td>
<td>45400</td>
<td>11300</td>
<td>29</td>
</tr>
<tr>
<td>Co</td>
<td>11200</td>
<td>1620</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Fe</td>
<td>24900</td>
<td>9640</td>
<td>652</td>
</tr>
</tbody>
</table>

Time: 30 weeks
# Industrial landfill, site 2, evolution As concentration (µg/l)

<table>
<thead>
<tr>
<th>aquifer PB11 + groundwater</th>
<th>T0</th>
<th>T4</th>
<th>T6</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>groundwater</td>
<td>8400</td>
<td>5190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aquifer + groundwater</td>
<td>7170</td>
<td>3130</td>
<td>2180</td>
<td>974</td>
</tr>
<tr>
<td>aquifer + groundwater + 0.5 mM HgCl2</td>
<td>5920</td>
<td>2070</td>
<td>1150</td>
<td>550</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%)</td>
<td>5730</td>
<td>2100</td>
<td>1190</td>
<td>817</td>
</tr>
<tr>
<td>aquifer + groundwater + 1 ml K-acetate (25%) + Dd301</td>
<td>5600</td>
<td>1540</td>
<td>940</td>
<td>679</td>
</tr>
<tr>
<td>aquifer + groundwater + Postgate C medium 10x + 1 ml K-acetate (25%) + Dd301</td>
<td>5750</td>
<td>5610</td>
<td>1410</td>
<td>608</td>
</tr>
<tr>
<td>aquifer + groundwater + Postgate C medium 10x + 1 ml K-acetate (25%)</td>
<td>5230</td>
<td>5090</td>
<td>1370</td>
<td>591</td>
</tr>
<tr>
<td>aquifer + groundwater + Fe-A4</td>
<td>5290</td>
<td>3840</td>
<td>2740</td>
<td>2250</td>
</tr>
<tr>
<td>aquifer + groundwater + 0.5 mM HgCl2 + Fe-A4</td>
<td>5750</td>
<td>2810</td>
<td>1550</td>
<td>1190</td>
</tr>
<tr>
<td>aquifer + groundwater + Fe-A4 + 1 ml K-acetate (25%)</td>
<td>5030</td>
<td>3740</td>
<td>2710</td>
<td>805</td>
</tr>
<tr>
<td>aquifer + groundwater + Fe-A4 + 1 ml K-acetate (25%) + Dd301</td>
<td>6230</td>
<td>4260</td>
<td>2740</td>
<td>660</td>
</tr>
</tbody>
</table>
## Redox zone: In situ redox manipulation

<table>
<thead>
<tr>
<th>Conditions</th>
<th>pH</th>
<th>T0</th>
<th>T3</th>
<th>T7</th>
<th>T12</th>
<th>T16</th>
<th>T26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>3.1</td>
<td>3.3</td>
<td>3.2</td>
<td>3.2</td>
<td>3.0</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + HgCl₂</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
<td>3.4</td>
<td>ND</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + RMC</td>
<td>3.5</td>
<td>3.8</td>
<td>3.9</td>
<td>4.1</td>
<td>4.4</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + acetate</td>
<td>3.8</td>
<td>3.9</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater</td>
<td>3.3</td>
<td>3.2</td>
<td>2.0</td>
<td>3.2</td>
<td>3.3</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + acetate + RMC</td>
<td>3.9</td>
<td>4.0</td>
<td>4.2</td>
<td>5.4</td>
<td>5.4</td>
<td>5.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditions</th>
<th>ORP</th>
<th>T0</th>
<th>T3</th>
<th>T7</th>
<th>T12</th>
<th>T16</th>
<th>T26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>440</td>
<td>455</td>
<td>402</td>
<td>262</td>
<td>167</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + HgCl₂</td>
<td>392</td>
<td>380</td>
<td>280</td>
<td>292</td>
<td>ND</td>
<td>329</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + RMC</td>
<td>339</td>
<td>363</td>
<td>57</td>
<td>32</td>
<td>-80</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + acetate</td>
<td>294</td>
<td>336</td>
<td>215</td>
<td>280</td>
<td>188</td>
<td>294</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater</td>
<td>321</td>
<td>441</td>
<td>409</td>
<td>340</td>
<td>208</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Aquifer + groundwater + acetate + RMC</td>
<td>287</td>
<td>315</td>
<td>274</td>
<td>-58</td>
<td>-123</td>
<td>-12</td>
<td></td>
</tr>
</tbody>
</table>
Redox zone: In situ redox manipulation

Evolution heavy metal concentration:

![Graph showing evolution of heavy metal concentration over time (Ni and Zn)]
Redox zone: In situ redox manipulation

