Ground Monitoring
using
Resistivity Measurements
in
Glaciated Terrains

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Dissertation

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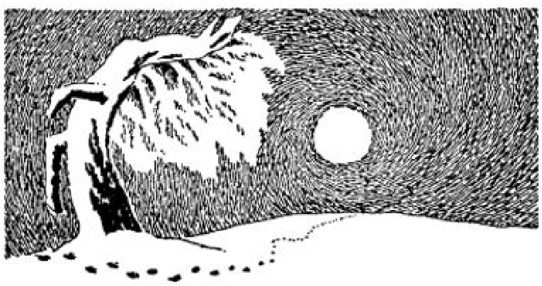

"Hallo, said Sniff. I have found an altogether own road. It looks dangerous.
How dangerous, the Moomintroll asked.
I would say enormously dangerous, the small animal Sniff answered seriously.
Then we need sandwiches, said the Moomintroll. And lemonade.
He went to the kitchen window and said: You know, Mother. We will eat out today."

Comet in Moominland, 1968 by Tove Jansson
(Translation to English by J. Aaltonen)
Picture from Moominland Midwinter, 1957 by Tove Jansson

Preface and Acknowledgements

This work began on a sunny day in August 1994, when for the first time I used resistivity measurements to determine the structure of a till aquifer in Southern Sweden. Although the topography was undulating, any interpretational experience totally lacking on my part and the cables altogether entangled, my interest in the field of geophysics was awakened. During the years since then I have visited, measured and tried to understand a number of different hydrogeological environments using resistivity measurements, not always under sunny conditions. There is still a lot to learn and it is always hard to try to conclude a project which seems never-ending, even more so today than a year ago, but hopefully this thesis will highlight some of the qualities of resistivity measurement and by that promote its use.

Over the years, I have been supported by a large number of people. First of all I would like to thank the Ragnar Sellbergs Foundation (especially Staffan Ågren) and the Geological Survey of Sweden for financial support during the final steps of this work, together with the Ernst Johansson Scholarship, Royal Institute of Technology, for long-time support of my first years.

Secondly, I want to thank my supervisors; Professor Gert Knutsson and Associate Professor Bo Olofsson, both at the Division of Land and Water Resources, Royal Institute of Technology. My sincerest thanks to them! I am also grateful to Professor Per-Erik Jansson and Tech. Dr. Lena Maxe, also at the Division of Land and Water Resources, Royal Institute of Technology, for their comments on the thesis at a final stage.

A special thank you to RagnSells AB (and especially Ingemar Stenbeck), for letting me run around their landfill facilities during the past few years and to Jehanders AB, NCC and VBB Viak for letting me carry out and take part in tracer tests.

I am also most thankful to all of my colleagues at the Division of Land and Water Resources, for an enjoyable working environment and of course to Göran Blomqvist for long-time encouragement, Edward Sjögren for assistance in the field and to Mary McAfee and Erik Danfors for valuable help with the English language.

Finally, to family and friends, a large hug for putting up with me!

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Abstract

The most common method of monitoring and mapping groundwater contaminants is to extract and analyse a number of groundwater samples from wells in the investigation area. However, there are a number of limitations with this type of point-wise investigation, as it is hard to acquire an adequate picture of a heterogeneous and anisotropic subsurface using a few points.

To overcome the limitations of point investigations and to improve ground monitoring investigations in a cost-effective way, support can be provided by direct current resistivity measurements, which give a characterisation of the electrical properties of a ground volume.

The main objective with this work was to investigate the usability of the resistivity method as a support in monitoring groundwater contaminants in glaciated terrains and under different seasons, both in long-term monitoring programmes and in tracer tests.

The work comprised field investigations at several different sanitary landfills and four tracer tests in different geological environments, around the Stockholm region. The main investigations have been done at Högbytorp, Stockholm which has been used for long-term investigations of the resistivity variation, together with a field set up for monitoring and measurements on seasonal variation in soil moisture, ground temperature and precipitation.

