Direct current (DC) resistivity measurements in long-term groundwater monitoring programmes

J. Aaltonen · B. Olofsson

Abstract Effective leak detection systems are most often needed to enable early warnings of groundwater contamination from landfill areas. In order to monitor the groundwater chemical changes over time direct current (DC) resistivity measurements have been used, since variation in groundwater ion concentration give changes of the electrical potential field. A simple, low-cost system for long-term monitoring has been developed and used for 4 years at an existing operational landfill in central Sweden. The paper describes the construction and operation of the geoelectrical monitoring system based on a fixed electrode Wenner array, situated in a glaciated terrain. The simplicity of the system enables non-experts in geophysics to run the system and evaluate the results. The lateral resistivity variations (up to 10,000% from the mean lateral value) clearly reflect strongly different natural geological conditions, whereas the variations over time (15% from the mean value at each specific point) reflect mainly the seasonal soil humidity and groundwater level variations. Leachates from the landfill have a low resistivity (about 1 ohmm) and the moderate seasonal variations in electrical resistivity favour the possibilities for identification of leakage from the landfill. Evaluation of resistivity data comprises modified double mass calculations versus data from reference measurement sites, which enables detection of contamination although it influences the resistivity less than the natural seasonal variations.

Keywords Resistivity · Monitoring · Landfill · Groundwater · Högbytorp · Sweden

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Introduction

The most common method, when monitoring groundwater conditions around landfills in Sweden and elsewhere, is to analyse a large number of groundwater samples from observation wells up and down gradient from the landfill area. Groundwater contaminants often move along preferential pathways caused by lateral and vertical heterogeneities. Several of the monitoring wells must be placed within these heterogeneities to provide an accurate detection of the contaminant migration (e.g. Benson and others 1988; Osiensky 1995). However, even if many landfills today are constructed on impermeable layers, an example by Colucci and Lavagnalo (1995) shows on average 15 leaks per hectare on impermeable layers investigated. Thus the need of finding a less expensive and more areally covering investigation method has increased during recent years, as the awareness of the risk of groundwater contamination has extended. One way of improving today's methods is to use them in combination with direct current (DC) resistivity methods as the resistivity has been shown to give a good correlation with, for example, chloride and sodium content in the groundwater (e.g. Benson and others 1988; Buselli and others 1992). This combination is also to a large extent seen as a suitable method among Swedish county government boards, which authorize monitoring programmes in Sweden. However, the need for practical experience and information is still great (Aaltonen 2000).

Experiences of long-term monitoring by repeated DC resistivity measurements have been quite encouraging around the world with different types of systems and aims, e.g. Benson and others (1988), Henderson (1992), Osiensky (1995), Bernstone and others (1996), Binley and others (1997), Taylor and others (1997) and Kayabali and others (1998). The method has been used both around and underneath different types of landfills and pond constructions. Bernstone and others (1996) are of the opinion that monitoring of hazardous waste and the changes due to alteration of physical properties of the ground with resistivity is a comparably easy task compared to the actual detection of a contaminant by a single geophysical survey. The monitoring systems around a landfill can principally be done by using some of the three following systems (e.g. Henderson 1992; Aaltonen 1998):

- Permanently installed electrodes and cables around or under a landfill or pond construction.

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- Semi-permanent system with electrodes permanently installed and cables connected while measuring.
- Fully mobile system, all needed equipment is arranged approximately in the same position for each new measurement turn.

The aim of this paper is to present the experiences achieved during four full years of monitoring outside parts of a waste deposit at Högbytorp, near Stockholm, Sweden, using permanently installed electrodes and a free cable. The paper presents and discusses methods for measuring and analyses of resistivity data in order to separate between natural resistivity values and resistivity values that are affected by leachates from the waste deposit.

The investigation area

An overview of the investigation area is given in Fig. 1. The landfill covers an area of about 27 ha and the major part of the deposited masses originates from industrial and domestic waste. The monitoring profiles do not extend around the whole landfill, and cover approximately 1,130 m (480+650 m).

The topography of profile 1 is characterized by two tectonically formed valleys. The southernmost is filled with silty clay or clay on till, and within the uppermost metres thin layers of sand can be found. The northern valley comprises gyttja clay layers, underlain by silty clay and sandy till. The topographical higher positions are dominated by sandy till and outcropping hard crystalline rock, consisting mainly of gneiss, gneiss–granite and amphibolites. The topography of profile 2 is also undulating and contains silt and clay in the lower eastern parts and sandy till and hard rock in the higher western parts. The bedrock topography in the area is mainly a result of fractures and fracture zones, indicated by geophysical methods. This paper only describes the results and analysis of resistivity data from profile 1. A generalized section of profile 1 is presented in Fig. 2.

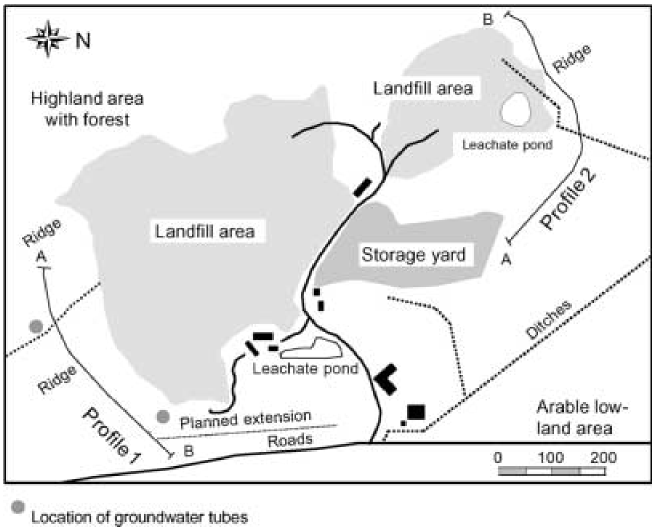

Fig. 1
Sketch map of the investigation area at Högbytorp The *lines* (*A* to *B*) show the two monitored profiles. profile I was installed in December 1996 and profile 2 in September 1997

Method

The measurement system

The system layout is described in Fig. 3.

