Leaching of Contaminants from an Old Industrial Landfill into a Railway and Road Construction

Master of Science Thesis in the Master´s Programme Geo and Water Engineering

MATTIA TESSARO

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ABSTRACT

The aim of this thesis work was to determine the degree of contamination and contaminants mobility from an old industrial landfill to a new rebuilt road and railway construction in Nol north of Göteborg. The landfill was in use until 1984 and contains large amounts of residues from battery production and is highly contaminated with lead, oils and polycyclic aromatic hydrocarbons (PAHs).

The concentrations of contaminants were determined through analysis of soil depth profiles and groundwater samples from six spots/wells located in the landfill. Standard leaching test consisting of two consecutive leaching steps were performed on three soil samples with high, medium and low concentration of lead. Also eight different possible environmental conditions that could affect the leachability of metals were evaluated with beaker tests, performed on the soil sample with the medium concentration of lead. The different conditions used were: increase and decrease of pH, oxidizing and reducing environment with input of air and N_2 respectively, addition of iron and organic colloids, strong mixing and undisturbed environment. After all batch and beaker tests, dissolved and total content of metals were analyzed in the leachates with ICP-MS technique. Total and dissolved organic carbon (TOC/DOC), carbonate alkalinity, conductivity, pH, temperature, turbidity, UV adsorption, true and apparent colour were also analyzed in some of the leachates.

Results from the analysis of soil samples confirmed a strong contamination of lead, with almost all the concentrations over the Swedish guidelines for contaminated sites. The dissolved lead concentration of 16 and 20 µg/l in groundwater in well 2A pose a high risk of biological effects, and theses concentrations are also higher than the health related guideline value for drinking water and the threshold value for groundwater at contaminated sites of 10 µg/l. Both the dissolved and total concentration of lead in groundwater increased from November 2009 until March 2010 in most of the wells. Results from the two step leaching batch test classified one of the three soil samples as non hazardous waste, and the other two as inert waste considering dissolved lead content in the leachates. Results from the beaker tests showed that a decrease of pH and presence of humic colloids increased the leaching of all metals. Lead and copper are known to adsorb strongly to organic matter as humic colloids. The input of iron colloids had the opposite effect, with a decreased leaching of all the metals, probably due to co-precipitation. Evaluation of Kd values of dissolved lead in both "field" measurements (groundwater and soil analysis) and laboratory measurements (two steps batch and beaker tests) showed the following order of pollution of the wells: 2A>>2B>1B>1A. The lower Kd values from the laboratory tests indicate that the leaching tests may overestimate the real leaching depending on smaller particles formed in the shaking procedure.

The high concentration of pollutants as lead, cadmium and PAHs in the landfill, suggests monitoring of sediment and water in the river close to the landfill. Continuous measurements of concentrations of metals and PAHs in all the groundwater wells are suggested, and remedial actions to protect the surroundings of contamination from the landfill may be necessary.

Key words: Leaching, Lead, Kd, Metals, Mobility, Contamination, Polycyclic Aromatic Hydrocarbons (PAHs)

Lisciviazione di contaminanti da una discarica industriale verso un tracciato stradale e ferroviario

SOMMARIO

Lo scopo di questo lavoro di tesi è stato quello di determinare il grado di contaminazione e la migrazione degli inquinanti da una vecchia discarica industriale verso il terreno di riempimento di una nuova strada e ferrovia costruite a Nol a nord di Göteborg. La discarica era in uso fino al 1984 e contiene grandi quantità scarti di produzione di batterie ed è altamente contaminata da piombo, oli e idrocarburi policiclici aromatici (IPA).

Le concentrazioni dei contaminanti sono state determinate attraverso l'analisi dei diversi strati del terreno e dei campioni delle acque sotterranee da sei punti situati nella discarica. Strandard leaching batch test costituiti da due fasi consecutive lisciviazione sono state effettuati su tre campioni di terreno con alta, media e bassa concentrazione di piombo. Sono inoltre state valutate otto diverse condizioni ambientali, tali da cambiare la percolazione dei metalli dal suolo, attraverso beaker test eseguiti sul campione di terreno con la concentrazione media di piombo. Le diverse condizioni utilizzate sono state: aumento e diminuzione del pH, ambienti ossidante e riducente ottenuti con ingresso di aria e N_2 rispettivamente, l'input di colloidi organici e ferrosi, agitazione forte e ambiente indisturbato. Dopo tutte i test i contenuti di metalli disciolti e totali sono stati analizzati con la tecnica ICP-MS. Carbonio organico totale e disciolto (TOC/DOC), alcalinità carbonatica, conducibilità, pH, temperatura, torbidità, assorbimento UV, colore reale e apparente sono stati analizzati anche in alcuni dei percolati.

I risultati dall'analisi di campioni di terreno hanno confermato una forte contaminazione da piombo, con quasi tutte le concentrazioni oltre le linee guida svedesi per i siti contaminati. La concentrazione di piombo disciolto nelle acque sotterranee di 16 e 20 mg/l pone un rischio elevato di effetti biologici nel pozzo 2A, e queste concentrazioni superano il relativo valore guida per l'acqua potabile (10 mg/l), che è stato scelto come parametro di confronto, perché dal fiume è estratta l'acqua potabile di Goteborg. La concentrazione di piombo disciolto e totale nelle acque sotterranee è aumentata da novembre 2009 fino a marzo 2010, nella maggior parte dei pozzetti. I risultati dei test di lisciviazione in batch hanno portato a classificare uno dei tre campioni di terreno, come rifiuto non pericoloso, e gli altri due come rifiuti inerti. I risultati dei beaker test hanno dimostrato che una diminuzione del pH e la presenza di colloidi organici aumentato la lisciviazione di tutti i metalli sopratutto di piombo e rame conosciuti per la forte coesione con la materia organica. L'input di colloidi ferrosi ha rivelato un comportamento opposto, con un lisciviazione minore di tutti i metalli, probabilmente a causa di una co-precipitazione. La valutazione dei valori delle Kd del piombo, per misure in "campo" (acque sotterranee e analisi del suolo) e

misure di laboratorio (batch e beaker test) ha mostrato il seguente ordine di inquinamento dei pozzi: 2A>> 2B> 1B> 1A. I valori più bassi delle Kd dei test di laboratorio indicano che il test di lisciviazione può sovrastimare la lisciviazione reale dovuta alla formazione di particelle più piccole durante la procedura di agitazione.
L'alta concentrazione di sostanze inquinanti come piombo, cadmio e di IPA nella discarica, suggerisce di monitorare anche tali concentrazioni nelle acque del fiume e nei sedimenti vicino alla discarica. Sono suggerite inoltre continue misure delle concentrazioni di metalli e idrocarburi policiclici aromatici nella acque di falda di tutti i pozzetti considerati e saranno probabilmente necessarie azioni di bonifica e contenimento dell'inquinamento al fine di proteggere l'ambiente circostante.

Parole chiave: Lisciviazione, Piombo, Kd, Metalli, Mobilità, Contaminazione, Idrocarburi Policiclici Aromatici (IPA)

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Contents

1 Background

1.1 Site description

BanaVäg i Väst is a project organization performing rebuilding of road 45 and the railway from Trollhättan to Agnesberg north of the city of Göteborg. Along the road length and railway section there are several contaminated sites that will affect the project. One of these sites is an old industrial landfill situated in Nol. The new railway is now built through the landfill area and the road is closed to it. The landfill, property of Tudor AB battery factory, was in use until 1984 and contains large amounts of residues from battery production *(J&W, 2002)* such as and Bakelite, but also wood, paperboard and plastic materials (*BanaVäg i Väst, 2009*). The landfill is highly contaminated with lead, oils and polycyclic aromatic hydrocarbons (PAHs). Parts of the soil in the landfill have during the rebuilding been excavated and sent for deposition and is replaced with new clean filling materials.

Figure 1.1 Highway 45 and railway track from Göteborg to Trollhättan [http//www.vv.se]

The valley bottom is mostly located only 1 – 3 m above the river Göta älv water level *(J&W, 2002;FB Engineering, 2006; Vattenfall, 2006)*. Surrounding elevation areas are located up to 150 m above sea level. The valley geology is characterized by a thick clay layer, which has sedimented in the valley and in acceding low parties. Clay thickness increases from east towards the river in the west, and is already at small distances from a fixed land line up to several tens of meters. For a long distance in the valley there are clay thickness over 50 m and locally it can be up to 100 m. The dense clay soil means that the bulk of the precipitation drains into streams and rivers, and a limited amount of water infiltration contributes to the flow of groundwater. At Nol there is a smaller area of alluvial materials going up to the surface. The Tudor landfill area is situated on the bank of the river Göta älv. The groundwater in the overburden above the clay is relatively shallow in the low-lying areas. The valley is very flat which gives a weak groundwater gradient, where levels and groundwater flow is largely controlled by the river. Groundwater flow can sometimes be locally directed from the river at high water levels.

The Göta älv is Gothenburg's drinking water supply for more than 500 000 people. The intake is located 18 km downstream of the Tudor landfill area.

1.2 Aim and Goals

The critical question to be solved is to determine if there is any risk of leaching of contaminants from the Tudor landfill into the newly built railway and adjacent road, but also to consider if the construction of both road and railway has changed the mobility conditions of contaminants. The specific goals with the project are to determine the:

- Concentrations of the contaminants in the groundwater wells, and changes of the concentrations in the wells with time:
    - analysis and evaluation of groundwater sampling data from BanaVäg i Väst and decision of what type of contaminants that should be analyzed.
    - groundwater sampling in wells, analysis, and evaluation of data on the above type of contaminants (previously chosen).
- Degree of contamination levels in the soil profiles at the groundwater wells:
    - analysis and evaluation of soil sampling data from BanaVäg i Väst.
- Leaching of contaminants from soil to groundwater:
    - analysis and evaluation of leaching test made by BanaVäg i Väst.
    - performing of standard batch leaching test on three soil samples from Nol with high, low and medium concentrations of pollutants. Most of the metals will be analyzed by ICP/MS in the WET laboratory at Chalmers. Both total and dissolved phases will be analyzed.
    - evaluation and discussion of the results from standard leaching test performed in the WET laboratory and those made by BanaVäg i Väst.
- Most important environmental conditions/changes that could affect the leachability of the contaminants:

- perform beaker test of soil samples from Nol with different conditions: changes of pH, undisturbed environment, mixing, inert atmosphere, input of air and mixing, addition of iron and humic acid colloids. Both total and dissolved phases are analyzed. Most of the metals will be analyzed in all samples with ICP/MS at Chalmers.
- evaluation and discussion of results of tests.

2 Previous investigations

In Table 2.1 - 2.3, the main concentration classification data and guideline values for dissolved metals and PAHs in soil, groundwater and hazardous waste, used as comparison for all the results data found in this thesis work, are presented.

Table 2.1 Swedish and Canadian guideline values for major contaminants concentration in soil (mg/kg DS)

	As	Pb	Cd	Cu	Cr	Hg	Ni	Zn	carcinogenic PAHs[b]	Other PAHs[b]
KM[a]	10	50	1	80	80	0.25	40	250	0.3	20
MKM[a]	25	400	15	200	150	2.5	120	500	7	40
Canadian Industrial[c]	12	260-600	22	91	1.4-87	24-50	50	360		

[a](Swedish EPA, 2009); [b](Swedish EPA, 2002); [c] (*CCME, 2007*)

Table 2.2 Swedish classification data, Canadian and European guideline values for major contaminants concentration in groundwater (µg/l)

	Cr	Cu	Hg	Ni	Carcinogenic PAHs [e]	Other PAHs [e]
Slightly serious[a]	<50	<2000	<1	<50	<0.2	<10
Moderately serious[a]	50-150	2000-6000	1-3	50-150	0.2-0.6	10-30
Very serious[a]	150-500	6000-20000	3-10	150-5000	0.6-2	30-100
Extremely serious[a]	>500	>20000	>10	>500	>2	>100
Canadian guidelines[b]		2-4	0.026	25-150		
European guidelines[c]			0.05	20		

	As	Cd	Pb	Zn
Very low[d]	<1	<0.05	<0.2	<5
Low[d]	1-5	0.05-0.1	0.2-1	5-20
Moderate[d]	5-10	0.1-1	1-3	20-300
High[d]	10-50	1-5	3-10	300-1000
Very high[d]	>50	>5	>10	>1000
Canadian guidelines[b]	5	0.017	1-7	30
European guidelines[c]		0.08-0.25	7.2	
Swedish drinking water guideline[d]	>10	>1	>10	>300

[a](*Swedish EPA, 2002*) Classification of current conditions for contaminated groundwater, based on health-related threshold values for drinking water;

[b](*CCME, 2007*); [c](*2006/60/EC, 2006*); [d](*Swedish EPA, 2001*) "Assessment of current conditions";

[e](*Swedish EPA, 2002*) guidelines for contaminated petrol stations

Table 2.3 European threshold values (mg/kg DS) of major contaminants for acceptance of waste at landfills (2003/33/EC) leaching properties (L/S =10 l/kg)

	As	Cd	Cu	Cr	Hg	Ni	Pb	Zn
Inert waste	0.5	0.04	2	0.5	0.01	0.4	0.5	4
Non Hazordous waste	2	1	50	10	0.2	10	10	50
Hazardous waste	25	5	100	70	2	40	50	200

Previous geotechnical and environmental investigations concerning the rebuilding of the road and railway are:

- Road and railway plan, general environmental engineering survey and land proposals for action, J & W, 2002.
- Norway / Vänern Line and Highway 45, part Angered bridge-Älvängen. PM Environmental Engineering surveying, Nol-Nödinge, FB Engineering, 2006.
- Additional environmental sampling for the design of Road 45 / Norway Vänerbanan part Nödinge-Nol, Vattenfall Power Consultant AB, 2006.
- Final report for remediation work and treatment of soil areas for bridge pillar in Nol, area 1, part of the property Nol 2:298, BanaVäg i Väst, 2009.

Figure 2.1 shows the study area and the sampling points included in the three different investigations that gave results of contaminants concentration in soil and groundwater *(J & W, 2002; FB, 2006; Vattenfall, 2006).*

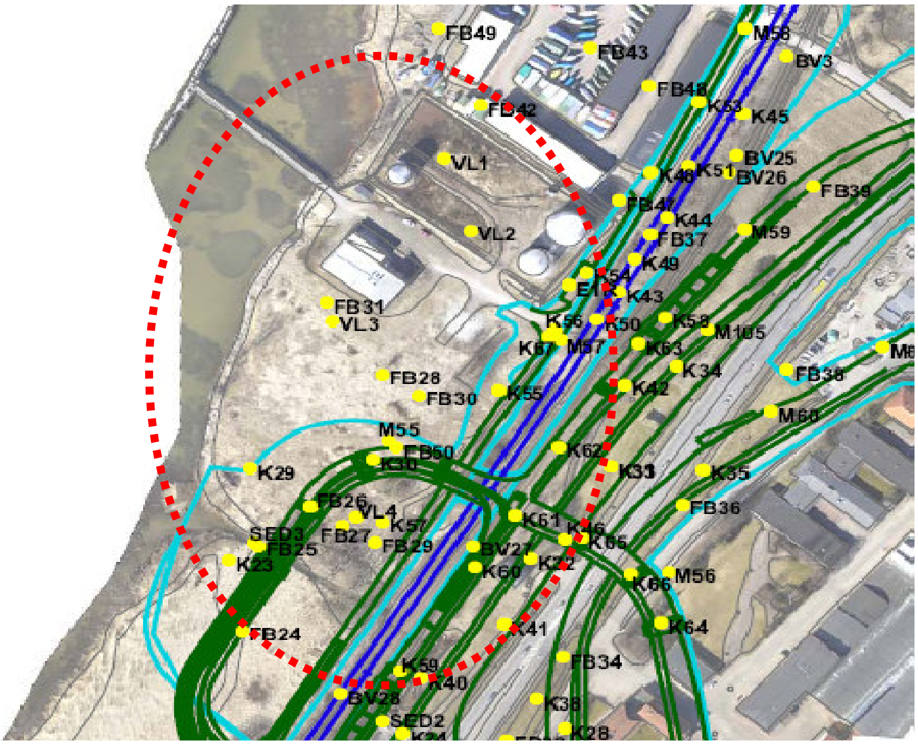

Figure 2.1 Sampling points near the landfill area (Vattenfall, 2006) (the red dashed line indicates the study area of the landfill)

2.1 Contaminants in soil

The concentrations of contaminants in soil at the Tudor landfill, from the investigations before construction of the new road and railway area, are presented in Table 2.4 *(J & W, 2002; FB, 2006; Vattenfall, 2006).*

Pollutant concentrations are evaluated and compared with the limits of the Swedish guidelines for contaminated sites (*Swedish EPA, 2009*), and Canadian soil quality guidelines threshold values for industrial land use (*2007*) (see Table2.1).

Table 2.4 Concentrations of contaminants in soil close to or in the landfill area.

Sampling year	2002[b]			2006 [c]						2006 [d]			
Sampling point	**SED3**	**M55**	**M57**	**FB24**	**FB25**	**FB26**	**FB27**	**FB29**	**FB50**	**K29**	**K30**	**K55**	**K57**
Depth (m)	0-0.08	2-2.5	0.3-0.5					0-0.6		0.0-1.0	0.0-1.0	0.0-0.5	0.0-0.5
Al				12300	18600	13300		8500	12900				
As	<9.76	<9.92	138**	3.5	8.6	5.3		4.8	5.3		4.2		4.2
Cd	<1.95	17.4**	<1.95	<0.33	3.5*	0.035		0.37	2.7*		0.34		0.82
Co	13.6	9.31	37.6	8.9	7.6	7.8		9.1	10		5.4		8.8
Cr	45.2	28.6	23.9	19	450**	20		19	27		14		23
Cu	21.6	292**	230**	10	300**	23		52	59		69		25
Fe				20400	21400	26600		17700	28900				
Hg	0.0861	1.29*	0.0505	<0.05	2.4*	0.15	0.13	0.12	0.23		0.052		0.1
Mn				260	230	320		190	270				
Ni	30.4	70.7*	99.2*	10	50*	13		8.6	18		10		17
Pb	169 *	5780**	194 *	19	7800**	700**		1900**	9900**	190*	1300**	1056**	2300**
V	65.1	28.5	257	32	40	35		20	35		26		38
Zn	103	2440**	283*	59	500**	85		330*	300*	119	62	365*	120
Carcinogenic PAHs					7.4**	13**							
Other PAHs[a]					7.5	35*							
Total PAHs[a]	<3												
Total PCB	<1				1.2	0.04							
Dry matter(%)	67.9	35.2	83.6	53.8	39.7	75.2	79.8	78.9	65.8		76.4		82.6

* >KM "Land with sensitive use" (Swedish EPA, 2009) ; [a] (Swedish EPA, 1997)

** >MKM "Land with less sensitive use " (Swedish EPA, 2009) ; [a] (Swedish EPA, 1997)

[b](J & W, 2002);[c](FB, 2006); [d](Vattenfall,2006)

The results (Table 2.4) showed very high level concentrations of lead up to 9900 mg/kg DS, and some of these twenty times higher than the MKM. High level concentrations (>MKM) of cadmium up to 17.4 mg/kg DS, copper up to 300 mg/kg DS, zinc up to 2440 mg/kg DS were found in some of the samples. In two soil samples, carcinogenic PAHs up to 13 mg/kg DS were very high (>MKM).

2.2 Contaminants in groundwater

Table 2.5 presents the groundwater concentrations of pollutants in two wells of interest for the area, before the construction of road and railway.

Pollutant concentrations were evaluated in accordance with Environmental Quality Criteria for groundwater (*Swedish EPA, 2001*), European (*2006/60/EC, 2006*) and Canadian guidelines (*CCME, 2007*) for surface water protection (see Table 2.2).

Table 2.5 Concentrations of contaminants in groundwater at the landfill area.

Sampling year	2002[c]	2006[d]	Sampling year	2002[c]	2006[d]
Sampling point	**M55**	**FB27**	Sampling point	**M55**	**FB27**
pH ()	6.77		Fe dissolved		4200
Conductivity (mS/m)	147.7		Fe total		280000
As dissolved[a]	<3.4	<2	Hg dissolved	0.0065	<0.1
As total[a]		160**	Hg total		1.5*
Pb dissolved[a]	13.7**	<0.5	Ni dissolved	32.8	2.9
Pb total[a]		31000**	Ni total		170**
Cd dissolved[a]	0.14*	<0.2	V dissolved		<2
Cd total[a]		25**	V total		550
Co dissolved	0.72	4.1	Zn dissolved[a]	12.9	10
Co total		70	Zn total[a]		1700**
Cu dissolved	1.24	<2	PAHs carcinogenic[e]		5.1**
Cu total		540	PAHs other[e]		8.4
Cr dissolved	0.77	<2			
Cr total		160 *			

*Moderately serious risk of biological effects [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

**Very serious risk of biological effects [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

***Extremely serious risk of biological effects [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

++ European Environmental quality standards for priority substances in surface water

[c]*(J & W, 2002);*[d]*(FB, 2006);*

[e] guidelines for contaminated petrol stations (Swedish EPA, 2002)

Water samples taken near the landfill area are highlighted because of very high concentrations of lead in both filtered (13.7 µg/l) and unfiltered (31000 µg/l) samples, and high concentrations of arsenic (16 µg/l), cadmium (25 µg/l) and zinc (1700 µg/l) in unfiltered samples. Carcinogenic PAHs were found in high concentrations up to 5.1 µg/l and can cause extremely serious risk of biological effects (*Swedish EPA, 2002*).

3 Theory

3.1 Leaching tests

The problem with waste materials is that they contain not only inert components, but also environmentally dangerous substances. A few examples are metals such as zinc and lead, organics like polycyclic aromatic hydrocarbons (PAHs) and anions like chloride and sulfate (*Mulder et al., 2001; Fernandez-Sempere, 1997*). To estimate the environmental threat, leaching tests have proven to be indispensable characterization tools. These leaching tests can yield information about the leaching behavior of materials in natural conditions and outdoor situations (*Hage & Mulder, 2003*).

In this chapter a short description and comparison between three leaching tests is described: the Dutch column leaching test (*NNI, 1995*), that is being standardized within CEN, and has been published as prEN 14405 (*CEN, March 2002*), the new European pH-stat test (*CEN, 2000*) and the new European shake test (*CEN, May 2002*), that was used in this study and has been published as EN 12457, part 3.

3.1.1 Column leaching test/percolation test

The column test is run in up-flow mode (*Hage and Mulder, 2003*). The liquid used i. e. the leachant is demineralised water (DMW), and the test material should have a particle size < 4 mm. The total test duration is approximately 21 days. The column leaching procedure addresses both inorganic and organic contaminants. A column with a diameter of 5 cm is filled with approximately 500 ml test material. The column is placed vertically and is continuously flushed with simulated rainwater, which can be a mix of demineralised water acidified with nitric acid to pH=4, for 3 weeks. The liquid flow is from bottom to top. The total amount of rainwater should be 10 times the weight of the sample, so the flow rate depends on the weight of the sample. The leachate is collected in several fractions, within the range of L/S = 0.1-10 l/kg, which can be analyzed with AAS-, IC- and ICP-techniques. This leaching test is described in the Dutch standard NEN-7343, and is standardized within the CEN framework (CEN-TC292/wg6) as prEN 14405, and called 'up-flow percolation test' (see Figure 3.1).

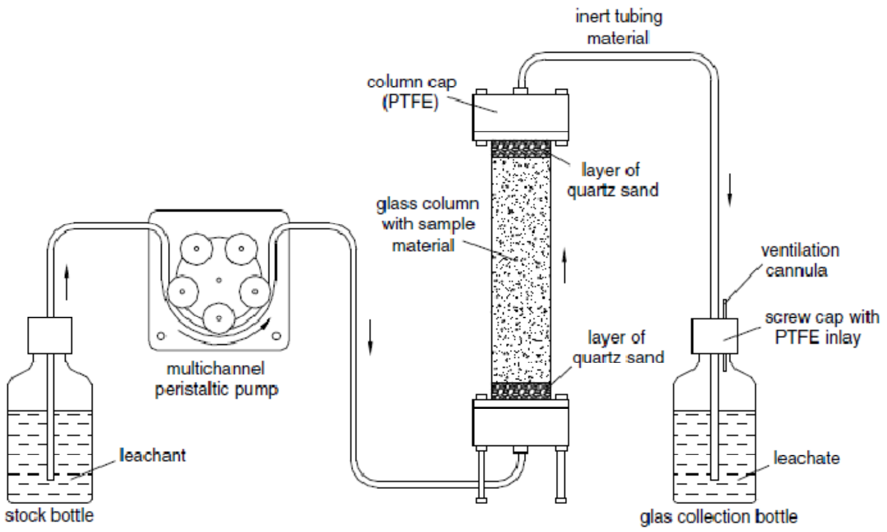

Figure 3.1 *Schematic diagram of column leaching test set-up* (*Kalbe et al., 2008*)

3.1.2 pH-stat test

For this method a bulk laboratory sample should be divided into at least eight identical sub-samples (*Hage and Mulder, 2003*). The soil sample also required no grain size reduction for this test, so the test is performed on soil conditions like in field. The weight of each sub-sample is about 60 g, which is placed in a closed vessel. Water is added with an L/S ratio of about nine, leaving some space for addition of pH-regulating solutions. Acids and bases, like diluted nitric acid or diluted sodium hydroxide, should be added to set the pH on at least 8 different pH values in the range of 4-12. The pH is monitored constantly and alterations should be compensated to maintain a constant pH-value. After a leaching period of 24 h the sample was filtered through a 0.45 µm filter. The liquid can be analyzed by IC, AAS and ICP-techniques. This test is also being standardized by Working Group 6 of CEN-TC 292.