It can be concluded that the use of resistivity measurements supplies valuable information in the case of mapping and monitoring conductive groundwater contaminants and furthermore:

- The variation in resistivity (in shallow investigations < 1 m) can be extensive between different seasons (around 30 % compared to a mean value in till and clay soils) and should be considered, so that anthropogenic affects can be separated from natural resistivity variation. For deeper investigations (> 5 m) the seasonal resistivity variation was more moderate (around 15% compared to a mean value in till and clay soils).
- Soil moisture variation shows a strong relationship to resistivity variation in the investigated clay and till soils. Together with temperature correction 47 to 65% of the variation has been explained.

- Three types of monitoring systems can be applied: Permanently installed, partly installed and fully mobile systems. For the actual measurements, all three types can use either high-density techniques such as CVES (Continuous Vertical Electrical Sounding) or low-density measuring with one or some different electrode spacings.
- The suggested evaluation tool for monitoring programmes showed that it was possible to detect a decrease of 15 % in the mean value at a specific site using Modified Double Mass calculations between resistivity time series and time series at a reference site with a comparable seasonal variation.
- Resistivity measurements may be used as a valuable complement to groundwater sampling in tracer tests. A decrease in resistivity, a minimum and a recovery phase reflect the passage of a NaCl-solution, which can be used to estimate flow velocity and flow patterns of the investigated aquifer. The achieved recovery of NaCl in the tracer tests carried out was estimated to 20 to 70 %.
- The measurement system for long-term monitoring or tracer tests, which should be chosen with regard to layout and frequency, depends on the purpose of measurement and on site-specific conditions and therefore no standard solution can be proposed.

Key words: Resistivity, Direct Current, Monitoring, Groundwater, Contaminant, Tracer test, Geophysics.

List of Papers

This thesis is based on the following papers and manuscripts, which are referred to in the text by their Roman numerals. The papers are appended at the end of the thesis.

I. Aaltonen, J., 2000. The applicability of DC resistivity in some geological surroundings in Sweden. In: Sililo, O. et al. (eds.). Groundwater Past Achievements and Future Challenges, Proceedings of the XXX IAH Conference, Cape Town, 26 November –1 December: 61-65.
II. Aaltonen, J., 2001. Mapping and monitoring landfill leachate with DC resistivity and EM conductivity in glaciated till terrain. Submitted to Journal of Environmental and Engineering Geophysics, 22 p.
III. Aaltonen, J., 2001. Seasonal resistivity variations in some different Swedish soils. European Journal of Environmental and Engineering Geophysics, Vol. 6: 33-45.
IV. Aaltonen, J. and Olofsson, B., 2001. DC resistivity measurements in groundwater monitoring programmes. Submitted to Journal of Contaminant Hydrology, 17 p.
V. Aaltonen, J., 2001. Resistivity measurements in tracer test analyses. Manuscript, 22 p.
VI. Aaltonen, J., 2001. Consideration of seasonal resistivity variation. Manuscript, 8 p.

The experimental parts of the thesis are based on fieldwork carried out during 1994 to 2001 at several locations in Sweden, predominantly in the Stockholm area. The results of these investigations are to a large extent shown in appendix I to VI and in Aaltonen, 1998a and b.

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Introduction

As aquifers become more exploited and the numbers of contaminated land areas are increasing, the need for improved monitoring tools is also increasing. The most common method when monitoring contaminants is to extract and analyse a number of groundwater samples from observation wells around the contaminated area. However, there are limitations with these types of investigations, some of which are listed in the following:

- Water often moves along preferential flow paths caused by heterogeneities in geology, and therefore wells would have to be placed within these heterogeneities to provide an accurate picture of the contaminant migration, which might be difficult.
- Using groundwater sampling from points, there would be great difficulties in detecting leachates with unknown positions when the lateral extension of the same is less than 10 % of the investigation area (SEPA, 1994).
- When a dense sampling network is needed together with a dense interval of measuring, the cost of both installation of wells and analyses of water samples is considerable.
- Installation of wells may create new pathways and cause further migration of contaminants.

