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A GEOCHEMICAL ANALYSIS OF LEACHATE PLUMES FROM TWO ABANDONED LANDFILLS. PRESENT AND LONG-TERM EFFECTS ON GROUNDWATER

En geokemisk analys av lakvattentransport från två nedlagda soptippar. Nuvarande och långsiktiga effekter på grundvatten

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Abstract

Groundwater samples have been taken from two abandoned landfills Måsängen and Lackalänga in Kävlinge community. The results show that groundwater from Lackalänga is a mixture of reduced and oxidized waters due to above-normal iron, manganese and ammonium as well as high nitrate and sulfate concentrations. Meanwhile, high bicarbonate buffers the pH between 7.7 and 8. The reduced water is most likely contributed by the landfill while the oxidized water most likely comes from upstream. Agricultural fertilizers also play a role in increased nitrogen concentrations. The concentrations are not high enough to be considered for risk assessment especially when high dilution into the Kävlinge River is considered. The Lackalänga landfill is therefore not a contributor to significant amounts of contaminants to the groundwater in the culvert and is therefore not a threat to surrounding waters, namely the Kävlinge River. The landfill in Måsängen showed high concentrations of reduced species, low concentrations of oxidized species, very high COD and high phosphate. It is therefore considered to be reduced water and highly contaminated. Polycyclic aromatic hydrocarbons were also found in concentrations above normal, which present a 1/100 000 cancer risk. The flow of the groundwater was calculated to be 0.001 % of that of the Kävlinge River. The rates at which the groundwater contaminants enter the Kävlinge River are too low to cause any change in the water quality of the river.

Key words – leachate, closed landfills, long-term emission, risk assessment, Kävlinge

Sammanfattning

Grundvattenprover från de två nedlagda soptipparna Måsängen och Lackalänga i Kävlinge kommun har analyserats. Resultaten visar att grundvatten från Lackalänga består av en blandning av reducerat och oxiderat vatten, på grund av en förhöjd halt järn, mangan och ammonium tillsammans med nitrat och sulfat. Vattnet är välbuffrat av vätekarbonat och har ett pH mellan 7,7 och 8. Det reducerade vattnet kommer troligtvis från soptippen, medan det oxiderade kommer från källor uppströms soptippen. Utläckande gödningsmedel från jordbruk ökar nitrathalten i vattnet. Koncentrationerna är inte tillräckligt höga för att en riskbedömning skall vara meningsfull, särskilt om hänsyn tas till den stora utspädningen som sker i recipienten Kävlingeån. Soptippen Måsängen hade ett lakvatten med höga halter reducerade ämnen, låga halter oxiderade ämnen, mycket hög halt COD och hög fosfathalt. Lakvattnet därifrån bedöms som kraftigt påverkat av sopor. Polycykliska aromatiska kolväten kunde detekteras i koncentrationer över de förväntade, vilket motsvarar en förhöjd cancerrisk med 1/100 000. Grundvattenflödet påverkat av Måsängens lakvatten representerar 0,001 % av Kävlingeåns flöde. Hastigheten, med vilken föroreningarna i Måsängens lakvatten transporteras till ån, bedöms vara så låg, att åns vattenkvalitet inte förändras.

Introduction

What shall we do with the abandoned landfills? Most old landfills lack protective liners, drainage systems and post-closure maintenance and supervision. The greatest and most important environmental threat by landfill leachate is the contamination of groundwater (Bjerg *et al.*, 2003). Due to dysfunctional liners or lack thereof in older landfills, leachate infiltration tends to create a higher contamination risk to ground waters than surface waters (Kjeldsen *et al.*, 2002).

This paper presents the work that has been done in order to evalute if two abandoned landfills in the southwestern section of Scania, south Sweden, might be hazardous. The landfills have been closed for around 40 years and their effects on the local groundwater are previously unknown. Groundwater samples and tests have been taken in past years. However, no complete analyses has been done that concludes the present or future threats of these landfills to the groundwater. Emissions are generally modest, due to natural attenuation – the natural way in which contaminants decay, decrease in concentration. Natural attenuation dampens the organic effluent from large natural organic sinks, like bogs or peat-lands, and also from abandoned landfills due to dilution, dispersion, biodegradation, irreversible sorption and radioactive decay (SNL, 2000; Bjerg *et al.*, 2003; Kjeldsen *et al.*, 2002; El-Fadel *et al.*, 1997). Advection and dispersion govern the movement of all compounds in leachate plumes as they mix with groundwater (Bjerg *et al.*, 2003). The horizontal advection and dispersion of leachate is typically greater than the vertical due to the horizontal forces of flowing groundwater.

Leachate is highly reduced upon entering a typically oxidized pristine aquifer and has a strong capacity to donate electrons to available acceptors. Predictions and analyses of redox conditions and developments of a leachate plume in an aquifer are crucial since they determine the extent of organic contaminant degradation. As dissolved organic substances (DOC) in leachate travel through the aquifer and away from the landfill they are degraded by available electron acceptors already present in the aquifer material which create a series of redox zones (van Breukelen, 2003). The most common redox reactions in leachate that involve electron acceptors are aerobic respiration, denitrification, manganese reduction, iron reduction, sulfate reduction, carbon dioxide reduction, methanogenesis, ammonium oxidation and methane oxidation, *i.e.* fermentation. By aerobic degradation, nitrate reduction and sulfate reduction organic carbon is oxidized on the outer fringes of the leachate plume, which creates a slight inhibition to leachate movement.

Anaerobic degradation occurs inside the leachate plume in the order of metal oxide dissolution followed by sulfate reduction and finally methanogenesis. Each of these zones may tend to overlap according to pH, redox species concentration, and the solubility of iron-oxide minerals. Sulfate is present in the aquifer and acts as an oxidizing agent on the outer fringes of the plume (Svensson, 2003; van Breukelen, 2003). Sulfate also is a component of leachate, which creates a zone of sulfate reduction where leachate enters the aquifer. As electron acceptors are consumed degradation rates of organic chemicals are reduced and a steady-state plume is created and enlarges (van Breukelen, 2003). The presence of buffers in the aquifer will prevent enlargement of the plume and will continue to do so until either the buffering capacity is reached or the organic chemicals are depleted.

Field site descriptions

The subject areas are located in southwestern Sweden in the province of Scania (See figure 1). The landfills are located in Kävlinge and Lackalänga. The landfill Måsängen in Kävlinge was once a municipal landfill that covered an area of 1.35 hectares until a depth of 1.5 meters. The landfill operated from the late 1940's until 1957 and the deposited refuse was mainly household waste. The abandoned landfill in Lackalänga opened in the mid-1950's and closed around 1966. This landfill allowed disposal of both municipal and industrial wastes. The landfill had a total area of 3.7 hectares, a volume of 90 to 100,000 m^3 and a depth of about 2.5 meters. Before the landfill was constructed, a small ravine crossed the area from east to west. Therefore, when the landfill was built a pipeline was installed beneath the landfill to transport the water without allowing it to contact the waste. When the landfill was closed, a thin layer of earth was used to cover the waste as it appears today meanwhile leaving the pipeline in place. This means that all groundwater typically infiltrates downwards and into the pipeline, which empties into a small ravine just northwest of the landfill. This is an important consideration since the water samples are not taken from within an aquifer but rather from an underground river that is constantly fed by surrounding groundwater. This underground pipeline transports groundwater from the eastern end of the landfill to a stream outlet about 500 meters northwest of the landfill.