The system is based on permanently installed electrodes and a free cable, which is connected to the electrodes for each measurement turn. The cable can be combined in any way to suit the prevailing conditions. In this case a simple combination of two Wenner arrays (5 and 10 m electrode spacing) have been used, to reach investigation depths of approximately 2.5 4.5 m, which comprises a sufficiently large part of the groundwater zone. This enables three measurements for each set up. The electrodes are made of thin stainless steel rods, placed approximately 30 cm down in the ground.

Prior to the development of the long-term monitoring an assessment of the site conditions was made, especially to determine the depth to the groundwater. The location of the permanent electrode set up was done based on knowledge of the ground, achieved with rather comprehensive geophysical investigations, comprising GPR (ground penetrating radar), VLF (very low frequency) and DC (direct current) mapping (Dahllöf and Nilsson 1998),

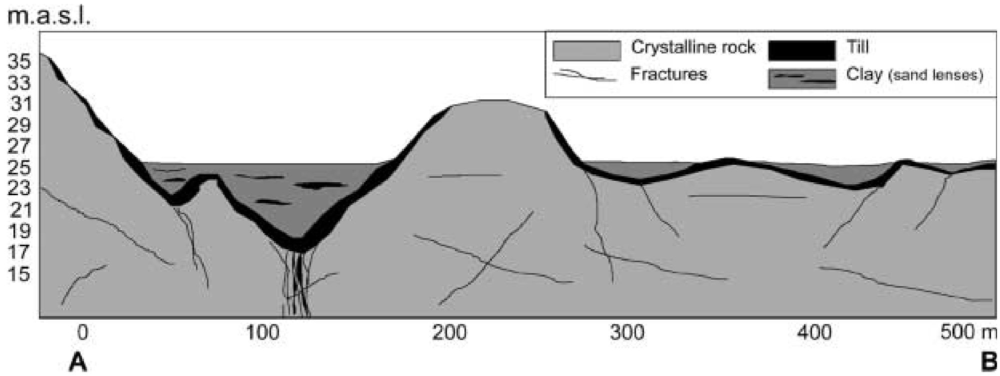

Fig. 2
A generalized geological section along profile 1 at Högbytorp. The section is made from geological surface mapping, ground penetrating radar investigations (GPR) and manual sounding

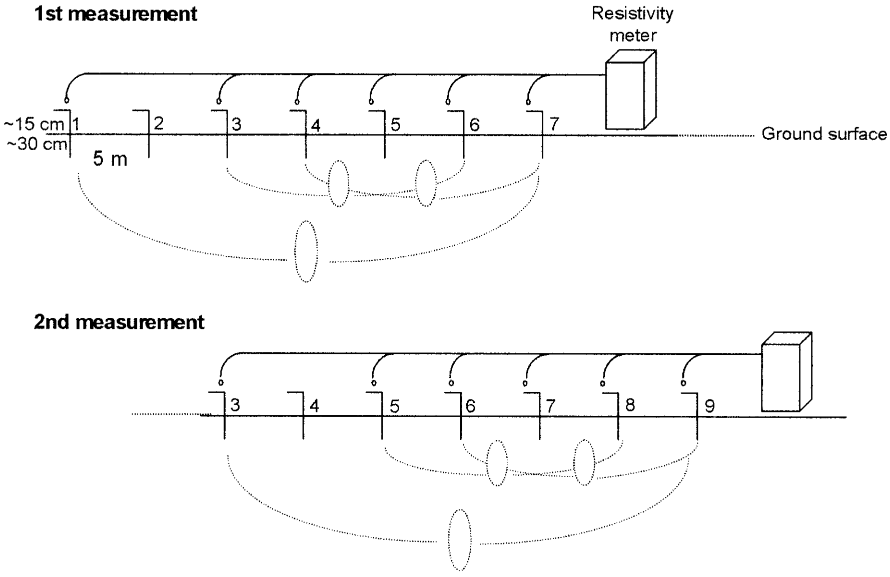

Fig. 3
System layout The *dotted lines* and *ovals* indicate the different measured earth volumes at each set up

together with older geotechnical investigations. The profiles are closely located to existing groundwater tubes in order to enable a close comparison with the groundwater composition.

Between December 1996 and December 1999 profile 1 has been measured roughly once a month. The first 2 years of measuring were carried out in order to obtain a picture of the natural seasonal variations of the electrical resistivity. The measured variations were used for setting up alarm levels for separation between natural resistivity changes and major changes of groundwater conductivity. Profile 2 was installed in late 1997 and measured roughly once a month until December 1999. Since then, both profiles have been measured approximately twice a year, in late spring (May) and late autumn (Oct.–Nov.). One person measures the two different electrode spacings (5 and 10 m) at a rate of 150–200 m/h.

The evaluation method

The monitoring system comprises a specially developed computer program for storage, presentation and evaluation of the measurement data. The seasonal variation of measurement data during the reference period (1.5 years) has been used for analyses of the range of variations and the set up of acceptable variation limits. The percentage of variation of resistivity from the mean values during the reference period along the measurement profile is presented over time using kriging techniques, in order to enable us to find significant changes of resistivity.