- GW
- GW Aq
- HgCl₂
- RMC
- Acetate

**Cu (µg/L)**
- T0
- T3
- T7
- T12
- T16
- T26

**Cd (µg/l)**
- T0
- T3
- T7
- T12
- T16
- T26

**Cr (µg/l)**
- T0
- T3
- T7
- T12
- T16
- T26
### Column experiments

<table>
<thead>
<tr>
<th></th>
<th>Cd (mg/l)</th>
<th>Zn (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>0.20</td>
<td>146</td>
</tr>
<tr>
<td>Control</td>
<td>0.18</td>
<td>152</td>
</tr>
<tr>
<td>+ HgCl₂</td>
<td>0.18</td>
<td>148</td>
</tr>
<tr>
<td>+ methanol</td>
<td>0.03</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>+ ethanol</td>
<td>0.01</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>+ acetate</td>
<td>0.02</td>
<td>40.6</td>
</tr>
<tr>
<td>+ lactate</td>
<td>0.01</td>
<td>&lt; 0.010</td>
</tr>
<tr>
<td>+ molasse</td>
<td>0.01</td>
<td>0.8</td>
</tr>
</tbody>
</table>
# Sustainability of the heavy metals precipitation in column tests

<table>
<thead>
<tr>
<th></th>
<th>Zn</th>
<th>Cd</th>
<th>As</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input water</td>
<td>146</td>
<td>0.2</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>+ HgCl2</td>
<td>122</td>
<td>0.2</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>+ ethanol</td>
<td>0.12</td>
<td>&lt;0.002</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>- ethanol</td>
<td>80</td>
<td>&lt;0.002</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Pilot tests: MF04

MF04: SO4, sugar and fatty acids (mg/l)

- SO4
- Sugar
- Fatty acid

MF04: Zn en SO4 (mg/l)

- Zn
- SO4

MF04: pH, EC (mS), O2 (mg/l)

- pH
- EC
- O2
- Redox

Redox (mV)
In situ remediation activities

- Soil
- Groundwater
- Landfill
- Rocks
- Adsorption barrier
- Removed to new landfill
- A-biotic NA
- River
Physical techniques: sorption barriers

Metal + Sorption material $\rightarrow$ adsorbed metal
## Sorption barriers: Zn removal

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Zn concentration (mg Zn/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Initial concentrations</td>
<td>0</td>
</tr>
<tr>
<td>Activated coal</td>
<td>0.01</td>
</tr>
<tr>
<td>Synthetic zeolite</td>
<td>0.02</td>
</tr>
<tr>
<td>Ironoxide-hydroxide</td>
<td>0.04</td>
</tr>
<tr>
<td>Silicate</td>
<td>0.02</td>
</tr>
<tr>
<td>Mordenite</td>
<td>0.03</td>
</tr>
<tr>
<td>Zeolite X</td>
<td>0.00</td>
</tr>
<tr>
<td>Anaerobic compost</td>
<td>0.23</td>
</tr>
<tr>
<td>As-adsorbent</td>
<td>0.06</td>
</tr>
<tr>
<td>Zerovalent iron</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Concentrations in mg Zn/l
## Sorption barriers: metal removal

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Cd</th>
<th>Zn</th>
<th>Ni</th>
<th>Cr</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated coal</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Synthetic zeolite</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Ironoxide-hydroxide</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Silicate</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mordenite</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zeolite X</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Anaerobic compost</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>As-adsorbent</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Zerovalent iron</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Measurements after 24 hour
Sorption test (columns)

Objective:
Evaluation of the use of compost for the immobilisation of heavy metals

Set-up:
- Column test
- 18 g compost
- Room temperature
- 17-18 cm/day
- Monitoring:
  - Zn, Cr, Cd, Ni, Cu, Pb
  - pH, ORP

Conclusion:
- Fast breakthrough after 3 - 25 PVs
- pH-effect: pH_{in}: 2.5; pH_{out}: 6.5 --> 3.85
- Sorption barrier with compost is not a good alternative for bioprecipitation.

Results:

Location S1

<table>
<thead>
<tr>
<th>Effluent conc. (µg/L)</th>
<th>Pore volumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb (27)</td>
<td>0</td>
</tr>
<tr>
<td>Ni (726)</td>
<td>2</td>
</tr>
<tr>
<td>Zn (3700)</td>
<td>4</td>
</tr>
<tr>
<td>Cu (405)</td>
<td>6</td>
</tr>
<tr>
<td>Cd (3920)</td>
<td>8</td>
</tr>
<tr>
<td>Cr (153)</td>
<td>10</td>
</tr>
</tbody>
</table>

Location S2

<table>
<thead>
<tr>
<th>Effluent conc. (µg/L)</th>
<th>Pore volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb (140)</td>
<td>0</td>
</tr>
<tr>
<td>Ni (3600)</td>
<td>1</td>
</tr>
<tr>
<td>Zn (18200)</td>
<td>2</td>
</tr>
<tr>
<td>Cu (3570)</td>
<td>3</td>
</tr>
<tr>
<td>Cd (24100)</td>
<td>4</td>
</tr>
<tr>
<td>Cr (1440)</td>
<td>5</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- Large measures as prevention of disasters (e.g. dikes, slurry walls)
- IMS approach can be used on Mining sites
- Source – path – receptor: risk evaluation
- Clustering (old mining, new activities)
- Conceptual model
- Measures:
  - Natural Attenuation
  - Pump & treat
  - In situ heavy metal bioprecipitation in groundwater
  - In situ groundwater redox manipulation
  - Permeable Reactive Barriers
    ➔ MULTIBARRIER (e.g. treatment of cyanides and metals)
  - Wetlands