Presently, both abandoned landfills go completely unnoticed as the area in Lackalänga is covered by fields of wild grass and wheat fields while Måsängen is a well-kept grass area that is bordered by the Kävlinge River on the south side and by a residential area to the north.

The recharge area of both landfills provides the groundwater to both landfills. Geological barriers can separate a recharge area into separate aquifers, but no

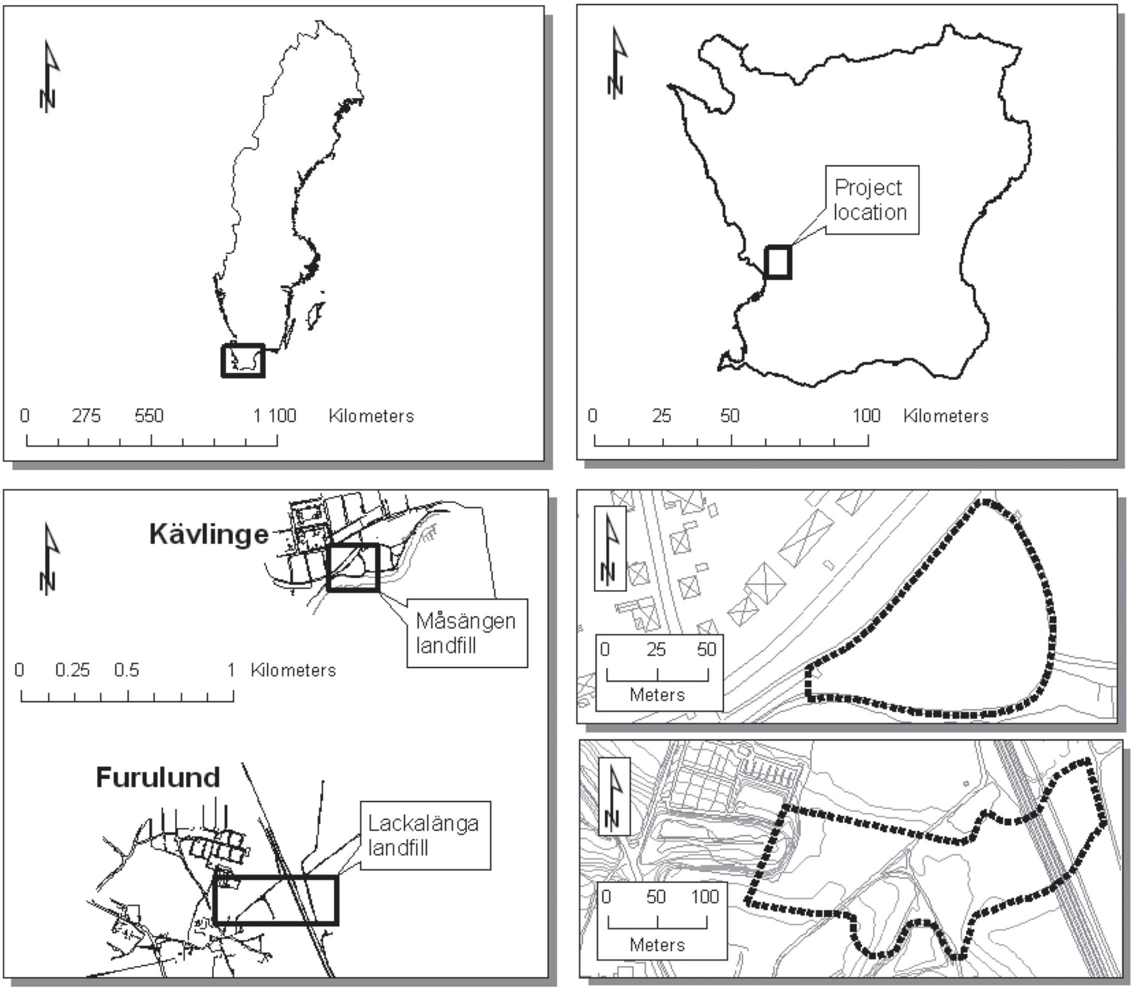

Figure 1. *Maps of the project sites. The two abandoned landfills are located in Kävlinge and Furulund, which lie in mid-western Scania in southern Sweden.*

such geological barriers are known of at either landfill so the recharge area is considered to be the size of the aquifer at both locations. The recharge area at Lackalänga is about 290 ha. The topology creates groundwater barriers to the north, east and south, creating water flow in a northeasterly direction. The recharge area in Måsängen is very small, only about 1.5 ha as water flows mainly north to south ending in the Kävlinge River.

Hydrogeological features

The uppermost bedrock at Lackalänga and Måsänge is about 300 meters thick and is made of different sedimentary rocks that are attributed to the Kågeröd formation from the Upper Triassic period. The dominant rocks are clays, sandstones and conglomerates (Sivhed *et al.*, 2001; VBB, 1995). Underneath the Triassic bedrock are layers of Silurian mudstone and shale with intruding dolerite dikes, followed by Ordovician shale and limestone, Lower Cambrian sandstone and finally gneiss of unknown origin (Sivhed *et al.*, 2001).

The location of the groundwater sampling wells and surface deposits at the Måsängen landfill are shown in figure 2. At the site surrounding well 0401 in the northern part of the landfill, the upper deposits consist of 1.4 meters of topsoil filling, which was applied artificially when the landfill closed in order to cover the waste. Underneath the filling lies about four meters of thick sandy clays. The geology surrounding well 0402 is made of 0.6 meters of filling with fluvial deposits of peat, mud, clay and sand from river sediments until three meters depth. Underneath the fluvial sediments lies about

