ORIGINAL ARTICLE

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Tracing leachates at waste sites using geophysical and geochemical modelling

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Abstract Tracing leachates at landfills is usually carried out using either geophysical methods or chemical analyses of groundwater. There are often problems with fingerprinting pollution sources or clarifying the spreading pattern due to a wide variety of possibilities giving similar anomalies. The aims of the project were to evaluate the advantages of combining results from multigeophysical modelling and statistical/chemical modelling in order to identify pollution sources and the spreading pattern and to test a new technique for chemical fingerprinting. The project was carried out at a landfill in central Sweden using geophysical measurements and modelling of CVES, GPR and VLF as well as chemical modelling using M3 (multivariate mixing and mass balance calculations). The results indicate that by combining geophysical modelling and chemical calculations, the possibilities of fingerprinting the origin of pollution as well as delineating the spreading pattern are significantly increased.

Keywords Landfill · Groundwater · Geophysics · Modelling · PCA · Pollution

Introduction

Pollution from landfills is a serious environmental problem. In Sweden, more than 300 active landfills exist, while more than 4,000 old, abandoned landfills are registered (SEPA 1994). Many of these landfills are of a composite type with a mixture of household and industrial waste. Most of the abandoned landfills are left without monitoring of the surrounding groundwater quality or other monitoring systems, albeit some of them may pose a serious threat to the environment. Several of the recently closed waste deposits and most of the active landfills are subjected to regular water sampling of groundwater and surface water. However, many of the abandoned landfills were constructed several decades ago and were located directly on the original land surface without liners or drainage layers, and today they are often left without protection measures. Although the waste has been covered with compacted soils and vari-

ous types of liners, production of leachate will still continue to some extent, due to a humid cold climate in Sweden. Leachates from composite landfills usually have a strongly varying composition, which depends on the waste content, the age and the redox conditions (Chian and deWalle 1976). The life of a landfill with organic compounds usually comprises several stages, such as the acid and the methane stages, due to the bacterial processes involved. Various parts of a landfill can be in different stages, producing different compositions of the leachates (Bozkurt 1998). However, most composite landfills produce a leachate rich in chloride since chloride ions usually follow the water flow. Therefore, analyses of chloride and conductivity are among the most common chemical analyses in the monitoring programmes of the surrounding groundwater and surface water. Since the chloride ions significantly increase the conductivity of groundwater, indirect measurement techniques using geophysical methods have often been

used in Sweden and elsewhere for tracing leakage (e.g. Kelly and Asce 1977; Barker et al. 1990; Olofsson and Fleetwood 1994; Walraevens et al. 1997; Bernstone and Dahlin 1998; Aaltonen 2001). However, the natural variations of resistivity in the Swedish terrain are more than 10^4 (Aaltonen and Olofsson 2001). Thus, a low resistivity of the ground, detected by geoelectrical measurements, cannot be strictly related to leachates if there are no long-term monitoring measurements carried out pointing towards an increasing plume. Resistivity methods are still not commonly used in long-term monitoring programmes at landfills, although some examples exist in literature (Benson et al. 1988; Osiensky 1995; Aaltonen and Olofsson 2001). There are also several other sources of groundwater composition, many of them natural, which significantly change the electrolytic characteristics of the groundwater. These may include fossil seawater from previous stages after the last glaciation period when salt and brackish water covered parts of the Nordic countries, de-icing road salt used on major roads in Sweden, impact from sewage water and the recent intrusion of seawater in coastal areas (Fabricius and Olofsson 1996). Therefore, in order to identify any impact on groundwater from landfills, the geophysical measurements must preferably be combined with other information, providing sound geological and hydrogeological knowledge of the area studied and analyses of groundwater chemistry enabling a fingerprinting technique pointing towards the specific source of salinity. Combining DC resistivity measurements and

other geophysical techniques, such as ground penetrating radar (GPR) and electromagnetic measurements (EM), may improve the knowledge of the stratigraphy and composition of the soils enabling better mapping of contaminated sites (McNeill 1990; Nobes 1996; Aaltonen 2000, 2001) and increasing the possibilities for a separation between the natural and man-made variations in the measured geoelectrical properties. Chemical analyses have often been used at polluted sites for a comparison to geophysical anomalies. The components may either be naturally resistive, such as oil pollution (Mazac et al. 1989; Atekwana et al. 2000), or highly conductive, such as liquid wastes including salts and metals (Stierman 1984; White et al. 1984).

At Tveta waste site, today a modern recycling plant situated a few kilometres southwest of Södertälje, increased salinity was recognized in some monitoring wells during the 1990s. The wells are located between the landfill, which in this area consists mainly of an ash pile from the Igelstaverket power plant in Södertälje, central Sweden, and a major road on which a considerable amount of de-icing salt is used during winter (Fig. 1). No increased salinity was measured in wells between the high salinity area and the ash pile. The area is located below the highest marine shoreline (HS) after the last glaciation period, hence fossil seawater frequently exists in valleys, especially in areas covered with marine clays. Since the area is located far from the coastline, recent intrusion of seawater was excluded as a possible source of salinity. The main purpose of this project was to
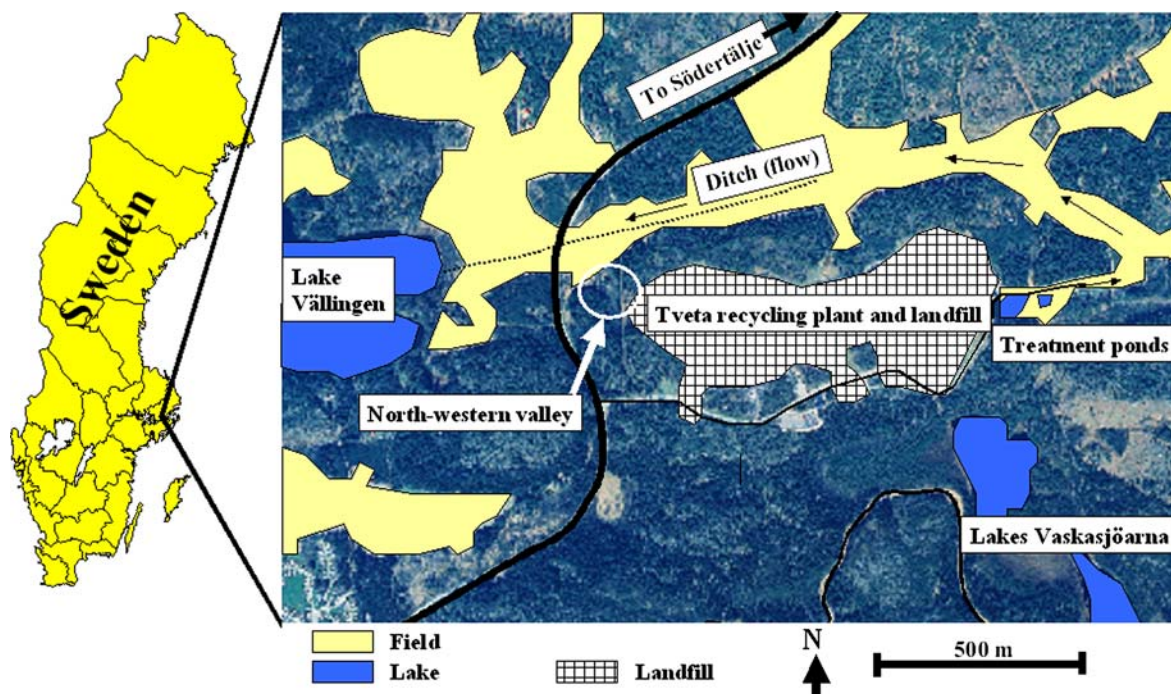