Similar limitations are often encountered when performing tracer tests in order to obtain a picture of groundwater flow patterns and velocities. The location of observation wells between the infiltration point and the discharge point is critical, as the tracer pulse can be lost in between the positions of observation wells due to a heterogeneous flow pattern.

To overcome the limitation of point investigations and thus improve monitoring programmes and tracer tests in a cost-effective way, direct current (DC) resistivity measurements can be very valuable in characterisation of the physical properties of larger laterally and vertically covering volumes of the ground.

An inquiry to the Swedish County Government Boards, which authorise monitoring programmes, showed a large interest in the use of geophysical methods, indicating a need for better monitoring tools (Aaltonen, 2000).

The DC resistivity method is one of several geophysical methods, which have been used for a long time for investigating leaching from landfills and for studying other environmental problems. The use of resistivity methods in contamination investigations in based on the fact that the resistivity of the saturated soil depends on the groundwater resistivity and the properties of the porous matrix. This creates the potential to detect leachate, as part of the change in resistivity is due to a change in the concentration of dissolved ions (contamination) in the groundwater.

As early as 1978, EPA in USA produced guidelines for electrical resistivity evaluations of landfills. From then onwards, the development of resistivity measurements have been progressing and it has increased dramatically during the last few years. There are numerous examples where resistivity has been used to map contaminants (e.g. Kelly & Asce, 1977; Stierman, 1984; Ebraheem et al., 1990; Barker et al., 1990; Senos Matias et al., 1994; Bernstone et al., 1996 and Meju, 2000). However, there are only a few examples in which resistivity has been used as a monitoring tool around contaminated areas (e.g. Benson et al., 1988; Osiensky, 1995 and Kayabali et al., 1998) and also only a few where resistivity has been used to evaluate tracer tests (e.g. White, 1988 and 1994).

Scientific problems

Resistivity measurements have been used with success in a number of investigations in connection with contaminated groundwater, but the method and its applications have limitations, which need to be resolved.

Resistivity measurements and the interpretation of the results are to a large part based on a simplified model of the subsurface, with only a few different layers. A complicated heterogeneous environment such as glaciated terrain, with several intermixed layers, will give ambiguous interpretations of the resistivity results (e.g. Greenhouse & Harris, 1983; White et al., 1984; Mazac et al., 1987 and Paillet, 1995). In addition, the measurements are also affected by seasonal variation in, for instance, groundwater table and soil moisture (e.g. Buselli et al., 1992 and Nobes, 1996), which are especially large in minor aquifers and in humid climate types.

The subsurface in most areas of Sweden, for instance, would give rise to a complex electrical model of the subsurface, in which interpolation of the results could be quite difficult. To reach reliable resistivity results more knowledge is needed of how the resistivity method reacts in a heterogeneous environment in combination with other natural variations and how anthropogenic anomalies can be distinguished from these natural variations.

The resistivity method is quite suitable for relative measurement, and by that for monitoring for instance leachate flow in the ground (Mazac et al., 1987; Benson et al., 1988 and Karous et al., 1994). Most current work is, however, concentrated on minor systems, which is especially suitable beneath ponds but not for more large-scale improvements of traditional groundwater sampling programmes around operational sites. The knowledge of resistivity use in monitoring programmes can also be applied in tracer tests, which are valuable tools for investigating flow patterns and velocities of the groundwater.

Objectives

The main objective was to investigate the usability of the DC resistivity method as a support in groundwater contaminant monitoring programmes and in tracer tests, and to investigate advantages and limitations with the method. The thesis clarifies:

- How the resistivity varies due to changes in seasonal weather conditions, such as soil moisture and temperature.
- How long-term monitoring programmes based on resistivity measurements can be designed and operated for control of contaminant migration in the groundwater zone.
- How resistivity measurements can be used in tracer tests investigating flow patterns and groundwater flow velocities.