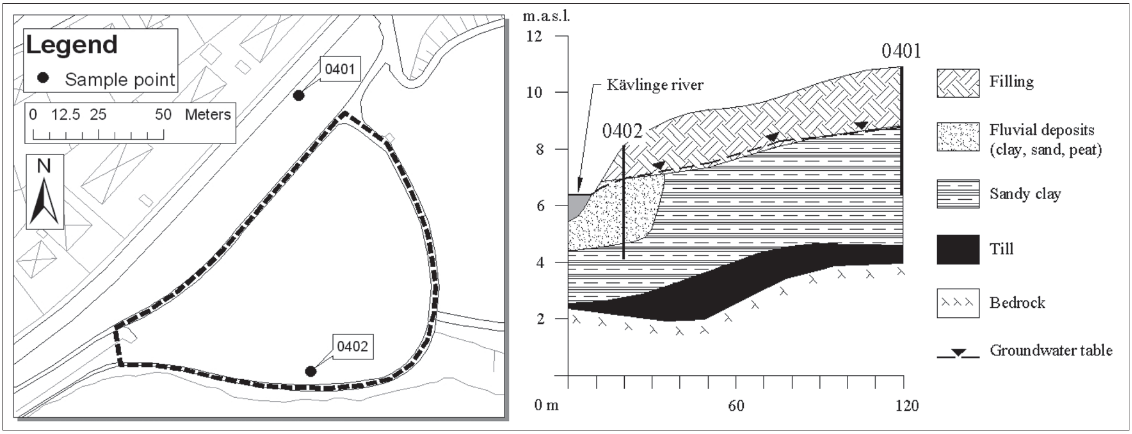

Figure 2. *Location of the groundwater wells 0401 and 0402 at the Måsängen landfill. Side profile shows geological layers and groundwater table depth from south to north (left to right). Interpreted from field work analysis as well as from VBB (1995).*

two meters of sandy clay. Underneath the sandy clay lies a thin (0–1m) rather impermeable layer of till with a clay content of 15–25 %, which slopes slightly uphill as it approaches the northern part of the subject area. This clay till layer marks the bottom of the aquifer as groundwater flow is inhibited by the low permeability. Underneath the till lies the bedrock, which begins at between two and four meters above sea level.

The topology of the land at Måsängen slopes downward from 10.9 meters above sea level at well 0401 of the landfill and slopes down to 8.1 meters above sea level at well 0402. The Kävlinge River acts as a constant head boundary whose level lies at around 6.5 meters (VBB, 1995). Thus, any leachate-contaminated groundwater will enter the stream as baseflow or interflow, depending on the permeability of the unsaturated zone and the height of the groundwater table.

The landfill in Lackalänga is located about 2 kilometers southwest of the Kävlinge landfill. Figure 3 shows a side geological profile of the landfill and locations of the

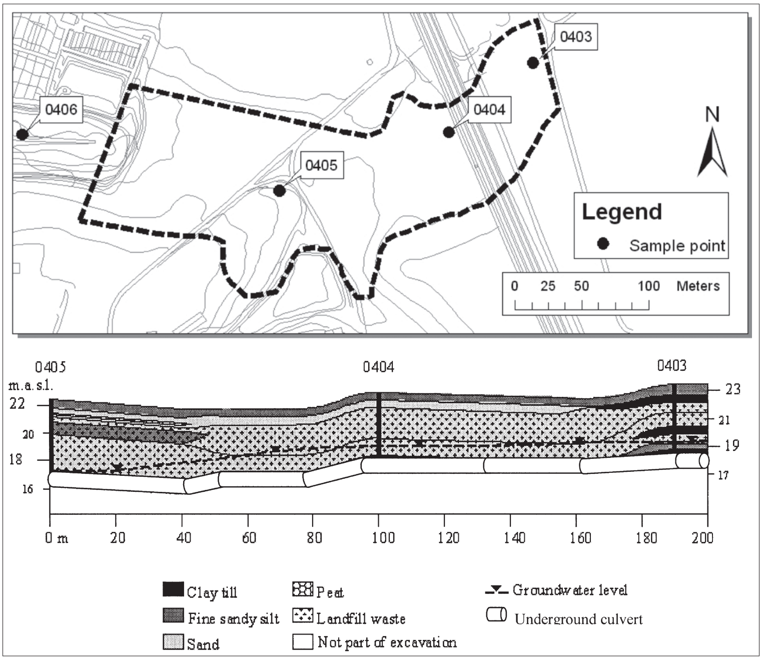

Figure 3. *Locations of each sampling point and side profiles at wells 0403, 0404 and 0405 at the abandoned Lackalänga landfill. Profile shows the location and depth of current geological layers, landfill waste and groundwater levels. An underground pipeline which transports the groundwater in the area runs from east to west directly below each well and disposes groundwater at an outlet at point 0406. From VBB (1994).*

observation wells. The Quaternary deposits are about 10 meters deep, although samples were taken to only 7.5 meters. The deposits include of a combination of clay, clay till, silt and sand. The clay till on the east side has a clay content of 5–15 % while the clay on the west side ranges between 15–25 % (Ringberg, 1987).

These cross sections reveal that the majority of soil above the landfill are relatively to highly permeable, mostly sands ranging from gravelly sand to fine sandy silt. The soil underneath the landfill waste consists of clays with low permeability. In some areas the clays are wet, which may indicate the presence of a leaky confined aquifer. The general trend of permeability is relatively high in the shallow deposits and becomes lower in the deeper deposits under the landfill.

At Lackalänge, there is a storm drain outlet and ravine to the northwest just outside of the landfill area where the terrain drops sharply about 8 meters. The groundwater flows towards the center of the landfill and if it infiltrates deep enough, it is transported by the underground pipeline to the outlet where the ravine transports the water to the Kävlinge River.

Hydrology and hydraulics

Kävlinge and Furulund receive an average yearly rainfall of about 700 mm with an evaporation rate of around 480 mm/year. This creates an estimated yearly runoff of around 220 mm. The groundwater hydraulic gradient of Måsängen 0.01. The northern end of the landfill has lower permeability than the southern end due to the high clay content in the north and more permeable fluvial sediments in the south. Hydrological and hydraulic parameters for Måsängen are presented in Table 1.

The groundwater level at the Lackalänga landfill begins upstream at 19.03 meters above sea level at well number 0403. Midstream at well 0404 the level is 18.73 m, downstream at well 0405 the level lowers to 17.30 m. Thus the gradient upstream is 0.003 while the gradient in the middle of the landfill is 0.017. The groundwater level lies rather deep in the sandy deposits and actually is at the same level as the landfill waste. The flow of leachate is 0.2 L/s to 5 L/s depending on the amount of infiltrating water and season (VBB, 1994). The aquifer is made up of sands and landfill waste, however, the top layer of soil consists of a thin layer of silt and topsoil, which have relatively low permeabilities. The water level in the underground pipe at well 0403 is 5.58 meters below ground surface while that at well 0404 is about the same, and the level at well 0405 is 6.2 meters deep. Thus, the groundwater in the culvert has a gradient of 0.006. However, since the groundwater in the culvert comes from the watershed upstream, the flow of the water is depicted by the upstream topology more than the slope of the culvert pipes.

Table 1. *Approximate hydraulic characteristics of the aquifer at the Måsängen landfill.*

Parameter	Value
Hydraulic gradient	0.015
Intrinsic permeability (Darcys)	$10 \cdot 10^{-3}$–$10 \cdot 10^{-1}$
Hydraulic conductivity (cm/s)	$3 \cdot 10^{-4}$–$7 \cdot 10^{-4}$
Average aquifer thickness (m)	7
Specific yield (%)	10
Porosity (%)	35
Transmissivity (m²/s)	$2 \cdot 10^{-5}$–$5 \cdot 10^{-5}$
Storativity	$2 \cdot 10^{-5}$–$3 \cdot 10^{-5}$

From Fetter (2001) and VBB (1997).

Table 2 shows the hydraulic characteristics from the Lackalänga landfill.