Fig. 1 The location of Tveta landfill

develop and test a combination of geophysical and geochemical/statistical modelling, in order to identify the source of salinity and the spreading pattern. The Tveta landfill was chosen for the study because there were several possible sources of salinity and because of the rather complex geological conditions present.

Site description

Tveta recycling plant is located in central eastern Sweden (Fig. 1). It is situated in a topographically undulating terrain consisting of outcrops of sedimentary gneiss and leptite gneiss at elevated areas. On the slopes of the hills, glacial till, mainly of a sandy–silty type, is deposited, which is covered with medium thick to thick layers (3–10 m) of glacial clay in the valleys (Möller and Stålhös 1969; Fig. 2). The landfill was originally located mainly on the clay in a marked valley, but the waste is now filling most of the valley and partly resting on till and hard rock. The natural drainage from most parts of the deposit is in an eastward direction, where a treatment plant is located. Finally, the leakage water enters a system of ponds before it is used for irrigation of the vegetation east of the deposit.

This study is concentrated to the northwestern part of the landfill. The affected monitoring wells are located in a minor valley stretching in northwest–southeast orientation. Geophysical measurements using very low frequency (VLF) have previously been carried out along a number of transects in the area. The results indicated a conductive steeply inclined zone with an east–west orientation, stretching along the main valley beneath the landfill. An 80 m deep borehole was therefore previously constructed between the deposit and the major road in order to investigate this zone. The clayey soils at the drilling site were approximately 5 m thick, with 0.5 m till, covering a fairly compact gneissic rock. Hydraulic fracturing was necessary in order to increase the water flow to the borehole; otherwise the borehole would have remained dry. The borehole water indicated increased salinity with an unclear origin. A map showing the main features and monitoring sites is presented in Fig. 3.

Methods

The geophysical part of the project aimed to clarify the geology and stratigraphy of the area and to delineate the extent of the high conductive area. The geophysical survey consisted of GPR measurements, VLF measurements and electrical resistivity. GPR measurements were made in transects through the area in order to define the stratigraphy and the depth to the bedrock surface. Measurements were performed using PulseEkko IV (Sensor & Softwares Inc.) system with an antenna

Fig. 2 Geological map of the Tveta area (modified after Möller and Stålhös 1969; Stålhös 1969)
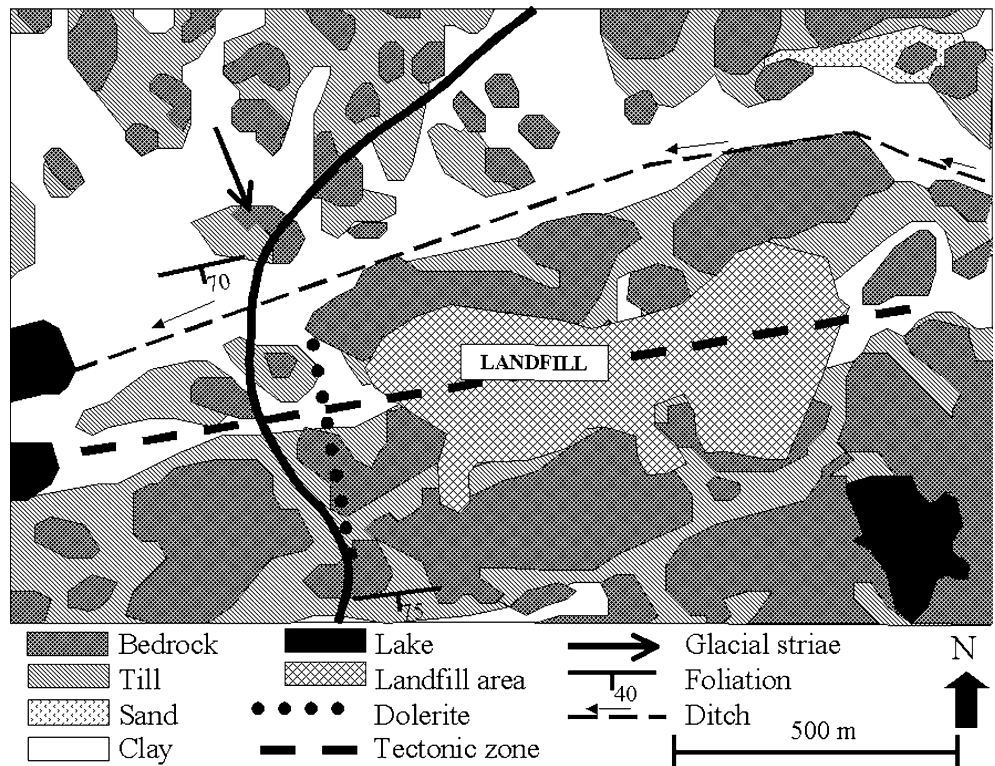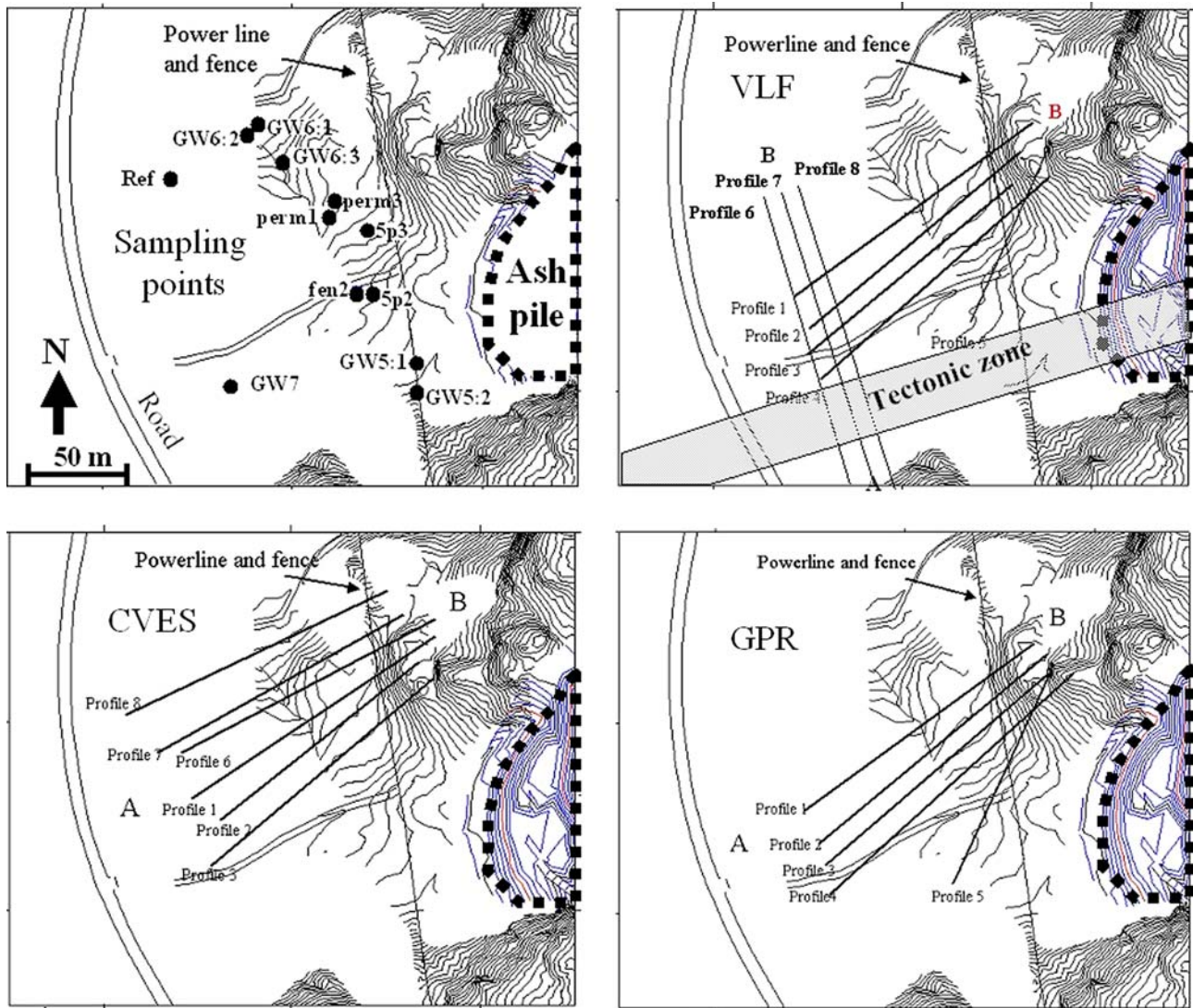
Fig. 3 Map showing the northwestern valley at Tveta, the measurement lines and the water sampling sites