Limitations

Over the years, the field of environmental monitoring has generated more and more interest and is today considerable, comprising a large number of different techniques and ways of measuring. This thesis concentrates on one particular technique, the DC resistivity method, and does not look deeper into other methods. The DC method was chosen due to the following:

- As the main focus was on the application, the measuring equipment had to be easily available and well known. Therefore no emphasis was placed on instrument development.
- The intention was also to use a simple technique which could be handled by non-geophysicists (in the case of relative measurements).

Furthermore, no borehole measurements were carried out. The groundwater contaminants investigated were dominated by chloride salts, typical of landfill leachates. No emphasis was placed on other contaminants such as organic spills or heavy metals.

The discussion on interpretation of single resistivity investigations as sounding curves was left with no further comment. More can be read in e.g. Parasnis (1997) and Zhadanov & Keller (1994). The case of handling monitoring data or resistivity data in tracer tests is, however, discussed in Chapters 4 and 5.

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Background

This chapter will provide a short theoretical background to DC resistivity measurements, together with characteristics of resistivity measurements for mapping and monitoring of groundwater contaminants. Finally, the last part summarises the chemical considerations of resistivity measurements.

Theory

DC resistivity measurements have been used since the beginning of the 20^{th} Century and are one of several geoelectrical techniques. The resistivity (measured in Ωm) is a physical property of a material, whereas resistance is a characteristic of a particular path of electric current (Parasnis, 1997). The resistivity is related to resistance by a modified Ohm's Law ($U=R*I$). For a cylindrical solid of length L and cross section A the resistivity, ρ, is

$$\rho = U/I * A/L = R * A/L \qquad (1)$$

where R is the resistance, U the potential and I the current.

Instead of resistivity, the conductivity, which is the inverse of the resistivity, can also be used. The conductivity is measured in S/m.

In simple terms, the resistivity measurements are performed by applying a current I, which is introduced into the soil between two electrodes A and B. A potential difference (ΔU) can then be measured by electrodes M and N, situated between A and B (Fig. 1).

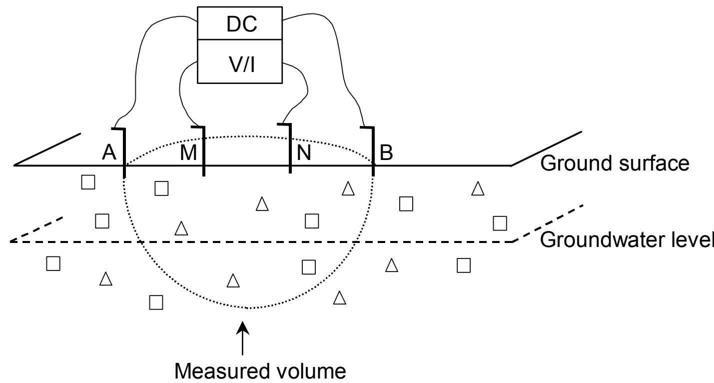


Fig. 1. The principle of resistivity measurements. A and B are the current electrodes, while M and N are the potential electrodes.

The resistivity of soil depends on the method of measuring and is formulated as apparent resistivity (ρ_a), which is a function of the true layer resistivities, their boundaries and the location of electrodes:

$$\rho_a = \Delta U / I * K \tag{2}$$

where K is a geometrical factor, which depends on the geometry of the array used. In a homogeneous soil, the apparent resistivity is a good approximation of the resistivity. More can be read in for example Griffiths & King (1975), Milsom (1989) and Parasnis (1997).

The apparent resistivity varies from fractions of a Ωm to several tens of thousands of Ωm. The resistivity of some soils is listed in Table 1 below. The resistivity is mainly dependent on the:

- degree of water saturation
- amount of dissolved solids
- content of organic matter
- grain size
- grain shape of the soil matrix.

Table 1. Resistivity of some common soils. The values represent saturated conditions, for dry conditions the resistivity is about one power of ten higher (Peltoniemi, 1988).