Materials and methods

At Lackalänga landfill, the old obeservation wells could be used for water sampling. Two new groundwater observation wells were constructed at the project site at Måsängen. One (no. 0401) upstream and the other (no. 0402) downstream the landfill about 10 meters north of Kävlinge River where the plume was predicted to be located.

Groundwater sampling in Måsängen and Lackalänga was performed in October, 2004 as well as water-depth measurments at each well. A hand pump was used for taking samples in Måsängen, while a plastic bucket was used at Lackalänga. Two types of analysis were performed on the groundwater. In the first, physical and chemical parameters were analysed at all six sampling sites in Måsängen and Lackalänga, using one 500 mL plastic bottle per well. In the second analysis, a total number of 103 different heavy metals and xenobiotic

Table 2. *Hydraulic characteristics of the aquifer at the Lackalänga landfill.*

Parameter	Value
Hydraulic gradient	0.003–0.017
Intrinsic permeability (Darcys)	0.01–1
Hydraulic conductivity (cm/s)	$1 \cdot 10^{-5}$–$1 \cdot 10^{-3}$
Average aquifer thickness (m)	4
Specific yield (%)	21
Porosity (%)	35
Transmissivity (m²/s)	$4 \cdot 10^{-7}$–$4 \cdot 10^{-5}$

From Fetter (2001) and VBB (1997).

organic compounds in groundwater were analyzed. This analysis was performed at wells upstream and downstream the landfills (0401, 0402, 0404 and 0405) All groundwater samples were sent to Analytica AB:s laboratory for analysis.

For analysis of the water chemistry, PHREEQC was used, It is a computer program which calculates geochemical compositions and simultaes chemical reactions (Post, 1999). The calculated saturation index, SI values, are theoretical, hence they must first correlate with the geology of the area in order to be considered for analysis. Time is also a factor since some minerals may take longer periods of time to dissolve.

Results and discussion

Måsängen groundwater chemistry

Groundwater ions

In table 3, the chemical-physical parameters that were analyzed in the groundwater samples taken in Måsängen at points 0401 and 0402 are presented. The percentage of error between cations and anions in the groundwater analysis at point 0401 in Måsängen is 1.59 %. This indicates that the results are accurate with hardly any discrepancies. Point 0402 showed a much higher percentage error of 47.62 %, which is mostly attributed to the extremely high COD concentration. Organic material in water is generally negatively charged, thus it adsorbs to positively charged particles. This influences the amount of concentration of certain major ions in the groundwater and may produce a high percentage error. It is likely that calcium ions are adsorbed by the organic materials to increase the percentage error of the groundwater results.

Many parameters alters from an oxidized state upstream to a reduced state downstream. Alkalinity as bicarbonate, for example, rises from 870 mg/L to 3100 mg/L. This is a very large change and could be due to biological activity and calcite dissolution. The calcium concentration increases from 159 mg/L at point 0401 to 276 mg/L at point 0402, which explains the increase in hardness between the two points. This increase in calcium is due to calcite dissolution as calcite is a very common mineral in southern Sweden. Calcite dissolution produces calcium and bicarbonate ions, which is another explanation for the high bicarbonate. The high amount of acid produced in the previous reactions make calcite dissolution a clear possibility. Even though the acid content is high in the landfill aquifer, the pH remains near 7 due to the buffering capabilities of calcite and bicarbonate.

Table 3. *Physical chemical parameters in groundwater at wells 0401 and 0402 in Måsängen.*

Parameter	Unit	0401	0402
Turbidity	FNU	>2000	<2000
Color		25	35
COD-Mn	mg/L	110	1300
Conductivity	mS/m	96.60	157
pH		7.40	7.30
Alkalinity (HCO_3)	mg/L	370	3100
H_2CO_3	mg/L	<1	160
Hardness	°dH	25	45
$Ca^{(2+)}$	mg/L	159	276
$Mg^{(2+)}$	mg/L	11.20	27.70
$Na^{(+)}$	mg/L	19.90	54.50
$K^{(+)}$	mg/L	1.82	18.20
$Fe^{(2+)}$	mg/L	<0.02	0.073
$Mn^{(2+)}$	mg/L	<0.003	2.97
$Cu^{(2+)}$	µg/L	<7	<7
$Al^{(3+)}$	µg/L	5.17	2.60
NH_4-N	mg/L	<0.02	2.10
NH_4	mg/L	0.03	2.70
NO_3-N	mg/L	13	<0.02
NO_3	mg/L	57.57	0.09
NO_2-N	mg/L	0.35	0.01
NO_2	mg/L	1.15	0.04
PO_4-P	mg/L	4.80	31
PO_4	mg/L	14.72	95.06
$F^{(-)}$	mg/L	0.32	0.42
$Cl^{(-)}$	mg/L	105	72.30
$SO_4^{(2-)}$	mg/L	51.50	21.50

The Swedish groundwater standards for chemical oxygen demand (COD) is <12 mg/L (Tequila, 2001). COD is very high at point 0402 with a concentrations of 1300 mg/L. This is most likely due to the leftover organic river materials from when the Kävlinge River was higher and covered this portion of the land. This high COD level indicates that much oxygen is required from the groundwater and consequently, is creating a low oxygen supply in the groundwater thus reduced conditions.

Sulfate reduction also contributes to an increase in bicarbonate concentration. Organic degradation initiates sulfate reduction since organic carbon uses oxygen from sulfate in order to decompose and as a result produces bicarbonate and hydrogen. This is shown by the decrease in sulfate from 51.50 mg/L to 21.50 mg/L. This also indicates that the groundwater converts from a more oxidized environment upstream to a reduced environment in the landfill.

Iron(II) increases from less than 0.02 mg/L at point 0401 to 0.073 mg/L at point 0402, which is a result of iron reduction and a reduced environment at point 0402. Manganese(II) increases to 2.97 mg/L at point 0402, which adds to the assumption that the landfill groundwater is reduced. Other confirmations include a high ammonium-nitrogen level of 2.10 mg/L, which is rather high, as well as a nitrate-nitrogen concentrations of less than 0.02 mg/L. Upstream, the nitrate level is unusually high for groundwater (57.57 mg/L), which might be due to a leaky sewage line that crosses the northern section of the subject area. The sewage leak creates rather high COD concentration of 110 mg/L at point 0401, which is higher than the Swedish standard for groundwater (<12 mg/L). Thus the high nitrate and COD levels at point 0401 could be interpreted as a sewage leak, since such high concentrations of these parameters are not typically found in uncontaminated groundwater. The final confirmation of the reduced conditions of the groundwater at the landfill is the low amounts of sulfate, which is an oxidizing agent and is reduced from 51.50 mg/L upstream to 21.50 mg/L at point 0402. The sulfate level, however, is not as low as nitrate as one would expect of an oxidizing agent in a reduced environment. Sulfate may still be present at point 0402 because sulfate is a component of leachate, thus it may be leaching off of waste still present in the landfill.