frequency of 100 MHz. Data analysis was carried out using the programme PEIV and 2D interpretations were further processed in the software DIGIRAD, developed at KTH. This programme was used for depth and velocity corrections among the layers, which were statistically interpolated to 3D pseudosections using a kriging technique and finally presented in the programme SURFER. VLF measurements were carried out in transects perpendicular to the northwestern valley and the east-western valley, with the aim to identify steeply inclined conductive structures, which could be important for groundwater flow in the bedrock. The instrument used was a WADI from ABEM Inc. and the results were processed using the programme SECTOR, with filter designed by Karous and Hjelt (ABEM 1989). In total,

eight profiles were carried out, five of them in the northwestern valley and three perpendicular to the presumed fracture zone stretching in an east–west orientation beneath the waste deposit (Fig. 3). Resistivity measurements were carried out using a continuous vertical electrical sounding (CVES multielectrode) system along six parallel profiles in a Wenner array in the area. The instrument was SAS1000 and LUND Imaging System, provided by ABEM Inc. Inversion was made using programme Res2Dinv (Loke 2001) in order to determine a 2D resistivity model. The 2D results were used to construct a pseudo-3D model of the ground resistivity by solid modelling in RockWorks2002. All measured profiles from the geophysical investigations are shown in Fig. 3.

Chemical sampling was carried out in groundwater observation wells in the area, in surface water from ditches and from the nearby lake Vällingen, which is also used for municipal water supply. In addition, water samples were taken from leachates at the deposit. Comparable water analyses were collected from some deep-drilled wells affected by fossil seawater in the region, from Baltic seawater, from precipitation as well as from de-icing salt solution used on roads in eastern Sweden. The major ions, including Mg^{2+}, Ca^{2+}, Na^+, K^+, NH_4^+, SO_4^{2-}, NO_3^-, HCO_3^-, Cl^-, Br^-, F^-, COD, pH, hardness and conductivity were analysed, as well as a large amount of metals in the leachates and in the groundwater samples. The chemical analyses were studied using ion ratios, based largely on the assumption that the major chemical processes are true mixing and ion exchange. A statistical/chemical programme, M3 (multivariate mixing and mass balance calculations), developed by SKB (Swedish Nuclear Fuel and Waste Management Co.) was applied. The method is based on principal component analyses (PCA), which was developed 100 years ago (Pearson 1901). The M3 model was originally developed to analyse the mixing ratio between different waters in deep drillholes and leakage water at the hard rock laboratory at Äspö, Southern Sweden (Laaksoharju et al. 1999). The specific aims of the chemical studies were to identify the source of the increased salinity in groundwater and, if possible, to clarify the mixing proportions.

Results

VLF measurements

The VLF measurements across the presumed east–west orientated fracture zone indicated one or several parallel anomalies. The real and imaginary parts showed a rather shallow or highly conductive zone (Fig. 4). The profiles across the northwestern valley also indicated a possible zone along the western part of the valley. However, the eastern parts of the profiles were disturbed by a power line and could not be used for further analysis.

GPR measurements

An example of 2D interpretation of radar data is given in Fig. 5. Clay and silt exist as the upper layer, several meters thick, in part of the northwestern orientated valley. Due to a boulder-rich till on top of a fractured rock surface, it was rather difficult to identify the bedrock surface. Variation of soil thickness, based on manual interpretation of radargrams and statistical analyses using kriging, is shown in Fig. 5. The thickness of soils varies between 0 and 5 m and the bedrock surface is strongly undulating with a marked depression along the northwestern valley.