The separation between natural variations of resistivity and changes at specific sites due to leakage is made by a modified version of the double mass method. This method was developed by Merriam (1937) for the identification of the failure of meteorological stations. A modified version for analyses of groundwater levels in Sweden was used by Svensson (1988) and Olofsson (1991).

The modified double mass is based on the plot of the accumulated sum of ratios between the resistivity at a specific site at time i and the mean resistivity of a measurement series:

$$x_i = \sum_{j=1}^{i} \frac{x_j}{\bar{x}} - 1 \qquad i = 1, 2, \ldots N \tag{1}$$

versus similar accumulated ratios of a reference series:

$$y_i = \sum_{j=1}^{i} \frac{y_j}{\bar{y}} - 1 \qquad i = 1, 2, \ldots.N \tag{2}$$

N is the total number of measurements in the series and $\bar{x}$, $\bar{y}$ are the mean resistivities of the series.

Since the natural variations of resistivity at a specific site are mainly due to seasonal changes of soil humidity, temperature and groundwater levels (Aaltonen 2001), sites with similar geological conditions and topographical locations probably give comparable seasonal changes. If there are no differences between the test and reference measurement series, the differences between the accumulated values

$$z_i = x_i - y_i \qquad i = 1, 2, \ldots N \tag{3}$$

versus time i fall on a straight horizontal line. Breaks on the line mean that there are divergences between the two series, which can be a result of non-seasonal variations in one of the series. The break points are automatically identified in the computer program using inverse modelling and the amount of change can be calculated. Usually less than 300 iterations are required to roughly describe and calculate the differences between the series.

The selection of reference sites is carried out using linear regression analyses (LRA). Each test measurement series (the time series of resistivity values at a specific site) was analysed versus all other sites along the measurement profile using LRA within the reference time period. A synthetic reference site with synthetic s_i values was calculated from the mean of the sites (usually including 5 to 20 sites) with the best linear fits.

$$s_i = \frac{\sum_{j=1}^{M} r_j}{M} \qquad i = 1, 2, ...N; \quad M = 5 - 120 \tag{4}$$

where r_j is the ith value of the j=1 to M reference series have the best fitted linear regressions versus the investigation site within the reference period.

Since the spread of resistivity values among the series is significant and, hence, the variance of resistivity is very different between the sites, all measurement series were first normalized between 0 and 100.

Results

The electrical resistivity along profile 1 during the first 4 years is shown in Fig. 4. The lateral variation along the profile is considerable, from about 30 to more than 20,000 ohmm. The annual variation is usually less than 15% for both electrode spacings, compared to the mean values between 1996 and 2000. The southernmost part of the profile (>420 m) shows, however, a higher variation. The resistivity values clearly reflect the geological conditions. High resistivity values (>1,000 ohmm) are encountered at topographical higher positions where hard rock outcrops and till are found. The lowest values (<100 ohmm) are found at the thickest deposits of clay (Fig. 2).

A comparison over time at two single locations representing sandy till and clay is presented in Fig. 5. The two types of lithology clearly present a difference of the natural variation. The electrical resistivity of clay shows much lower values and small seasonal variations. A close presentation and discussion of the natural resistivity variations along the profile is made by Aaltonen (2001).

In Fig. 6, six different measurement occasions are compared to a mean of all measurements made at each position. The measurement occasions selected reflect different seasonal and different groundwater level situations.

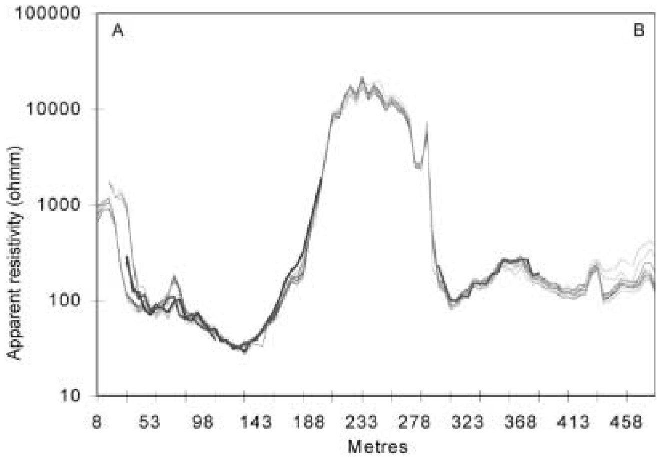

Fig. 4
Results from 26 measurement occasions along profile 1 using a 5 m Wenner array. The graph gives a rough picture of the variation during the measuring period

The groundwater level fluctuated approximately 1 m during the years 1996–2000. The groundwater levels were highest in December and early spring and lowest in late summer, in August/September. As can be seen the difference from the mean resistivity values at each site is generally a few per cent except at some specific sites. However, the variation is clearly different during the year.

In Fig. 7 the calculated differences from the mean and minimum values at all measurement sites along profile 1 during the reference period versus time are presented. Losses of measurement values are common, especially in the eastern part of profile 1. Changes of the stretch of the profile in this area (<75 m) give significant differences from the mean and minimum values. The last measurement turns have concentrated on measurements within the clay-filled topographically low areas, whereas measurements in the outcropping bedrock have been skipped. Analyses of leakage water and contaminated groundwater from boreholes at Högbytorp waste deposit (Olofsson 1998) indicate that leakage from the deposit significantly increases the conductivity. Leakage water has a conductivity of about 850 mS/m, which gives a resistivity of approximately 1.2 ohmm. Double mass calculations made along profile 1, according to the method previously described, indicate no non-natural changes of resistivity so far (Fig. 8B). Nor do the analyses of groundwater from two tubes along the profile. The differences between resistivity at test positions and synthetic resistivity series based on the means from 5–20 sites are generally low, often less than 20%.