Another interesting result is the rather high phosphate concentration of 95.06 mg/L at point 0402. Normally, phosphate does not naturally occur at such high concentrations, however, phosphate may have been left behind by the river that once covered this area. Like nitrate, phosphate is common on river bottoms since it provides food to algae-producing bacteria.

This correlates with the high amount of organic content near point 0402. Other reasons for the high amount of phosphate could be due to fertilizers or soaps in the landfill. However, it is more likely that the high phosphate is due to the presence of algae left behind by the river since degrading algae discharges phosphates that it once used for food (Puets, 2001).

Therefore, the groundwater is in a more oxidized state upstream at point 0401 with higher amounts of nitrate and sulfate while downstream chemical reactions and biodegradation create a reduced environment with low amounts of oxidizing agents and higher amounts of reducing agents such as ammonium, manganese(II) and a slight increase in iron(II).

Groundwater minerals

Table 4 shows the mineral compositions in the soil from a sample that was taken at point 0402 in Måsängen. This sample is compared with a theoretical representation of the precipitated minerals in the groundwater that was achieved by using the PHREEQC program and the ion concentrations in table 3. The results show that the main minerals that make up the total amount of solids in the soil are silicium dioxide (SiO_2), or quartz, aluminum oxide (Al_2O_3), calcium oxide (CaO), iron oxide (Fe_2O_3) and potassium oxide (K_2O). These soil minerals were taken from earth samples at point 0402 but can also be used to assess the dissolved groundwater minerals at point 0401 assuming that the two points share similar soil minerals.

The groundwater results show that at point 0401 gibbsite ($Al(OH)_3$), calcite and aragonite ($CaCO_3$), do-

Table 4. *Listing of minerals found in soil samples compared with minerals found in groundwater samples taken from points 0402 and 0401 in Måsängen.*

Soil minerals		
0402		
Total Solids	%	86.6
SiO_2	% TS	69.3
Al_2O_3	% TS	10
CaO	% TS	5.06
Fe_2O_3	% TS	3.8
K_2O	% TS	3.09
MgO	% TS	0.95
MnO	% TS	0.0831
Na_2O	% TS	2
P_2O_5	% TS	0.139
TiO_2	% TS	0.521
Total Sum	% TS	94.9
Level of ignition (LOI)	% TS	4.4

Groundwater minerals		
Mineral	Formula	SI
0401		
Gibbsite	$Al(OH)_3$	0.62
Calcite	$CaCO_3$	0.51
Aragonite		0.37
Dolomite	$CaMg(CO_3)_2$	0.16
Hydroxyapatite	$Ca_5(PO_4)3OH$	7.62
0402		
Gibbsite	$Al(OH)_3$	0.39
Calcite	$CaCO_3$	1.34
Aragonite		1.19
Dolomite	$CaMg(CO_3)_2$	1.95
Hydroxyapatite	$Ca_5(PO_4)3OH$	9.47
Rhodochrosite	$MnCO_3$	1.42

lomite ($CaMg(CO_3)_2$) and hydroxyapatite ($Ca_5(PO_4)_3OH$) have saturation index (SI) values greater than zero thus are supersaturated in the groundwater. Groundwater at point 0402 is supersaturated with the same minerals as point 0401 with the exception of rhodochrosite ($MnCO_3$), which is only found at point 0402. Almost all of the dissolved minerals in the groundwater at both points have calcium components, which correlates with the occurrence of calcium oxide in the soil and also the high calcium content in the groundwater. Gibbsite ($AlOH_3$) is a common hydroxide in groundwater. It is understandable that gibbsite is found in the groundwater due to the high percentage of aluminum oxide in the soil. The decrease in aluminum ions between points 0401 and 0402 indicates that gibbsite is precipitating.

An important contribution from gibbsite and calcite to the groundwater is their buffering capabilities. When calcite and gibbsite are dissolved by an acid, the hydroxide and bicarbonate anions in both minerals react with hydrogen ions in the acid and use them up so the pH does not increase very much. Meanwhile, the mineral continues to dissolve and produce free calcium and aluminum ions. However, each mineral will reach its capacity when enough acid is added so the pH changes significantly. Gibbsite typically buffers water at pH levels around 4 while calcite buffers to pH values around 6 or 7.

Heavy metals and xenobiotic organic compounds

Table 5 shows the concentrations of heavy metals and xenobiotic organic compounds (XOCs) at points 0401 and 0402 in Måsängen. Almost all species are found in minimal amounts, with the exception of the polycyclic aromatic hydrocarbons (PAHs).

Table 5. *Metals and XOC concentrations in groundwater in Måsängen and Lackalänga.*

Element	Unit	Måsängen		Lackalänga	
		0401	0402	0404	0405
Fraction >C10–C12	µg/l	<10	<10	<10	<10
Fraction >C12–C16	µg/l	<10	<10	<10	<10
Fraction >C16–C35	µg/l	<20	59	<20	39
Acenaftylen	µg/l	<0.10	<0.10	<0.10	<0.10
Acenaften	µg/l	<0.025	<0.025	<0.025	<0.025
Fluoren	µg/l	<0.020	<0.020	<0.020	<0.020
Fenantren	µg/l	0.048	0.11	<0.020	<0.020
Antracen	µg/l	<0.013	0.018	<0.013	<0.013
Pyren	µg/l	<10	<10	<0.020	<0.020
Bens(a)antracen	µg/l	0.022	0.073	<0.010	<0.010
Krysen	µg/l	0.033	0.12	<0.016	<0.016
Bens(b)fluoranten	µg/l	0.02	0.071	<0.020	<0.020
Bens(k)fluoranten	µg/l	0.013	0.044	<0.010	<0.010
Bens(a)pyren	µg/l	0.023	0.09	<0.010	<0.010
Dibens(ah)antracen	µg/l	<0.012	0.015	<0.012	<0.012
Benso(ghi)perylen	µg/l	0.019	0.062	<0.010	<0.010
Indeno(123cd)pyren	µg/l	0.02	0.066	<0.010	<0.010
Sum 16 EPA-PAH	µg/l	0.3	1	<0.42	<0.42
PAH carcinogenes	µg/l	0.13	0.48	<0.050	<0.050
PAH others	µg/l	0.17	0.55	<0.37	<0.37
As	µg/l	<0.50	1.8	0.59	<0.50
Ba	µg/l	77	340	100	110
Cd	µg/l	<0.20	<0.20	<0.20	<0.20
Co	µg/l	0.22	4.1	0.23	0.27
Cr	µg/l	<5.0	<5.0	<5.0	<5.0
Cu	µg/l	3.6	9.2	0.87	1.2
Hg	µg/l	<0.30	<0.30	<0.30	<0.30
Mo	µg/l	0.88	9.4	0.82	0.97
Ni	µg/l	1.1	5.9	1.7	1.7
Pb	µg/l	<0.20	0.35	<0.20	<0.20
Sn	µg/l	1.1	<0.50	<0.010	<0.010
V	µg/l	<5.0	<5.0	<5.0	<5.0
Zn	µg/l	51	410	5.9	8.6