Fig. 4 Filtered curves at a depth of 5 and 20 m, respectively, showing the real part of VLF profiles across the presumed fracture zone, orientated in an east–west direction
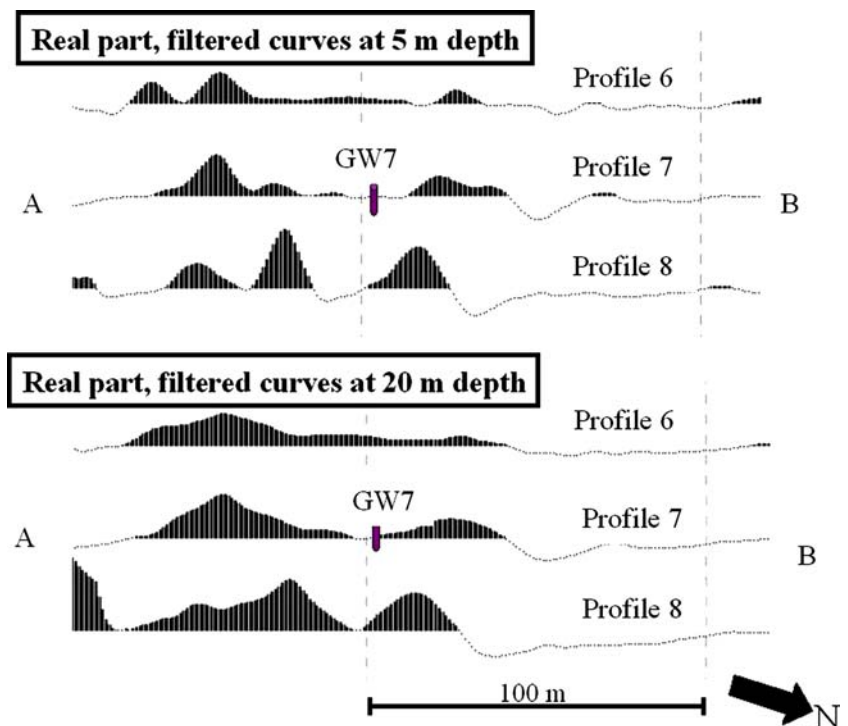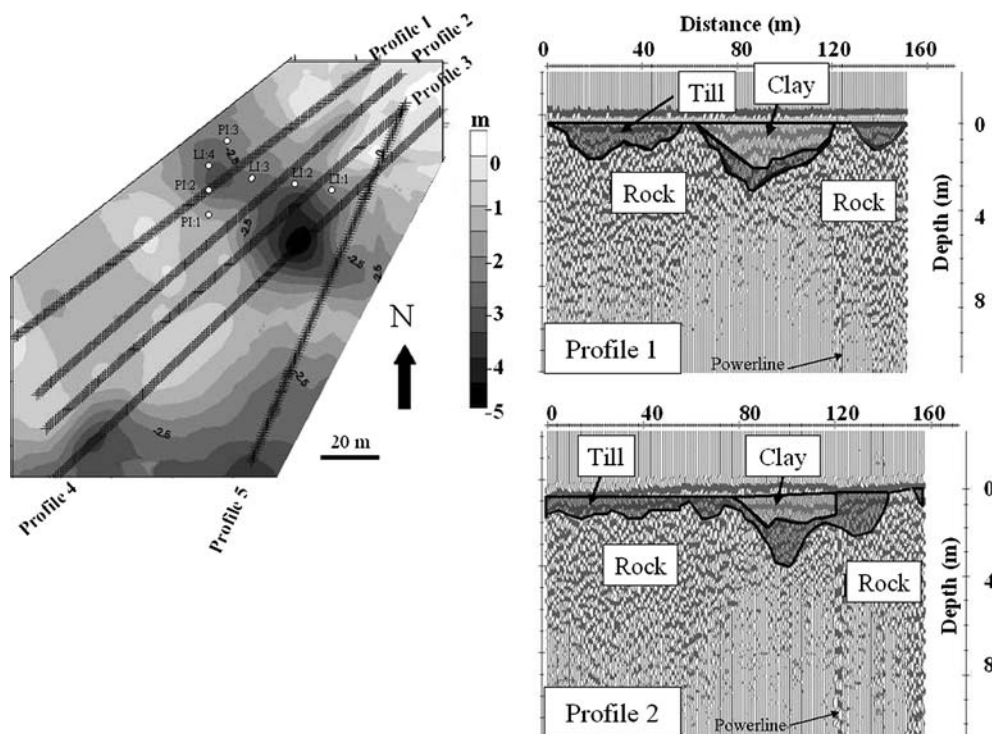
Fig. 5 Interpretation from GPR measurements in the northwestern valley and estimated depth (metre) to bedrock surface using a kriging technique

Electrical resistivity

Inverse modelling of resistivity data showed that low resistivity zones exist in all profiles. Zones with resistivities below 30 Ω m occur at depths between 5 and 20 m below the surface. A low resistivity horizon is observed in the shallow bedrock or deepest till-layer in the eastern central part of the valley. The lowest resistivity values occur furthest away from the ash pile (Fig. 6). The 2D results were interpolated and extrapolated using inverse distance solid modelling into a pseudo-3D vizualization. Zones of extremely low resistivity values (< 10 Ω m) are presented in Fig. 6. Horizontal slicing of the pseudo-3D model at a level approximately at the bottom of the valley, as well as 12 m below the valley bottom, indicates that the low resistivity zones are more prevailing in the till along the bedrock surface and the superficial fractured part of the bedrock, than at the surface, where clay is the predominant soil.

Chemical analyses

Some of the groundwater observation wells (GW6:1–3) indicate a significant increase of the chloride content at the end of 1990s. Many of the components, such as total nitrogenous, indicate low values. The contents of metals are low or very low. However, the content of chloride varies significantly from less than 10 mg/L in wells located close to the landfill (GW5) to more than 500 mg/ L at the wells furthest away from the deposit (GW6). The distribution of chloride in the east–west orientated valley is shown in Fig. 7. A summary of results is presented in Table 1 and some analyses of ion ratios are shown in Fig. 8. A plot of the ratio Mg^{2+}/Cl^- versus Na^+/Cl^- indicates that the groundwater samples stretch along a line towards leachate water LW3, whereas the drilled well GW7 falls in the area of seawater (fossil and recent) (Fig. 8).