The seasonal variation of resistivity compared to the mean of the time series at the site is also presented in Fig. 8A. The maximum difference from the mean is less than 20%.

Discussion

During the years numbers of examples of geoelectrical groundwater monitoring programmes have been presented. More and more examples are also presented on systems

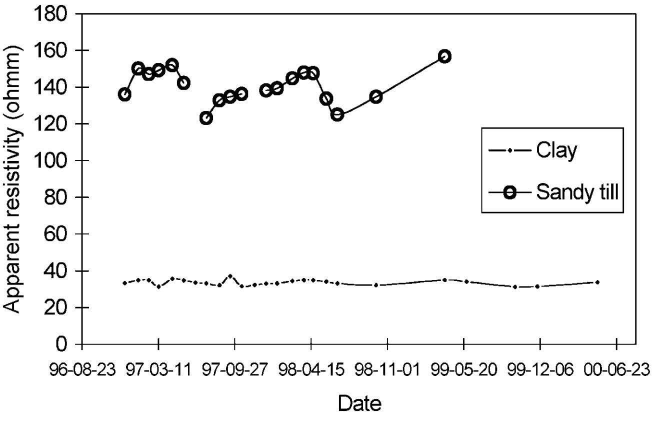

Fig. 5
Comparison of two different lithological environments versus time in profile 1

underneath landfill and pond constructions. Resistivity methods are considered to be quite suitable for measuring variation of groundwater composition since major chemical changes often alter the conductivity of the groundwater and by that also changes the geoelectrical fields (e.g. Mazac and others 1987; Van and others 1991; Karous and others 1994). Periodical repeated resistivity measurements can be used to document changes in contaminant concentrations and areal extent of the contaminated area with time, but also to estimate aquifer transport properties, since a change in contaminant concentration at a monitoring site can define the complete breakthrough curve as a function of time. However, this implies a rather extensive knowledge of the contamination concentration and resistivity relation. Still there are very few geoelectrically based monitoring programmes in glaciated terrains, such as in Sweden.

One of the most important parts of the development of a long-term groundwater monitoring programme is in minimizing the uncertainties in the assessment of the overall site conditions. If the soils consist of a uniform layered material with isotropic properties, an accurate site description would be simple to conduct with a single boring and soil sample analysis (Benson and others 1988). However, this is seldom the case and a site investigation for a monitoring programme at a waste deposit could consist of the following:

- Review of old investigation material, such as geological maps and borings.
- Complementary hydrogeological investigations including geophysical measurements in order to define groundwater and bedrock levels, clay zones etc.
- Formulation of a conceptual groundwater flow model at the deposit aiming to identify possible flow paths.

For the type of low-density measurements suggested in this paper, it is very important to know the groundwater level and its fluctuations, so that the electrode spacing, and by that the investigation depth, can be set correctly. The site investigations should give answers to the surrounding parts of a waste deposit where a DC resistivity monitoring programme is required. It is usually less valuable to install a system in areas where the geology comprises hard rock, as leachate in single fractures is difficult to detect by geoelectrical profiling. However, fracture zones and major parts of fractured rock can often be detected. Thick layers of clay are also difficult areas for separation between non-contaminated and contaminated groundwater and require very high increase of contaminated groundwater conductivity.

Other criteria to consider before establishing a monitoring programme are:

1. The input of contaminants into the aquifer must produce a measurable change of the conductivity, i.e. a significant increase in conductivity of the aquifer, which in turn must occupy an appreciable fraction of the measured earth volume (Greenhouse and Harris 1983).
2. Pre-contamination resistivity measurements are necessary for reliable estimations of the extent and degree of contamination (Karous and others 1994).
3. According to Greenhouse and Harris (1983), the lateral variation in electrical conductivity throughout the site due to changing lithology should also be appreciable smaller than – or separable from – conductivity variation due to groundwater contamination.

The most important question in formulating a geoelectrically based monitoring programme at a waste deposit is the possibility to detect and quantify the contaminants. Saksa and Korkealaakso (1987) state that the normal resistivity contrast between the leachate from a landfill and