Table 6. *Physical chemical parameters in groundwater at wells 0403, 0404, 0405 and 0406 in Lackalänga. Each parameter is allowed a percentage of expected error due to human error during laboratory analysis.*

Parameter	Unit	0403	0404	0405	0406	% expected error
Turbidity	FNU	32.00	23.00	46.00	17.00	+/– 10%
Smell strength		normal	normal	normal	weak	
Smell type		moss	moss	moss	mold	
Color		25.00	20.00	45	40.00	+/– 15%
COD	mg/L	4.10	3.50	3.40	3.40	+/– 15%
Conductivity at 25°C	mS/m	78.80	79.50	80.10	84.10	+/– 10%
pH at 25°C		7.90	8.00	7.70	7.80	+/– 10%
Temp	°C	18.00	19.00	19.00	19.00	
Alkalinity (HCO_3)	mg/L	350.00	350.00	360.00	380.00	+/– 10%
Hardness	°dH	23.00	25.00	23.00	25.00	
$Ca^{(2+)}$	mg/L	150.00	160.00	150.00	160.00	+/– 10%
$Mg^{(2+)}$	mg/L	11.00	10.00	11.00	11.00	+/– 10%
$Na^{(+)}$	mg/L	24.00	23.00	25.00	26.00	+/– 20%
$K^{(+)}$	mg/L	3.00	3.00	4.00	9.00	+/– 10%
Fe	mg/L	3.40	2.60	11.00	1.90	+/– 15%
$Mn^{(2+)}$	mg/L	0.16	0.14	0.27	0.23	+/– 10%
$Cu^{(2+)}$	mg/L	<0.01	<0.01	<0.01	<0.01	+/– 10%
$Al^{(3+)}$	mg/L	0.10	0.10	0.06	0.02	+/– 15%
NH_4-N	mg/L	0.04	0.12	0.57	0.81	+/– 20%
$NH_4^{(+)}$	mg/L	0.05	0.15	0.73	1.00	+/– 20%
NO_3-N	mg/L	1.50	1.50	1.80	2.40	+/– 20%
$NO_3^{(-)}$	mg/L	6.60	6.60	8.00	11.00	+/– 20%
NO_2-N	mg/L	0.019	0.026	0.07	0.09	+/– 20%
$NO_2^{(2-)}$	mg/L	0.062	0.085	0.230	0.280	+/– 20%
PO_4-P	mg/L	0.024	0.013	0.06	0.09	+/– 20%
$PO_4^{(3-)}$	mg/L	0.070	0.040	0.19	0.26	+/– 20%
$F^{(-)}$	mg/L	0.240	0.230	0.20	0.21	+/– 20%
$Cl^{(-)}$	mg/L	37.00	36.00	37.00	40.00	+/– 15%
$SO_4^{(2-)}$	mg/L	78.00	78.00	72.00	68.00	+/– 15%

According to Nagpal, (1993) the six main PAHs (i.e. fluoranthene, benzo[a]pyrene, benzo[g,h,i]perylene, benzo[b]fluoranthene, benzo[k]fluoranthene, and indeno[1,2,3-cd]pyrene) should have a sum of concentrations no larger than 0.2 µg/L. Point 0401 has a concentration of 0.15 µg/L while point 0402 has a total concentration of 0.523 µg/L. Therefore, point 0402 has a PAH limit above the allowable concentration in groundwater. Concentrations over the recommended 0.2 µg/L create a lifetime cancer risk level of 1/100 000 (Nagpal, 1993).

Lackalänga groundwater chemistry

Accuracy of analysis

The results from well 0403 in Lackalänga showed a 6.17 % error, well 0404 had an 8.25 % error, well 0405 had 6.3 % and results from the outlet at point 0406 had 7.76 % error. These percentages are low enough for the ion concentrations in the results to be considered correct with little deviances from actual concentrations.

Groundwater ions

Table 6 shows the results from the groundwater in the culvert in Lackalänga and include physical chemical parameters from the groundwater at wells 0403, 0404, 0405 and 0406. These results show nitrate concentrations between 6 mg/L and 11 mg/L, which are quite normal and indicate an oxidized environment. However, the nitrate steadily increases in the downstream direction, which seems unusual for groundwater where the opposite might be expected. The landfill area is also very near to farmland, so the nitrate levels may be influenced by nitrogen-rich pesticides. In fact, the highest increase in nitrate occurs between well 0405 in the landfill and the outlet at 0406. A wheat field lies between the landfill and the outlet, which may be the contributor to nitrate.

Ammonium levels increase from 0.05 mg/L upstream to 1 mg/L downstream. Groundwater standards require ammonium levels to be below 0.5 mg/L. The ammonium level recorded at the landfill indicates reduced conditions since it has a value of 0.73 mg/L. However, the high ammonium downstream is not attributed to the landfill. In fact, ammonium is a component of fertilizer and leaches rather easily through aquifers since it does not exchange with other ions. Therefore, the high ammonium at the outlet at point 0406 is most likely to leaching of fertilizers from nearby farms.

Total iron concentrations are higher than 1 mg/L, perhaps due to reduction of iron hydroxide. The high iron indicates that the groundwater is in a reduced state according to groundwater standards (Townsend *et al.,* 1999; SWEDAC, 1994). This conclusion contradicts the oxidized conditions indicated by the nitrate; therefore, there might be two types of groundwater combining in the culvert. The oxidized water may come from the watershed upstream while the reduced water most likely infiltrates down from the landfill. Point 0405 shows a total iron concentration of 11 mg/L. This is a bit remarkable considering the other points show much lower concentrations, especially downstream, which has an iron concentration of 1.9 mg/L.

There are two possible explanations for the high iron concentration. First, leachate from the landfill may be contributing a high amount of iron (II) at this location. When the iron-rich leachate mixes with the oxidized groundwater, iron (II) is converted into iron (III), taking the form of solid sludge at the bottom of the culvert and reducing the total iron concentration in the water downstream. However, if this were the case and leachate were contributing a high amount of iron (II), then one would expect to see high contributions of alkalinity, ammonium and chloride at the same point, all of which are typical to leachate.

According to table 6, all three parameters at point 0405 increases in concentration, but none are significant enough to be contributed to leachate. Furthermore, downstream concentrations in all three subjects are even higher than at point 0405. Therefore, it is unlikely that the high iron concentration at point 0405 is solely due to leachate. A second explanation is that during sampling, sludge high in iron (III) may have been scraped up from the bottom of the culvert during sampling, creating a high iron concentration in the results. Since the second explanation is more credible than the first, the iron concentration at point 0405 is therefore disregarded and considered an error.

The alkalinity is rather high in all wells, which is most likely due to weathering of calcite. This is confirmed by the high concentrations of calcium at each well. The pH remains between 7.7 and 8 throughout the groundwater and is most likely buffered by calcite as it dissolves.

Sulfate levels in the groundwater are all rather high at each well at concentrations between 68 and 78 mg/L. This also contradicts the reduced conditions that are indicated by the high iron (II) levels yet confirms that there are two different sources of groundwater infiltrating into the culvert. Therefore, the groundwater at the Lackalänga landfill is reduced by the leachate but with slightly oxidized properties caused by mixing with uncontaminated groundwater.