The results from the M3 model are presented in Fig. 9. Seven and nine components have been used in the calculations, which give similar results. The nine components used were chloride, sulphate, nitrogen, fluoride, bromide, sodium, potassium, magnesium and calcium. Extreme waters (end members) are represented by precipitation, some fossil seawater from Lake Mälaren region, leachates from the landfill and Baltic seawater. Waters from Lake Vällingen fall very close to precipitation. Some of the groundwater samples, such as the reference well (Ref.) and GW2, stretch along a mixing line from precipitation towards fossil seawater (Fig. 9). These samples have very low chloride content. GW2, located east of the waste deposit, represents an artesian well. Groundwater from wells GW6:1 and GW6:2 fall very close to the leachate sample (LW3). The groundwater sample GW6:3 has a lower chloride content (70–120 mg Cl/L) compared to GW6:1 and GW6:2 (300–690 mg Cl/L) and falls between precipitation and LW3. The samples from wells GW5:1 and GW5:2
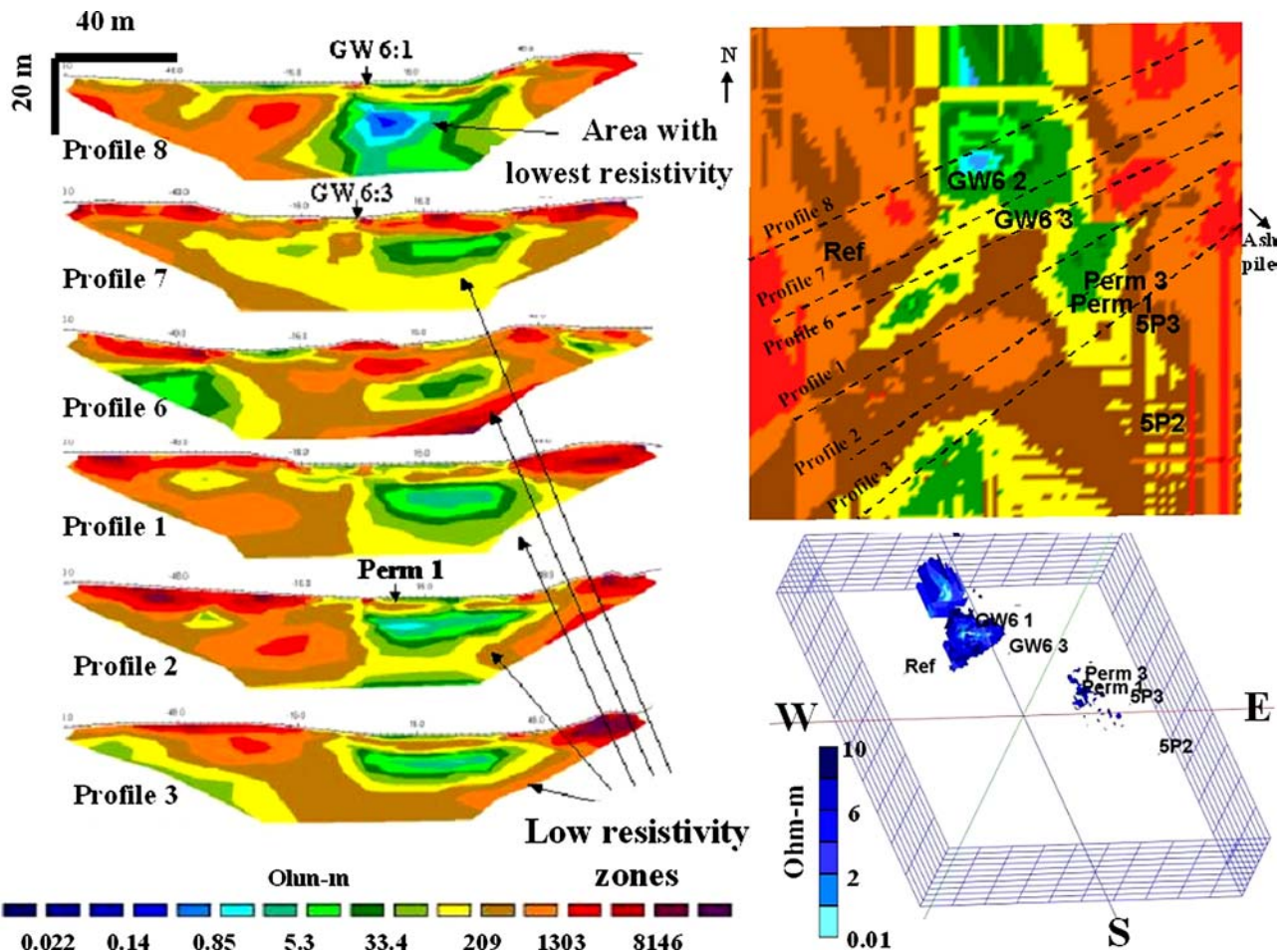
Fig. 6 Results from inverse modelling of resistivity profiles (*left*) were combined into a solid model and presented as low resistivity volumes (< 10 Ω m) (*lower right*). Horizontal slicing of the solid model at level + 28 m (approximately 12 m below the bottom of the valley) is shown in the *upper right* diagram

(named as GW5 in Fig. 9) represent low salinity wells and fall between precipitation and fossil seawater collected in the region, but with a slight attraction towards leachates. The drilled well, GW7, located in the presumed fracture zone west of the landfill, clearly falls within the samples of fossil seawater. Leachate collected from the eastern leachate pond LW1 fall close to leachate waters collected at the composite municipal waste deposit Högbytorp 30 km northwest of Stockholm.

Discussion

The combination of geophysical measurements provides a relatively consistent picture of the geological conditions. The soil thickness in the northwestern valley varies due to an undulating bedrock topography. Clayey and silty soils built up the top layers of the valley. GPR

measurements indicate that the maximum thickness of these sediments amounts to 5–7 m. This agrees with the geotechnical investigations carried out when the observation wells were constructed. There is a marked attenuation of the radar wave in the sediments, but not as distinct as it usually is in clay. Therefore, the sediments probably consist of layers and lenses of silt, also shown in the observation wells. Analysis of resistivity measurements reveals that the low resistivity zones occur at a depth between 5 and 12 m. GPR measurements show that these zones fall within till and the superficial fractured bedrock. Beneath these zones, the resistivity increases significantly downwards and the low resistivity values 0.1–20 Ω m cannot be simply explained by the geological conditions. Although the possibility that some graphites and pyrites exist in the bedrock is not excluded, the bedrock foliation in the area is subvertical and, hence, cannot explain the horizontal low resistivity zones. Therefore, the only plausible explanation is the
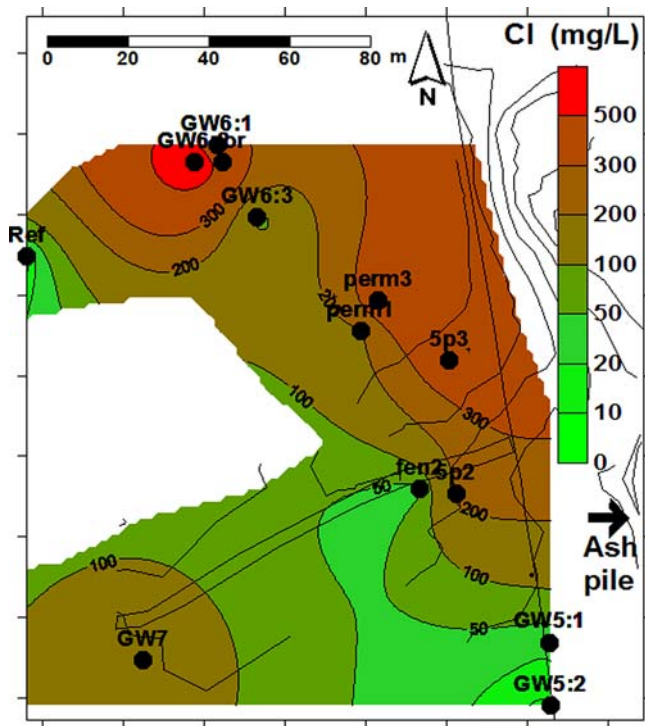
Fig. 7 Statistical distribution, using a kriging technique, of the chloride content (milligram/litre) in groundwater northwest of Tveta landfill. The *dots* represent sampling sites