Material	Resistivity (Ωm)	Conductivity (mS/m)
Gravel	1000 – 2000	0.5 – 1
Sand	500 – 1000	1 – 2
Till	200 – 500	2 – 5
Peat	100 – 300	3 – 10
Silt	80 – 200	5 – 12
Clay	30 – 70	15 – 30

The volume and hence the depth of investigation is decided by the distance between the outer electrodes in the electrode array used. Barker (1989) has estimated the depths of investigation for a Wenner configuration to be 0.17*L and for a Schlumberger configuration to be 0.19*L, where L is defined as the total array length. This is valid strictly for homogeneous ground. In layered soils, which are common in most terrains, the current distribution will be modified and will create difficulties in the interpretation of depth. A shallow layer of conductive material, for instance, will change this depth dramatically since the current will always travel by the easiest route through the ground.

The resistivity measurements are usually carried out in the following ways:

- Sounding or Vertical Electrical Sounding (VES): Vertical measurements at a single location but with increasing electrode spacing and by that increasing measured volume.
- Profiling: Laterally moved measurements made with constant electrode spacing.
- Continuous Vertical Electrical Sounding (CVES): Combination of sounding and profiling, which gives a vertical cross-section of the resistivity distribution.
- Spatial measurements: Measurements made with a grid of wires, giving an areal covering picture of the resistivity distribution.

The aims of resistivity measurements are usually to:

- Map: Measurements made to determine the spatial and/or vertical distribution of resistivity.
- Monitor: Measurements made at fixed locations as a function of time, with the focus on the time-dependent changes in resistivity.

The flow of electric current in a medium follows the path of least resistance, which is controlled more by porosity and water resistivity than by the resistivity of the mineral particles. The current is conducted through the ground by electrons or ions, in other words by metallic and half-conductors or by crystal solutions and electrolytes (Peltoniemi, 1988), where the conduction is dominantly done by ions, i.e. through electrolytes.

Contaminants dissolved in groundwater most often drastically change the electrical conductivity. One key component in contaminant studies is chloride, since it is not greatly affected by geochemical processes such as adsorption, precipitation or redox processes. It therefore has the ability to travel long distances in groundwater without great attenuation and thereby causing a measurable decrease in resistivity.

Since the electrical path is similar to the hydraulic path, electrical parameters, such as resistivity, can be related to hydraulic parameters.

A number of cases are reviewed in Table 2, showing different investigations where relationships between resistivity and hydraulic and chemical parameters have been outlined. However, these relationships are most often considered to be site-specific, and are not yet suitable for routine use (Aristodemeou & Thomas-Batts, 2000; Meju, 2000).

The more used relationships are Archie's Laws. They were formulated back in the 1940s (Ward, 1990; Parasnis, 1997) and show the relationship between soil and water resistivity in clay free environments, together with the formation factor, which is the ratio of the bulk resistivity to the resistivity of the groundwater:

$$1^{st} \quad \rho_r = a\, \rho_0\, \Phi^{-m} \tag{3}$$

$$2^{nd} \quad \rho_r = \rho_0\, \Phi^{-m}\, S^{-n} \tag{4}$$

and

$$F = \rho_r / \rho_0 \tag{5}$$

where ρ_r is the bulk resistivity of the ground, ρ_0 the resistivity of the water filling the pores, a a constant (approximately 0.6), Φ the porosity, S the fraction of pores filled with water, m the cementation factor (1.3 to 2), n the coefficient of saturation (approximately 2) and F the formation factor.