3.1.3 Shake-test/compliance leaching test

This test can be seen as a simplified and quick alternative for the percolation test (*Hage and Mulder, 2003*). An amount of 175 g sample material is placed in a 0.5 l bottle. Demineralised water is added in a ratio of L/S=2. The bottle is shaken for 6 h and subsequently filtered over a 0.45 µm filter. The solid is re-suspended in demineralised water with a ratio of L/S=8. Again the bottle is shaken, now for 18 h and subsequently filtered. Both filtrate fractions should be analyzed. This test has been standardized by CEN and has been published as EN 12457-3, and is one of the test methodologies used in this study

When looking at these three tests, one might notice that each test has its own strengths and weaknesses. The percolation test generates much information about leaching behavior of the sample, since the behavior of compounds with changing L/S is studied (*Hage and Mulder, 2003*). The material itself sets the pH. It's applicable to many materials but limited or not applicable to clayey soils and sediments (low permeability) *(Dijkstra et al., 2004).* The pH-stat test is different since the pH is forced by adding either an acid or a basis solution to lower or raise the pH respectively. It gives and identification of sensitivity of leaching to small pH changes and provides information on pH conditions imposed by external influences. The shake test is a quick and relatively cheap test, but generates limited information. Only two leaching values are generated. Since the same liquid/solid ratio is used as in the percolation test, this shake test can be seen as an alternative for the percolation test, especially in cases where the leaching pattern is already known. The column leaching or percolation test and the pH-stat test are so-called characterization tests because they give more information about the leaching behavior of the soil than the shake test that is a compliance test.

3.2 Main contaminants

Metals are introduced into the environment through natural processes and human activities, such as agricultural practices, transport, industrial activities and waste disposal (*Hani, 1990*).

3.2.1 Lead (Pb)

Lead is one of the first known metallic elements, probably as early as 5000 BC the Egyptians, the Phoenicians and then the Chinese around 2000 BC, and finally to the Romans, who used it on a large scale for water pipes *(www.chimica-online.it).* Lead is a bluish-white metal, shiny surface (if it is newly formed), low hardness and low melting point (327 °C), very ductile and malleable (*Baird and Cann, 2008*).

Elemental lead can be found in bullets, shotgun shells and ammunition used in huge quantities by hunters (especially of waterfowl), but it becomes a big problem when it dissolves to yield an ionic species (*Baird and Cann, 2008*). Lead occurs mainly as Pb^{2+}, and it forms other several minerals which are quite insoluble in natural waters, some compounds of lead are for example PbS (lead sulfide), $PbCO_3$ (lead carbonate), $PbSO_4$ (lead sulfate). During weathering, Pb sulfides slowly oxidize and have the ability to form carbonates and also to be incorporated in clay minerals, in Fe and Mn oxides, and in organic matter (*Martinez-Villegas et al., 2004*). Lead can also occur as the Pb^{4+} ion, and one form of Pb (IV) in PbO_2 (lead oxide) is used with elemental lead as electrode in storage batteries for vehicles. Storage batteries can be a big source of lead contamination if they are not recycled (*Baird and Cann, 2008*).

The mobility and the bioavailability of lead in soils are mainly governed by soil properties as pH, organic matter content, cation exchange capacity, texture, mineral species; specially those constituting the clay fraction (*Martinez-Villegas et al, 2004*).

3.2.2 Cadmium (Cd)

Cadmium has in its stable compounds (usually ionic) the oxidation number +2 *(www.chimica-online.it),* it is in the same subgroup of the periodic table as zinc and mercury, but its behaviour is more similar to the former (*Baird and Cann, 2008*). At room temperature is easily attacked by acids (even weak), dissolves in concentrated solutions of ammonium salts with formation of a complex, it reacts with ammonia and sulfur dioxide *(www.chimica-online.it).*

Most cadmium is produced as a by-product of zinc smelting, since the two metals usually occur together. Some environmental contamination by cadmium often occurs in the areas surrounding zinc, lead and copper smelters. A major use of cadmium is as an electrode in rechargeable nicad (nickel-cadmium) batteries used in calculators and similar devices.

3.2.3 Mercury (Hg)

Elemental mercury is a silvery white metal, the only liquid and highly volatile at room temperature. Exhibits low viscosity, high density and surface tension, while the thermal and electrical conductivity, however lofty, are significantly lower than those of other metals. Many metals (eg lead, zinc, cadmium, gallium, sodium, potassium, calcium, magnesium) are dissolved in mercury, forming amalgams.

The mercury forms compounds corresponding to its oxidation state +2 (the mercury compounds), which are typically covalent and only rarely as ionic and also including compounds according to the state +1 (mercurous compounds) in which two atoms of mercury are linked to form ion Hg_2^{2+} *(www.chimica-online.it).*

Metallic mercury, which is commonly sold in steel containers, is widely used because of its specific characteristics (low melting point, high density and surface tension, high chemical inertness) in electrical equipment of various types, such as ultraviolet lamps, vacuum pumps diffusion of mercury, dry batteries, gauges, thermometers and flow control of gases. Other uses we have for liquid cathodes in various industrial electrolytic processes, including the chlor-alkali (cell method amalgam), and to form amalgams with many metals. Organic and inorganic compounds of mercury are used as pesticides and fungicides in agriculture, certain pharmaceuticals and chemical synthesis of several catalysts (*Baird and Cann, 2008*). The mercury fulminate is an explosive used in detonators *(www.chimica-online.it).*

3.2.4 Arsenic (As)

Arsenic metal is quite reactive: stable in dry air at room temperature, it starts to oxidize at about 200 ° C giving phosphorescence, and burns at about 400 ° C with white fumes trioxide (As_4O_6). It combines easily with halogens, with sulphur and with many non- metals.

Arsenic behaves as a non-metal compounds and, given its central position in the periodic system, practically only by covalent bonds. Its most important oxidation states are -3, +3 and +5 *(www.chimica-online.it).* Arsenic(III) commonly exists in aqueous solution and in solids as the arsenite ion, AsO_3^{3-}(which can be considered to be As^{3+} bonded to three surrounding O^{2-} ions), or in one of its successively protonated forms: $HAsO_3^{2-}$, $H_2AsO_3^-$, or H_3AsO_3 (*Baird and Cann, 2008*). Arsenic(V) also commonly exists as an oxyanion, the arsenate ion**,** AsO_4^{3-} (equivalent to As^{5+} bound to four O^{2-} ions), or one of its successively protonated forms:$HAsO_4^{2-}$, $H_2AsO_4^-$, H_3ASO_4. As(V) is dominant in oxidizing environments and present as $HAsO_4^{2-}$ in alkaline and as $H_2AsO_4^-$ in acidic environments(*Sracek et al., 2004*). In reducing environments, As(III) is dominant in the neutral form of H_3AsO_3 and only occurs in the ionized form $H_2AsO_3^-$ in basic environments at pH>9.2. Arsenic is phytotoxic and hazardous to living organisms, the most toxic and mobile forms being inorganic As(III) species (*Petänen et al., 2003*).

Arsenic metal has limited applications in some alloys, for example is used in small concentrations in the high zinc content brass to improve some characteristics in lead and some alloys to increase hardness in steels at elevated temperatures and for certain special applications. Most arsenic is used as As_4O_6 (as an oxidant in the manufacture of glass, leather industry, insecticide), or in the form of compounds obtained from this oxide. In particular there is considerable use of arsenic acid and arsenates of calcium and sodium ($Ca_3(AsO_4)_2$, Na_3AsO_3) in agriculture as insecticides, fungicides, herbicides and defoliants (eg for cotton) *(www.chimica-online.it).* Arsenic, especially in the form of inorganic compounds, is highly toxic to humans and animals (*Baird and Cann, 2008*).

3.2.5 Chromium (Cr)

Chromium normally occurs in the form of inorganic ions. Its common oxidation states are +3 and +6 (Cr(III) and Cr(VI)), known as trivalent and hexavalent chromium, respectively (*Baird and Cann, 2008*). Under oxidizing (i.e., aerobic) conditions, chromium exists in the (VI) state, usually as the cromate ion, CrO_4^{2-}, though under even slightly acidic conditions this oxyanion protonates to $HCrO_4^-$. The oxyanions of Cr(VI) are highly soluble in water. Under reducing (i.e., anaerobic) conditions, chromium exists in the (III) state. In aqueous solution, this state occurs as the 3+ ion Cr^{3+}. The aqueous solubility of this ion is not so high. Thus whether chromium occurs as an ion dissolved in water or as a precipitate depends on whether the aqueous environment is oxidizing or reducing. This difference is important because hexavalent Cr(VI) is toxic and suspected carcinogenic, whereas trivalent Cr(III) is much less toxic and even acts as a trace nutrient.

The major industrial consumption of chromium occur in the protective coating and decorative (usually obtained by electrolytic deposition) of metal objects (chrome), and the preparation of various alloys. Among these, nickel (used for electrical purposes) and various types of steel, especially stainless steels containing about 15-25% chromium and 5-20% nickel. Some chromium compounds, including the Cr_2O_3 oxide (chrome green) and $PbCrO_4$ lead chromate (chrome yellow), are widely used as pigments in paints for glass and ceramics, and other salts (especially alum basic chromium sulfate and chromium) are used for tanning of leather, textile and dyeing industry and for the preparation of various chemicals.

3.2.6 PAHs

Polycyclic aromatic hydrocarbons are composed of two or more benzene rings linked together, in a single flat structure, through pairs of carbon atoms shared between adjacent rings (*Baird and Cann, 2008*). PAHs consist of three to five rings and may be present either as gases in the atmosphere or as particulate matter, while those with five or more rings tend to occur mostly in solid form. They are characterized by their low degree of water solubility, high adhesion to organic material and good solubility in lipids and in many organic solvents.

PAHs are everywhere in the atmosphere and are produced by incomplete combustion of organic material derived from the use of fuel oil, gas, coal and wood in energy production. PAHs are generated in substantial quantity in the production of such coal-tar derivatives as creosote, a wood preservative used especially on railway ties. Up to 85% of the 200 compounds in creosote are PAHs, including some carcinogenic ones. The most notorious and common carcinogenic PAH is benzo[a]pyrene that is a common by-product of the incomplete combustion of fossil fuels, of organic matter (including garbage) and of wood. Another example of carcinogenic PAH is benz[a]anthracene.

3.3 Conditions that could affect leachability

Metal availability is determined by its activity in the soil solution, which is controlled by both the solid and the solution phase characteristics of the soil. The most relevant parameters that could affect the mobility of metals are pH and the presence of organic matter.

In general, soil pH seems to have the greatest effect of any single factor on the solubility or retention of metals as Ni, Cu, Zn, Cd and Pb in soils, with a greater retention and lower solubility of metal cations occurring at high pH (*Cavallaro and McBride, 1980, 1984; Harter, 1983; Garcia-Miragaya, 1984; Stahl and James, 1991; Basta et al., 1993*). On the other hand is well know that solubilization of metals increased with decreasing pH (*Yang et al., 2005*), and an acidification, due for example to spring snow melting, can lead to an increase in mobility of metals bound to soil (*Bathelor, 1998*). Arsenic and chromium have different behaviour due to their speciation. Arsenic binds strongly on soil colloids and is highly dependent on the content of clay, hydr/oxides surfaces of Fe, Mn and Al, and organic matter (*Sadiq, 1997*). In general, Fe hydr/oxides have the highest degree of involvement in the adsorption of As in both acid and alkaline soils, but Al, Mn and organic matter may be important in the former (*Johansson, 2009*). Arsenite binds more weakly and is less dependet on pH than As(V). The adsorption of As(V) on iron hydr/oxides is higher at low pH while that of As(III) is higher at higher pH. In reducing conditions, iron hydr/oxides are dissolved, making the adsorbed As more mobile (*Sracek et al., 2004; Smedley et al.,2002).* Cr(VI) does not precipitate out at any pH since it does not exist as a cation but rather as an oxyanion in water; the usual way to extract Cr(VI) from water is to use a reducing agent to convert Cr(VI) to Cr(III) that has low solubility and low mobility due to its preference to precipitate as hydroxide $Cr(OH)_3$ under alkaline, neutral and even slightly acid conditions(*Baird and Cann, 2008*).

Figure 3.2 show the leachabilty behavior of some metals, at acid conditions, pH is the parameter that control the dissolution of metals, instead at high pH i.e. alkaline conditions, complexations with organic matter (humic and fulvic acids) and with iron and manganese hydr/oxides seem to be the major factors of dissolution.

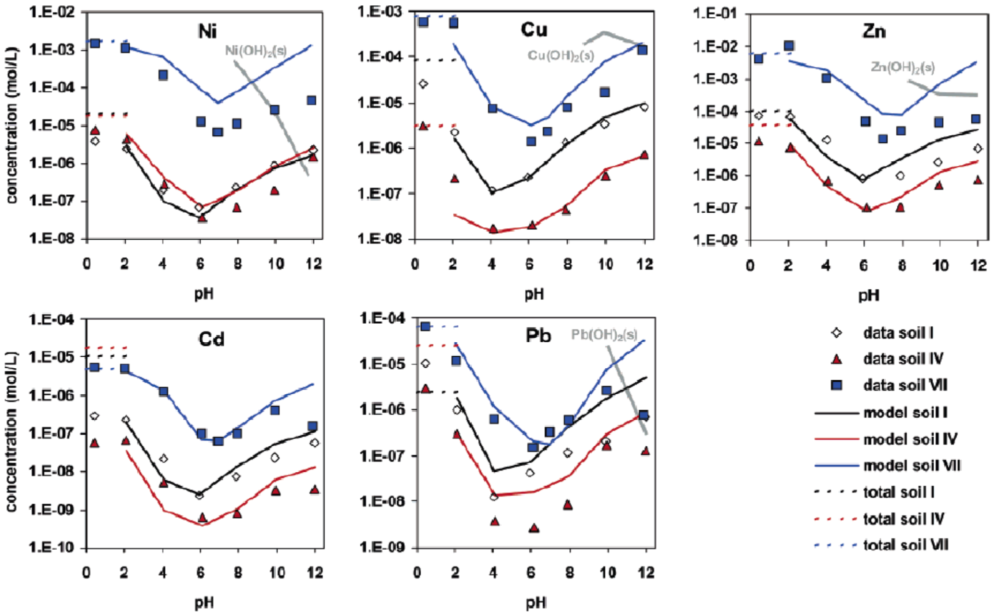

Figure 3.2 Leached concentrations and model predictions as a function of pH of Ni, Cu, Zn, Cd, and Pb from three soil samples (Dijkstra et al, 2004.)

Metal adsorption experiments on soil show that, in addition of pH, organic matter has a strong importance on metal solubility in many soils (*Mc bride et al., 1997*). Soluble organic matter (fulvic acid), which can suppress heavy metal adsorption on Fe and Al oxides and silicate at high pH (*Zachara et al., 1994; Xu et al., 1989*), generally has a sufficiently strong affinity for metals such as Cu, Ni, Hg and Pb that it promotes dissolution of these metals. Organic matter content often dominates adsorption and complexation reactions that control free metal activity (*Mc bride et al., 1997*). The release of metals from soils and sediments is to a large extent determined by the release of DOC. Organic carbon can bind metals and organic contaminants, whereas DOC can mobilize metals and organic contaminants (*Cappuyns and Swennen, 2008*). DOC is a sum of parameters for all organic species in solution, such as sugars, organic acids, amino acids, lignin, humic and fulvic acids. In natural soil systems, humic and fulvic acids control heavy metal binding. Fulvic acids are soluble under acid and alkaline conditions, while humic acids are only soluble under alkaline conditions. Generally, the solubility of DOC increases with increasing pH (*Cappuyns and Swennen, 2008*).

Also iron and manganese oxides and hydroxides are known to be strong adsorbent of heavy metals (*Forstner and Wittman, 1979*). Figure 3.1 explain that solubility of metals at high pH can be controlled by iron and manganese oxides and hydroxides. As example it has been reported that lead is accumulated in the surface soil horizon because of its low mobility and strong association to soil constituents (*Banuelos and Ajwa, 1999*) as organic matter, minerals of the clay fraction, and oxides of iron and manganese (*Walton and Conway, 1988; Kabata-Pendias and Pendias, 2001*).

4 Materials and methods

4.1 Standard batch leaching test (SS-EN 12457-3)

Soil samples were collected by means of an auger sample by BanaVäg i Väst in November 2009 at four spots in the Tudor landfill. The samples were collected in special plastic bags designed for soil samples and then stored in a refrigerator at +4 °C.

Batch tests were performed on three of the nineteen soil samples collected, with different concentration of lead, according to a standardized procedure with two steps leaching (SS-EN 12457-3) with different liquid-to-solid ratios (L/S, where L is the volume of leachant and S is the weight of soil sample).

Soil samples for these standard batch leaching test were chosen as follows:

- **1A 1-2m:** highest concentration of 9800 mg Pb/kg DS.
- **2B 1-2m:** "low" concentration of 2400 mg Pb/kg DS.
- **1B 2-4m:** mean concentration of 2800 mg Pb/kg DS, the amount of sample available of this sample was also the highest (3 kg).

Determination of dry substances and loss of ignition

Dry substances (water content) and loss of ignition (organic content) were determined in the soil samples used for the leachates test following a standardiesed procedure (*filed method 2540 G., 2000*). The soil samples were mixed without crushing in order to obtain a homogeneous mixture. Particle fractions >10mm in diameter were removed by hand but there were very few particles of that size.

Pretreatment of ceramic vessel: a clean ceramic vessel was heated at 550 °C for 1 hour in a muffle furnace. Then it was cooled in desiccator, weighed and stored in the desiccator until ready for use.

Dry substances and water content: 35 g of wet soil were placed in a ceramic vessel and weighted, and then placed in an oven at 105 °C overnight. After this the sample was cooled in a desiccator and then weighted again. Repetitions of drying (1h), cooling, weighting, and desiccating steps were made until the weight of the samples change were less than 4% or 0.50 mg.

Loss of ignition (inorganic and organic content): the dried residue from the dry substances determination were transferred into a muffle furnace and heated at 550°C for 1 h. After this the sample were cooled into the desiccator and weighed. Repetitions of igniting (30 min), cooling, desiccating , and weighing steps were made until weight of samples change were less than 4% or 0.50 mg.

4.1.1 First step L/S ratio 2 l/kg

In the first step (see Figure 4.1), a test portions of each soil with the total mass corresponding to 175 g of dry mass were placed in high-density polyethylene (PEHD) bottles (500 ml) with an appropriate volume (calculated taking into account the moisture content of each sample) of Milli-Q water in order to obtain the right liquid/solid ratio (L/S=2). The samples were agitated for 6 h in a shaker with a speed of about 36 r.p.m. The pH was measured directly after the agitation, and 45 ml of the sample was collected into a plastic tube with 0.45 (1%) ml of HNO_3 for total elements concentration analysis. Then the remaining leachate water was centrifuged (3000 g for 10 min), and thereafter 30 ml of the water was filtrated trough a cellulose acetate filter (0.45µm), and transferred to a plastic tube with 0.3 ml of HNO_3 for total element concentration analysis. The rest of the water after centrifugation was divided in three other samples, 30 ml for total elements analysis (also these with 0.3 ml of HNO_3) and at least 50 ml for each of the other two samples: one for DOC analysis and the other for TOC analysis. All samples were kept in refrigerator (+4°C) before the chemical analysis.

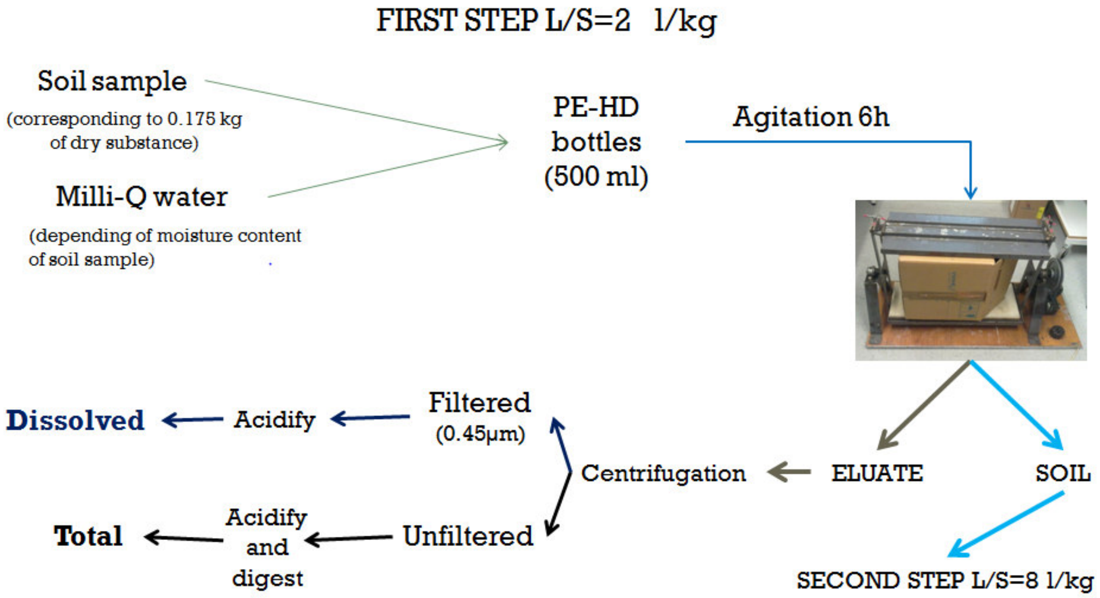

Figure 4.1 The procedure for the first step of the batch leaching test.

4.1.2 Second step L/S ratio 8 l/kg

In a second step (see Figure 4.2), the soil sample left over from the previous step was shaken with 1400 ml of Milli-Q water (L/S=8) in high-density polyethylene (PEHD) bottles (2000 ml) for 18h. The pH was measured on the liquid directly after the shaking, and 45 ml of the water was transferred into a plastic tube with 0.45 ml of HNO_3 for total elements concentration analysis. The remaining leachate water was centrifuged to obtain the maximum settlement of particles, and 30 ml of this water were filtrated through a cellulose acetate filter (0.45µm), and transferred to a plastic tube with 0.3 ml of HNO_3 for total elements analysis. The rest of the centrifuged water was divided in three other samples with 30 ml for total elements analysis (also these with 0.3 ml of HNO_3) and at least 50 ml for each of the other two samples: one for DOC analysis and the other for TOC analysis. A small amount of the soil left after the leaching test was washed and centrifuged twice, and dried at 105 °C for 6h in oven, for total elements concentration analysis. Also small amounts of the original soil samples were dried and stored for total elements analysis.

All the tests were carried out at a temperature of approximately 20°C. Two blank tests were also carried out: a 440 ml (first step) and a 1500 ml (second step) volumes of leachates were submitted to the whole procedure in order to check for possible pollution contributions from the laboratory equipment. Total element concentrations were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Environmental Chemistry Laboratory at Chalmers following a standardized procedure. For TOC and DOC analysis the samples were sent to an external certified laboratory.

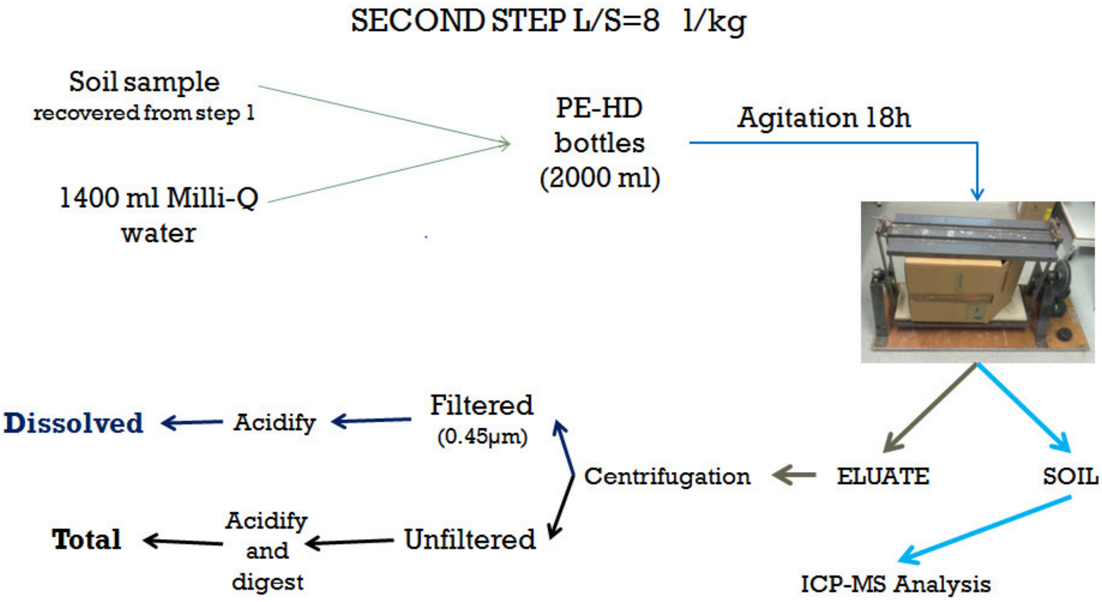

Figure 4.2 The procedure for the second step of the batch leaching test.

On the test portions were calculated dry matter content and moisture content needed to determine exact quantities of leachant and soil. The following formulas were used:

$$DR = 100 \times M_D / M_W$$

DR is the dry matter content ratio (%)

M_D is the mass of the dried test portion at 105° C ± 5 °C (kg)

M_W is the mass of undried test portion (kg)

The moisture content ratio (MC in %) was calculated as:

$$MC = 100 \times (M_W - M_D)/M_D$$

Also the percentage of fixed solids and loss of ignition were estimated on the three soils:

$$FIXS(\%) = (M_{D550}/M_D) \times 100$$

where M_{D550} is the mass of the dried test portion at 550° C ± 5 °C (kg).

$$LOSS\ OF\ IGNITION\ (\%) = (M_D - M_{D550})/M_D$$

For each sample a test portion was prepared of soil with a total mass M_{W175} (measured with an accuracy of 0,1g) corresponding to 0,175 kg of dry mass (M_D), Mw was calculated as follow:

$$M_{W175} = 100 \times M_D/DR$$

The amount of leachant added in the first step (L_2) in order to obtain the liquid to solid ratio of 2 l/kg was:

$$L_2 = (2 - MC/100) \times M_D$$

where in this case M_D is the dry mass of the test portion that is the same for each soil samples and is equal to 0.175 kg.

The volume of leachant used in the second step (L_8) in order to obtain the liquid solid ratio of 8l/kg was:

$$L_8 = 8 \times M_D$$

where in this case M_D is the dry mass of the test portion that is the same for each soil sample and is equal to 0.175 kg.