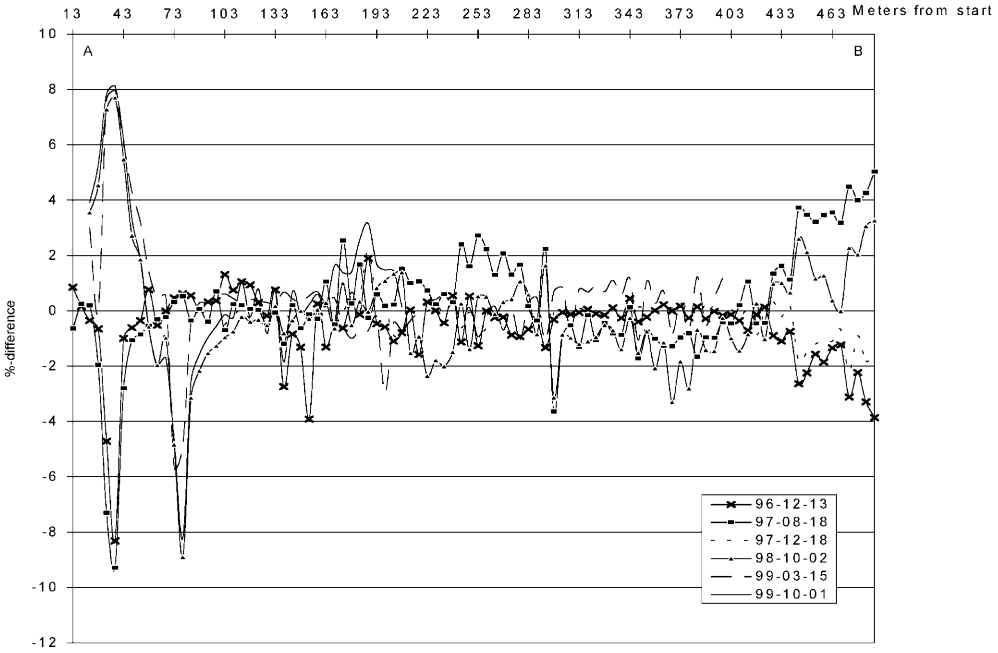

Fig. 6
Comparison of single measurements (in %-difference) to a mean value based on all time points. Measurements along profile 1 at Högbytorp

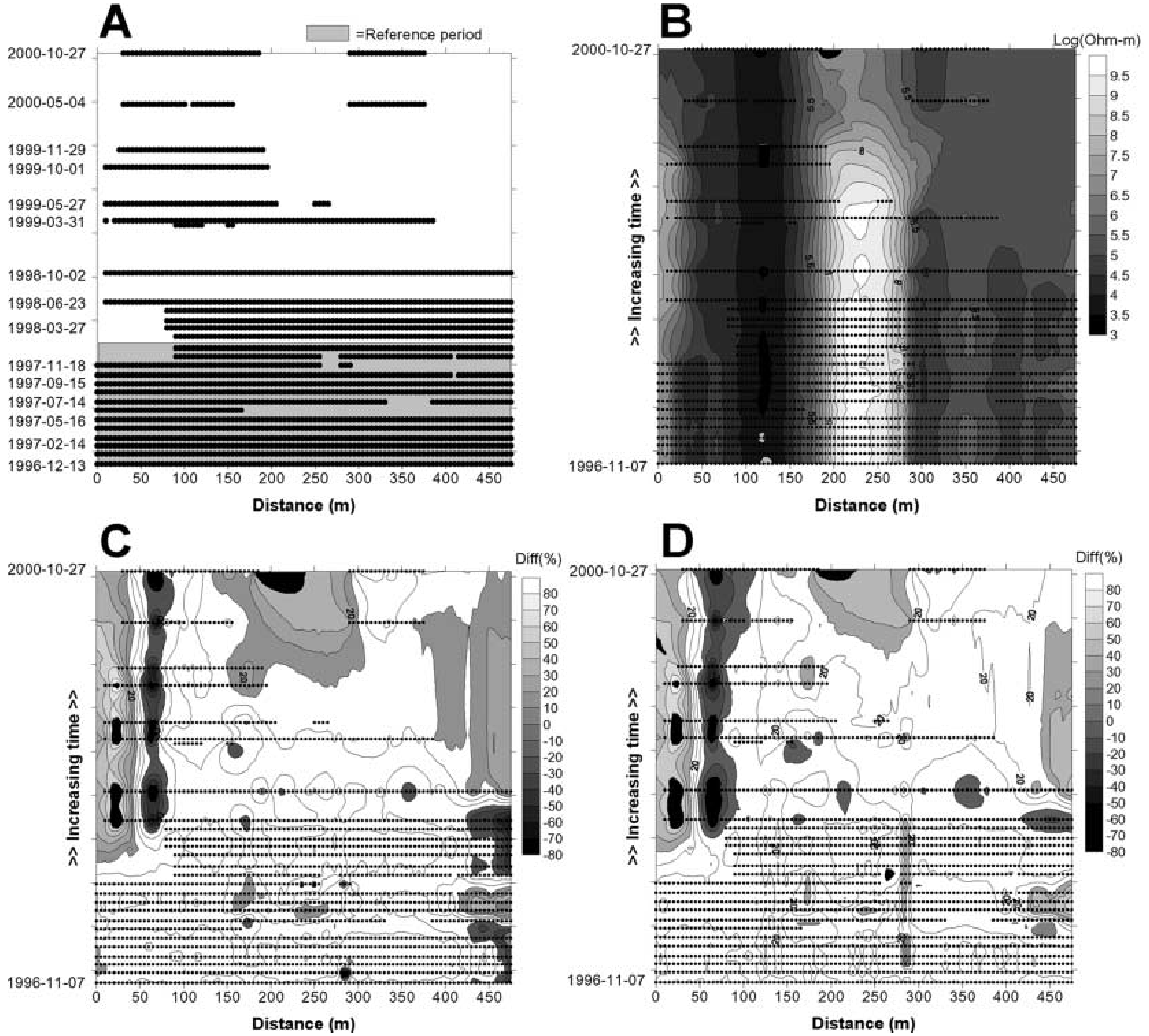

Fig. 7
Variation in resistivity versus time along profile 1 using kriging. **A** Measurement lines (*grey* raster indicates the reference period). **B** Logarithmic values of resistivity. **C** Differences (%) from the mean value of resistivity within the reference period. **D** Differences (%) from the minimum value of resistivity within the reference period

an unaffected groundwater is usually within the range of 10 to 100, but after dispersion and sorption along flow lines in permeable soils this contrast falls to less than 10. At Högbytorp, the leachate has a resistivity of about 1 ohmm. In an imaginary scenario 1% of the saturated zone in a till aquifer (60% unsaturated zone and 40% saturated zone) is invaded by leachate. This will result in a resistivity decrease of 70% at the point of measurement for a dilution of 1/10, and a decrease of 20% for a dilution of 1/100. The corresponding results for a clayey environment is a 20and 0% decrease respectively.