Table 2. Sources of investigations aiming to provide different relationships between geoelectrical parameters and hydraulic and chemical parameters

	Reference	Relationship between
Hydraulic conductivity	Kelly, 1978; Mazac et al., 1988 and 1990; Frolisch et al., 1996; Singhal et al., 1998; Yadav & Abolfazli, 1998; Aristodemeou & Thomas-Batts; 2000; deLima & Niwas, 2000	Aquifer electrical resistivity and aquifer hydraulic conductivity.
	Kalinski et al., 1993a and b	Geoelectrical parameters and time-of-travel through unsaturated layers.
	Edet & Okereke, 1997; Singhal et al., 1998; Yadav & Abolfazli, 1998	Transverse resistivity and aquifer transmissivity.
	Curtis & Kelly, 1990	Soil resistivity and recharge characteristics of vadose and soil zones.
Water resistivity	Kelly & Asce, 1977; Barker, 1990; Ebraheem et al., 1997	Soil resistivity and water resistivity.
	McNeill, 1990	Bulk resistivity and water resistivity in clayey environments.

Table 2. (Continuation from previous page)

Water chemistry	Cahyna, 1990	Water resistivity and concentration of dissociated salts.
	Rhoades et al., 1990	Soil electrical conductivity and soil salinity.
	Frolisch et al., 1994	Pore water resistivity and NaCl-equivalents.
	Simon et al., 1994	Electrical conductivity and dissolved salts.
	Ebraheem et al., 1997	Earth resistivity and TDS.
	Meju, 2000	Bulk conductivity of the formation and TDS.
Other	Biella et al., 1983	Formation factor, porosity and permeability.
	Kelly & Reiter, 1984	Electrical properties and hydrology under anisotropy.
	Mazac et al., 1987	Geoelectrical and hydrological parameters, such as mineralisation, porosity, hydraulic conductivity and clay content.
	Goyal et al., 1996	Resistivity and moisture content.
	Singhal et al., 1998	Apparent formation factor and hydraulic conductivity.
	Yadav & Abolfazli, 1998	Formation factor and hydraulic conductivity or porosity.

Characteristics of resistivity measurements

Resistivity measurements have been used for a great variety of purposes in environmental applications. Some of these are listed below in no particular order of preference.

- Characterization of landfill deposits (thickness, internal structure, cover) (e.g. Carpenter et al., 1990; Whiteley & Jewell, 1992; Kobr & Linhart, 1994; Cardarelli & Bernabini, 1997; Bernstone & Dahlin, 1998b; Meju, 2000)
- Location of the extent of capped landfills (e.g. Cardarelli & Bernabini, 1997; Bernstone & Dahlin, 1998b)
- Hydrogeological, lithological and structural characterisation of the investigation site (e.g. Schröder & Henkel, 1967; Masac et al., 1987; Petersen et al., 1987; Barker et al., 1990; Christensen & Sørensen, 1994; Sørensen, 1994)
- Groundwater flow, including relationships and connections between the ground surface and the groundwater (e.g. Kelly & Acse, 1977; Nobes, 1996; Lile et al., 1997; Cimino et al., 1998)
- Composition of the groundwater (e.g. Masac et al., 1987; Nobes, 1996)
- Detection of the presence of contaminants in the vadose and groundwater zones, patterns of movement (e.g. Kelly & Acse, 1977; EPA, 1978; Masac et al., 1987; Buselli et al., 1992; Chapman & Bair, 1992; Hannula & Lanne, 1995; deLima et al., 1995; I & II)
- Extrapolation between well data (e.g. Draskovits & Fejes, 1994; Christensen & Sørensen, 1994).

DC resistivity measurements have a number of advantages compared to other more traditional techniques used for groundwater investigations. Of course the method has a number of limitations as well. Some of the important characteristics, both positive and negative, are listed below.

Advantages

- It may give a general characterization of a large area, from which the most interesting smaller site, for example with suspected contamination, can be delineated and the location of monitoring wells can be optimised (e.g. Draskovits & Fejes, 1994).
- It is a non-destructive remote sensing technique that minimises the necessity for intrusive techniques such as construction of monitoring wells and direct sampling of groundwater (e.g. Ebraheem et al., 1990).
- It gives resulting maps showing the areal validity of information obtained by drilling, water sampling or any other point information (e.g. Draskovits & Fejes, 1994).
- It is based on a relatively simple theory and on well-developed interpretation techniques (e.g. Goldman & Neubauer, 1994).
- It provides a relatively inexpensive way of obtaining data on electrical properties of the ground (e.g. Ebraheem et al., 1990; Aaltonen, 1998b).