Chemical oxygen demand (COD) is low at each well in Lackalänga. This explains the small amount of deviation between reduced and oxidized species at each well. A low COD level indicates a low amount of oxygen needed by organic carbon, which means the organic substance in the water is low. It makes sense that COD levels in the culvert are low since the water is not in the presence of an aquifer with soils where organic materials often lie. The lack of oxygen demand explains the presence of nitrate and sulfate and only minor reduced species in the groundwater.

Groundwater minerals

The minerals with SI values greater than zero are those which are theoretically precipitated in the groundwater and are the same in all four wells (See table 7).

The groundwater minerals found in the groundwater are common at each point. Calcite, dolomite and siderite are common carbonates found in southwestern Scania. Calcite might be the most common due to the presence of the limestone bedrock, which due to mechanical and chemical weathering produces the calcite mineral.

As calcite dissolution takes place calcium and bicarbonate ions are produced and the bicarbonate anions readily accept the free hydrogen cations, which buffers the water as long as the calcite is still in precipitated form and continues to dissolve.

Gibbsite ($Al(OH)_3$) is a hard to dissolve mineral that and is commonly found in clay. It often precipitates at

Table 7. *Hydrochemical characteristics of the aquifer at the Lackalänga landfill.*

Mineral	Formula	Saturation Index			
		0403	0404	0405	0406
Calcite	$CaCO_3$	0.97	1.11	0.8	0.95
Dolomite	$CaMg(CO_3)_2$	1.07	1.28	0.73	1.01
Gibbsite	$Al(OH)_3$	1.52	1.37	1.44	0.87
Hydroxyapatite	$Ca_5(PO_4)3OH$	2.56	2.42	3.04	4.05
Siderite	$FeCO_3$	1.42	1.39	1.77	1.11

pH values around 3 and buffers water to pH values near 4 (Fransson, 2004). The groundwater shows low amounts of aluminum, which is most likely because gibbsite is precipitating.

Hydroxyapatite is an inorganic mineral that is produced by a chemical reaction between calcium phosphate and water (Miller, 2004). Hydroxyapatite is in fact a helpful mineral to have in an aquifer where high amounts of lead are present. This is because it dissociates to produce free phosphate which attaches to lead to create insoluble lead phosphate, thus immobilizing the lead in groundwater (Whitlock, 1995).

Siderite is an iron ore that is commonly found in groundwater with traces of iron. Iron carbonate typically forms in groundwater with high bicarbonate concentrations (Descostes *et al.*, 2002).

Heavy metals and xenobiotic organic compounds

In table 5, concentrations of heavy metals and xenobiotic organic compounds (XOCs) at wells 0404 and 0405 in Lackalänga are presented. These results show slight increases in some heavy metal concentrations from point 0404 and 0405, however, they are rather low thus not a threat to the groundwater. The XOC concentrations are also minimal and thus pose little to threat to the groundwater in the area. The Swedish Environmental Protection Agency has standards regarding maximum concentrations of contaminants in groundwater that should be allowed for human consumption. The main criteria that the SEPA focuses on when assessing groundwater quality is alkalinity, pH, nitrogen, chloride, redox conditions and metals. A risk assessment is not only required to examine the groundwater quality, but also the potential or current impact on receiving waters. Therefore, the amount of groundwater flow is calculated at each landfill in order to estimate the amount of water the landfills contribute and in what time frame. The risk assessment will be performed by calculating the percentage of yearly leachate flow of each landfill and comparing it with the yearly flow of the river to see what percentage of contaminants the leachate contributes. Groundwater flow in the Måsängen aquifer is calculated as:

$$Q = K * A * dh/dl$$

Q is measured in m^3/s, K is the hydraulic conductivity of the groundwater as it flows through the aquifer, A is the cross sectional area of flow and dh/dl is the hydraulic gradient of the groundwater in the aquifer. The percentage of leachate contribution in the form of groundwater should be weighed along with the groundwater quality in order to determine if the abandoned landfill is indeed a threat to the local water sources.

The parameters for the flow in the aquifer are already known and have been previously explained in tables 2 and 3. In Måsängen the hydraulic conductivity is estimated as the higher value of $7 \cdot 10^{-4}$ cm/s, while the cross sectional flow area is about 480 m^2 and the gradient is 0.015. Therefore the average groundwater flow through the Måsängen landfill is about 0.0001 m^3/s. The distance of groundwater travel through the recharge area is 100 meters. Thus, the time it takes for groundwater to flow through the entire recharge area until the Kävlinge River can then be calculated at about 3 years.

In Lackalänga the hydraulic conductivity is estimated as the higher value of $1 \cdot 10^{-3}$ cm/s, while the cross sectional area of flow is about 8400 m^2 and the gradient is estimated as the higher value of 0.017. The average groundwater flow through the Lackalänga landfill is about 0.001 m^3/s. The distance for groundwater flow from the outskirts of the recharge area until the end of the underground culvert ranges from about 2000 meters from the shortest distance west to east, to about 2800 meters from northwest to southeast. Therefore, the time it will take the groundwater to travel through the recharge area ranges from 80–110 years.

The average flow of the Kävlinge River is about 11.3 m^3/s (VBB, 1997). This value was taken about 5 km downstream from the Måsängen landfill, where the river does not have the exact same flow or dimensions as at the landfill area. Therefore, the average flow can be assumed to have about a 10–15 % error, which creates an average flow within the interval of 9.6 and 13 m^3/s. With this information, the percentage of groundwater contributed by the Måsängen landfill is between 0.001 % and 0.0008 %. Since the difference between these values is small, 0.001 % will be used as the contribution by the Måsängen landfill to the Kävlinge River.

According to the groundwater flow through the Lackalänga landfill the percentage of contribution to the Kävlinge River is between 0.01 % and 0.007 %. For estimating purposes, 0.01 % will be used as the value representing addition of flow by the Lackalänga landfill. The values for all the previous calculations are listed in Table 8.

Table 8. *Risk evaluation parameters.*

	Recharge area	GW flow	Time to flow recharge area	Contribution to Kävlinge River
Måsängen	1.5 ha	0.0001 m^3/s	5.5 months	0.001%
Lackalänga	290 ha	0.001 m^3/s	6 – 9 years	0.01%

Table 9. *Contribution of Måsängen landfill contaminants to Kävlinge River with a dilution factor of 100 000.*

Parameter	Unit	Contribution to river
COD	mg/L	0.01
Fe	mg/L	0.000001
$Mn^{(2+)}$	mg/L	0.00003
$NH_4^{(+)}$	mg/L	0.00003
$NO_3^{(-)}$	mg/L	0.000001
$PO_4^{(3-)}$	mg/L	0.001
$SO_4^{(2-)}$	mg/L	0.0002
$Cl^{(-)}$	mg/L	0.0007
Total N	mg/L	0.00002

According to a sensitivity analysis the groundwater flow values are not highly affected by changing values of parameters. If the hydraulic conductivity in the aquifer of either landfill were to increase or decrease, it would have little effect on the amount of flow. The same goes for the gradient and the cross sectional area since if the height of the groundwater table were to increase in either landfill aquifer it would have a slight but not significant effect on the flow. The most important factor in this evaluation is that even if the groundwater flow were to increase at either landfill, the contribution to the Kävlinge River would still be rather low since the flow of the river will always be much higher. An estimated highest contribution of flow either landfill aquifer would be about 1 % assuming the river had a low flow period and all the aquifer parameters were at a maximum.