Figure 9 shows the response in double mass calculations of a decrease amounting to 15 and 30% of resistivity (a decrease of 35–75 ohmm) at the test sites shown in Fig. 8, representing a thin layer of clay on top of till. This decrease corresponds to an increase of approximately 10 to 30 ppm TDS.

The anomalous decrease of resistivity in Fig. 9 is clearly seen using double mass analyses. This type of analysis is valuable especially in areas where the resistivity varies naturally, for example seasonally. Double mass calculations, however, need reference measurements of resistivity in comparable hydrogeological situations. Such measurements can either be carried out in similar geological conditions far from the waste deposit or, as in this case, be selected from the same geoelectrical profile, assuming that the leakage only affects some of the measurement locations and not all sites at the same time along the whole profile. Figure 10 shows the results of introducing an up to 30% decrease of resistivity values at three closely located positions in 1999. Calculations were automatically carried out for all measurement sites, using double mass analyses

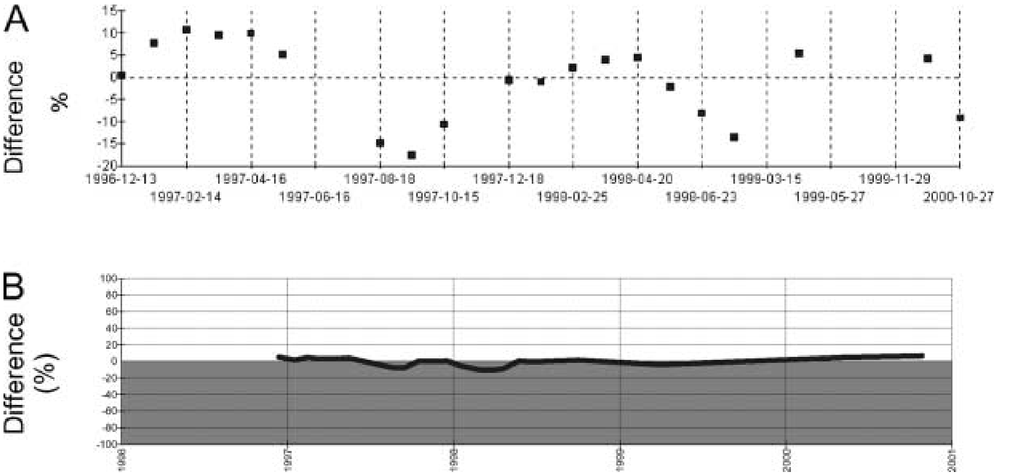

Fig. 8
A Difference (%) from mean value of resistivity at the test position 350 m along profile 1. **B** Example showing calculated differences between resistivity at test position 350 m and a synthetic site based on five sites along profile 1. The calculations are carried out by a modified double mass method

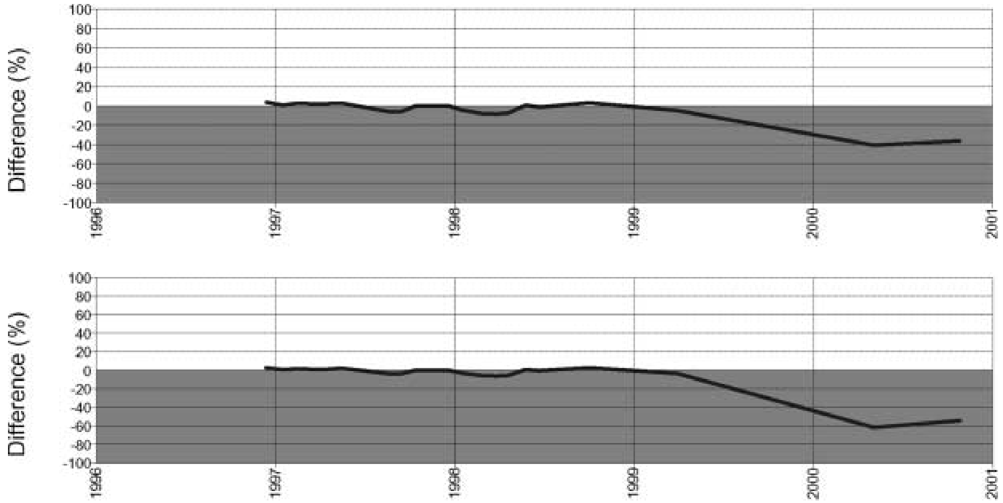

Fig. 9
Differences between resistivity at test position 350 m and a synthetic site based on mean values of five sites along profile 1, calculated by modified double mass. A decrease of resistivity amounting to 15% of original values (*above*) and 30% (*below*) was introduced after May 1999

versus a synthetic site, based on the mean of five automatically selected reference sites along the same measurement profile.

McNeill (1990) reported that an addition of 25 ppm conductive material (TDS, total dissolved solids) to the groundwater increases the groundwater conductivity by about 1 mS/m. The relationships between the decrease of normal specific resistivity of till and clay environments due to the addition of TDS is shown in Fig. 11 for some different ratios of unsaturated and saturated volumes of the ground measured. The relationships for till are in accordance with empirical relationships established by Archie (Parasnis 1997), while the relationship for clay is somewhat underestimated compared to Patnode and Wyllie (1950).