existence of a highly conductive groundwater in the coarse till material and in the uppermost fractured part of the bedrock in the eastern part of the northwestern valley. Saline water (> 300 mg Cl/L) is also verified in the chemical sampling in some of the observation wells. It is probable that most of the saline water is found in the till on top of the bedrock surface. There are usually very different values of hydraulic conductivity and porosity between soil and rock in the recently glaciated Swedish terrain. Measurement values for soils are often 10–100 times higher than for rocks (Knutsson and Morfeldt 2002). Therefore, the crystalline bedrock, although superficially fractured, should have a much higher resistivity. Inverse modelling cannot fully represent the resistivity distribution at depth, due to the undulating bedrock topography and lack of horizontal strata. The combined interpretation of CVES and GPR measurements therefore gives a more realistic picture of the geological conditions.

There is no clear explanation for the low resistivity zones at depth in the western part of the northwestern valley, mainly identified in CVES profiles 3 and 6. There are no observation wells in the area and no water sampling has been possible. A minor and shallow conductive zone is recognised in the western half of the VLF profiles perpendicular to the northwestern valley, although the eastern part of the profiles is heavily disturbed by a

power line. A small depression in the bedrock topography is also shown in the GPR data in this area, which must be explained by either a more easily eroded rock type or a fracture zone. The clear disturbance in some of the radargrams favours either a steeply inclined fracture zone or a dolerite dike. Such dolerites exist in the surroundings and have been identified in the area during the geological mapping, stretching roughly in a northwest–southeast orientation (Stålhös 1969). It is not uncommon that the contraction of dolerites leads to an increased porosity in the contact zones between the dolerite and the surrounding host rock, locally increasing the hydraulic conductivity (Olofsson et al. 2001). Nevertheless, the low resistivity zones (< 50 Ω m) cannot be fully explained by mafic rocks. Instead, saline groundwater probably exists in the bedrock and the coarse till on top of the bedrock. Construction of a new observation well in this area is recommended.

The combination of results from the various geophysical measurements has clearly identified the distribution of low conductive volumes in the soil and the superficial bedrock, probably as a result of the electrolytic composition of the groundwater. Combining results from different geophysical techniques at landfills are nowadays rather common in literature, especially measurements of resistivity and conductivity (e.g. Walraevens et al. 1997; Bernstone and Dahlin 1998). GPR measurements are not that common, although its use for groundwater evaluations in combination with geoelectrical measurements has increased (e.g. Tronicke et al. 1999; Aaltonen and Olofsson 2001; Garambois et al. 2002). However, the origin of the increased electrolytic properties and the actual flow situation cannot be explained based on these measurements alone. As stated previously, there are several possible sources of increased salinity, natural as well as man-made. Chemical sampling and analysis of groundwater from wells in the area revealed that the low resistivity zones represented an increased chloride content in the groundwater. The location of the wells was rather successful, enabling chemical sampling from most of the low resistivity zones, although the wells were constructed long before the geophysical measurements were carried out. However, the low resistivity area along the western side of the northwestern valley was not previously known. Geophysical measurements therefore provided a good measure of the representativity of the sampling sites.

The origin of the salinity has been established from the M3 modelling, using PCA. The way of using this type of method for tracing salinity at landfills is rather uncommon. Generally, either more comprehensive water chemical reaction models, such as PHREEQE (Parkhurst et al. 1980), or simple ion balance diagrams, such as piper plots (Piper 1944) and durov plots, are used. However, PCA is rather sensitive to the selection of included variables. In this case, mainly major ions

Table 1 Results from chemical analyses of groundwater and ion ratio calculations

	Median values						
	Groundwater	Surface water	Lake Vällingen	Reference	Leachate	Road salt[a]	Fossil seawater[b]
pH	7.30	7.30	6.90	6.80	7.30	–	–
Cond. (mS/m)	94.10	36.30	17.80	15.10	239.00	543.00	1282.50
P-tot (mg/L)	0.02	0.06	0.03	0.01	0.05	–	–
N-tot (mg/L)	0.13	0.99	0.92	0.39	68.00	–	0.42
PO_4 (mg/L)	0.01	0.02	0.00	0.01	0.01	–	–
Fe (mg/L)	1.00	1.45	0.20	0.75	5.00	–	257.73
NH_4 (mg/L)	0.04	0.03	0.06	0.07	25.50	–	–
Cl (mg/L)	200.00	23.00	16.00	4.20	537.50	249.00	270.59
Mn (mg/L)	0.31	0.04	8.70	0.32	1.00	–	–
As (μg/L)	1.00	0.40	0.50	0.35	1.20	–	–
Pb (μg/L)	0.20	1.00	0.20	0.45	0.40	–	–
Cd (μg/L)	0.02	0.04	0.11	0.03	0.08	–	–
Hg (μg/L)	0.10	0.10	0.10	0.10	0.04	–	–
Zn (μg/L)	9.00	14.00	2.00	6.00	50.00	–	–
Cr (μg/L)	0.65	1.50	0.40	1.55	5.20	–	–
Cu (μg/L)	0.60	3.50	1.40	2.80	3.70	–	–
Ni (μg/L)	1.00	2.00	2.00	5.45	12.50	–	–
K (mg/L)	3.10	–	2.00	2.00	77.00	0.54	2.07
Ca (mg/L)	69.00	–	18.00	9.90	230.00	14.00	83.00
Na (mg/L)	42.50	–	10.00	11.00	218.50	168.50	166.94
Mg (mg/L)	19.00	–	4.10	7.40	61.50	0.85	7.33
SO_4 (mg/L)	49.50	–	18.00	16.00	245.00	–	–
Br (mg/L)	1.25	–	1.00	1.00	3.95	3.18	2.71
F (mg/L)	0.34	–	0.24	0.51	0.43	0.00	1.60
Mg/Cl	0.18	–	0.26	1.95	0.20	0.00	0.02
Na/Cl	0.33	–	0.63	2.89	0.56	0.68	0.59
Ca/Cl	0.65	–	1.13	2.61	0.93	0.06	0.24
F/Cl	0.00	–	0.02	0.15	0.00	0.00	0.00
Br/Cl	0.01	–	0.06	0.26	0.01	0.02	0.01
SO_4/Cl	0.46	–	1.13	4.21	1.03	–	–
K/Cl	0.01	–	0.13	0.53	0.20	0.00	0.01

[a]Analysis of diluted road salt
[b]Samples from drilled wells in the region of Lake Mälaren

were used, except bromide and fluoride. Bromide analyses were included since the component has been found to be very promising for analyses of leachates from household waste (Vengosh and Pankratov 1998). It would have been advantageous to include analyses of natural isotopes, such as oxygen isotopes and deuterium (Olofsson 1999), but such analyses were not available at Tveta landfill. M3 modelling, however, using seven and nine components gave similar results, indicating a rather robust statistical model.