The release of all contaminants were estimated as:

$$A_2 = C_2 \times [(L_2/M_D) + (MC/100)]$$

Where

A_2 is the release of constituent for the first step with L/S=2 (mg/kg DS)

C_2 is the concentration of constituent in the eluate (in mg/l)

The cumulative release after the end of the second step with L/S=8 ($A_{2\text{-}10}$ in mg/kg DS) also include the concentration of contaminant released in the first batch step and it was calculated from the following equation:

$$A_{2-10} = C_2 \times (VE_1/M_D) + C_8 \times [(L_2 + L_8 - VE_1)/M_D + (MC/100)]$$

Where

C_8 is the concentration of contaminant in the eluate from the second extraction (mg/l)

VE_1 is the volume of eluate recovered from the first extraction (l)

4.2 Beaker leaching tests with different boundary conditions

In order to understand the behavior of soil subjected to different conditions, eight batch leaching tests were done on soil samples **1B 2-4m**. These tests were done to determine the degree of leaching of metals from the soil if the physical/chemical conditions change. In real life, and at the landfill site, these changes of physical/chemical conditions could occur under excavation activities, snow melting, heavy rain fall and flooding of the Göta river.

The eight bacth leaching tests were:

1. Air input and mixing.
2. High pH.
3. Addition of humic colloids.
4. Addition of iron colloids.
5. Inert atmosphere
6. Strong mixing.
7. Low pH.
8. Undisturbed environment.

For each leaching test, soil with the total mass corresponding to 100 g of dry mass were placed in a glass beaker with an appropriate volume (calculated taking into account the moisture content of the sample) of 554 ml of Milli-Q water in order to obtain the liquid/solid ratio (L/S=6).

1. Air input and mixing: compressed air was input to the soil/water samples through a cylindrical diffuser in order to obtain high level of dissolved oxygen in the beaker and also to get a good mixing of the sample.

2. pH high: 1M of NaOH was drop wise input to the beaker to maintain a pH value between 8 and 9 (but never higher than 9). The sample was also gently mixed with a magnetic stirrer in order to avoid strong sedimentation of soil particles.

3. Addition of humic colloids: 111 ml of organic colloids, made from humic acid, were added in order to obtain a high concentration of 200 mg/l. The sample was also gently mixed with a magnetic stirrer in order to avoid strong sedimentation of soil particles

4. Addition of iron colloids: 0.96 ml of organic colloids, made from iron hydroxide, were added in order to obtain a high concentration of 50 mg/l. The sample was also gently mixed with magnetic stirrer in order to avoid strong sedimentation of soil particles.

5. Inert atmosphere: compressed nitrogen N_2 was added with a cylindrical diffuser in order to obtain an anaerobic environment, and also to give a good mixing of the sample.

6.Strong mixing: strong mixing of the sample was done with a magnetic stirrer in order to obtain the best contact of soil particles and water and to avoid sedimentation. This strong mixing could simulate a situation of excavation.

7. pH low: HNO_3 (65%) was drop wise input to the beaker to maintain a pH value around 4 (but never lower than 4). The sample was also gently mixed with a magnetic stirrer in order to avoid strong sedimentation of soil particles.

8. Undisturbed environment: after addition of Milli-Q water the sample was left without any input of chemicals and without mixing.

All tests consisted of a single step for 24 hours during which conductivity, temperature, Eh, pH and dissolved oxygen were measured every hour for the first four hours, and then after 24 hours.

For each sample (after the last measurement of parameters mentioned above), 45 ml was transferred to a plastic tube with 0.45 (1%) ml of HNO_3 in order to acidify the sample for total element concentration analysis. Then the remaining leachate was centrifuged to obtain the maximum settlement of particles, and 30 ml of this water were filtrated through a cellulose acetate filter (0.45µm), and collected into a plastic tube with 0.3 ml of HNO_3 for total element concentration analysis (see Figure 4.3).

The rest of the centrifuged leachate was divided in eight other samples:

- 30 ml for total elements concentration analysis (also these with 0.3 ml of HNO_3).
- 35 ml was filtered with micro fiberglass filter without organic binder for UV absorption (10ml) and true color analysis.
- 50 ml for turbidity and apparent color analysis.
- 75 ml in three different plastic tubes (25+25+25) for carbonate alkalinity analysis.
- 50 ml for DOC analysis.
- 50 ml for TOC analysis.

A small amount of the soils left after each leaching test was extract and dried at 105 °C for 6 h in the oven; stored for total elements concentration analysis. The tests were carried out at a temperature of around 20°C. Total element concentrations were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Chemical Environmental Laboratory at Chalmers following a standardized procedure. For TOC and DOC analysis the samples were sent to an external laboratory in Stockholm.

The release of all contaminants was estimated as:

$$A_6 = C_6 \times [(L_6/M_D) + (MC/100)]$$

Where

A_6 is the release of constituent after 24 hours (mg/kg DS)

C_6 is the concentration of constituent in the eluate (in mg/l)

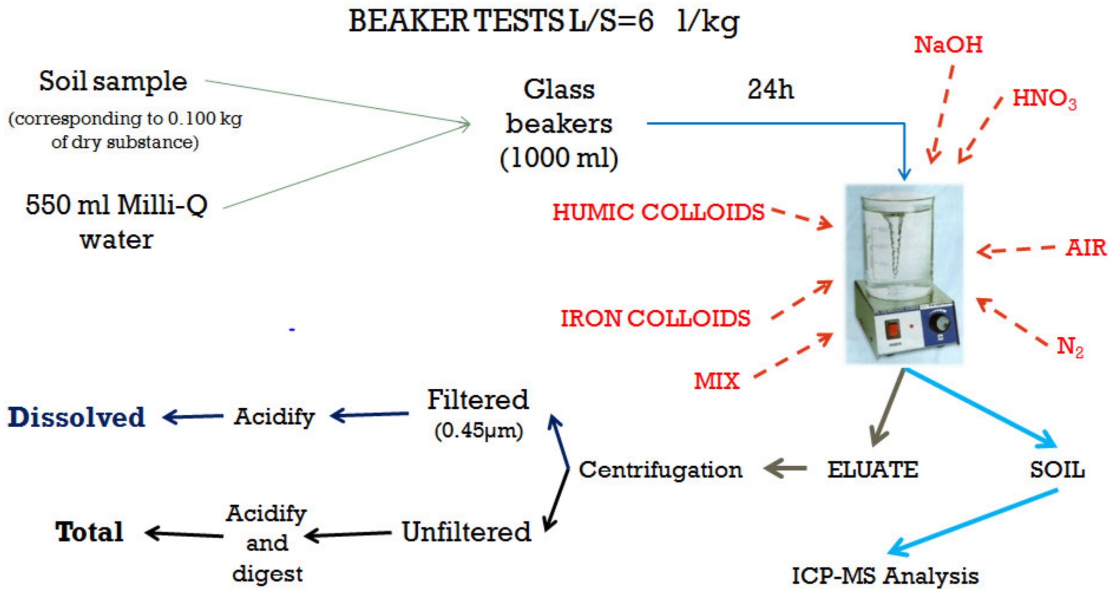

Figure 4.3 The procedure for the batch tests with soil exposed to changes in physical/chemical conditions.

Other parameters analyzed after collection of the leachate were:

- Turbidity
- Apparent color
- True color
- UV adsorption
- Carbonate alkalinity

Turbidity can be an indirect measure of suspended solids and colloidal matter content. Material that causes turbidity include: clay, silt, finely divided organic and inorganic matter and soluble colored organic compounds *(USGS- U.S., 2010*).The measurements of turbidity were carried out with a portable Hach instrument, and measured in FAU (Formazin Attenuation Units). After a primary calibration with a blank sample, a cell of 10ml of well mixed sample was placed into the instrument that gave an instant value of turbidity between 0 and 1000 FAU.

Color in water can be caused by dissolved and particulate material. Test of color can often reflects the amount of organic material in the water, but also the presence of minerals like iron and manganese that may cause variation of color in water/leachate samples.

The color of both water/leachate samples was reported as:

- ***Apparent color*** that is the color of the samples as it was collected, and consists of color from both dissolved and suspended components.
- ***True color*** that is the color after filtration of the water/leachate sample to remove all suspended material

The measurements of true and apparent color were carried out with a portable Hach instrument. Color unit with Hach is mg/l Pt-Co (Platinum-Cobalt Units). After a primary calibration with a blank sample, a cell of 25 ml of well mixed sample was placed into the instrument that gave an instant value of True/Apparent color between 0 and 500 Pt-Co Units.

Some organic compounds commonly found in water and wastewater strongly absorb ultraviolet (UV) radiation, and good correlations may exist between **UV absorption** and organic carbon content (*5190 UV-absorbing organic constituents)*. In this case UV absorption was used only to provide an indication of the content of UV-absorbing organic constituents (*5190 UV-absorbing organic constituents).*

UV-absorbing organic constituents in a sample absorb UV light in proportion to their concentration. Samples were filtered with micro fiberglass filter without organic binder to avoid disturbance caused by particles. The measurements of UV absorption were carried out with UNICAM UV/Vis spectrometer; the wavelength for the measurements is 253.7 nm. UV absorption unit with UNICAM UV/Vis spectrometer is ABS (absorbance units). After a primary calibration with a blank sample, a cell providing a light path of 1cm of well mixed sample was placed into the instrument that gave an instant value of UV absorption.

Alkalinity (A) is the quantitative capacity of aqueous media to react with hydrogen ions (*ISO 6107-02,1989*).The assessment of groundwater's capacity to resist acidification is based on its alkalinity (*Swedish EPA, 2010*). Alkalinity was determined by titration with hydrochloric acid (HCl=0.020 mol/l), with simultaneous removal of carbon dioxide. The indicator used was a mixed indicator so the endpoint was at pH=5.4. Samples of 25/50 ml of volume were titrated slowly with hydrochloric acid until the color changed, and remained for at least 30 seconds, to grey. Three titrations for each sample were performed and it was chosen the lower value to calculate alkalinity. Three titration in the same way were performed on blank samples of 50 ml of Milli-Q water.

Conductivity can give an indication of the content of ions content in water. Measurements of conductivity were made during and at the end of all the leaching tests. All the measurements were carried out with a multiliner (WTW Multiline P4 Universal Meter), conductivity unit is mS/m.

pH provides an assessment of the acidity or alkalinity of a solution. pH is defined as:

$$\mathrm{pH} = -\log_{10}[\mathrm{H_3O^+}]$$

Measurements of pH were made using a pH meter (name and number) and a multiliner (WTW Multiline P4 Universal Meter), pH was during and at the end of all the leaching tests and also on the groundwater samples.

Redox potential is the general term for the chemical reactions involved in the transfer of electrons. When a molecule is OXidized, it gives up electrons to another molecule which is thereby REDuced – hence the term "redox" (*Swedish EPA, 2010*). Oxygenated (aerobic) water has a higher redox potential (Eh) than water devoid of oxygen (anaerobic). Redox potential is an index of water's capacity to support redox reactions (Swedish EPA, 2010).The redox conditions of groundwater affect the concentration, solubility and mobility of many elements as for example Fe, S and C, as well as those of a number of other metallic elements; depend strongly on redox conditions. A low redox potential indicates several risks, including: the release of hydrogen sulphide and methane; precipitation of iron (Fe) and manganese (Mn); and difficulty in reducing the water's concentration of those metals in soluble form (*Swedish EPA, 2010*). Measures of redox potential were performed with HANNA INSTRUMENT Eh-meter, units of redox potential are mV.

The concentration of **dissolved oxygen** in groundwater samples can depend on many factors such as ventilation in deeper layers, presence of biodegradable organic matter etc. In the leaching test was measured to understand better how the different boundary conditions could change the oxygen supply to the interface soil-leachant. The dissolved oxygen measurements were made with an electrode method (WTW Multiline P4 Universal Meter).

Temperature is an important parameter of reference for all other parameters analyzed. The leaching tests were done at the standard laboratory temperatures (20ºC). The measurements were made with WTW Multiliner P4 Universal Meter.

TOC (total organic carbon) is a measure of organic carbon content present in dissolved form **DOC** and in particulate form POC and it derives from the sum of these two *(www.iss.it)*:

DOC is the organic carbon passing through a membrane filter of 0.45 µm POC is the fraction of organic carbon retained on the filter. An aliquot of the sample, treated according to the type of carbon analysis, is introduced in the equipment where the carbon is oxidized to CO_2. The CO_2 formed by oxidation of carbon is driven by a suitable carrier gas, where it is determined with a special non-dispersive infrared detector *(www.iss.it).*

4.3 Acid digestion

The methods consist of a concentrated acid hot digestion of aqueous samples in closed tubes in a microwave oven or in a heating reactor in order to dissolve metals associated with particles or present in colloidal and/or organic form.

Regarding the analysis of total elements (ICP-MS) for each leaching test performed according to standard SS-EN 12457-3, and the leaching tests with different boundary conditions, five types of samples were obtained:

1. filtered leachate (0.45 µm filter): acidified and analyzed for total dissolved elements.
2. leachate and soil: acidified, digested and analyzed for total elements dissolved, particulate, colloidal and attached to soil particles.
3. centrifuged leachate: acidified, digested and analyzed for total elements dissolved, colloidal and particulate.
4. original dry soil: digested and analyzed for total elements associated with soil particles.
5. dry soil remaining after each test: digested and analyzed for total elements associated with soil particles.

For all the samples of leachate and soil (2-5), a digestion with nitric acid (ultra pure HNO_3 65%) in special Teflon sealed tubes using the microwave oven with temperature control and pressure was performed:

- **leachate:** 9 ml sample mixed with 1 ml of HNO_3

- **soil:** 0.5 g of dry soil mixed with 5 ml HNO_3 and 5 ml of Milli-Q water

Both samples were heated in the microwave oven at 180 ° C for 20 minutes in two steps of 10 minutes with controlled increase of temperature and pressure. With this first digestion problems were found due to evaporation of some samples, especially those of soil (4,5) probably due to reaction between acid and organic matter and subsequent evaporation.

Thus it was therefore decided to carry out an acid digestion in microwave oven with hydrogen peroxide (H_2O_2) pretreatment for soil samples:

- **soil:** 0.3 g of dry soil mixed with 1 ml of H_2O_2 and allowed to react for 30 minutes after which were added 5 ml HNO_3 and 5 ml of Milli-Q water and start heating to 180° C for 20 minutes.

For leachate samples an acid digestion (ultra pure HNO_3 65%) was performed in special glass tubes using a heating reactor:

- **leached:** 4ml of sample mixed with 1 ml of HNO_3, subsequently samples were sent to heating at 150 ° C for 2 hours

The digestion step was then followed by analysis of total elements (ICP-MS).

4.4 ICP-MS

The schematic diagram of an ICP-MS instrument is shown in Figure 4.4. Basically, liquid samples are introduced by a peristaltic pump to the nebulizer where a sample aerosol is formed. A double-pass spray chamber ensures that a consistent aerosol is introduced to the plasma. Argon (Ar) gas is introduced through a series of concentric quartz tubes, known as the ICP torch (*Yoko,1997*).The torch is located in the center of an RF coil, the intense RF field causes collisions between the Ar atoms, generating a high-energy plasma. The sample aerosol is instantaneously decomposed in the plasma (plasma temperature is in the order of 6,000 to 10,000K) to form analyte atoms, which are simultaneously ionized. The ions produced are extracted from the plasma into the mass spectrometer region, which is held at high vacuum (typically 10–6 Torr, 10–4 Pa). The vacuum is maintained by differential pumping.

The analyte ions are extracted through a pair of orifices, approximately 1 mm in diameter, known as the sampling cone and the skimmer cone (*Yoko,1997*). The analyte ions are then focused by a series of ion lenses into a quadrupole mass analyzer which separates the ions based on their mass/charge ratio (m/z). The term quadrupole is used because the mass analyzer is essentially four parallel molybdenum rods to which a combination of RF and dc voltages is applied. The combination of these voltages allows the analyzer to transmit only ions of a specific mass/charge ratio. Finally, the ions are measured using an electron multiplier, and data at all masses is collected by a counter. The mass spectrum generated is extremely simple. Each elemental isotope appears at a different mass (e.g. 27Al would appear at 27 amu) with a peak intensity directly proportional to the initial concentration of that isotope.

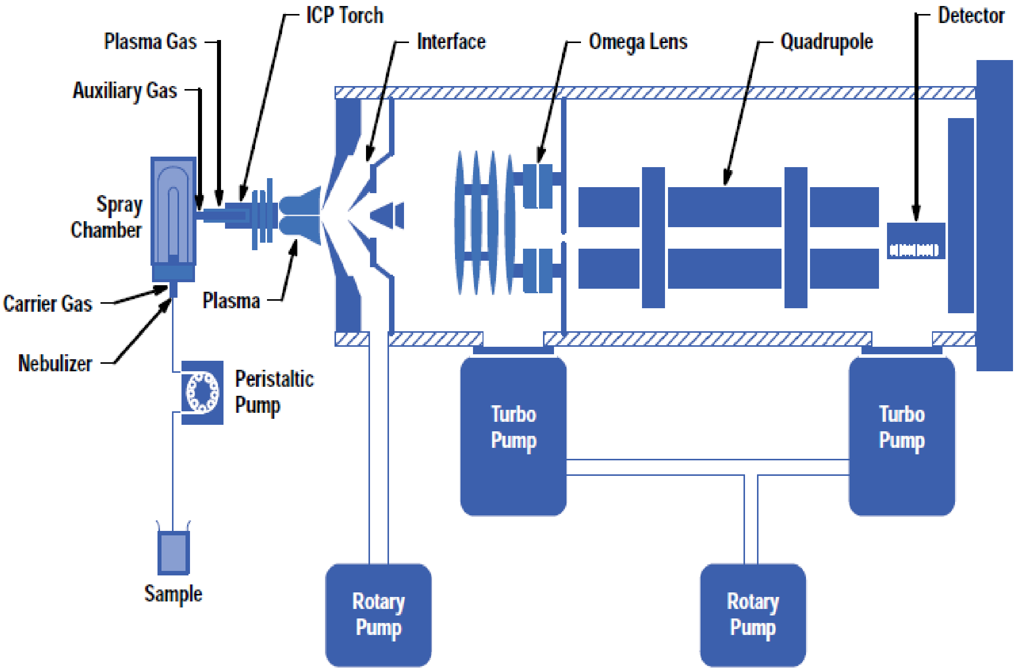

Figure 4.4 ICP-MS Schematic diagram (Yoko,1997).

4.4.1 Sample preparation for ICP-MS

Four calibration standards with 1, 10, 100, 1000 ppb of stock solution of 23 element multi standard plus a blank were prepared in order to calibrate the ICP-MS. In all analyzed samples 0.1 ml of 1ppm solution of Rhodium Rh was added as internal standard. Problems caused by massive presence of particles that interfered with the analysis of metals, have exclude from further analysis the samples with soil and leachate together.

All the analyzed samples were divided in three classes with different dilution factor:

- filtered samples in which the analyzed was the dissolved content of metals.
- leachate samples in which the analyzed was the total content of metals.
- soil samples in which the analyzed were the metals in the solid phase.

Table 4.1 Preparation of sample for ICP-MS analysis

Type of sample	**Analyzed phase**	**Preparation**	**Dilution factor**
Filtered (0.45µm)	dissolved	9.9 ml sample + 0.1 ml Rh	1
Leachate	total	1 ml sample + 8.9 Milli-Q W + 0,1 ml Rh	10
Soil	solid	0.5 ml sample + 9.4 Milli-Q W + 0.1 ml Rh	10

ICP-MS gives concentration measurement results in µg/l for each element considered.

For filtered and leachate samples the final concentration for each element was calculated with the following formula:

$$X_{(ug/l)} = X_{ICP-MS(ug/l)} \times DF$$

where

$X_{(\mu g/l)}$ is the final concentration of the considered element

$X_{ICP\text{-}MS(\mu g/l)}$ is the reveled measure from ICP-MS

DF is the dilution factor

For soil samples the final concentration is in mg/kg TS calculate as follows:

$$X_{(mg/kg\ DS)} = X_{\ ICP-MS(ug/l)} \times \frac{10\ ml}{0.5\ g\ DS} \times DF \times \frac{1}{1000}$$

where

$X_{(\mu g/l)}$ is the final concentration of the considered element

$X_{ICP\text{-}MS(\mu g/l)}$ is the reveled measure from ICP-MS

DF is the dilution factor

0.5 g DS is the dry substance of soil sample

1/1000 is the conversion factor between ml and l

5 Results and discussion

5.1 Soil samples

Soil samples were collected by an auger sample by BanaVäg i Väst in November 2009 from four established points in the Tudor landfill (1A, 2A, 1B, 2B, see Figure 5.1). For each spot/well one sample (1–2 kg of wet weigh) per meter was collected down to a maximum depth of 5 meters. The remaining two wells (1C and 2C, see Figure 5.1) were not sampled because they are situated close to the railway track, where the contaminated soil has been excavated. The soil in these wells consists of rock fill and clean clay.

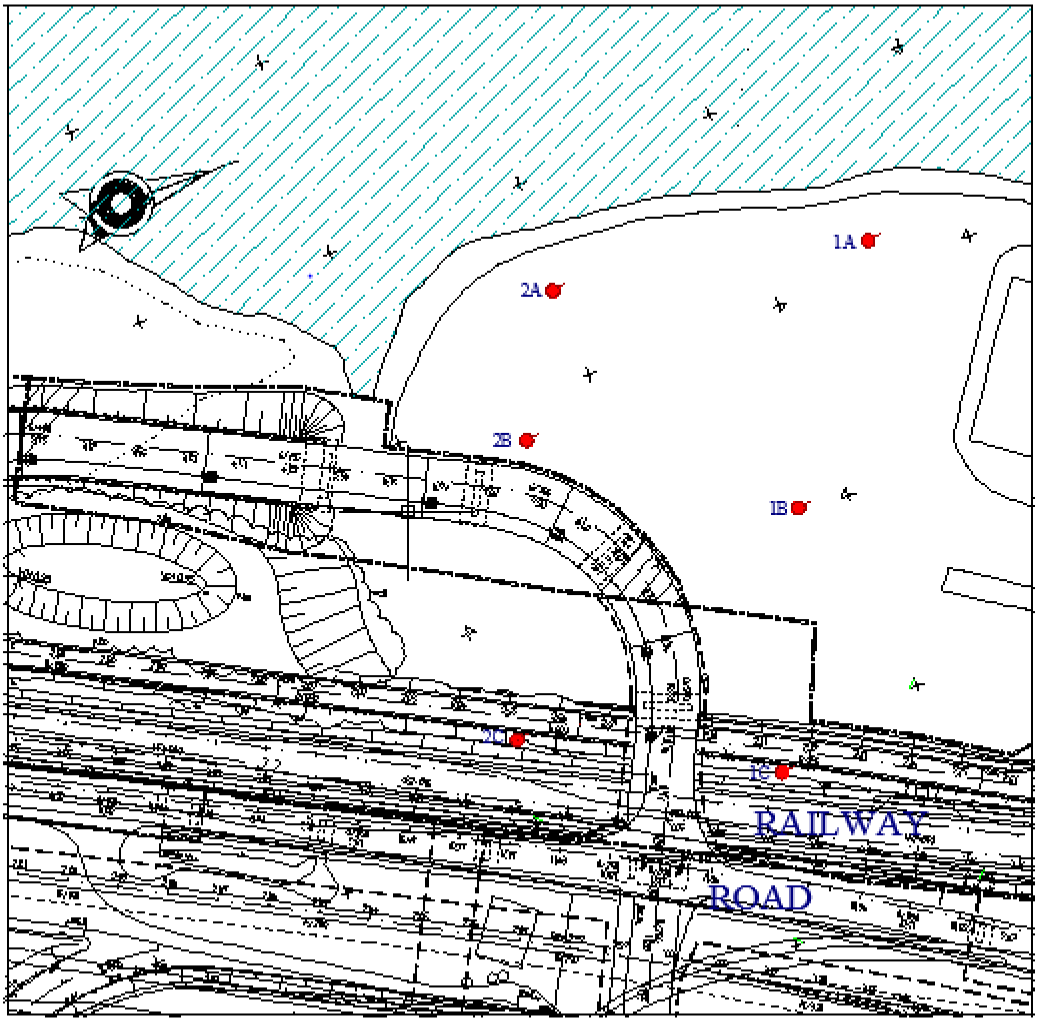

Figure 5.1 Landfill area with the six soil and groundwater sampling points

Concentrations of metals and PAHs, in the seventeen soil samples collected at the Tudor landfill site , are presented in Table 5.1

Table 5.1 Concentrations of metals and PAHs in soil samples from spots 1A, 2A, 1B, 2B at different depths (mg/kg DS).