Osiensky (1995) summarized the natural variations or deviations from idealized conditions as a result of heterogeneity, anisotropy, variations in topography, changes in moisture content and temperature of surface soils, fluctuations of groundwater levels and existence of conductive clay lenses. The site investigation should clear questions about geological and hydrogeological heterogeneity and variation in topography. The changes in moisture content and temperature are seasonal variations of climate, which will be of major importance when monitoring resistivity over the long term. An investigation of the seasonal variation in this presented area has shown variations usually less than 15% of the mean value at a specific site, but the range (max. to min.) varies up to 90% of the mean in certain geological environments (Aaltonen 2001). The variation was noticeably large within geological conditions comprising coarse-grained material and gyttja clay. Other investigations have shown rather large seasonal variation also comparing results from several years (e.g. Mazac and others 1988). Constantino and others (1978) have found a good correlation of the rainfall and the resistivity in the uppermost metre of cultivated soils. Similar correlation was reported by Buselli and others (1992) with high resistivity values within the dry season and vice versa. However, no correlation with precipitation was found in Swedish till terrain when comparing resistivity at a depth of approximately 2.5 m (Aaltonen 2001). It is therefore important to know what factors are most decisive for the annual variation of resistivity in the actual specific geological terrain where the monitoring programme is set up.

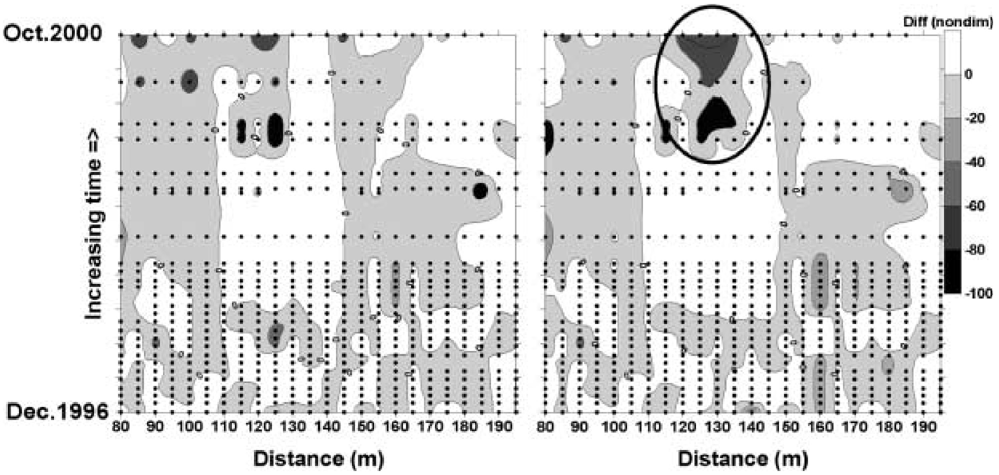

Fig. 10
Results of introducing a 30% decrease of resistivity in 1999 along a part of profile 1. Calculation was automatically carried out using a modified double mass method and inverse modelling, versus a synthetic reference site based on the mean from five sites. Contouring is made by kriging using original values (*left*) and disturbed values (*right*). Measurement sites and the main differences are marked in the figure

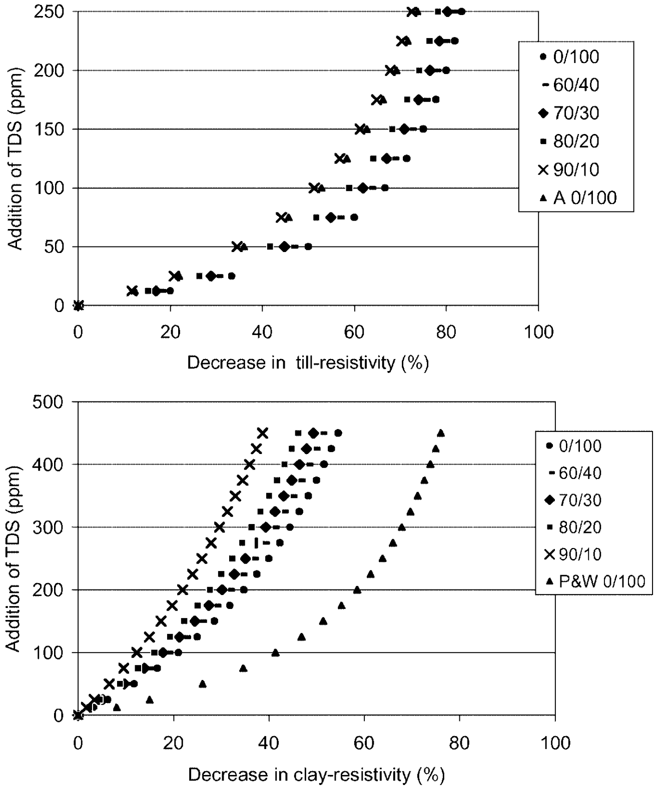

Fig. 11
Decrease in normal specific resistivity due to addition of TDS for different ratios of unsaturated/saturated ground. The graph is based on assumptions by McNeill (1990), Archie's law (Parasnis 1997) and Patnode and Wyllie (1950) The legend shows different ratios of percentage unsaturated ground to percentage saturated ground in the volume measured. The relation assumes that all of the TDS is moving in the saturated zone and with a small portion of soil moisture in the unsaturated zone. *A* Archie's law (Parasnis 1997) *P&W* Patnode and Wyllie (1950)