The leachate-contaminated groundwater in Måsängen contributes about 0.001 % of the flow in the Kävlinge River. The leachate is thus diluted about 100 000 times when it enters the Kävlinge River.

The main diluted concentrations of the major contaminating species in the landfill are shown in table 9 and reveal that the species that show the most potential for contamination of the Kävlinge River are COD and phosphate. However, their diluted concentrations are not high enough to be considered a threat to the Kävlinge River. Phosphate concentrations higher than 0.03 mg/L can trigger algae blooms in water (NCSU, 1976). The phosphate concentration in the river will increase by only 0.001 mg/L due to flow from Måsängen, which is not high enough to help sustain algae levels in the river.

PAH concentrations are higher than recommended, however, yet a 1/100 000 cancer risk is not very high, and is only accurate if it is consumed daily in drinking water. Since the groundwater at Lackalänga is not consumed and is diluted in the Kävlinge River, thus the PAHs are not hazardous.

Table 10. *Changes in concentration between upstream species at point 0403 and downstream species at point 0406.*

Parameter	Unit	Change in concentration
pH		–0.10
COD	mg/L	–0.70
Alkalinity (HCO_3)	mg/L	30.00
$Ca^{(2+)}$	mg/L	10.00
$Mg^{(2+)}$	mg/L	0.00
$Na^{(+)}$	mg/L	2.00
$K^{(+)}$	mg/L	6.00
$Fe^{(2+)}$	mg/L	–1.50
$Mn^{(2+)}$	mg/L	0.07
$Al^{(3+)}$	mg/L	–0.08
NH_4-N	mg/L	0.77
$NH_4^{(+)}$	mg/L	0.95
NO_3-N	mg/L	0.90
$NO_3^{(-)}$	mg/L	4.40
NO_2-N	mg/L	0.07
$NO_2^{(2-)}$	mg/L	0.22
PO_4-P	mg/L	0.06
$PO_4^{(3-)}$	mg/L	0.19
$F^{(-)}$	mg/L	–0.03
$Cl^{(-)}$	mg/L	3.00
$SO_4^{(2-)}$	mg/L	–10.00

Table 10 shows the changes in concentration between the upstream groundwater at point 0403 in Lackalänga and the groundwater at the outlet at point 0406. The small changes in concentration indicate that the leachate from the landfill is not contributing significant amounts of leachate to the groundwater. No risk is associated with neither the groundwater quality nor the addition of leachate from the landfill.

The rate of degradation of the contaminants in an aquifer is not only highly dependent on the amount of oxygen that is available, but also on the temperature of the soil, moisture content and transport velocity of materials. The COD levels in the Måsängen aquifer are very high, especially considering that the landfill has had 50 years to decompose. The COD level of 3100 mg/L is within the range of that found in typical landfill leachate. However, due to a low hydraulic conductivity and much lower flow rate in the aquifer compared to the Kävlinge River, the contaminant concentrations are diluted enough to make little impact on the river quality.

The hydraulic conductivity of both aquifers is low and the temperature is very cold during winters, which inhibits degradation reactions and slows down groundwater flow. Therefore, it may take many years for the contaminants to completely degrade. Fortunately, the groundwater flows in both aquifers are slow enough that

Table 11. *Contribution of Lackalänga recharge area contaminants to Kävlinge River with a dilution factor of 100 000.*

Parameter	Unit	Contribution to river
COD	mg/L	0.0003
Fe	mg/L	0.0002
$Mn^{(2+)}$	mg/L	0.00002
$NH_4^{(+)}$	mg/L	0.0001
$NO_3^{(-)}$	mg/L	0.001
$PO_4^{(3-)}$	mg/L	0.00003
$SO_4^{(2-)}$	mg/L	0.01
$Cl^{(-)}$	mg/L	0.004
Total N	mg/L	0.0003

the contaminants will not be presented to the Kävlinge River in high amounts at a time.

The groundwater at the abandoned landfill in Måsängen shows high levels of reducing agents such as ammonium, iron(II) and manganese(II). It also shows very low levels of the oxidizing agents sulfate and nitrate. The groundwater in the abandoned landfill is reduced. Other parameters indicate other types of contamination such as very high COD and phosphate levels, which may be harmful to the quality and aquatic life in receiving waters. However, a risk assessment concluded that the amount of leachate-contaminated groundwater contributes to only 0.001% of the total flow of the Kävlinge River. Therefore, all species in the groundwater are diluted by 100 000. After dilution, the species which seemed to pose a risk for contamination were diluted enough that their additions do not affect the quality of the Kävlinge River.

The groundwater at Lackalänga is a mixture of reduced and oxidized waters. It contains iron and ammonium levels which are high enough for the water to be considered reduced, but their concentrations are not so much higher than the Swedish groundwater standards. Sulfate and nitrate are also present in levels indicating oxidized conditions. The alkalinity is high, which is good for receiving waters in order to maintain the pH. Chloride and phosphate levels are also normal and COD levels are low according to Swedish standards. The results showed that there were not significant increases in reduced species in the samples taken at the Lackalänga landfill compared to upstream and downstream samples outside of the landfill. The landfill therefore concluded to provide only small additions of contaminants to the groundwater. Increases in certain concentrations such as nitrate, phosphate and ammonium may instead be due to local fertilizers. The flow of groundwater from the Lackalänga aquifer adds only 0.01% of the total Kävlinge River flow. All concentrations from the groundwater samples were thus diluted by 10 000. This dilution creates very little increase in contaminant concentrations to the Kävlinge River. Leachate from the Lackalänga landfill therefore is not a contaminating risk to the groundwater.

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Artiklar kan skrivas på skandinaviskt språk eller på engelska.

Alla artiklar ska ha abstract på engelska. Artiklar på skandinaviskt språk ska dessutom ha sammanfattning på samma språk som artikeln. Abstract och sammanfattning ska vardera omfatta högst 200 ord.

En lista med högst 10 key words bifogas artikeln.

Ange dignitet på rubriker, men minimera i övrigt layout.

Referenser ordnas alfabetiskt och skrivs enligt exempel:

Lindholm, T. & Ohman, P., 1996. Some advantages of studying living phytoplancton. Vatten 52:1, 9–14.

Författare erhåller särtryck av artikeln i form av pdf-fil utan kostnad.

Antagna artiklar får ej publiceras i annan tidskrift utan redaktionens medgivande.

Utförlig instruktion för författare

- Se www.foreningenvatten.se (under »Verksamheten/Tidskriften VATTEN»)
- Kan även erhållas från redaktionen.