1A Depth (m)	As	Pb	Cd	Cu	Cr	Hg	Ni	Zn	PAHs[a] carcinogenic	PAHs[a] other
0 – 1	7.4	740 **	1.4 *	16	31	< 0.05	22	95	3.8 *	19
1 – 2	6.2	9800 **	1.4 *	22	19	0.061	13	100	2.3 *	4.1
2 – 3	5.3	1000 **	3.7 *	28	22	0.062	16	110	1.4 *	3.9
3 – 4	3.8	4600 **	3.8 *	13	20	< 0.05	21	81	0.38 *	0.61

2A Depth (m)	As	Pb	Cd	Cu	Cr	Hg	Ni	Zn	PAHs[a] carcinogenic	PAHs[a] other
0 – 1	7.1	1400 **	2.4 *	30	24	0.42*	16	220	1.8 *	1.8
1 – 2	6.1	4000 **	5.6 *	21	21	1.7 *	17	110	4.0 *	4.7
2 – 3	4.5	610 **	0.63	80	33	0.54*	13	130	1.2 *	1.9
3 – 4	<2.9	190*	<0.29	11	18	0.083	11	64	<0.30	<0.30

1B Depth (m)	As	Pb	Cd	Cu	Cr	Hg	Ni	Zn	PAHs[a] carcinogenic	PAHs[a] other
0 – 1	8.8	1800 **	<0.25	23	31	< 0.05	23	96	4 *	3.9
1 – 2	9.9	2800 **	2.0 *	47	25	0.094	25	150	2.3 *	1.9
2 – 3	5.3	2400 **	0.68	24	13	0.064	12	120	10 **	8.9
3 – 4	5.1	1800 **	0.87	22	16	0.34*	15	140	4.5 *	4.8
4 – 5	3.1	28	<0.29	9.9	19	< 0.05	12	70	<0.30	<0.30

2B Depth (m)	As	Pb	Cd	Cu	Cr	Hg	Ni	Zn	PAHs[a] carcinogenic	PAHs[a] other
0 – 1	8.1	160 *	<0.24	15	30	< 0.05	21	69	<0.30	<0.30
1 – 2	3.8	1400 **	0.25	17	19	0.10	11	120	2.9 *	4.6
2 – 3	5.6	1700 **	0.27	16	22	< 0.05	14	76	3.6 *	6.1
3 – 4	3.5	2700 **	0.39	32	45	0.20	13	120	4.6 *	10

* >KM "Land with sensitive use"; (Swedish EPA, 2009) ; [a] (Swedish EPA, 2002)

** >MKM "Land with less sensitive use "; (Swedish EPA, 2009) ; [a] (Swedish EPA, 2002)

The results show a high lead contamination in all four points investigated (up to 9800 mg Pb/kg DS), and 14 out of 17 samples far exceed the Swedish guideline values for contaminated sites (*Swedish EPA, 2009*) (MKM for lead=400 mg Pb/kg DS). In many cases, these values are ten times higher, even in one sample more than twenty times. High values of cadmium concentrations (>KM) were found in seven samples (1.4 – 5.6 mg Cd/kg DS). In four samples the mercury concentration was over the limit value for sensitive land use (>KM); especially in soil sample from spot 2A (1.7 mg Hg/kg DS). Concentrations of PAHs, beyond the Swedish guidelines for sensitive land use (>KM) (*Swedish EPA, 2002*), were found in fourteen samples. In one of these samples, the value of PAHs even exceed the concentration limit for less sensitive use land areas (>MKM).

From the diagram in Figure 5.2, regarding lead concentration, the most polluted layer is at the depth of 1–2 m. It is also apparent that in the spots 2A and 1B, the concentration of lead decreases with increasing depth, while in the well 2B the lead concentrations increase with the depth. The depth profiles show that the contamination of the landfill is heterogeneous.

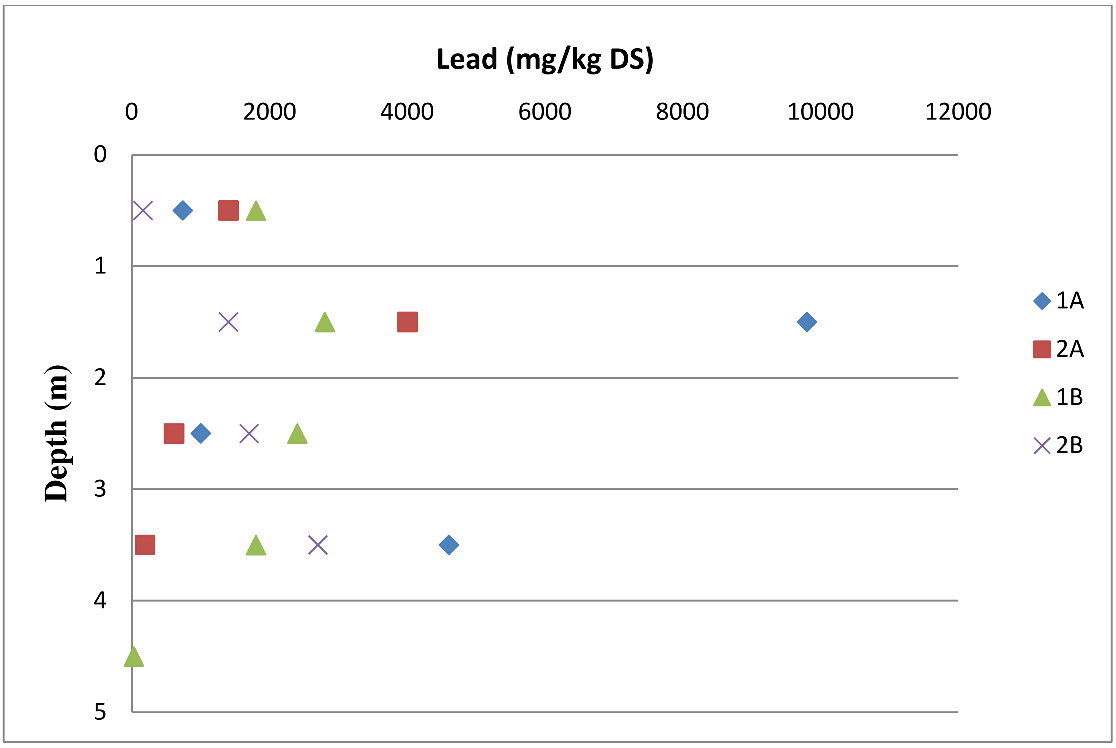

Figure 5.2 Variation of lead concentration in soil with depth at the Tudor landfill in Nol.

To get a better overview of the contamination degree in the landfill, the average concentration of specific metals and PAHs in each spot, are presented in Table 5.2.

Table 5.2 Contaminants average concentration in soil samples at the Tudor landfill in Nol (mg/kg DS)

	Soil 1A	Soil 2A	Soil 1B	Soil 2B
Arsenic As	5.68	5.15	6.44	5.25
Lead Pb	4040**	1550**	1780**	1490**
Cadmium Cd	2.58*	2.23*	0.820	0.290
Copper Cu	19.8	35.5	25.2	20.0
Chromium Cr	23.0	24.0	20.8	29.0
Mercury Hg	0.0600	0.690	0.170	0.150
Nickel Ni	18.0	14.3	17.4	14.8
Zinc Zn	96.5	131	115	96.3
Total carcinogenic PAHs[a]	1.97*	1.83*	4.22*	2.85*
Total other PAHs[a]	6.90	2.18	3.96	5.25

* >KM "Land with sensitive use"; (Swedish EPA, 2009) ; [a] (Swedish EPA, 2002)

** >MKM "Land with less sensitive use "; (Swedish EPA, 2009) ; [a] (Swedish EPA, 2002)

With regard to concentrations of lead, the most polluted point in the landfill is 1A (mean value 4040 mg Pb/kg DS) followed by 1B (mean 1780 mg Pb/kg DS), 2A (mean 1550 mg Pb/kg DS) and 2B (mean 1490 mg Pb/kg DS). All these average concentrations exceed the Swedish guidelines values for less sensitive land use of 400 mg Pb/kg DS (*Swedish EPA, 2009*) from five to over thirteen times. The cadmium mean concentration is above the limit for "Sensitive land use" in spots 1A and 2A. Mean total carcinogenic PAHs values show that the most polluted well is 1B, and the average concentrations exceed the Swedish guidelines for sensitive land use from six to ten times (*Swedish EPA, 2002*). Regarding all other metals there is a dispersed contamination that is evenly distributed throughout the area, however at concentrations below the levels of the Swedish guidelines for sensitive land use.

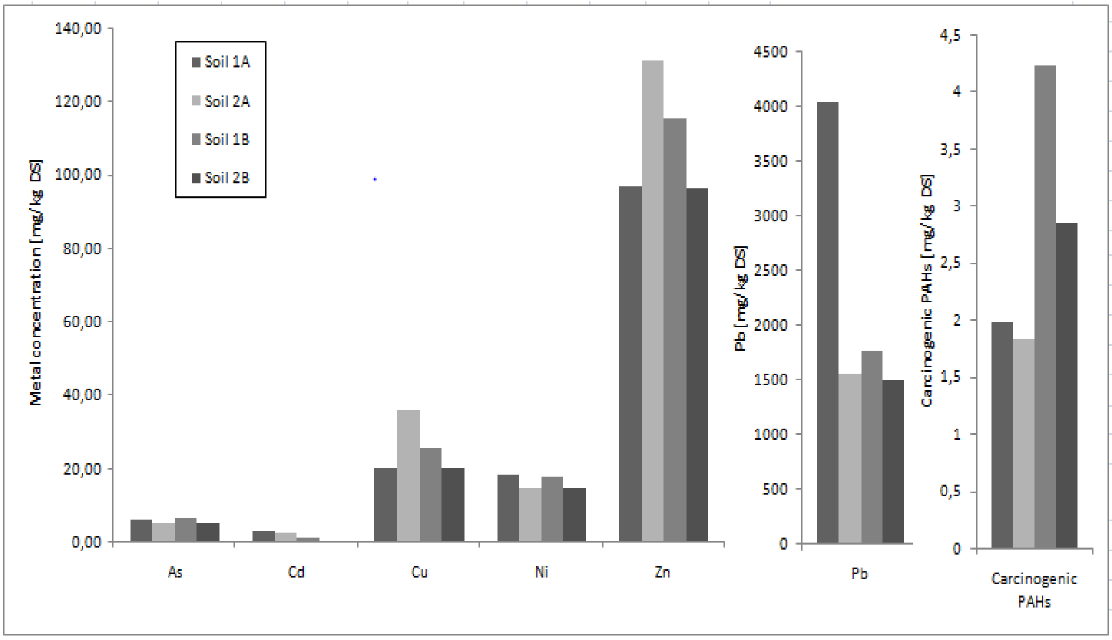

Figure 5.3 Metals and PAHs average concentration in soil samples from the Tudor landfill in Nol.

5.2 Groundwater samples

Groundwater samples were collected at two occasions from the six wells 1A, 2A, 1B, 2B, 1C, 2C, see Figure 5.1, on 20/11/2009 and four month later on 24/03/2010. All samples were analyzed by an accredited laboratory (EUROFINS).The main elements analysed were : metals on both dissolved and total phases, organic contaminants such as PAHs, DOC/TOC, alkalinity, turbidity, conductivity and suspended solids. In samples of groundwater from 24/03/2010 metals on both dissolved and total phases alkalinity, turbidity, conductivity, dissolved oxygen and UV absorption were also analyzed at the Environmental Chemistry laboratory, Department of Civil and Environmental Engineering, Chalmers University of Technology.

All concentrations of lead, arsenic, cadmium and zinc are compared with Environmental quality criteria for groundwater "assessment of current conditions" (*Swedish EPA, 2001*). Regarding the other metals concentrations the comparison is made with values from "Classification of current conditions for contaminated groundwater, based on health-related threshold values for drinking water" (Swedish EPA, 2002). PAHs concentrations are compared with contaminated groundwater values based on guidelines for contaminated petrol stations (*Swedish EPA, 2002*). This choice was made because the river Göta älv is Gothenburg's drinking water supply.

Groundwater sampling 20/11/2009

Dissolved metals concentration: Lead concentrations in the dissolved phase highlights well 2A as high risk point (16 µg/l), see Table 5.3. In this well dissolved cadmium concentration poses a moderately risk of biological effects.

Total metals concentrations: The comparison of measured data with the guideline values for groundwater should be done for the dissolves metals, i.e. for filtrated samples. In this study comparisons with the guideline values are also made for total concentrations of metals, because particle transport of metals from the groundwater may be possible in the case of the Göta river flooding into the landfill area. The data in Table 5.3 show that the concentration of total arsenic in well 2B is at a high level of risk of biological effects (39 µg/l) regarding the Environmental Quality Criteria for groundwater (*Swedish EPA, 2001*). Regarding total concentrations of cadmium, groundwater from wells 1A and 2B pose a very serious risk of biological effects, and wells 2A and 1B a medium risk. Total concentrations of zinc in well 2B pose a medium risk of biological effects, and a moderately serious risk of biological effect in wells 1A, 2A and 1B. Total lead concentrations reveal that wells 1A, 2A, 1B and 2B can be considered as extremely high risk points (respectively 69 µg/l 1A, 180 µg/l 2A, 190 µg/l 1B and 11000 µg/l 2B) and 1C bring to a serious risk of biological effects (4.8 µg/l). Total mercury concentration is over the limit of European guidelines for substances in surface water and Canadian water quality guidelines for the protection of aquatic life in wells 2A and 2B (respectively 0.21 µg/l and 0.16 µg/l).

Table 5.3 Dissolved and total metals concentrations in groundwater in the six wells at the Tudor landfill in Nol (20/11/2009).

POINT	1A	2A	1B	2B	1C	2C
As dissolved[a]	1.00	0.440	0.640	3.30	0.590	0.860
As total[a]	3.80	1.10	0.840	39.0**	0.680	1.10
Cd dissolved[a]	0.060	0.110*	<0.040	<0.040	0.050	0.030
Cd total[a]	1.20**	0.240*	0.130*	1.40**	<0.100	<0.100
Cr dissolved[b]	<0.200	<0.200	0.670	0.990	0.270	2.00
Cr total[b]	1.40	2.10	3.40	44.0	2.20	2.10
Cu dissolved[b]	0.780	5.50	0.450	0.980	10.0	6.40
Cu total[b]	3.50	8.50	3.40	59.0	15.0	8.10
Hg dissolved[b]	<0.100	<0.100	<0.100	<0.100	<0.100	<0.100
Hg total[b]	<0.100	0.210++	<0.100	0.160++	<0.100	<0.100
Pb dissolved[a]	0.050	16.0***	<0.100	0.360	0.150	0.060
Pb total[a]	69.0 ***	180***	190***	11000***	4.80**	1.80
Zn dissolved[a]	2.90	6.60	2.10	16.00	2.60	<1.00
Zn total[a]	23.0*	28.0*	27.0*	220**	11.0	<5.00

* Moderately serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

** Very serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

*** Extremely serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

++ European Environmental quality standards for priority substances in surface water

Groundwater sampling 24/03/2010

Dissolved metals concentration: For well 2A, see Table 5.4, the concentration of dissolved lead (20 µg/l) is classified with a high risk. Dissolved cadmium concentration is on medium level of risk in well 2A.

Total metals concentrations: Analysis carried out on the six groundwater samples in March confirmed that well 2B is considered with serious risk of biological effects with regard to the concentration of total arsenic (16 µg/l). Total concentration of cadmium is extremely high in well 2A, high in well 1A and moderately high in wells 1B, 2B and 1C. Total chromium concentration in well 2C poses a moderately serious risk of biological effects. The values of total lead concentrations in all the six wells bring to classify them as extremely serious risk points. Total mercury concentration in well 2A (3.2 µg/l) poses a very serious risk of biological effects and it is also over the limit of European guidelines for substances in surface water and Canadian water quality guidelines for the protection of aquatic life.Total zinc is present in moderately high concentration in all the wells.

Table 5.4 Concentrations of dissolved and total metals in groundwater in the six wells at Tudor landfill in Nol (24/03/2010).

POINT	1A	2A	1B	2B	1C	2C
As dissolved[a]	0.37	0.33	0.48	1.40	0.32	0.82
As total[a]	1.20	9.60*	1.30	16.0**	6.60*	7.80*
Cd dissolved[a]	0.09	0.48*	<0.020	<0.020	0.020	<0.020
Cd total[a]	1.20**	5.50***	0.360 *	0.470 *	0.380 *	0.260*
Cr dissolved[b]	<0.2	<0.2	0.930	0.610	<0.2	1.10
Cr total[b]	1.80	29.0	5.60	22.0	33.0	54.0*
Cu dissolved[b]	1.00	3.40	<0.400	0.520	3.90	6.30
Cu total[b]	6.70	51.0	9.90	23.0	66.0	47.0
Hg dissolved[b]	<0.100	<0.100	<0.100	<0.100	<0.100	<0.100
Hg total[b]	<0.100	3.20**	<0.100	<0.100	<0.100	<0.100
Pb dissolved[a]	0.250	20.0**	<0.100	<0.100	0.130	0.100
Pb total[a]	200 ***	3400 ***	440***	3000***	110***	140***
Zn dissolved[a]	6.00	3.60	2.00	7.00	1.10	2.70
Zn total[a]	33.0*	250*	88.0*	90.0*	150*	150*

* Moderately serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

** Very serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

*** Extremely serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

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Groundwater sampling of 24/03/2010(WET-Chalmers):

Dissolved metals concentration: Regarding the concentration of dissolved lead, laboratory tests carried out at the Chalmers University laboratory (Table 5.5) confirmed that well 2B can be classified as a very high risk point (16.2 µg/l). Dissolved cadmium concentration from well 2A poses a moderately serious risk of biological effects.

Total metals concentrations: The total concentration of lead exceed the limit values for extremely serious risk of biological effects in all wells. Total concentration of cadmium in well 1A poses a moderately serious risk and in well 2A a high risk of biological effects. Total concentration of zinc poses a moderately serious risk from four wells (2A, 1B, 1C and 2C).

Table 5.5 Concentrations of total and dissolved metals in the six wells at the Tudor landfill in Nol (24/03/2010).

POINT	1A	2A	1B	2B	1C	2C
Cd dissolved[a]	0.060	0.350*	0.000	0.000	0.020	0.080
Cd total[a]	0.910*	3.38**	0.070	-	-	-
Cr dissolved[b]	0.420	0.25	5.69	8.18	0.86	3.35
Cr total[b]	0.000	16.8	4.39	5.25	9.34	8.36
Cu dissolved[b]	1.31	3.49	5.65	6.02	4.84	15.3
Cu total[b]	3.66	33.4	10.7	6.39	21.2	15.7
Pb dissolved[a]	2.55*	16.2***	0.700	1.13*	0.420	1.62*
Pb total[a]	158***	2210***	611***	592***	29.9***	61.8***
Zn dissolved[a]	6.93	4.41	3.74	11.4	1.09	7.13
Zn total[a]	19.0	141*	65.7*	17.1	40.9*	29.8*

* Moderately serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

** Very serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

*** Extremely serious risk of biological effects from "Assessment of current conditions" [a](Swedish EPA, 2001); [b](Swedish EPA, 2002)

++ European Environmental quality standards for priority substances in surface water

Figure 5.4 shows the total concentrations of lead in groundwater in the six wells from two sampling occasions. The concentrations of total lead was higher in March 2010 than compared with the concentrations measured in November 2009 in all wells except 2B, that is the most polluted well. This higher concentration was prominent for the wells 1C and 2C, where Pb concentrations increased approximately 20 and 70 times, and enough to consider that these wells pose an extremely serious risk of biological effects (*Swedish EPA, 2001*).

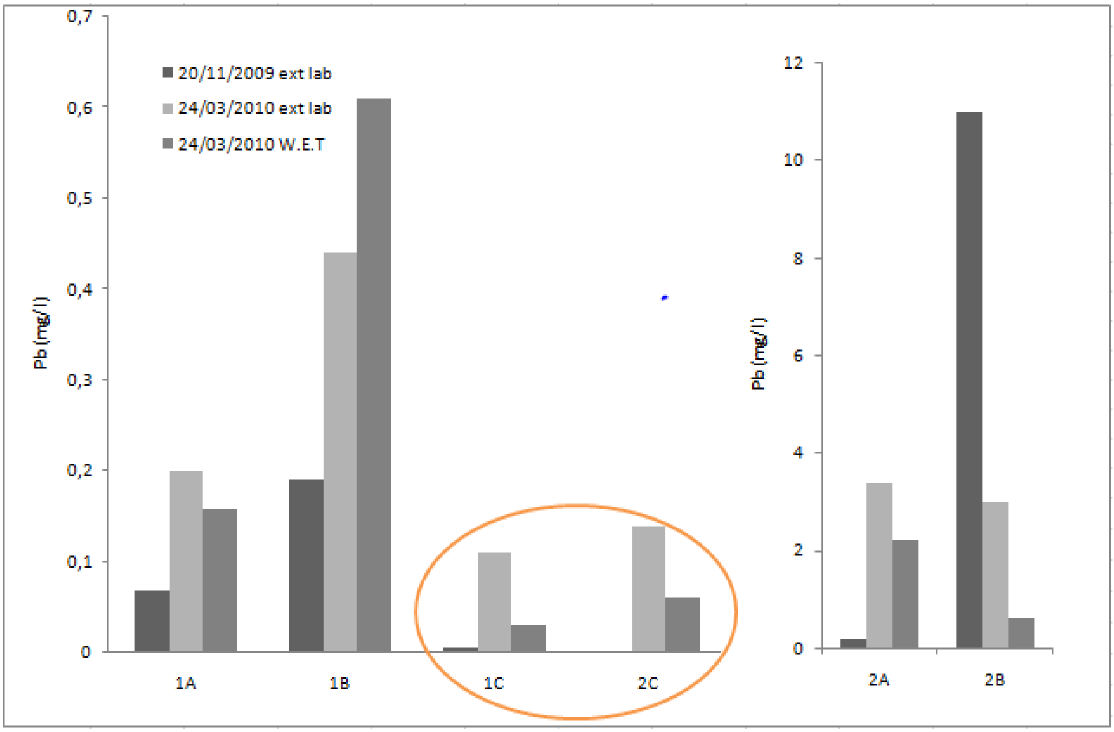

Figure 5.4 Concentration of total lead in groundwater at the Tudor landfill in Nol, sampled at two occasions.

According to the Swedish EPA assessment guidelines for contaminated sites (see Appendix B4) the carbonate alkalinity was found to be very high in wells 1A, 1B and 2B, and in high levels in the others three wells at all the sampling occasions. In addition, the pH was 7.0–8.7 (max and min values from all the sampling occasions) and over the suggested value of 6.5. It can be concluded that the values of alkalinity were adequate to maintain acceptable level of pH in the landfill area (*Swedish EPA, 2002*).

Table 5.6 Carbonate alkalinity and pH in groundwater at Tudor landfill in Nol.

Date		1A	2A	1B	2B	1C	2C
20/11/2009	Alkalinity (mg HCO_3/l)	480	160	790	970	170	83
20/11/2009	pH	8.4	8.5	8.0	7.0	8.5	9.5
24/03/2010	Alkalinity (mg HCO_3/l)	290	130	730	820	120	94
24/03/2010	pH	8.0	8.0	7.6	7	7.9	8.4
24/03/2010*	Alkalinity (mg HCO_3/l)	283	139	715	749	120	95
24/03/2010*	pH	7.0	7.2	6.9	6.8	7.6	8.7

5.3 Standard leaching batch tests

5.3.1 Batch test conducted by Eurofins lab

A summary of pollutants concentrations in soil samples and in eluate after batch leaching tests made by the commercial laboratory of two soil samples are shown in Figure 5.5 and 5.6. For more detailed information see appendices A2 and C1. The concentration of lead in soil sample 2B was higher than in 1B, with 3300 and 2400 mg Pb kg/DS respectively. High concentrations of mercury was found in soil 1B (4.3 mg Hg kg/DS) and higher than the MKM. Cadmium was also present in 1B in concentration over KM with 2 mg Cd kg/DS. Soil 1B was more polluted than soil 2B for all the other metals, but all their concentrations were below the guideline values. Concentrations of total carcinogenic PAHs were over MKM in soil 1B (7.3mg PAH* kg/DS) and over KM in soil 2B (4.6 mg PAH* kg/DS). Polychlorinated biphenyls (PCBs) concentrations were over the KM (0.19 mg PCB_{7st} kg/DS) in soil B and over MKM in soil 2B (0.26 mg PCB_{7st} kg/DS).

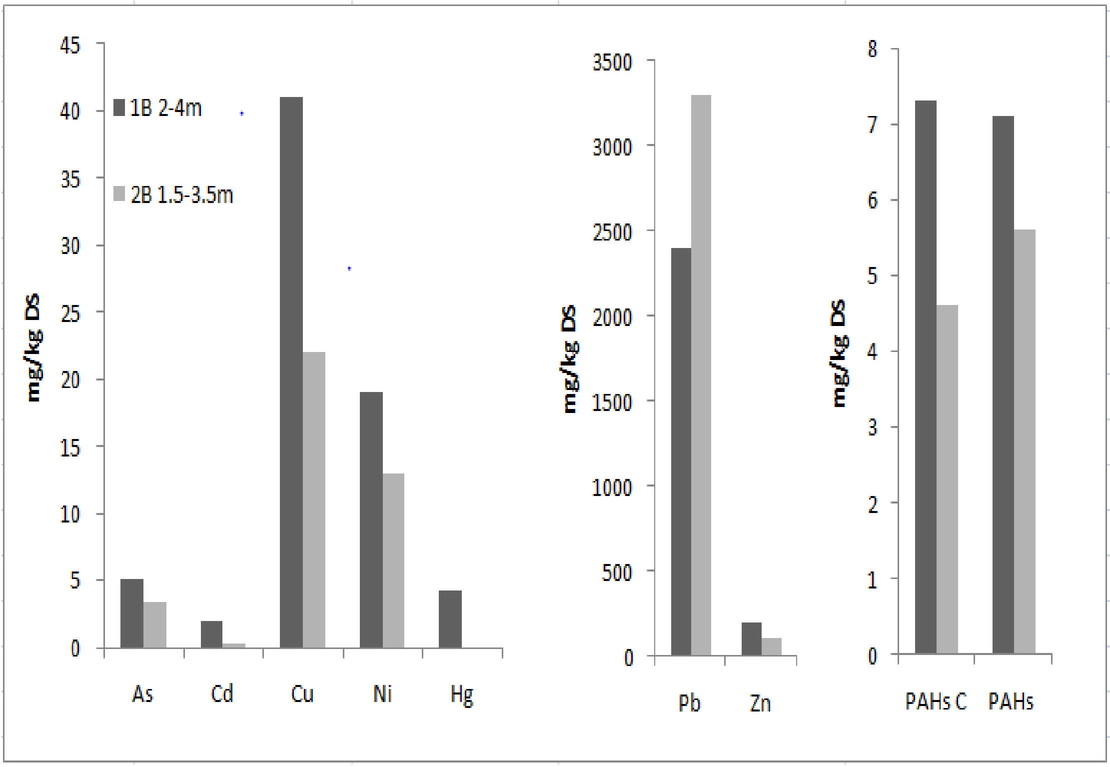

Figure 5.5 Concentrations of metals and PAHs in the soil samples (1B and 2B) used for batch leaching tests (commercial)

Following EU directive 2003/33/EG, the cumulative release of dissolved lead in the batch test classify both soil 1B and 2B as inert waste. The concentration of dissolved lead released from soil 2B makes this soil classified as very close to the limit value for non hazardous waste (0.5 mg/kg DS). When the cumulative release of total lead is considered, see Figure 5.6, both soil 1B and 2B are classified as hazardous waste (10.5 and 79 mg total Pb/kg DS respectively) .