The statistical chemical modelling clearly pointed out that the increased salinity in groundwater found in soil and superficial rock within the northwestern valley can be explained by leachate from the waste deposit. The groundwater composition indicated a mixture between water formed from precipitation and leachates collected at LW3, which represents sampling in a leachate collection pond west of the deposit. It is likely that the leachate from the western side comes partly from the ash pile.

Surprisingly, the increased salinity in the drilled well, GW7, west of the deposit, has another origin. It probably represents a deep and old groundwater, which is a mixture of percolated fresh rainwater and fossil seawater, since this area has been covered by salt and brackish water during periods after the last glaciation. This fact is also supported from a hydrogeological point of view, since it is rather common that deep-drilled wells in valleys in this region exhibit such fossil seawater (Lindell 1987; Olofsson 1996).

Although the origin of salinity has been identified by the statistical chemical modelling and the flow pattern has been shown from geophysical studies, the actual flow velocity and the amount of seepage from the waste deposit cannot be fully clarified. The flow can only be calculated either from variations of resistivity over time, which requires a long-term monitoring system (Aaltonen and Olofsson 2001), or by additional hydraulic measurements and calculations, establishing hydraulic properties of the soil and rock. The latter is, however, rather difficult to obtain with reasonable efforts, due to the highly heterogeneous hydraulic properties in till and crystalline rock.

As the highest groundwater salinity is recorded in the wells located furthest away from the landfill and leachate
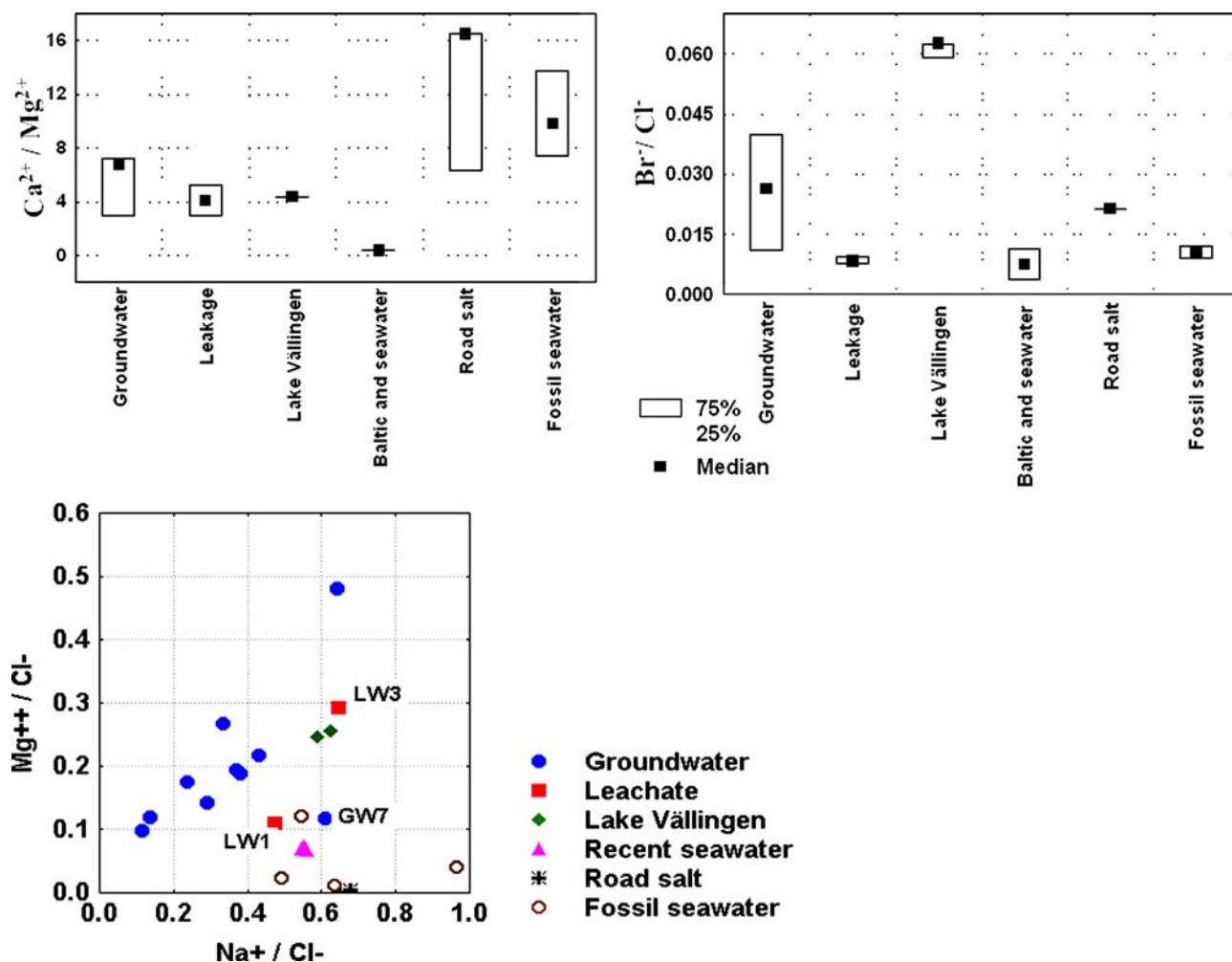
Fig. 8 Box plots of selected ion ratios divided into various sources (*top*). The ion ratios of magnesium/chloride versus sodium/chloride for different sources at Tveta (*bottom*). (All concentrations are in milligram/litre)

pond, one can speculate that this may be an effect of enrichment of leachates in this area, which in turn can be an effect of low hydraulic conductivity northwest of the polluted area.

The usefulness and combinations of various measurements carried out in Tveta landfill area in order to clarify the groundwater pollution situation are summarized in Fig. 10. Each method has given valuable input to the final conclusions and the combinations between different methods have facilitated reduction of possible explanations.

Conclusions

The project has pointed out the advantage of using a combination of various investigation methods for clarifying the pollution situation at a typical composite landfill in south central Sweden. Geophysical measurements, using CVES, GPR and VLF and the solid modelling in 3D from resistivity data, indicated spatially the spreading of low resistivity zones and the volumes of groundwater affected by increased salinity. However, to clarify the origin of the salinity it is preferable to combine the geophysical measurements with chemical analyses. The statistical chemical model M3, based on PCA and applied to this project, was successfully used to identify the origin of increased salinity in groundwater. A combination of results from the various investigations indicated that the groundwater is contaminated by leachate from Tveta landfill. An adjacent ash pile is largely responsible for the pollution. From the investigations carried out it was not possible to calculate the flow velocity and, hence, estimate the total amount of seepage.