Pre-contamination investigations are important if the results should be used for monitoring purposes over a longer period of time. Karous and others (1994) stated that without any information of natural resistivities it can be hard to make a separation between what is affected and not affected. However, using long-term monitoring programmes, which only take into account the specific changes with time at each measurement site, some of these identification problems can be overcome. A necessary requirement is then that there are some reference sites, which definitively are not affected by contamination and which have a natural variation similar to the investigated site. Specific reference profiles can be set up containing similar geological and hydrogeological conditions to the investigation profiles with the linear regression analysis method (LRA). Then, there are no absolute requirements that the reference sites should be placed in comparable hydrogeological conditions, only that they should react in a similar way to seasonal changes. The LRA needs sufficient data, i.e. the long-term monitoring programme must be run during a sufficient period of time in order to collect reference data. During this period, no other impacts on data other than natural seasonal variations are accepted. Groundwater test pumping, tree cutting and other activities, which impact on the soil humidity and, hence, on the resistivity levels, can destroy the reference data set.

The length of the reference period needed varies due to the natural variation pattern. A minimum requirement is a period covering one normal hydrological year, which gives resistivity data from both dry and wet seasons. If the specific year is anomalously dry or wet, the reference period has to be extended. The time lap between measurement turns depends on the natural variations, e.g. the immediate influence by precipitation. Since correlation between direct precipitation and conductivity was rather bad in this specific terrain consisting of till, outcropping bedrock and clay (Aaltonen 2001), monthly measurements were assumed to be sufficient in this study during the reference period (1–2 years).

The frequency of measurement turns during the operational phase of the monitoring programme must be chosen depending on the estimated groundwater flow and the type and dangerousness of the contaminants. The spreading at this particular waste deposit is assumed to be a rather slow process, hence, an annual frequency of 2–4 measurement turns was selected during the operational phase.

Separation between natural variations and non-natural changes in a time series can be carried out using several statistical methods, such as time series analysis, stepwise regression analysis and double mass analysis (Olofsson 1999). These methods are not commonly used in chemically based monitoring programmes since they need a sufficient amount of data, which can be expensive to collect when dealing with water chemical analyses. The resistivity method used here, however, enables a sufficient amount of measurements to be carried out to a reasonable cost. The modified double mass calculations have proved to be a simple but strong tool for the identification of anomalous data in the resistivity time series, providing the natural variation at a site is similar to reference sites.

In this specific project, no contamination has been indicated in the groundwater samples collected in tubes along the profiles. The method used here for identifying reference sites for each measurement site, taken from the same measurement profile, can only be used if a heterogeneous flow pattern with preferential flow paths is assumed. Then contamination is preferably affecting some of the measurement sites, whereas neighbouring sites having similar natural variations can still be unaffected. The construction of a synthetic natural fluctuation curve (reference data set) from several comparable measurement sites (in this case ten) minimizes specific and local variations, which can significantly influence the results if only one reference site is used.

The 4 years of DC monitoring at Högbytorp waste deposit have also given much experience, and many practical problems with the installation and maintenance of the monitoring system have been identified, such as:

- Electrodes disappear, due to interference by animals or people. This problem can be overcome if the monitoring system can be placed inside the fence of the landfill area.
- The electrodes tend to "shake loose" in terrain with more coarse-grained soils. It would, in such areas, be more reliable to have other types of electrodes, such as buried steel plates.
- Rust on electrodes can disturb the measurements due to a decreased soil–electrode contact.
- The electrodes should be properly marked, as the thin steel rods used in this project easily disappeared in the vegetation and especially under the snow cover. This problem can be overcome using a permanent and covered electrode and cable system.
- All non-natural changes of groundwater levels and soil humidity in the monitoring area, such as tree cutting and groundwater test pumping, should be avoided since it influences the measurements.

Finally, some advantages and disadvantages of the presented system can be summarized as:

- Adv. The system is non-expensive and simple in installation.
- Adv. The system can be varied in infinity, both regarding electrode spacing and type of electrode array.
- Adv. Landfill personnel can run the system, if experts set limits of acceptable resistivity variations.
- Disadv. The present DC system is far more time-consuming than a totally automatic permanent system, which can measure on daily basis or even more often by automatic computerized systems.
- Disadv. Electrodes disappear and are sometimes hard to find in dense ground vegetation and snow, a problem which does not arise when having a completely permanent and covered system.

Conclusions

The project shows that long-term DC resistivity measurements can improve existing monitoring programmes at contaminated areas such as waste deposits and that DC measurements are valuable as a basis for the set up of new monitoring programmes at contaminated land areas.

The 4 years of monitoring experiences using DC methods at Högbytorp waste deposit, central Sweden, have shown that the natural seasonal variations in DC resistivity usually are less than 15% from the mean value at fixed positions in an area consisting of till, outcropping bedrock and clay, whereas the spatial variations exceed many thousands of per cent from the lateral mean (varying from 30 to 20,000 ohmm). Hence, in order to effectively delineate leakage from the waste deposit using DC resistivity, time series of resistivity measurements are necessary.

During the 4 years no sign of leakage has been detected along the measurement profile at the deposit. Synthetic impact on original data, however, indicates that a decrease of the resistivity 15% from the mean value at a specific site can be detected using statistical analyses of time series. Modified double mass calculations versus a synthetic reference time series formed from other measurement sites with comparable seasonal variations along the same measurement profile have proved to be an effective tool for separation between effects of natural variations and contamination.

The system developed has a low installation cost but needs manual measurements. It can, however, be further developed to a totally automatic system.

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