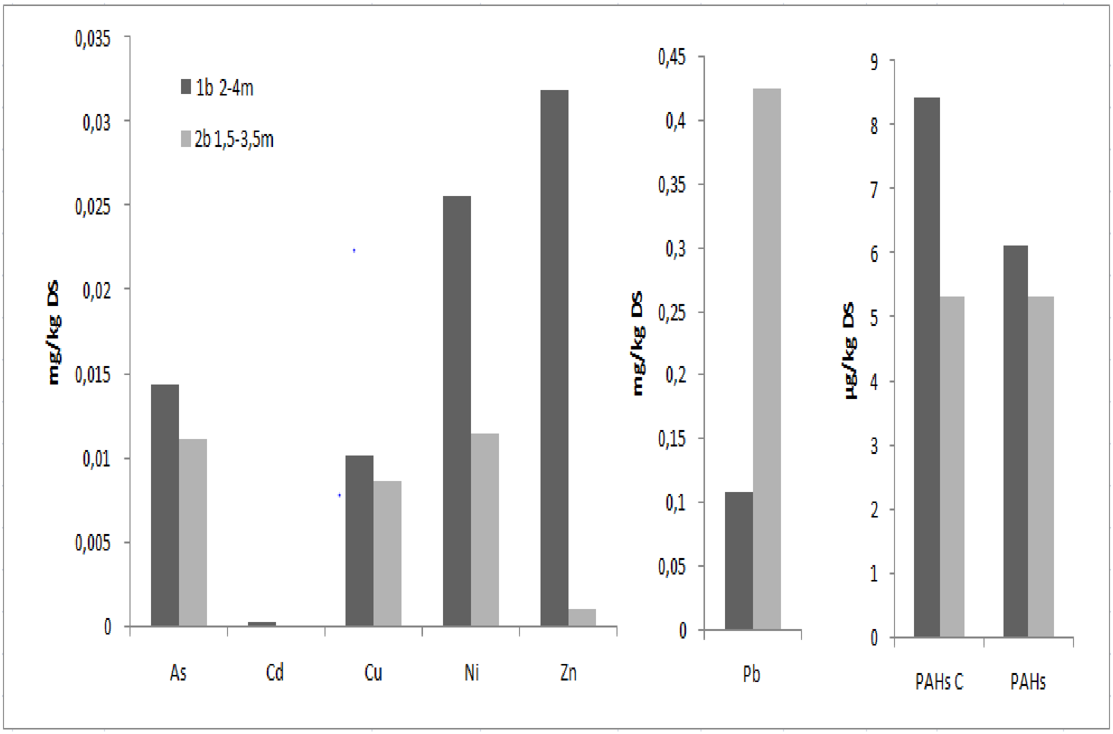

Figure 5.6 Cumulative release $A_{2\text{-}10}$ of dissolved metals and PAHs from the batch leaching test (on soil samples 1B and 2B)(commercial).

Dependence on concentration

The correlations between the amount of pollutants in soil and concentrations of these contaminants found in the eluate in the dissolved phase showed that the most polluted sample was also the one that leached the most. For example, soil 2B leached more lead than soil 1B. For other metals such as As, Cd, Cu, Ni, Zn and for PAHs, the most polluted soil 1B leached the most, see also Figures 5.5 and 5.6.

5.3.2 Batch test at Chalmers laboratory

Batch leaching tests were carried out on three soil samples 1A 1– 2m, 1B 2– 4m and 2B 1– 2m following the European standard EN 12457-3 with two steps at different liquid to solid ratio 2 l/kg and 8 l/kg.

Table 5.7 Main Characteristics and concentrations of metals (mg/kg DS) in the soils (1A, 1B and 2B) used for the leaching tests at Chalmers.

SAMPLE	1A 1-2m	1B 2-4m	2B 1-2m
MD (kg)	0.0346	0.0265	0.0366
MW (kg)	0.0436	0.0387	0.0433
M_{D550} (kg)	0.0332	0.0253	0.0352
FIXS %	95.9	95.2	96.2
LOSS OF IGNITION (%)	4.1	4.8	3.8
DR (%)	79.4	68.5	84.5
MC (%)	25.9	45.9	18.4
M_{W175}	0.2204	0.2554	0.2071
L_2 (l)	0.305	0.270	0.318
L_8 (l)	1.4	1.4	1.4

SAMPLE	1A 1-2 m	1B 2-4 m	2B 1-2 m
Al	15323	17256	10893
Cd	4.6*	3.3*	0.3
Co	7.6	9.0	7.1
Cr	25.0	30.5	24.2
Cu	23.6	24.1	49.3
Fe	14800	15730	11345
Mn	346	266	268
Ni	19.7	26.4	13.0
Pb	12009**	2785**	2876**
Zn	122	144	53

* >KM "Land with sensitive use"; (Swedish EPA, 2009) ; [a] (Swedish EPA, 1997)

** >MKM "Land with less sensitive use "; (Swedish EPA, 2009) ; [a] (Swedish EPA, 1997)

MD= dry weigth of sample after 105°C; MW= wet weight of sample; M_{D550}= dry weight of sample after 550°C;

FIXS= fixed solids (after 550°C); DR= dry ratio MD/MW *100; MC= moisture content; MW_{175}= weight of sample corresponding to 0.175 kg of dry substance.

A summary of metals concentrations in soil samples and in eluates after batch leaching tests are shown in Table 5.7, and in Figures 5.7 and 5.8. For more detailed information see appendices A3 and C2. Two of the three leached soil samples gave cadmium concentrations over KM, precisely 1A (4.6 mg Cd kg/DS) and 1B (3.3 mg Cd kg/DS); these results were approximately the same as those found at the test made by the commercial laboratory. In all soil samples the concentration of lead was over the MKM value.

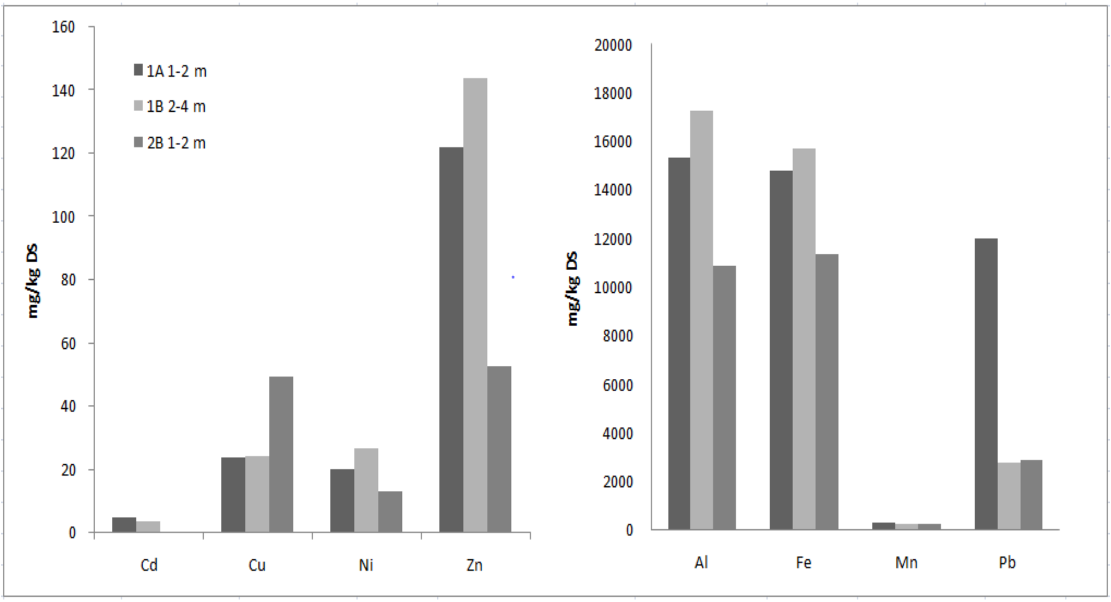

Figure 5.7 Metal concentrations in soil samples (1A, 1B and 2B) used for batch leaching tests (Chalmers).

The leaching Chalmers tests on the three soil samples highlighted that lead leached especially from soil 1A, see Figure 5.8 where the cumulative release of dissolved lead is compared with European guidelines for waste acceptance in landfills *(2003/33/EC)*. The result shows that the soil 1A is classified as non hazardous waste. But if consider the cumulative release of total lead, both soil 1A and 2B are classified as hazardous wastes (63.5 and 12.8 mg total Pb/kg DS respectively). Soil 1B is very close to the boundary level of non hazardous and hazardous waste (9.2 mg total Pb/kg DS and the limit is 10 mg/kg DS) see also Figure 5.9.

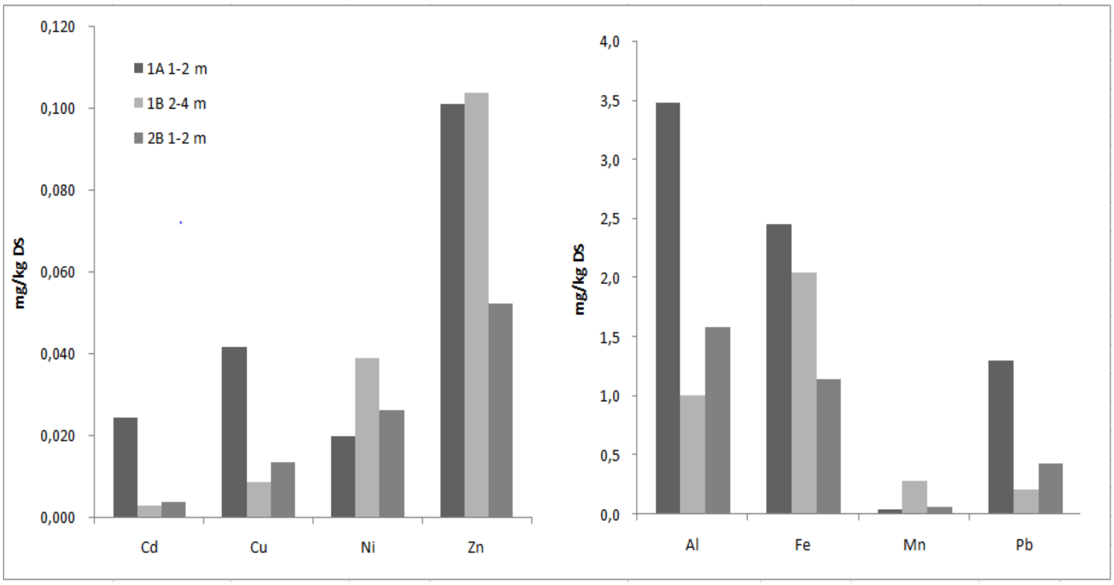

Figure 5.8 Cumulative release $A_{2\text{-}10}$ of dissolved metals after the Chalmers leaching test (on soil samples 1A, 1B and 2B).

Concentration behaviour and binding with DOC

Correlations between the amount of metals in soil and concentrations of these contaminants found in the eluate in the dissolved phase, proved for lead and zinc that the most polluted soil is the one that releases the most, see Figure 5.9.

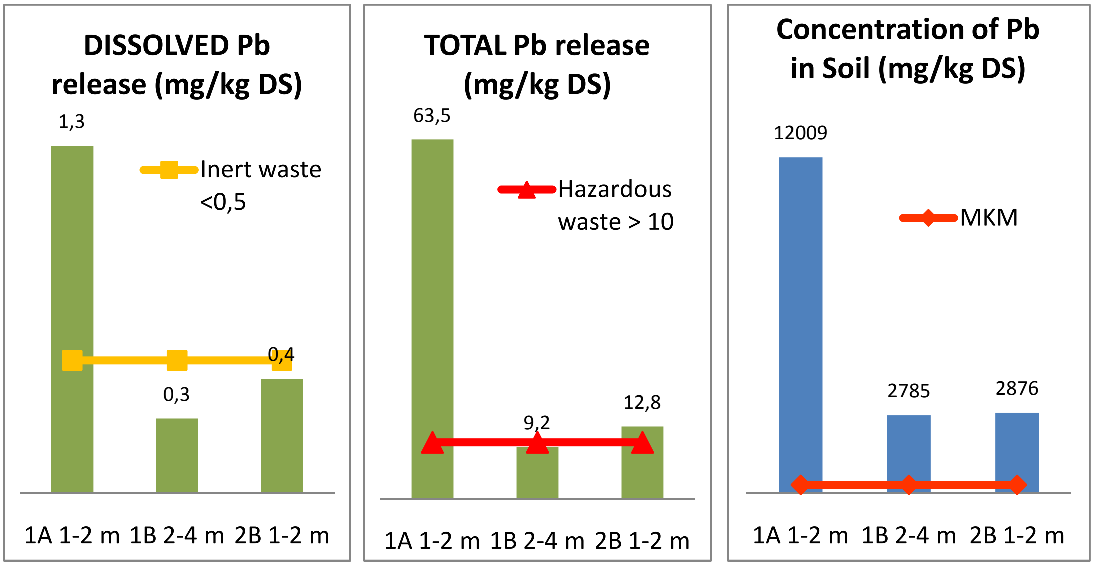

Figure 5.9 Release of dissolved and total content of lead from the soils in the batch test (Chalmers) and their correlation with concentration of lead in the soil samples subjected to the batch test.

Correlation between leached DOC and leaching of metals showed dependence between DOC and lead (ρ= 0,58), which indicate that Pb leaching could increase by complexation with dissolved organic matter (*Van Herwijnen et al., 2007; Wong et al. 2007*), see Figure 5.10.

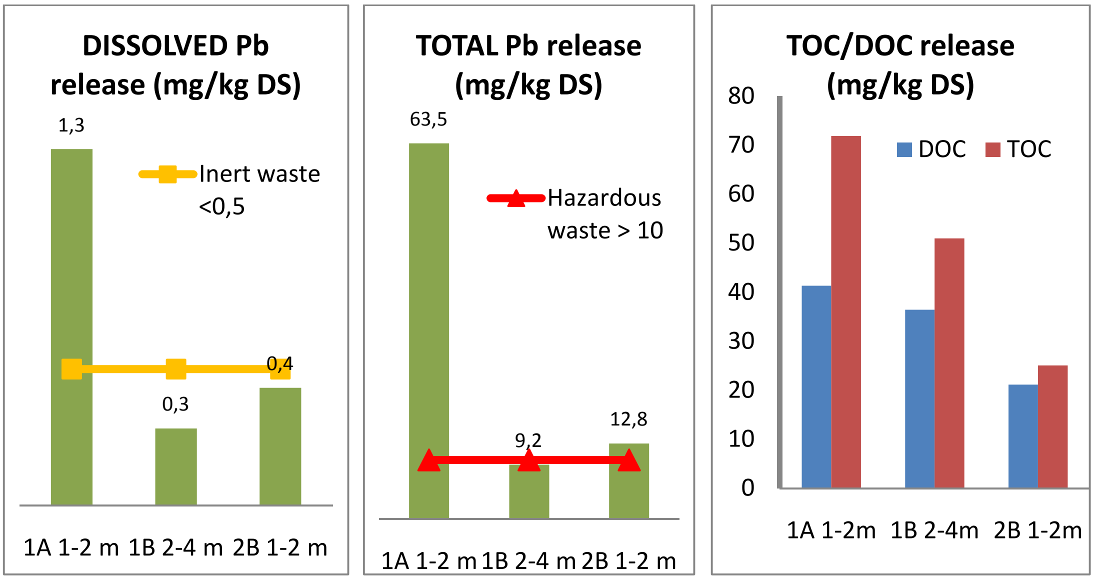

Figure 5.10 Release of dissolved and total lead from the soils used in the batch test (Chalmers) and their correlation with leached TOC and DOC.

5.4 Beaker tests

Figure 5.11 shows the leaching of lead, zinc and iron under the eight boundary conditions during the beaker tests. Lead, zinc and iron had the same leaching behaviour under the different conditions, and decrease in pH caused the highest leaching of the metals. Lower quantities of metals were leached as a result of the presence of organic colloids (humic acids). Under all other conditions (air input, high pH, addition of iron colloids, strong mixing, input of N_2 and undisturbed environment) the leaching of these metals remained constant. Cadmium was released in significant quantities at low pH, and in lower concentrations with the addition of organic and iron colloids, and also under high pH. The behaviour of copper and aluminium was rather different, their leaching increased in the presence of organic colloids. Aluminium was also leached at low pH. Manganese was leached mostly at low pH, but also in the presence of iron colloids.

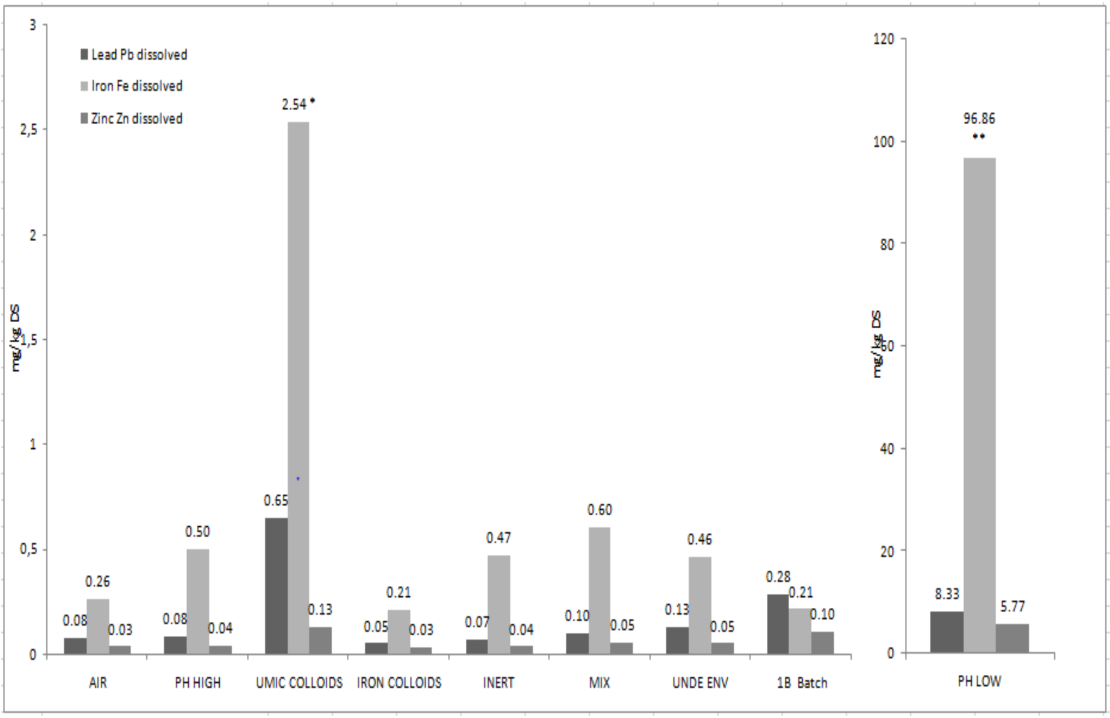

Figure 5.11 Concentration of lead, iron and zinc in leachates from soil 1B 2-4 m under different environmental (physical/chemical) conditions

* value divided for 2 in order to have it in the graph

** value divided for 10 in order to have it in the graph

5.4.1 Effect of environmental conditions on contaminants leaching

pH effect on metals

The results of the beaker leaching tests performed on the soil sample 1B 2 – 4 m confirmed the hypothesis that pH is one of the most important factors for the metal solubility and subsequent mobility (*Dijkstra et al, 2004*). The pH = 4 caused high leaching of almost all metals except copper, cobalt and aluminium see also Appendix D1. The pH is known as a governing factor of metals solubility which was also confirmed by the results of this study. Decrease in pH, from 7–8 that was the equilibrium pH of the soil solution, into pH 4–5 in the beaker experiment caused extensive leaching of almost all the metals (see Figure 5.12). This effect was especially important for Pb, Zn and Cr concentrations.

Copper and Cobalt leachate concentrations were instead much lower with decreased pH. It has been showed that Cu builds complexes and adsorb effectively to the organic matter and minerals at pH 4–5 (Bailey et al. 1999). Therefore some part of the Cu stayed adsorbed to soil at pH 4–5. In addition, Cu that becomes desorbed can re-adsorb to the sorption sites of the soil left by other desorbed metals. It is unclear whether Co may be re-adsorbed in the same way.

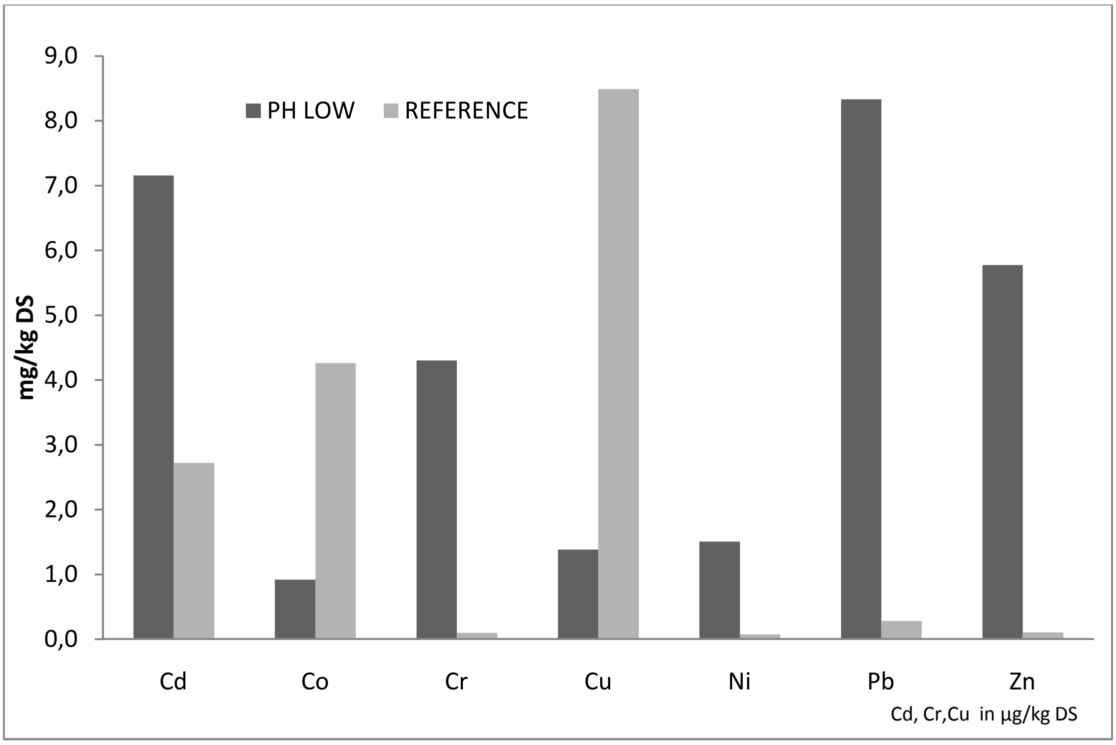

Figure 5.12 Release of dissolved metals from the contaminated soil 1B 2-4 m at low pH (4).

On the other hand increase in pH had no statistically significant effect on the leaching of the metals analyzed in this study.

Effect of the presence of humic and iron colloids

Humic colloids increased leaching of Cu, Pb and Zn and the effect was especially important for Pb and Cu that increased by 2.5 and 7 times respectively. Copper and Pb are also the metals that have the highest affinity for adsorption to organic matter and probably change the place from soil to DOC and therefore found in the water. This effect is important because organic colloids are very small and stable (don't aggregate or precipitate) and can therefore transport metal pollutants on long distances

(*Kalmykova et al. 2010*). Nickel and Cd have also high affinity for humic acids (see Table 5.8) however, no increased mobilization of Cd and Ni was observed.

Table 5.8 Stability constants for metal ions with humic acid (Pandey et al. 2000)

	Pb^{2+}	Cu^{2+}	Ni^{2+}	Zn^{2+}	Cd^{2+}
with Humic Acid	3.7	5.3	3.2	2.7	2.3

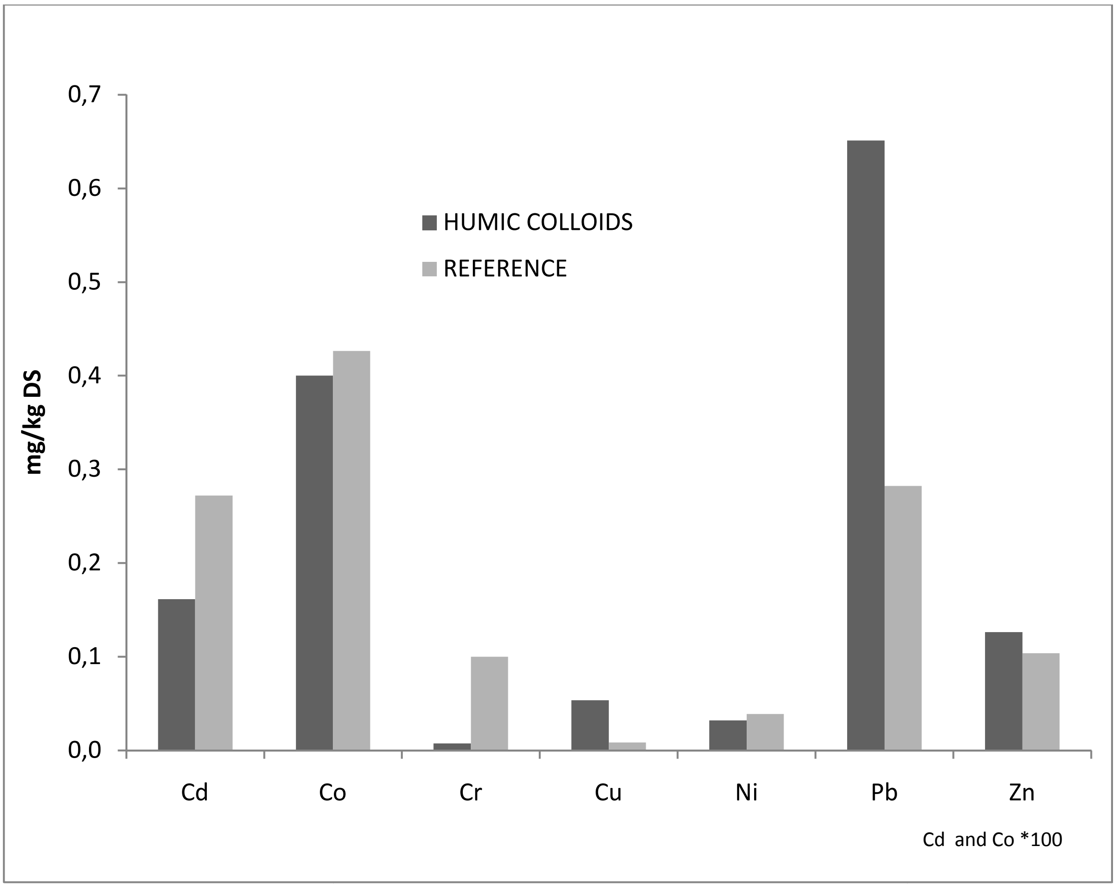

Figure 5.13 Release of dissolved metals from the contaminated soil 1B 2-4 m in the beaker test with addition of humic colloids

Presence of iron colloids had the opposite to organic colloids effect and decreased the water phase concentrations of all the metals. Iron oxides are known to adsorb metals or co-precipitate with them (Cornell and Schwertmann 1996). Contrary to organic colloids, iron oxides may aggregate together and build bigger particles that may eventually sediment *(Cornell and Schwertmann 1996; Kalmykova et al., 2010*). With time precipitated iron oxides may mineralize and therefore immobilize metal pollutants (*Kalmykova et al., 2010*). The decrease of metals in the water phase in this study is probably due to co-precipitation with iron oxides separated from the water phase by filtration.