Fig. 9 A plot from the M3 model using PCA. The first principal component is plotted against the second principal component
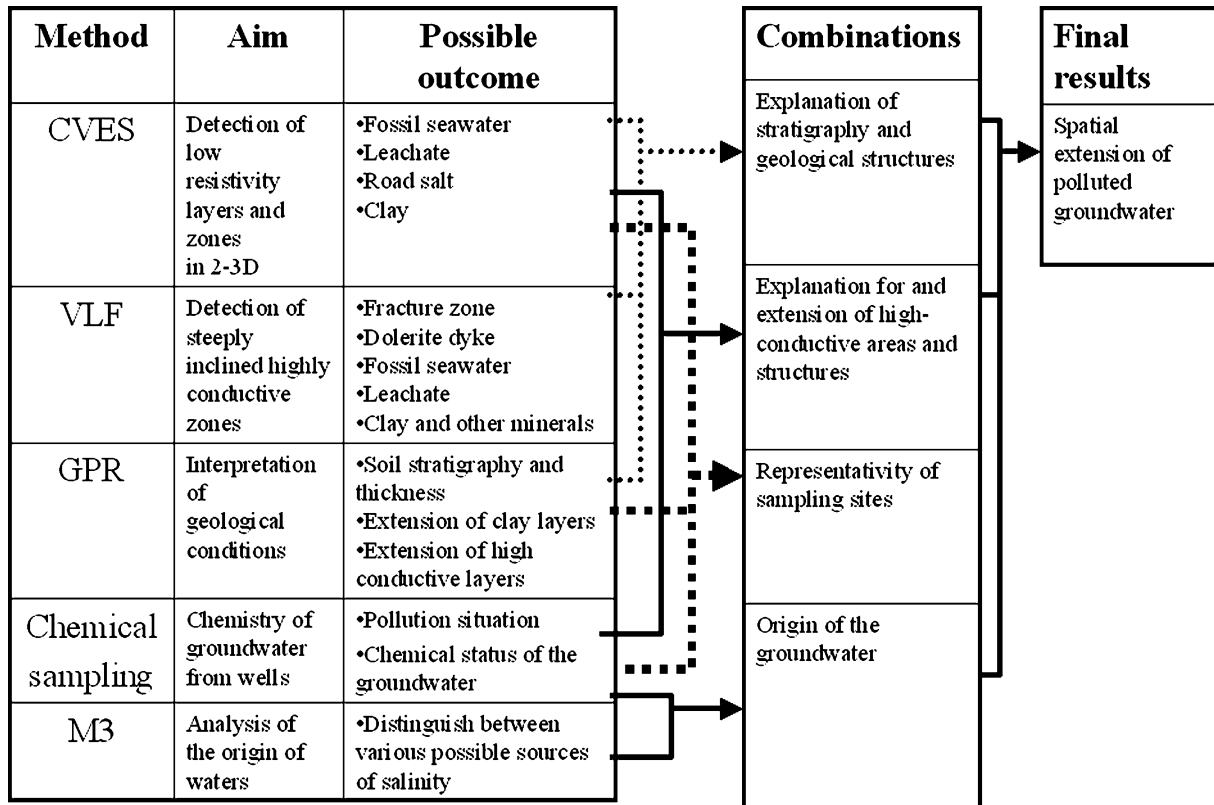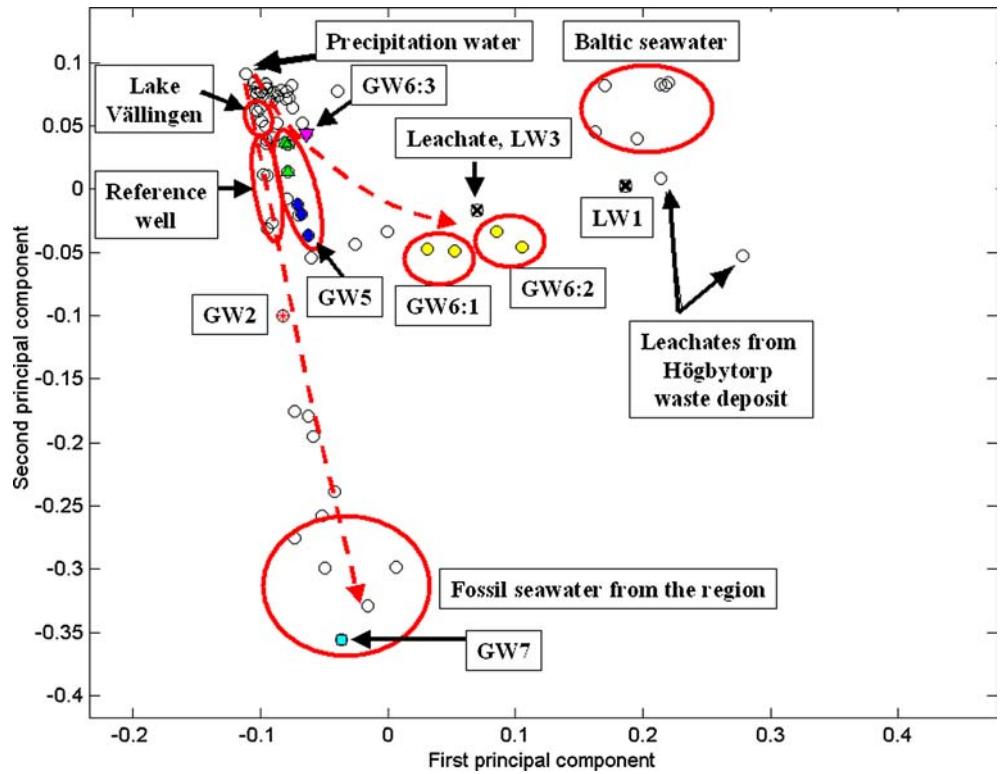

Fig. 10 The usefulness and combinations of the investigations carried out in Tveta area

Method	Aim	Possible outcome		Combinations	Final results
CVES	Detection of low resistivity layers and zones in 2-3D	•Fossil seawater •Leachate •Road salt •Clay		Explanation of stratigraphy and geological structures	Spatial extension of polluted groundwater
VLF	Detection of steeply inclined highly conductive zones	•Fracture zone •Dolerite dyke •Fossil seawater •Leachate •Clay and other minerals		Explanation for and extension of high-conductive areas and structures	
GPR	Interpretation of geological conditions	•Soil stratigraphy and thickness •Extension of clay layers •Extension of high conductive layers		Representativity of sampling sites	
Chemical sampling	Chemistry of groundwater from wells	•Pollution situation •Chemical status of the groundwater		Origin of the groundwater	
M3	Analysis of the origin of waters	•Distinguish between various possible sources of salinity			

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