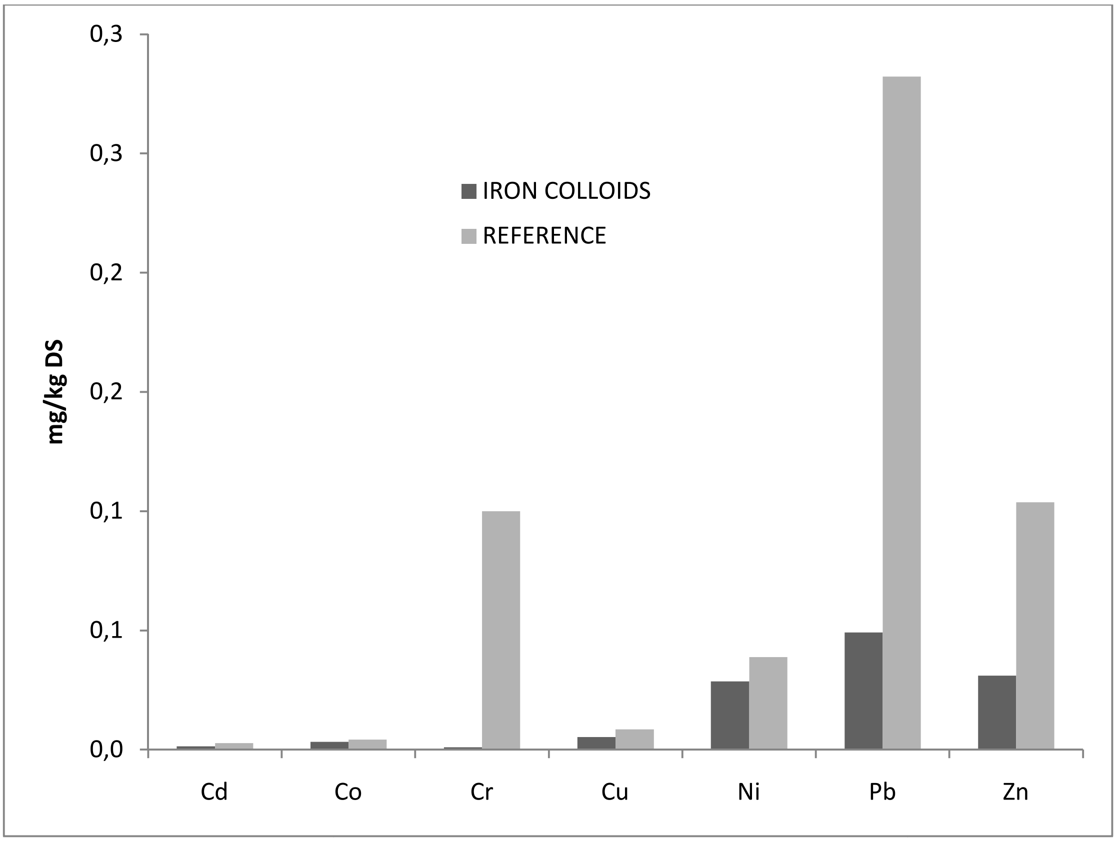

Figure 5.14 Release of dissolved metals from the contaminated soil 1B 2-4 m in the beaker test with addition of iron colloids

5.5 Effect of batch/beaker test for metals concentration in soil after leaching

In almost all soil samples collected after both batch and beaker tests, the concentrations of many metals were higher compared to those analyzed in the same soil samples before testing. These results can be explained with the break of soil grains into small particles and colloids (*Bergendahl and Grasso, 1997*), due to the vigorous agitation inherent the batch tests.

5.6 Evaluation of leachability through Kd estimation

The general leachability of contaminants can be estimated with the Kd value, which is the ratio between the concentration of the substance in the solid and the dissolved phase:

5.6.1 Soil and Groundwater

The general leachability of the four pollutants with concentrations exceeding the reference limits in groundwater or in soil samples, was estimated with Kd value. The average concentrations of these pollutants in the soil and groundwater from three different tests in November 2009 and March 2010 have been used for calculations. The obtained values were compared to the Kd estimated by the Swedish EPA (Report 4639). Referring to dissolved lead (see Table 5.9), the Kd values calculated from results in this study are at least 80 times higher than the references of 1000 l/kg DS, see Table 5.9, The well 2A is the most polluted (at least 200 times more than the others) and the level of pollution in the wells decreases in the following order 2A>> 2B> 1B> 1A.With regard to the total lead concentration, well 2A but also 2B can be considered as high leaching points because the Kd values are below the reference (456 l/kg DS 2A and 497 l/kg DS 2B). Regarding the total chromium concentration, wells 2A and 2B showed Kd values below the reference value for trivalent chromium at two occasions. Also for copper the Kd was below the reference in well 2B in November. For all the other metals Kd values estimated with both dissolved and total phase are over the references values, see Table 5.9, and the data confirms that general leachability is highest in the well 2A.

Table 5.9 K_d values of Pb, Cd, As, Hg, Cr and Cu measured between average concentrations in soil and three different analysis of groundwater samples and K_d reference values (last table) (Swedish EPA, 1997) (all values in bold font are below reference Kd values)

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d Pb dissolved	79117647	96875	-	4138889
20/11/2009	K_d Pb Total	58478	8611	9293	**135**
24/03/2010	K_d Pb dissolved	16140000	77500	-	-
24/03/2010	K_d Pb Total	20175	**456**	4013	**497**
24/03/2010*	K_d Pb dissolved	1582974	95697	2540066	1317302
24/03/2010*	K_d Pb Total	25504	**700**	2889	2518
	Pb soil (mg/kg DS)	4035	1550	1766	1490

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d Cd dissolved	46818	20273	-	-
20/11/2009	K_d Cd Total	2146	9292	6292	205
24/03/2010	K_d Cd dissolved	28297	4646	-	-
24/03/2010	K_d Cd Total	2146	405	2272	612
24/03/2010*	K_d Cd dissolved	40551	6395	-	84559
24/03/2010*	K_d Cd Total	2827	661	11686	-
	Cd soil (mg/kg DS)	2.58	2.23	0.82	0.29

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d As dissolved	5675	11705	10063	1591
20/11/2009	K_d As Total	1493	4682	7667	135
24/03/2010	K_d As dissolved	15338	15606	13417	3750
24/03/2010	K_d As Total	4729	536	4954	328
	As soil (mg/kg DS)	5.68	5.15	6.44	5.25

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d Hg dissolved	-	-	-	-
20/11/2009	K_d Hg Total	-	3265	-	938
24/03/2010	K_d Hg dissolved	-	-	-	-
24/03/2010	K_d Hg Total	-	214	-	-
	Hg soil (mg/kg DS)	0.06	0.69	0.17	0.15

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d Cr dissolved	-	-	31045	29293
20/11/2009	K_d Cr Total	16429	11429	6118	**659**
24/03/2010	K_d Cr dissolved	-	-	22366	47541
24/03/2010	K_d Cr Total	12778	**828**	3714	**1318**
24/03/2010*	K_d Cr dissolved	55011	95923	3656	3544
24/03/2010*	K_d Cr Total	-	**1433**	4742	5528
	Cr soil (mg/kg DS)	23	24	21	29

Date	Metal	1A	2A	1B	2B
20/11/2009	K_d Cu dissolved	25321	6455	55956	20408
20/11/2009	K_d Cu Total	14107	16905	7406	**455**
24/03/2010	K_d Cu dissolved	19750	10441	-	38462
24/03/2010	K_d Cu Total	2948	696	2543	870
24/03/2010*	K_d Cu dissolved	15120	10180	4459	3321
24/03/2010*	K_d Cu Total	5402	1062	2357	3131
	Cu soil (mg/kg DS)	4035	1550	1766	1490

Arsenic As	30
Cadmium Cd	30
Chromium (III)	2000
Copper Cu	500
Mercury Hg	200
Lead Pb	1000

5.6.2 Estimated Kd Batch tests Eurofins

The Kd values were estimated between the concentrations of contaminants in the soil sample used in the leaching test and the eluate concentrations at different liquid to solid ratios. Dissolved lead leachability estimated with K_{d8} showed values from 68 up to 320 times higher than the reference, but for the total content of lead K_{d8} values were very close to the reference and in one case for soil sample 2B this level was lower than the suggested that confirms well 2B being one of the most polluted regarding the groundwater contamination. From the K_{d8} values (see Table 5.10) calculated with dissolved lead it can be seen that the level of pollution spread from soil 2B was higher than in soil sample 1B, and this result is supported by the Kd values estimated with groundwater samples (see Table 5.9).

On the contrary, K_{d8} values estimated from the batch test, showed that for total chromium well 1B was leaching more than 2B in opposite to Kd estimated between groundwater and soil samples (see Table 5.9). It must be noted that Kd for the total Hg is the half of presented in reference (200 l/kg DS). This finding is supported by the results on concentrations of mercury analysis of groundwater in November 2009 where the component of the total metal concentration exceeded the maximum permitted by Canadian guidelines.

Table 5.10 K_d values of Pb, Cd, As, Hg, Cr and Cu measured between concentrations in soil samples object of batch leaching tests and three different analysis of groundwater samples (all values in bold font are below reference Kd values)

1B 2-4m	release$_{2-10}$%	K_{d2}	K_{d8}
As dissolved	0.28	2550	3643
As total	1.14	1342	750
Cd dissolved	0.01	68966	95238
Cd total	0.43	8696	1818
Cr dissolved	-	-	-
Cr total	1.46	**2000**	**545**
Cu dissolved	0.02	29286	41414
Cu total	0.42	3417	2050
Hg dissolved	-	-	-
Hg total	0.026	172000	30070
Pb dissolved	0.004	92308	320000
Pb total	0.44	5581	1846

2B 1,5-3,5m	release$_{2-10}$%	K_{d2}	K_{d8}
As dissolved	0.32	1944	3500
As total	3.86	80	556
Cd dissolved	0.02	8462	-
Cd total	2.42	106	1375
Cr dissolved	-	-	-
Cr total	2.57	**113**	**947**
Cu dissolved	0.04	26829	23404
Cu total	2.10	**138**	1158
Hg dissolved	-	-	-
Hg total	2.45	**96**	2000
Pb dissolved	0.013	103125	68750
Pb total	2.39	**114**	1179

5.6.3 Estimated Kd Batch tests Chalmers laboratory

The Kd, estimated between the concentrations of contaminants in the soils in the leaching tests and the eluate concentrations at different liquid solid ratios, showed another time higher values compared with the references for all dissolved metals. Regarding total content of metals only chromium was below the Kd reference values in soil sample 1A 1-2m and in 2B 1-2m (see Table 5.11). Kd$_8$ values calculated with dissolved lead (see table) showed the following decreasing order of leaching from the three different soil samples 2B>1B>1A and this is a confirmation of the results obtained from previous leaching test made by the external laboratory (order 2B>1B) and by Kd values from groundwater analysis (order 2A>>2B>1B>1A).

Table 5.11 K_d values of Cd, Cr, Cu and Pb, measured between concentrations in soil samples object of batch leaching tests and three different analysis of groundwater samples (all values in bold font are below reference Kd values)

1A 1-2 m	release$_{2\text{-}10}$%	K$_{d2}$	K$_{d8}$
Cd dissolved	0.056	6201	27345
Cd total	0.529	6484	1669
Cr dissolved	0.010	29650	167340
Cr total	2.344	4797	**364**
Cu dissolved	0.176	3059	6788
Cu total	1.507	2305	585
Pb dissolved	0.011	56349	104288
Pb total	0.529	10796	1637

2B 1-2 m	release$_{2\text{-}10}$%	K$_{d2}$	K$_{d8}$
Cd dissolved	0.079	227	1297
Cd total	-	-	-
Cr dissolved	0.000	-	-
Cr total	0.422	-	**1909**
Cu dissolved	0.056	26156	40323
Cu total	0.314	27709	5806
Pb dissolved	0.015	58045	68749
Pb total	0.444	12268	1946

1B 2-4 m	release$_{2\text{-}10}$%	K$_{d2}$	K$_{d8}$
Cd dissolved	0.059	22287	11304
Cd total	0.014	32940	58821
Cr dissolved	0.000	1120324	-
Cr total	0.415	11121	2634
Cu dissolved	0.036	20109	30313
Cu total	0.329	3471	3062
Pb dissolved	0.010	125294	95546
Pb total	0.329	7725	2778

5.6.4 Estimated Kd in beaker tests

The Kd values were calculated on the two conditions: most similar to the real environment - undisturbed environment and the most comparable to the batch tests - strong mixing. The results showed that the Kd was higher than the reference only for total chromium concentration (see Table 5.12).

Table 5.12 K_d values of Cd,Cr,Cu and Pb measured between concentrations in soil samples object of leaching in beaker and the concentration of metals in the eluate after the tests with strong mixing and undisturbed environment (all values in bold font are below reference Kd values)

1B 2-4 m	release $_{\% \text{ Mix}}$	$K_{d6 \text{ Mix}}$	release $_{\% \text{ Unde}}$	$K_{d6 \text{ Unde}}$
Cd dissolved	0.007	89027	0.018	33959
Cd total	0.083	7192	0.030	20209
Cr dissolved	0.002	243199	-	-
Cr total	0.302	**1990**	0.116	5180
Cu dissolved	0.015	41322	0.055	10890
Cu total	0.350	1714	0.157	3827
Pb dissolved	0.003	172416	0.005	130873
Pb total	0.219	2744	0.104	5794

Another comparison on the strength of leachability of all the analysis can be done considering soil sample 1B 2-4 m that was used in both the batch tests and also in all the beaker tests. The following Kd are estimated for dissolved lead concentration in groundwater and in the eluates from both batch and beaker tests performed at WET laboratory:

- Kd (well 1B) soil/groundwater =**2540000 l/kg DS**
- Kd BATCH TEST (soil sample 1B 2-4m) =**95000 l/kg DS**
- Kd BEAKER TEST (mixing) =**172000 l/kg DS**
- Kd BEAKER TEST (undisturbed environment) = **131000 l/kg DS**

Thus Kd values between groundwater and soil samples of well 1B (see Table 5.9) is 26 times higher than the one of batch test performed at WET (see Table 5.11), and is also 15 and 20 times higher than the K_{d6} of beaker test respectively with mix strong and undisturbed environment conditions (see Table 5.12). These results show that the leaching in batch procedure is more aggressive compared to beaker tests (Kd value of batch lower than in beaker mixing), which is supported by previous studies (*Swedish EPA, 1997*).

6 Conclusions

The following conclusions can be drawn from the results:

- Concentrations of lead in the soil in the landfill area is very high, and in almost all the soil samples (14 of 17 samples) these concentrations are over the MKM (less sensitive land use) value, and in some cases these values are ten times higher, even in one sample more than twenty times. In soil samples from spots/wells 1A and 2A, cadmium concentrations are over the KM (sensitive land use) value, and soil from well 2A is also contaminated by mercury (>KM). Carcinogenic PAHs are high and over the KM limit value in most of the soil samples.
- For groundwater pollutants concentrations, a distinction has to be made between dissolved (that are the concentrations that have to be compared with the guidelines values) and total content. Dissolved concentrations of lead were high at both sampling occasions, and classified as high risk of biological effect in water from well 2A, in which also cadmium concentration poses a moderately serious risk. Regarding the total content of lead the concentrations in all the wells are very high and increased in all the wells except 2B from November 2009 to March 2010 In the wells 1C and 2C, close to the railway construction, the increase of total lead was 20-70 fold.
- Results from the two step leaching batch tests, suggest to classify soil sample 1A 1 – 2 m (1.3 mg Pb/kg DS) as non hazardous waste, and the other two as inert waste (1B 2– 4 m and 2B 1– 2 m 0.3 mg Pb/kg DS and 0.4 mg Pb/kg DS respectively) but very closed to the boundary (inert waste < 0.5 mg Pb/kg DS). Considering total release of lead, soil samples 1A 1– 2 m and 2B 1– 2 m have to be classified as hazardous waste, and soil sample 1B 2– 4 m as non hazardous waste.
- Different conditions applied in beaker tests suggest that a decrease of pH, due to as for example snowmelt during springtime, increases significantly the leaching of metals. Moreover an input of organic matter as humic acid colloids, as for example if organic rich water from the river flood into the landfill, increases the leaching of metals. Especially lead and copper are known to build strong complexes with dissolved humic acid colloids. The input of iron colloids on the contrary has the oppositeeffect, with a decrease of leaching of all the metals, probably due to an iron/metal co-precipitation.
- Evaluation of Kd values of dissolved lead in both "field" measurements (groundwater and soil analysis) and laboratory measurements (two step batch and beaker leaching tests) showed the following order of pollution of the wells: 2A >> 2B > 1B > 1A. The lower Kd values from laboratory tests, indicate that the leaching tests may overestimate the real leaching. This is also confirmed by the increased concentrations of metals in most of the soils after the leaching tests, due to break of soil grain into small size grains.

Suggestions for future monitoring and remediation:

- The high concentration of pollutants as lead, cadmium and PAHs in the landfill, suggests that concentrations of these contaminants should be monitored in both sediment and water in the river close to the landfill. Continuous measurements of concentrations of metals and PAHs in all the groundwater wells are suggested.
- Risk assessment is on-going in another masters thesis project and the results will be presented in August 2010. Probably protection and treatment barriers are needed to hinder further leaching of contaminants from the landfill into the surrounding railway construction and the Göta river.

REFERENCES

Ashok K. Pandey, Shri Dhar Pandey, and Virendra Misra, (2000). *Stability Constants of Metal-Humic Acid Complexes and its Role in Environmental Detoxification.* Ecotoxicology Section, Industrial Toxicology Research Centre, Lucknow, India

Bailey, S. E., T. J. Olin, et al., (1999). *A review of potentially low-cost sorbents for heavy* metals Water Research 33(11): 2469-2479

Baird C. , Cann M., (2008). *Environmental Chemistry* ISBN 1-4292-0146-0, pp. 663-708

BanaVäg i Väst, (2009-06-11), *Final report for remediation work and treatment of soil areas for bridge pillar in Nol, area 1, part of the property Nol 2:298.*

Banuelos, G.S., Ajwa, H.A., (1999). *Trace elements in soils and plants: an overview.* J. Environ. Sci. Health A 34 (4), 951–974.

Basta, N.T., Pantone, D.J., Tabatabai, M.A., (1993). *Path analysis of heavy metal adsorption by soil.* Agron. J. 85, 1054-1057.

Batchelor B., (1998). *Leach models for contaminants immobilized by pH-dependent mechanisms.* Environ. Sci. Technol.;32(11):1721–6.

Cavallaro, N., McBride, M.B., (1980). *Activities of* Cu^{+2} *and* Cd^{+2} *in soil solutions as affected by pH.* Soil Sci. Soc. Am. J. 44, 729-732.

Cavallaro, N., McBride, M.B., (1984). *Zinc and copper sorption and fixation by an acid soil clay: effect of selective dissolutions.* Soil Sci. Soc. Am. J. 48, 1050-1054.

CCME (Canadian Council of Ministers of the Environment), (2007). *Canadian soil quality guidelines for the protection of environmental and human health.*

CCME (Canadian Council of Ministers of the Environment), (2007). *Canadian water quality guidelines for the protection of aquatic life.*

CEN (Comite´ Europeen de Nonnalisation), (March 2002). *Draft prEN 14405, Characterization of waste–Leaching behavior test .–Up-flow percolation test,* CEN TC 292.

CEN (Comite´ Europeen de Normalisation), (August 2000). *pH-stat test, draft 7, Basic Characterization Tests for Leaching Behavior*, doc. Nr. CEN/TC292/WG6 N213.

CEN (Comite´ Europeen de Normalisation), (May 2002). *Final draft prEN 12457, part 3, Characterisataion of waste–Leaching–Compliance test for leaching of granular waste materials and sludges – Part 3: Two stage batch test at a liquid to solid ratio of 2 1/kg and 8 1/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction)*, CEN TC 292.

Color, true and apparent, APHA Platinium-Cobalt standard Method, Hach instrument

Cornell, R. M. and U. Schwertmann (1996). *The iron oxides : structure, properties, reactions, occurence and uses.* Weinheim, VCH Verlagsgesellschaft.

Council of the European Union, EU directive (2000/60/EC) (2006-06-17). *Environmental quality standards in the field of water policy and amending,.*

Council of the European Union, EU directive (2003/33/EC), (2002-12-19). *Criteria* *and procedures for the acceptance of waste at landfills.*

Department of Environment and Primary Prevention and Department of Inland Water Hygiene, (2010).*Determination of total organic carbon*. www.iss.it.

FB Engineering, (2006-02-22). *Norway / Vänern Line and Highway 45, part Angered bridge-Älvängen*. PM Environmental Engineering surveying, Nol-Nödinge,

Fernandez-Sempere, J., Barrueso-Martinez, M.L., Font-Montesinos,R., Sabater-Lillo, M.C., (1997). *Characterization of Tannery Wastes,Comparison of Three Leachabiity Tests.* Journal of HazardousMaterials 54, 31–45.

Forstner, U., and Wittman, G. T. M. (1979), *Metal Pollution in the Aquatic Environment*, 2nd ed., Springer Verlag, Berlin.

Garcia-Miragaya, J., (1984). *Levels, chemical fractionation, and solubility of lead in roadside soils of Caracas, Venezuela.* Soil Sci. 138, 147-152.

Hani H. (1990). *The analysis of inorganic and organic pollutants in soil with special regard to their bioavailability*. In. J. Environ. Anal. Chem.;39(2):197–208.

Hani H., (1990). *The analysis of inorganic and organic pollutants in soil with special regard to their bioavailability*. In. J. Environ. Anal. Chem.;39(2):197–208.

Harter, R.D., (1983). *Effect of soil pH on adsorption of lead, copper, zinc, and nickel.* Soil Sci. Soc. Am. J. 47, 47-51.

J & W, Highway 45 - Norway / Vänern Line, part Angered bridge-Älvängen, (2002-02-02). *Road and railway plan, general environmental engineering survey and land proposals for action.*

J.L.T. Hage, E. Mulder, (2003). *Preliminary assessment of three new European leaching tests.* Waste Management 24 (2004) 165–172

J.Y. Yang, X.E. Yang, Z.L. , T.Q. Li, J.L. Shentu, P.J. Stoffella, (2005). *Effects of pH, organic acids, and inorganic ions on lead desorption from soils.* Environmental Pollution 143 (2006) 9-15.

Johansson E., Ek K., Norin M., Strömvall A.M. (2009). *Arsenic contamination after wood impregnation: speciation, sorption and leaching*. High way and urban environment 9th Ed., 287-299

John Bergendahl , Domenico Grasso, (1997). *Colloid generation during batch leaching tests:mechanics of disaggregation.* Colloids and Surfaces A: Physicochemical and Engineering Aspects 135 (1998) 193-205

Jorisj . Dijkstra ,Johannesc. L. Meeussen ,Robn . J . Comans, (2004). *Leaching of Heavy Metals from Contaminated Soils: An Experimental and Modeling Study.* Environ. Sci. Technol. 2004, 38, 4390-4395

Kabata-Pendias, A., Pendias, H., (2001). *Trace elements in soils and plants, third ed.* CRC Press, Boca Raton.

Kalmykova, Y., S. Rauch, et al., (2010). *Colloid-facilitated transport of metals in peat filters* Water Environment Research 82(6): 506-511.

M. Mcbride, S. Sauve & W. Hendershot, (1997). *Solubility control of Cu, Zn, Cd and Pb in contaminated soils.* European Journal of Soil Science, 48, 337-346.

Mulder, E., Brouwer, J.P., Blaakmeer, J., Frenay, J.W., (2001). *Immobilization of PAH in waste materials.* Waste Management 21, 247–253

N. Martınez-Villegas, L.Ma. Flores-Velez , O. Domınguez, (2004). *Sorption of lead in soil as a function of pH: a study case in Mexico.* Chemosphere 57 (2004) 1537–1542

Naturvårdsverkets Report 4639, (1997). *Development of generic guideline values- Model and data used for generic guideline values for contaminated soils in Sweden,* Swedish *EPA.*

Naturvårdsverkets Report 5053, (2002). *Methods for inventories of Contaminated sites: environmental quality criteria guidance for data collection,* Swedish *EPA.*

NNI (Nederlands Normalisatie Instituut), (February 1995). NEN 7343, *Leaching Characteristics of Solid Earthy and Stony Building and Waste Materials. Leaching Tests. Determination of the Leaching of Inorganic Components from Granular Materials with the Column Test, 1st Edition*, ICS 13.030-70;91.100.

Oxidation-reduction potential(ORP), filed method *2580,* WET laboratory Chalmers, 1994

Petanen T., Lyytikainen M., Lappalainen J., Romantschuk M., Kukkonen J.V.K. (2003). *Assessing sediment toxicity and arsenite concentration with bacterial and traditional methods*. Environ. Pollution 122:407-415.

Sadiq M., (1997). *Arsenic chemistry in soils: an overview of thermodynamic predictions and field observations*. Water air soil pollution. 93:117-136.

Smedley P.L., Kinniburgh D.G., (2002). *A review of source, behaviour and distribution of arsenic in natural waters*. Appl. Geochem. 17:517-568.

Sracek O., Bhattacharya P., Jacks G., Gustafsson J.-P., Bromssen M., (2004). *Behavior of arsenic and geochemical modelling of arsenic enrichment in aqueous environments*. Appl. Geochem. 19:169-180.

Stahl, R.S., James, B.R., (1991). *Zinc sorption by B horizon soils as a function of pH.* Soil Sci. Soc. Am. J. 55, 1592-1597.

Total, Fixed, and Volatile Solids in Solid and Semisolids Samples, filed method 2540 G., WET laboratory Chalmers, 2000

USGS (2010) *Understanding Turbidity*, http://ga.water.usgs.gov, 2010-20-05

Ute Kalbe, Wolfgang Berger, Jurgen Eckardt, Franz-Georg Simon, (2007). *Evaluation of leaching and extraction procedures for soil and waste.* Federal Institute for Materials Research and Testing (BAM), Berlin, Germany.

UV-absorbing organic constituents, filed method *5190,* WET laboratory Chalmers, 1994

Valerie Cappuyns, Rudy Swennen, (2008). *The application of pHstat leaching tests to assess the pH-dependent release of trace metals from soils, sediments and waste materials.* Journal of Hazardous Materials 158 (2008) 185–195

Vattenfall, (2006). *Additional environmental sampling for the design of Road 45 / Norway Vänerbanan part Nödinge-Nol*, 2006-11-20

Walton, B.I., Conway, R.A., (1988). *Trace elements.* In: Bodek, I., Liman, W.J., Reehl, W.F., Rosenblat, D.H. (Eds.), Environmental Inorganic Chemistry. Pergamon Press, USA, p. 7.8-1.

Water quality - Determination of alkalinity - part 1: determination of total and composite alkalinity , ISO 9963-1, 1994

Water quality - Vocabulary - part 2, ISO 6107-2, 1989

Wong, J.W.C., Li, K.L., Zhou, L.X., Selvam, A., (2007). *The sorption of Cd and Zn by different soils in the presence of dissolved organic matter from sludge*. Geoderma 137, 310–317

Xu, H., Ephraim, J., Ledin, A. & Allard, B., (1989)**.** *Effects of fulvic acid on the adsorption of Cd (11) on alumina. Science of the Total Environment,* 81/82, 653-660.

Yoko Kishi, (1997). *A Benchtop Inductively Coupled Plasma Mass Spectrometer*, Hewlett-Packard.

Zachara, J.M., Resch, C.T. & Smith, S.C. (1994). *Influence of humic substances on* Co^{2+} *sorption by a subsurface mineral separate and its mineralogic components.* Geochimica et Cosmochimica Acta,58, 553-566.

APPENDIX

A. SOIL CONCENTRATION

A.1 Contaminants concentrations in soil samples (20/11/2009)

A.2 Contaminants concentrations in soil samples used for batch leaching test (Eurofins)

A.3 Contaminants concentrations in soil sample used in Chalmers laboratory for batch leaching tests (mg/kg DS)

A.4 Contaminants concentrations after the tests in soil sample used in Chalmers laboratory for batch leaching tests (mg/kg DS)

B. GROUNDWATER

B.1 Contaminants concentrations in groundwater: sampling 20/11/2009 (Eurofins)

B.2 Contaminants concentrations in groundwater: sampling 24/03/2010 (Eurofins)

B.3 Contaminants concentrations in groundwater: sampling 24/03/2010 (Chalmers)

B.4 Assessment of Alkalinity of groundwater (Swedish EPA)

C. BATCH TESTS

C.1 Results from batch leaching test performed at Eurofins laboratory

C.2 Results from batch leaching tests performed at Chalmers laboratory

D. BEAKER TEST

D.1 Results from beaker tests with different boundary conditions performed at Chalmers laboratory

D.2 Parameters analyzed during the beaker tests

A. SOIL CONCENTRATION

A.1 Contaminants concentrations in soil samples (20/11/2009)

Well name	1A				2A				1B					2B			
Sample depth	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**4-5m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**
Arsenic As (mg/kg DS)	7.4	6.2	5.3	3.8	7.1	6.1	4.5	<2.9	8.8	9.9	5.3	5.1	3.1	8.1	3.8	5.6	3.5
Barium. Ba (mg/kg DS)	78	110	98	100	98	160	320	110	72	130	83	78	100	53	86	70	97
Lead Pb (mg/kg DS)	740	9800	1000	4600	1400	4000	610	190	1800	2800	2400	1800	28	160	1400	1700	2700
Cadmium Cd (mg/kg DS)	1.4	1.4	3.7	3.8	2.4	5.6	0.63	<0.29	<0.25	2	0.68	0.87	<0.29	<0.24	0.25	0.27	0.39
Cobalt Co (mg/kg DS)	9.9	5.1	5.7	6.7	6.5	8.4	8.2	5.9	9.3	8.4	4.7	5.6	7.1	9.7	6.1	6.7	5.8
Copper Cu (mg/kg DS)	16	22	28	13	30	21	80	11	23	47	24	22	9.9	15	17	16	32
Chromium Cr (mg/kg DS)	31	19	22	20	24	21	33	18	31	25	13	16	19	30	19	22	45
Mercury Hg (mg/kg DS)	< 0.05	0.061	0.062	< 0.05	0.42	1.7	0.54	0.083	< 0.05	0.094	0.064	0.34	< 0.05	< 0.05	0.1	< 0.05	0.2
Nickel Ni (mg/kg DS)	22	13	16	21	16	17	13	11	23	25	12	15	12	21	11	14	13
Vanadium V (mg/kg DS)	49	31	32	35	42	33	33	35	45	43	24	29	37	42	36	41	38
Zinc Zn (mg/kg DS)	95	100	110	81	220	110	130	64	96	150	120	140	70	69	120	76	120
Aliphatics >C5-C8 (mg/kg DS)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Aliphatics >C8-C10 (mg/kg DS)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Aliphatics >C10-C12 (mg/kg DS)	<5	5.8	<5	<5	<5	<5	12	<5	<5	<5	<5	<5	<5	<5	<5	<5	12
Aliphatics >C12-C16 (mg/kg DS)	<5	6.2	<5	<5	<5	<5	11	<5	<5	<5	<5	<5	<5	<5	<5	<5	7.2
Aliphatics >C16-C35 (mg/kg DS)	35	160	62	17	12	50	68	<10	11	<10	18	19	<10	<10	100	92	180
Aromatics >C8-C10 enl NV081024 (mg/kg DS)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Aromatics >C10-C16 enl NV081024 (mg/kg DS)	4.6	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Benzene (mg/kg DS)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ethylbenzene (mg/kg DS)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
M / P / O-Xylene (mg/kg DS)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Well name	1A				2A				1B					2B			
Sample depth	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**	**4-5m**	**0-1m**	**1-2m**	**2-3m**	**3-4m**
Toluene (mg/kg DS)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total TEX (mg/kg DS)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Acenaphthene (mg/kg DS)	2.4	0.54	0.51	0.07	0.03	0.03	0.09	<0.03	0.04	<0.03	0.16	0.12	<0.03	<0.03	0.12	0.21	0.38
Acenaftylen (mg/kg DS)	0.18	0.13	0.04	<0.03	0.07	0.14	0.04	<0.03	0.09	0.05	0.11	0.06	<0.03	<0.03	0.12	0.14	0.19
Anthracene (mg/kg DS)	0.78	0.2	0.16	0.03	0.09	0.35	0.07	<0.03	0.22	0.08	0.43	0.23	<0.03	<0.03	0.36	0.48	0.8
Benzo (a) anthracene (mg/kg DS)	0.91	0.4	0.23	0.06	0.27	0.62	0.19	<0.03	0.73	0.36	1.5	0.68	<0.03	<0.03	0.6	0.69	1
Benzo (a) pyrene (mg/kg DS)	0.35	0.33	0.23	0.05	0.3	0.66	0.17	<0.03	0.68	0.39	1.8	0.79	<0.03	<0.03	0.54	0.55	0.69
Benzo (b. k) fluoranthene (mg/kg DS)	1.1	0.74	0.43	0.12	0.57	1.2	0.41	0.03	1.3	0.81	3.3	1.5	<0.03	0.04	0.91	1	1.3
Benzo (g. h. i) perylene (mg/kg DS)	0.14	0.27	0.16	0.04	0.24	0.52	0.11	<0.03	0.42	0.27	1.2	0.51	<0.03	<0.03	0.3	0.35	0.42
Dibenzo (a. h) anthracene (mg/kg DS)	0.04	0.07	0.04	<0.03	0.05	0.1	<0.03	<0.03	0.11	0.07	0.27	0.12	<0.03	<0.03	0.06	0.07	0.11
Phenantrene (mg/kg DS)	6.9	0.94	1	0.14	0.27	0.73	0.47	<0.03	0.62	0.22	1.6	1.1	<0.03	<0.03	0.85	1.3	2.5
Fluoranthene (mg/kg DS)	2.5	0.74	0.78	0.13	0.47	1.3	0.42	<0.03	1.1	0.59	2.4	1.2	0.03	0.05	1.4	1.7	2.6
Fluorene (mg/kg DS)	1.9	0.33	0.35	0.05	0.06	0.03	0.15	<0.03	0.09	<0.03	0.27	0.15	<0.03	<0.03	0.18	0.35	0.65
Indeno (1.2.3-cd) pyrene/ (mg/kg DS)	0.21	0.27	0.2	0.05	0.29	0.69	0.13	<0.03	0.53	0.34	1.6	0.7	<0.03	<0.03	0.3	0.48	0.42
Chrysene (mg/kg DS)	1.2	0.47	0.27	0.08	0.28	0.69	0.24	<0.03	0.69	0.37	1.5	0.72	<0.03	<0.03	0.48	0.83	1.1
Naphthalene (mg/kg DS)	1.4	0.13	0.2	<0.03	0.03	<0.03	0.09	<0.03	0.1	<0.03	0.18	0.12	<0.03	<0.03	0.06	0.07	0.3
Pyrene (mg/kg DS)	2.4	0.8	0.74	0.12	0.54	1.6	0.48	0.03	1.2	0.61	2.5	1.3	<0.03	0.04	1.2	1.5	2.2
Total PAHs (LMW) (mg/kg DS)	4	0.8	0.75	< 0.30	< 0.30	< 0.30	< 0.30	< 0.30	< 0.30	< 0.30	0.45	0.3	< 0.30	< 0.30	0.3	0.42	0.87
Total PAHs (MMW) (mg/kg DS)	14	3	3	0.47	1.4	4	1.6	< 0.30	3.2	1.5	7.2	4	< 0.30	< 0.30	4	5.3	8.8
Total PAHs (HMW) (mg/kg DS)	4	2.6	1.6	0.43	2	4.5	1.3	< 0.30	4.5	2.6	11	5	< 0.30	< 0.30	3.2	4	5
Total carcinogenic PAHs	3.8	2.3	1.4	0.38	1.8	4	1.2	<0.30	4	2.3	10	4.5	<0.30	<0.30	2.9	3.6	4.6
Total other PAHs (mg/kg DS)	19	4.1	3.9	0.61	1.8	4.7	1.9	<0.30	3.9	1.9	8.9	4.8	<0.30	<0.30	4.6	6.1	10
Dry matter(%)	73.4	78.5	68.3	65.3	75.9	75.2	53.8	62.8	70.7	71.6	66.1	72.8	61.7	75.5	83.9	77.1	70.9

A.2 Contaminants concentrations in soil samples used for batch leaching test (Eurofins)

Sample name	1B 2-4m	2B 1.5-3.5m
Arsenic As (mg/kg DS)	5.1	3.5
Barium, Ba (mg/kg DS)	93	72
lead Pb (mg/kg DS)	2400	3300
Cadmium Cd (mg/kg DS)	2	0.33
Cobalt Co (mg/kg DS)	5.1	5.1
Copper Cu (mg/kg DS)	41	22
Chromium Cr (mg/kg DS)	12	18
Mercury Hg (mg/kg DS)	4.3	0.078
Nickel Ni (mg/kg DS)	19	13
Vanadium V (mg/kg DS)	20	43
Zinc Zn (mg/kg DS)	200	110
Aliphatics >C5-C8 (mg/kg DS)	<5	<5
Aliphatics >C8-C10 (mg/kg DS)	<5	<5
Aliphatics >C10-C12 (mg/kg DS)	<5	18
Aliphatics >C12-C16 (mg/kg DS)	<5	37
Aliphatics >C16-C35 (mg/kg DS)	30	500
Aromatics >C8-C10 enl NV081024 (mg/kg DS)	<5	<5
Aromatics >C10-C16 enl NV081024 (mg/kg DS)	<3	5.6
Benzene (mg/kg DS)	<0.01	<0.01
Ethylbenzene (mg/kg DS)	<0.1	<0.1
M / P / O-Xylene (mg/kg DS)	<0.1	<0.1
Toluene (mg/kg DS)	<0.1	<0.1
Total TEX (mg/kg DS)	< 0.1	< 0.1
Acenaphthene (mg/kg DS)	0.12	0.24
Acenaftylen (mg/kg DS)	0.1	0.12
Anthracene (mg/kg DS)	0.38	0.37
Benzo (a) anthracene (mg/kg DS)	1.2	0.86
Benzo (a) pyrene (mg/kg DS)	1.4	0.86
Benzo (b, k) fluoranthene (mg/kg DS)	2.4	1.3
Benzo (g, h, i) perylene (mg/kg DS)	0.8	0.49
Dibenzo (a, h) anthracene (mg/kg DS)	0.2	0.12
Fenantrene (mg/kg DS)	1.3	1.1
Fluoranthene (mg/kg DS)	1.6	1.2
Fluorene (mg/kg DS)	0.31	0.37
Indeno (1,2,3-cd) pyrene/ (mg/kg DS)	0.92	0.49
Chrysene (mg/kg DS)	1.2	1
Naphthalene (mg/kg DS)	0.49	0.12
Pyrene (mg/kg DS)	2	1.6
Total carcinogenic PAHs (mg/kg DS)	7.3	4.6
Total other PAHs (mg/kg DS)	7.1	5.6

Total PAHs with low molecular weight (mg/kg DS)	0.71	0.48
Total PAHs of medium molecular weight (mg/kg DS)	5.6	4.6
Total PAHs with high molecular weight (mg/kg DS)	8.1	5.1
1 ,2,3,4,6,7,8-HeptaCDD (ng/kg DS)	50.2	36.7
1 ,2,3,4,6,7,8-HeptaCDF(ng/kg DS)	27.5	16.9
1,2,3,4,7,8,9-HeptaCDF (ng/kg DS)	0.741	1.46
1,2,3,4,7,8-HexaCDD (ng/kg DS)	1.12	<0.945
1,2,3,4,7,8-HexaCDF (ng/kg DS)	1.54	2.45
1,2,3,6,7,8-HexaCDD (ng/kg DS)	2.49	2.07
1,2,3,6,7,8-HexaCDF (ng/kg DS)	0.781	<0.787
1,2,3,7,8,9-HexaCDD (ng/kg DS)	1.43	<0.945
1,2,3,7,8,9-HexaCDF (ng/kg DS)	<0.776	<0.787
1,2,3,7,8-PentaCDD (ng/kg DS)	0.874	0.632
1,2,3,7,8-PentaCDF (ng/kg DS)	1.48	3.29
2,3,4,6,7,8-HexaCDF (ng/kg DS)	1.16	1.13
2,3,4,7,8-PentaCDF (ng/kg DS)	1.22	2.74
2,3,7,8-TetraCDD (ng/kg DS)	0.379	0.556
2,3,7,8-TetraCDF (ng/kg DS)	1.71	4.78
I-TEQ (NATO / CCMS) excl LOQ (ng/kg DS)	3.57	4.33
I-TEQ (NATO / CCMS) incl LOQ (ng/kg DS)	3.64	4.68
OktaCDD (ng/kg DS)	192	275
OktaCDF (ng/kg DS)	68.1	59.6
Total HeptaCDD (ng/kg DS)	104	74.1
Total Hepta CDF (ng/kg DS)	60.3	49.3
Total HexaCDD (ng/kg DS)	42.8	12.1
Total HexaCDF (ng/kg DS)	33.2	29.8
Total PentaCDD (ng/kg DS)	35.3	10.6
Total PentaCDF (ng/kg DS)	21.1	33.8
Total Tetra empty OktaCDD / F (ng/kg DS)	620	601
Total Tetra empty OktaCDD (ng/kg DS)	412	385
Total Tetra empty OktaCDF (ng/kg DS)	208	216
Total TetraCDD (ng/kg DS)	38.2	13.3
Total TetraCDF (ng/kg DS)	25.5	43.4
WHO(1998)-PCDD/F TEQ excl LOQ (ng/kg DS)	3.77	4.35
WHO(1998)-PCDD/F TEQ incl LOQ (ng/kg DS)	3.85	4.7
PCB 101 (mg/kg DS)	0.045	0.059
PCB 118 (mg/kg DS)	0.039	0.035
PCB 138 (mg/kg DS)	0.044	0.06
PCB 153 (mg/kg DS)	0.029	0.054
PCB 180 (mg/kg DS)	0.0071	0.021
PCB 28 (mg/kg DS)	< 0.002	< 0.002
PCB 52 (mg/kg DS)	0.024	0.031
S:a PCB (7st) (mg/kg DS)	0.19	0.26
Dry matter(%)	74.9	81.7

A.3 Contaminants concentrations in soil sample used in Chalmers laboratory for batch leaching tests (mg/kg DS)

Sample name	1A 1-2 m	1B 2-4 m	2B 1-2 m
Aluminium Al	15323.37	17256.19	10893.36
Cadmium Cd	4.58	3.29	0.26
Cobalt Co	7.60	9.02	7.10
Chromium Cr	25.00	30.47	24.15
Copper Cu	23.56	24.09	49.27
Iron Fe	14800.10	15730.08	11345.45
Manganese Mn	346.17	265.62	267.81
Nickel Ni	19.68	26.37	13.03
Lead Pb	12009.43	2785.31	2876.40
Zinc Zn	122.12	143.96	52.81

A.4 Contaminants concentrations after the tests in soil sample used in Chalmers laboratory for batch leaching tests (mg/kg DS)

Sample name	1A 1-2m	1B 2-4m	2B 1-2m
Aluminium Al	28448.62	24416.58	27564.22
Cadmium Cd	6.37	4.08	0.88
Cobalt Co	13.26	17.17	15.94
Chromium Cr	44.73	47.66	46.41
Copper Cu	40.39	47.03	43.73
Iron Fe	23835.97	28186.79	27300.36
Manganese Mn	544.65	494.68	672.79
Nickel Ni	33.86	50.75	34.23
Lead Pb	11746.25	7272.47	7516.79
Zinc Zn	178.19	254.41	145.83

B.GROUNDWATER

B.1 Contaminants concentrations in groundwater: sampling 20/11/2009 (Eurofins)

Sample name	GV1A	GV2A	GV1B	GV2B	GV1C	GV2C
Turbidity (FNU)	62	28	260	3600	15	3.4
Alkalinity (mg HCO_3/l)	480	160	790	970	170	83
Suspended solids (mg/l)	41	12	77	1600	45	4
Conductivity (mS/m)	85	32	250	540	61	42
pH ()	8.4	8.5	8	7	8.5	9.5
DOC (mg/l)	6.3	6.8	11	45	5.4	3.7
TOC (mg/l)	7.8	7.9	14	38	5.7	4.3
Arsenic As (dissolved) (mg/l)	0.001	0.00044	0.00064	0.0033	0.00059	0.00086
Arsenic As (total) (mg/l)	0.0038	0.0011	0.00084	0.039	0.00068	0.0011
Cadmium Cd (dissolved) (mg/l)	0.000055	0.00011	<0.00004	<0.00004	0.000054	0.00003
Cadmium Cd (total) (mg/l)	0.0012	0.00024	0.00013	0.0014	<0.0001	<0.0001
Cobalt Co (dissolved) (mg/l)	0.00047	<0.0002	0.00065	0.012	0.00054	0.00046
Cobalt Co (total) (mg/l)	<0.001	<0.001	0.0011	0.025	0.0018	<0.001
Chromium Cr (dissolved) (mg/l)	<0.0002	<0.0002	0.00067	0.00099	0.00027	0.002
Chromium Cr (total) (mg/l)	0.0014	0.0021	0.0034	0.044	0.0022	0.0021
Copper Cu (dissolved) (mg/l)	0.00078	0.0055	0.00045	0.00098	0.01	0.0064
Copper Cu (total) (mg/l)	0.0035	0.0085	0.0034	0.059	0.015	0.0081
Mercury Hg (dissolved) (mg/l)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Mercury Hg (total) (mg/l)	<0.0001	0.00021	<0.0001	0.00016	<0.0001	<0.0001
Nickel Ni (dissolved) (mg/l)	0.00058	0.00089	<0.0004	0.0069	0.0023	0.0024
Nickel Ni (total) (mg/l)	0.0011	0.0015	<0.001	0.033	0.003	0.0021
Lead Pb (dissolved) (mg/l)	0.000051	0.016	<0.0001	0.00036	0.00015	0.000055
Lead Pb (total) (mg/l)	0.069	0.18	0.19	11	0.0048	0.0018
Vanadium V (dissolved) (mg/l)	<0.0002	0.00034	<0.0004	<0.0004	0.0013	0.0039
Vanadium V (total) (mg/l)	0.0028	0.0035	0.0073	0.079	0.0075	0.0046
Zinc Zn (dissolved) (mg/l)	0.0029	0.0066	0.0021	0.016	0.0026	<0.001
Zinc Zn (total) (mg/l)	0.023	0.028	0.027	0.22	0.011	<0.005
Aliphatics >C5-C8 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C8-C10 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C10-C12 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C12-C16 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C16-C35 (mg/l)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Aromatics >C8-C10 (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Aromatics >C10-C16 (mg/l)	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Acenaphthene (ug/l)	0.12	<0.02	0.63	0.893	<0.02	<0.02
Acenaftylen (ug/l)	<0.02	<0.02	0.02	<0.02	<0.02	<0.02
Anthracene (ug/l)	0.02	<0.02	0.1	0.32	<0.02	<0.02
Benzo (a) anthracene(ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo (a) pyrene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Benzo (b, k) fluoranthene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Sample name	GV1A	GV2A	GV1B	GV2B	GV1C	GV2C
Benzo (g, h, i) perylene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Dibenzo (a, h) anthracene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Phenanthrene (ug/l)	0.06	<0.02	0.23	1.44	<0.02	<0.02
Fluoranthene (ug/l)	0.07	<0.02	0.1	0.28	<0.02	<0.02
Fluorene (ug/l)	0.04	<0.02	0.95	0.853	<0.02	<0.02
Indeno (1,2,3-cd) pyrene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Chrysene (ug/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Pyrene (ug/l)	0.04	<0.02	0.06	0.187	<0.02	<0.02
Naphthalene (ug/l)	0.02	<0.02	0.07	2.19	<0.02	<0.02
Total carcinogenic PAHs (ug/l)	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Total other PAHs (ug/l)	0.37	<0.30	2.2	6.2	<0.30	<0.30
Toluene (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M / P / O-Xylene (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total TEX (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

B.2 Contaminants concentrations in groundwater: sampling 24/03/2010 (Eurofins)

Sample name	GV 1A	GV2A	GV1B	GV2B	GV1C	GV2C
Temp (C)	22.2	22.6	22.4	22.2	22.3	22.2
pH ()	8	8	7.6	7	7.9	8.4
Conductivity (mS/m)	59	27	270	410	43	42
Alkalinity (mg HCO_3/l)	290	130	730	820	120	94
Hardness total (dH)	13	6.5	34	61	6.6	5.2
Redox (mV)	473	596	268	259	380	607
DOC (mg/l)	4.8	4.1	12	32	3.7	3.2
TOC (mg/l)	4.8	4.7	12	32	3.7	3.2
Suspended solids (mg/l)	19	480	140	590	1700	1300
Turbidity (FNU)	41	310	260	1100	3400	650
Arsenic As (dissolved) (mg/l)	0.00037	0.00033	0.00048	0.0014	0.00032	0.00082
Arsenic As (total) (mg/l)	0.0012	0.0096	0.0013	0.016	0.0066	0.0078
Lead Pb (dissolved) (mg/l)	0.00025	0.02	<0,0001	<0,0001	0.00013	0.000095
Lead Pb (total) (mg/l)	0.2	3.4	0.44	3	0.11	0.14
Cadmium Cd (dissolved) (mg/l)	0.000091	0.00048	<0,00004	<0,00004	0.000022	<0,00002
Cadmium Cd (total) (mg/l)	0.0012	0.0055	0.00036	0.00047	0.00038	0.00026
Cobalt Co (dissolved) (mg/l)	0.00043	0.00032	0.00062	0.0052	0.00038	0.00038
Cobalt Co (total) (mg/l)	<0,001	0.0094	0.0014	0.012	0.024	0.018
Copper Cu (dissolved) (mg/l)	0.001	0.0034	<0,0004	0.00052	0.0039	0.0063
Copper Cu (total) (mg/l)	0.0067	0.051	0.0099	0.023	0.066	0.047
Chromium Cr (dissolved) (mg/l)	<0,0002	<0,0002	0.00093	0.00061	<0,0002	0.0011
Chromium Cr (total) (mg/l)	0.0018	0.029	0.0056	0.022	0.033	0.054
Mercury Hg (dissolved) (mg/l)	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001
Mercury Hg (total) (mg/l)	<0,0001	0.0032	<0,0001	<0,0001	<0,0001	<0,0001

Sample name	GV 1A	GV2A	GV1B	GV2B	GV1C	GV2C
Nickel Ni (dissolved) (mg/l)	0.0025	0.00046	<0,0004	<0,0004	0.0015	0.0017
Nickel Ni (dissolved) (mg/l)	0.006	0.022	0.002	0.018	0.022	0.029
Vanadium V (dissolved) (mg/l)	<0,0002	0.00027	<0,0004	<0,0004	0.0014	0.0022
Vanadium V (total) (mg/l)	0.0026	0.047	0.008	0.038	0.11	0.1
Zinc Zn (dissolved) (mg/l)	0.006	0.0036	0.002	0.007	0.0011	0.0027
Zinc Zn (total) (mg/l)	0.033	0.25	0.088	0.09	0.15	0.15
Aluminium Al (mg/l)	0.0018	0.019	0.003	<0,002	0.037	0.04
Iron Fe (dissolved) (mg/l)	<0,02	<0,02	0.022	25	<0,02	<0,02
Calcium Ca (mg/l)	81	40	170	320	34	28
Magnesium Mg (mg/l)	9	4	46	71	8.2	5.4
Manganese Mn (dissolved) (mg/l)	0.53	0.24	1.8	2.1	0.2	0.0018
Sodium Na (mg/l)	20	9.9	270	250	36	37
Sulfur S (uppslutet) (mg/l)	5.5	3.5	3.4	8.9	10	14
Tin Sn (mg/l)	<0,0001	<0,0001	<0,0002	<0,0002	<0,0001	<0,0001
Aliphatics >C5-C8 (mg/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Aliphatics >C8-C10 (mg/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Aliphatics >C10-C12 (mg/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Aliphatics >C12-C16 (mg/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Aliphatics >C16-C35 (mg/l)	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05
Aromatics >C8-C10 (mg/l)	<0,10	<0,10	<0,10	<0,10	<0,10	<0,10
Aromatics >C10-C16 (mg/l)	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1
Acenaphthene (ug/l)	0.03	<0,02	0.21	0.74	<0,02	<0,02
Acenaftylen (ug/l)	<0,02	<0,02	0.04	0.14	<0,02	<0,02
Anthracene (ug/l)	<0,02	<0,02	0.03	0.13	<0,02	<0,02
Bensen (mg/l)	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Benzo (a) anthracene(ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Benzo (a) pyrene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Benzo (b, k) fluoranthene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Benzo (g, h, i) perylene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Dibenzo (a, h) anthracene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Ethylbenzene (mg/l)	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Phenanthrene (ug/l)	<0,02	<0,02	0.07	0.58	<0,02	<0,02
Fluoranthene (ug/l)	<0,02	<0,02	0.04	0.15	<0,02	<0,02
Fluorene (ug/l)	<0,02	<0,02	0.24	0.49	<0,02	<0,02
Indeno (1,2,3-cd) pyrene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
Chrysene (ug/l)	<0,02	<0,02	<0,02	<0,02	<0,02	<0,02
M / P / O-Xylene (mg/l)	<0,001	<0,001	<0,001	0.0011	<0,001	<0,001
Naphthalene (ug/l)	<0,02	<0,02	0.05	2.5	<0,02	<0,02
Pyrene (ug/l)	<0,02	<0,02	0.03	0.09	<0,02	<0,02
Toluene (mg/l)	<0,001	<0,001	<0,001	<0,001	<0,001	<0,001
Total carcinogenic PAHs (ug/l)	<0,20	<0,20	<0,20	<0,20	<0,20	<0,20
Total other PAHs (ug/l)	<0,30	<0,30	0.71	4.8	<0,30	<0,30
Total TEX (mg/l)	<0,001	<0,001	<0,001	0.0011	<0,001	<0,001
Turbidity (FAU)	54	293	230	595	806	487

Sample name	GV 1A	GV2A	GV1B	GV2B	GV1C	GV2C
UV adsorption (ABS)	0.118	0.577	0.362	1.048	0.425	0.276
TRUE color (mg Pt-Co)	75	384	344	117	464	281
APPARENT color (mg Pt-Co)	437	>550	>550	>550	>550	>550
Alkalinity (mg HCO_3/l)	283.1	139.1	715.1	749.3	119.6	95.2
Conductivity (mS/m)	55	26.4	264	416	41	42.6
pH ()	7	7.2	6.9	6.8	7.6	8.7
DO (mg/l)	2.5	10.4	5.5	3.3	9.1	12.6
Temperature (C°)	6.4	5.3	5.2	6	5.3	5.2
Aluminium Al (dissolvedl) (mg/l)	0.02337	0.12549	0.01297	0.00867	0.13119	0.18450
Aluminium Al (total) (mg/l)	3.37104	18.95418	6.21494	5.03529	23.17191	14.30761
Cadmium Cd (dissolvedl) (mg/l)	0.00006	0.00035	0.00000	0.00000	0.00002	0.00008
Cadmium Cd (digested) (mg/l)	0.00091	0.00338	0.00007	0.00000	0.00000	0.00000
Cobalt Co (dissolvedl) (mg/l)	0.00042	0.00028	0.00056	0.00486	0.00037	0.00076
Cobalt Co (digested) (mg/l)	0.00068	0.00666	0.00170	0.00457	0.00765	0.00394
Chromium Cr (dissolvedl) (mg/l)	0.00042	0.00025	0.00569	0.00818	0.00086	0.00335
Chromium Cr (digested) (mg/l)	0.00000	0.01675	0.00439	0.00525	0.00934	0.00836
Copper Cu (dissolvedl) (mg/l)	0.00131	0.00349	0.00565	0.00602	0.00484	0.01528
Copper Cu (digested) (mg/l)	0.00366	0.03342	0.01068	0.00639	0.02117	0.01574
Iron Fe (dissolvedl) (mg/l)	0.72944	0.09547	16.39106	74.90185	0.10936	0.11008
Iron Fe (digested) (mg/l)	2.47729	13.25995	15.58478	42.22290	13.90713	8.14117
Manganese Mn (dissolvedl) (mg/l)	0.53624	0.20953	1.78561	2.01394	0.15308	0.00453
Manganese Mn (digested) (mg/l)	0.34525	0.49838	1.16412	1.22966	0.46721	0.19083
Nickel Ni (dissolvedl) (mg/l)	0.00457	0.00163	0.00491	0.01026	0.00223	0.00591
Nickel Ni (digested) (mg/l)	0.00376	0.01545	0.00733	0.00989	0.00885	0.00748
Lead Pb (dissolvedl) (mg/l)	0.00255	0.01620	0.00070	0.00113	0.00042	0.00162
Lead Pb (digested) (mg/l)	0.15821	2.21389	0.61123	0.59177	0.02987	0.06182
Zinc Zn (dissolvedl) (mg/l)	0.00693	0.00441	0.00374	0.01137	0.00109	0.00713
Zinc Zn (digested) (mg/l)	0.01897	0.14074	0.06574	0.01710	0.04085	0.02980

B.4 Assessment of Alkalinity of groundwater (Swedish EPA)

Class	Designation	Alkalinity (mg HCO_3/l)	pH	Description
1	Very high alkalinity	>180	>6.5	Adequate to maintain acceptable pH level in the future
2	High alkalinity	60-180	>6.0	
3	Moderate alkalinity	30-60	5.5-7.5	Inadequate to maintain stable, acceptable pH level in areas with heavy acid precipitation
4	Low alkalinity	10-30	5.0-6.0	Inadequate to maintain stable, acceptable pH level
5	Very low alkalinity	<10	<6.0	Unacceptable pH level under all circumstances

C. BATCH TESTS

C.1 Results from batch leaching test performed at Eurofins laboratory

Sample name	1B 2-4m					2B 1.5-3.5m				
	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 mg/kg DS	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 (mg/kg DS)
Conductivity (L/S=2) (mS/m)	85	85				83		80		
Conductivity (L/S=8) (mS/m)			33					20		
pH (L/S=2) ()	7.6	7.6				7.8		8.2		
pH (L/S=8) ()			8.1					8.7		
Temperature (L/S=2) (C)	21.5	21.5				22.2		22.1		
Temperature (L/S=8) (C)			19.9					23.6		
Arsenic As dissolved	0.002	0.004	0.0014	0.0112	0.0152	0.0018	0.0036	0.001	0.0075	0.0111
Arsenic As total	0.0038	0.0076	0.0068	0.0544	0.062	0.044	0.088	0.0063	0.04725	0.13525
Lead Pb dissolved	0.026	0.052	0.0075	0.06	0.112	0.032	0.064	0.048	0.36	0.424
Lead Pb total	0.43	0.86	1.3	10.4	11.26	29	58	2.8	21	79
Cadmium Cd dissolved	0.000029	0.000058	0.000021	0.000168	0.000226	0.000039	0.000078	<0.00002	<0.00002	0.000078
Cadmium Cd total	0.00023	0.00046	0.0011	0.0088	0.00926	0.0031	0.0062	0.00024	0.0018	0.008
Cobalt Co dissolved	0.00053	0.00106	0.00029	0.00232	0.00338	0.00048	0.00096	<0.0002	<0.0002	0.00096
Cobalt Co total	0.0024	0.0048	0.007	0.056	0.0608	0.051	0.102	0.0061	0.04575	0.14775
Copper Cu dissolved	0.0014	0.0028	0.00099	0.00792	0.01072	0.00082	0.00164	0.00094	0.00705	0.00869
Copper Cu total	0.012	0.024	0.02	0.16	0.184	0.16	0.32	0.019	0.1425	0.4625
Chromium Cr dissolved	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Chromium Cr total	0.006	0.012	0.022	0.176	0.188	0.16	0.32	0.019	0.1425	0.4625
Mercury Hg dissolved	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002	<0.000002
Mercury Hg total	0.000025	0.00005	0.000143	0.001144	0.001194	0.00081	0.00162	0.000039	0.0002925	0.0019125
Nickel Ni dissolved	0.0028	0.0056	0.0027	0.0216	0.0272	0.002	0.004	0.001	0.0075	0.0115

Sample name	1B 2-4m					2B 1.5-3.5m				
	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 mg/kg DS	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 (mg/kg DS)
Nickel Ni total	0.0098	0.0196	0.022	0.176	0.1956	0.1	0.2	0.013	0.0975	0.2975
Vanadium V dissolved	0.00092	0.00184	0.00076	0.00608	0.00792	0.00052	0.00104	0.00052	0.0039	0.00494
Vanadium V total	0.01	0.02	0.038	0.304	0.324	0.24	0.48	0.034	0.255	0.735
Zinc Zn dissolved	0.0026	0.0052	0.0036	0.0288	0.034	<0.001	<0.001	<0.001	<0.001	<0.001
Zinc Zn total	0.05	0.1	0.13	1.04	1.14	0.63	1.26	0.072	0.54	1.8
Aliphatics >C5-C8 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C8-C10 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C10-C12 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C12-C16 (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Aliphatics >C16-C35 (mg/l)	0.06	0.12	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Aromatics >C8-C10 enl NV081024 (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Aromatics >C10-C16 enl NV081024 (mg/l)	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Benzene (mg/kg DS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethylbenzene (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M / P / O-Xylene (mg/kg DS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene (mg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Total TEX (mg/kg DS)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Acenaphthene (ug/l)	0.02	0.04	<0.02	<0.02	0.04	<0.02	<0.02	<0.02	<0.02	<0.02
Acenaftylen (ug/l)	0.04	0.08	<0.02	<0.02	0.08	<0.02	<0.02	0.02	0.15	0.15
Anthracene (ug/l)	0.06	0.12	<0.02	<0.02	0.12	<0.02	<0.02	0.05	0.375	0.375
Benzo (a) anthracene(ug/l)	0.46	0.92	0.08	0.64	1.56	0.03	0.06	0.1	0.75	0.81
Benzo (a) pyrene (ug/l)	0.4	0.8	0.09	0.72	1.52	0.04	0.08	0.13	0.975	1.055
Benzo (b, k) fluoranthene (ug/l)	0.86	1.72	0.17	1.36	3.08	0.05	0.1	0.24	1.8	1.9
Benzo (g, h, i) perylene (ug/l)	0.2	0.4	0.05	0.4	0.8	0.02	0.04	0.08	0.6	0.64

Sample name	1B 2-4m					2B 1.5-3.5m				
	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 mg/kg DS	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A8 (mg/kg DS)	A 2-10 (mg/kg DS)
Dibenzo (a, h) anthracene (ug/l)	0.05	0.1	<0.02	<0.02	0.1	<0.02	<0.02	<0.02	<0.02	<0.02
Fenantrene (ug/l)	0.1	0.2	0.02	0.16	0.36	0.02	0.04	0.08	0.6	0.64
Fluoranthene (ug/l)	0.66	1.32	0.12	0.96	2.28	0.06	0.12	0.21	1.575	1.695
Fluorene (ug/l)	0.03	0.06	<0.02	<0.02	0.06	<0.02	<0.02	0.02	0.15	0.15
Indeno (1,2,3-cd) pyrene (ug/l)	0.26	0.52	0.06	0.48	1	0.02	0.04	0.11	0.825	0.865
Chrysene (ug/l)	0.41	0.82	0.09	0.72	1.54	0.03	0.06	0.13	0.975	1.035
Naphthalene (ug/l)	0.04	0.08	0.04	0.32	0.4	0.06	0.12	0.05	0.375	0.495
Pyrene (ug/l)	0.62	1.24	0.11	0.88	2.12	0.08	0.16	0.2	1.5	1.66
Total carcinogenic PAHs (ug/l)	2.4	4.8	0.49	3.92	8.72	<0.20	<0.20	0.71	5.325	5.325
Total other PAHs (ug/l)	1.8	3.6	0.34	2.72	6.32	<0.30	<0.30	0.71	5.325	5.325
PCB 101 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 118 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 138 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 153 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 180 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 28 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01
PCB 52 (µg/l)	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01

C.2 Results from batch leaching tests performed at Chalmers laboratory

Sample name	GV1A 1-2m				GV1B 2-4m				GV2B 1-2m			
	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)
Conductivity (L/S=8) (mS/m)				23.7				49.0				29.3
pH (L/S=2) ()				8.0				7.2				7.4
pH (L/S=8) ()				8.5				7.9				7.9
Redox potential (L/S=8) (mV)				138.1				156.3				156.7
DO (L/S=8) (mg/l)				7.6				6.35				7.25
Temperature (L/S=8) (C)				18.9				18.9				19.1
DOC	8.5	17.0	3.3	41.3	7.5	15.0	2.9	36.4	4.4	8.8	1.7	21.1
TOC	10.3	20.6	6.6	71.9	7.9	15.8	4.6	51.0	5.2	10.3	2.0	25.0
Aluminium Al dissolved	0.63813	1.27627	0.29466	3.49025	0.15704	0.31407	0.09233	1.01018	0.03820	0.07640	0.18237	1.58888
Aluminium Al total	8.28328	16.56656	53.82779	466.18742	6.27961	12.55923	14.98633	138.17146	4.32589	8.65178	14.86977	131.52621
Cadmium Cd dissolved	0.00074	0.00148	0.00017	0.00258	0.00015	0.00030	0.00029	0.00272	0.00116	0.00232	0.00020	0.00359
Cadmium Cd total	0.00071	0.00141	0.00274	0.02421	0.00010	0.00020	0.00006	0.00062	-0.00016	-0.00033	-0.00014	-0.00141
Cobalt Co dissolved	0.00047	0.00093	0.00019	0.00234	0.00063	0.00127	0.00039	0.00426	0.00072	0.00144	0.00014	0.00233
Cobalt Co total	0.00184	0.00368	0.01326	0.11448	0.00181	0.00361	0.00407	0.03767	0.00120	0.00241	0.00383	0.03400
Chromium Cr dissolved	0.00084	0.00169	0.00015	0.00259	0.00003	0.00005	-0.00031	-0.00268	-0.00015	-0.00030	-0.00021	-0.00200
Chromium Cr total	0.00521	0.01042	0.06866	0.58614	0.00274	0.00548	0.01157	0.10384	-0.00032	-0.00065	0.01265	0.10539
Copper Cu dissolved	0.00770	0.01540	0.00347	0.04140	0.00120	0.00240	0.00079	0.00849	0.00188	0.00377	0.00122	0.01330
Copper Cu total	0.01022	0.02044	0.04027	0.35513	0.00694	0.01388	0.00787	0.07742	0.00178	0.00356	0.00849	0.07394
Iron Fe dissolved	0.43140	0.86279	0.21023	2.45239	0.02864	0.05728	0.02009	0.21236	0.00613	0.01226	0.13593	1.14793

Sample name	GV1A 1-2m				GV1B 2-4m				GV2B 1-2m			
	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)	C2 (mg/l)	A2 (mg/kg DS)	C8 (mg/l)	A 2-10 (mg/kg DS)
Iron Fe total	4.62845	9.25690	35.55622	306.60792	2.87810	5.75619	8.54842	77.86973	1.62243	3.24485	9.76795	84.41389
Manganese Mn dissolved	0.00813	0.01626	0.00370	0.04400	0.61807	1.23615	0.14007	2.04256	0.02475	0.04951	0.00210	0.05792
Manganese Mn total	0.05112	0.10224	0.41531	3.57661	0.46886	0.93772	0.18373	2.22016	0.03205	0.06409	0.10097	0.89748
Nickel Ni dissolved	0.00420	0.00839	0.00154	0.01959	0.00548	0.01097	0.00363	0.03878	0.00882	0.01764	0.00141	0.02621
Nickel Ni total	0.00633	0.01266	0.03657	0.31787	0.00698	0.01396	0.01208	0.11392	0.00721	0.01442	0.00866	0.08426
Lead Pb dissolved	0.21313	0.42625	0.11516	1.30663	0.02223	0.04446	0.02915	0.28222	0.04956	0.09911	0.04184	0.43096
Lead Pb total	1.11244	2.22488	7.33577	63.50707	0.36056	0.72112	1.00267	9.16445	0.23447	0.46894	1.47834	12.75770
Zinc Zn dissolved	0.03064	0.06127	0.00623	0.10092	0.03204	0.06409	0.00701	0.10371	0.02066	0.04132	0.00222	0.05221
Zinc Zn total	0.03290	0.06580	0.19929	1.72950	0.04419	0.08838	0.04585	0.45623	0.00767	0.01534	0.04165	0.36113

D. BEAKER TEST

D.1 Results from beaker tests with different boundary conditions performed at Chalmers laboratory

	AIR		PH HIGH		ORGANIC COLLOIDS		IRON COLLOIDS		INERT		MIXING STRONG		PH LOW		UNDISTURBED ENVIRONMENT	
	C6 (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)
Turbidity (FAU)	451		558		1100		112		260		390		111		327	
UV adsorption (ABS/cm)	5.6		5.646		9.275		0.745		2.975		3.712		0.522		2.019	
TRUE color (mg Pt-Co)	>550		>550		>550		>550		>550		>550		242		>550	
APPARENT color (mg Pt-Co)	>550		>550		>550		>550		>550		>550		>550		>550	
Alkalinity (mg HCO3/l)	78.1		97.6		156.2		141.6		43.9		146.4		24.4		73.2	
DOC	4.92	29.52	3.6	21.6	9.45	56.7	3.78	22.68	4.74	28.44	5.37	32.22	3.64	21.84	1.96	11.76
TOC	3.72	22.32	2.92	17.52	11.3	67.8	3.54	21.24	3.61	21.66	3.87	23.22	3.12	18.72	2.06	12.36
Aluminium Al dissolved	0.1607	0.9640	0.1200	0.7198	1.0148	6.0886	0.0736	0.4414	0.1638	0.9827	0.173	1.0398	0.4751	2.8508	0.1819	1.0917
Aluminium Al total	38.83	233.00	28.68	172.11	46.09	276.56	5.16	30.99	29.18	175.10	19.93	119.60	4.76	28.56	12.22	73.29
Cadmium Cd dissolved	0.0001	0.0007	0.0002	0.0012	0.0003	0.0016	0.0002	0.0014	0.0002	0.0011	0.0000	0.0002	0.0012	0.0072	0.0001	0.0006
Cadmium Cd total	0.0007	0.0045	0.0007	0.0040	0.0019	0.0116	-0.0001	-0.0005	0.0005	0.0029	0.0005	0.0027	0.0010	0.0060	0.0002	0.0010
Cobalt Co dissolved	0.0003	0.0019	0.0002	0.0013	0.0007	0.0040	0.0005	0.0032	0.0002	0.0013	0.0004	0.0022	0.1537	0.9220	0.0001	0.0007
Cobalt Co total	0.0111	0.0669	0.0077	0.0460	0.0134	0.0802	0.0014	0.0084	0.0077	0.0463	0.0048	0.0287	0.1183	0.7097	0.0025	0.0152
Chromium Cr dissolved	0.0001	0.0008	0.0002	0.0013	0.0012	0.0073	0.0001	0.0004	0.0000	0.0000	0.0001	0.0008	0.0007	0.0043	-0.0002	-0.0013
Chromium Cr total	0.0452	0.2710	0.0308	0.1848	0.0570	0.3422	0.0001	0.0004	0.0301	0.1808	0.0153	0.0919	-0.0005	-0.0029	0.0059	0.0353
Copper Cu dissolved	0.0012	0.0074	0.0009	0.0055	0.0089	0.0534	0.0009	0.0052	0.0008	0.0050	0.0006	0.0035	0.0002	0.0014	0.0022	0.0133
Copper Cu total	0.0222	0.1332	0.0168	0.1009	0.0421	0.2525	0.0039	0.0234	0.0182	0.1093	0.0141	0.0843	0.0027	0.0162	0.0063	0.0378
Iron Fe dissolved	0.0431	0.2588	0.0835	0.5012	0.8452	2.5356	0.0346	0.2079	0.0779	0.4673	0.1006	0.6036	161.4293	96.8576	0.0773	0.4640
Iron Fe total	22.90	137.41	18.05	108.27	30.63	183.80	2.44	14.66	17.86	107.14	10.79	64.75	110.75	664.52	5.69	34.11
Manganese Mn dissolved	0.1611	0.9664	0.1075	0.6450	0.2400	1.4399	0.5830	3.4977	0.0777	0.4661	0.3370	2.0218	10.8608	65.1647	0.0818	0.4909

	AIR		PH HIGH		ORGANIC COLLOIDS		IRON COLLOIDS		INERT		MIXING STRONG		PH LOW		UNDISTURBED ENVIRONMENT	
	C6 (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)	**C6** (mg/l)	**A6** (mg/kg DS)
Manganese Mn total	0.3858	2.3148	0.2759	1.6554	0.5779	3.4675	0.4431	2.6584	0.2434	1.4604	0.3723	2.2338	7.2235	43.3408	0.1529	0.9173
Nickel Ni dissolved	0.0031	0.0185	0.0031	0.0189	0.0053	0.0320	0.0048	0.0286	0.0034	0.0205	0.0042	0.0250	0.2515	1.5088	0.0013	0.0077
Nickel Ni total	0.0307	0.1841	0.0224	0.1342	0.0388	0.2326	0.0048	0.0290	0.0222	0.1333	0.0146	0.0877	0.1997	1.1980	0.0077	0.0462
Lead Pb dissolved	0.0127	0.0759	0.0141	0.0848	0.1085	0.6512	0.0082	0.0491	0.0111	0.0665	0.0162	0.0969	1.3885	8.3309	0.0213	0.1277
Lead Pb total	1.7319	10.3912	1.1851	7.1103	2.4456	14.6734	0.2370	1.4221	1.4216	8.5297	1.0151	6.0904	1.6586	9.9518	0.4807	2.8845
Zinc Zn dissolved	0.0057	0.0344	0.0063	0.0378	0.0210	0.1261	0.0052	0.0310	0.0059	0.0353	0.0090	0.0538	0.9624	5.7743	0.0084	0.0502
Zinc Zn total	0.1122	0.6733	0.0866	0.5195	0.1551	0.9305	0.0117	0.0704	0.0918	0.5510	0.0642	0.3850	0.9188	5.5129	0.0381	0.2288

D.2 Parameters analyzed during the beaker tests

	AIR						**PH HIGH**						**ORGANIC COLLOIDS**						**IRON COLLOIDS**					
Time (h)	0	1	2	3	4	24	0	1	2	3	4	24	0	1	2	3	4	24	0	1	2	3	4	24
Conductivity (mS/m)	29	33.8	34.9	36.8	37.9	48.8	24.3	27.1	28.9	29.8	33.3	42.3	26.9	29.3	30.3	33.5	33.5	40.9	65	67.2	70.9	72.7	77	85.5
pH ()	8.1	8.3	8.3	8.3	8.3	8.1	8.1	8.9	8.6	8.6	8.6	8.3	7.9	8	8	7.9	7.9	8.2	7.4	7.3	7.5	7.3	7.5	7.7
Redox potential (mV)	274	193	175	165	159	186	138	130	130	126	122	146	32	-97	-10	41	-61	-130	-33	-15	-13	-63	-77	-84
DO (mg/l)	7.8	10.2	10.7	11.4	11.2	10	2.4	1.2	0.9	1.2	1	1.7	1.6	1.1	1.3	1.2	1.2	1	1.6	1.5	1.3	1.4	1.2	1.3
Temperature (C°)	20.2	17	15.1	15	15.3	15.6	20	20.3	20.7	20.6	20.7	20.5	17.9	18.8	18.9	19.8	19.8	20.1	17.5	18.3	19.1	19.5	19.1	18.7

	INERT ATMOSPHRE						**MIXING STRONG**						**PH LOW**						**UNDISTURBED ENVIRONMENT**					
Time (h)	0	1	2	3	4	24	0	1	2	3	4	24	0	1	2	3	4	24	0	1	2	3	4	24
Conductivity (mS/m)	27.1	28.3	29.1	29.3	30.1	37.5	29.1	34.1	38.1	38.5	43.5	48.7	210	286	343	381	403	523	8.1	14.1	15.3	16.8	17.8	23.1
pH ()	8.2	8.4	8.5	8.4	8.6	8.5	7.3	7.7	7.9	7.8	7.7	7.4	4.3	4	5.2	4.9	4.8	5.5	7.4	7.4	7.1	6.8	6.9	6.9
Redox potential (mV)	108	155	149	80	134	164	-145	-134	-156	-154	-137	-147	69	106	160	155	160		57	75	101	126	139	
DO (mg/l)	2.6	2.8	2.8	3.2	3.1	2.1	1	1	1	1.1	1	1.3	1.8	2	2.1	2.3	1.9	2.1	5.5	3.3	3.4	3.5	2.8	3.1
Temperature (C°)	18.2	18.5	18.2	18.5	18.8	16	20	19.5	19.5	20.2	20.3	19.5	18.4	18.8	18.9	19.1	19.4	19.1	18.4	18.2	18.7	18.8	18.7	18.5