Disadvantages

- Direct contact between the electrodes and the soil is required (e.g. Goldman & Neubauer, 1994).
- It can only be used for such contaminants that in some way affect the electrical conductivity.
- It is not suitable if the concentrations of contaminants fall below the detection threshold (e.g. Karous et al., 1994).
- It gives a non-unique solution, as results achieved, i.e. the physical model, can often be interpreted as several geological models (e.g. Goldman & Neubauer, 1994).
- The sensitivity decreases with depth (not if borehole resistivity measurements are applied).
- It is sensitive to the presence of even thin resistive layers, which may shield underlaying targets (e.g. White et al., 1984; Goldman & Neubauer, 1994).
- It is sensitive to disturbances such as rapidly changing topography, near surface lateral changes, seasonal changes, irregular subsurface conditions, buried objects, power lines, fences and railroads (e.g. EPA, 1978; Dahlin, 1993; Nobes, 1996; Aaltonen, 1998a).
- It can be difficult to detect and map thin, highly conductive layers of contamination (e.g. Whiteley & Jewell, 1992).
- It gives only a rough determination of the groundwater table. In fact only the top of the capillary fringe is found, since pore water in the capillary zone is most often connected to each other and this lowers the resistivity (e.g. Van Dam, 1976; Aaltonen, 1998a).

The resistivity method results in an average of a large volume of ground, a bulk integrated value, which can of course be both an advantage and a disadvantage. It is an advantage when the aim is to characterize a larger area, especially in heterogeneous environments, as it gives an average of the volume instead of a specific value valid only for a minor part of the measured volume. It is a disadvantage as it can be hard to map minor objects, for instance thin, highly conductive layers or single flow paths.

Hydrogeological and chemical considerations

The problem of resolving the question of detectability of contaminants in the ground is complex and comprises the definition of flow lines of groundwater in the aquifer, the travel times of water along these flow lines and the prediction of chemical reactions, together with the factors of mass transport (advection and dispersion) (e.g. Gelhar et al., 1992 and Appelo & Postma, 1994).

In Swedish moraine terrain the transport velocity of the groundwater decreases remarkably with depth due to the higher degree of consolidation at depth. Often the ability to transport water in the horizontal direction is 1:100 to 1:1000 greater than in the vertical direction (Espeby & Gustafsson, 1997). Thus, in general the plume has a horizontal dimension much larger than the vertical. Figure 2 presents common hydrological structures in Swedish terrain, which affect tracer flow or groundwater contaminant patterns from a landfill.

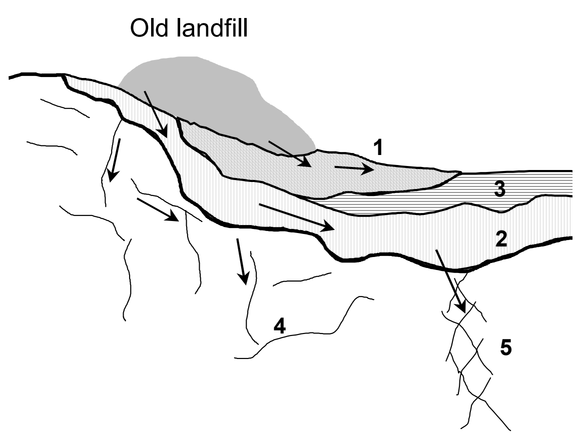


Fig. 2. Sketch of some common hydrogeological structures in Sweden and their influence on the spread of contaminants. (1) Highly permeable sand. (2) Semi-permeable till (leakage moves along specific pathways). (3) Poorly permeable clay (aquitards). (4) Semi-permeable fractures, forming interconnected fracture systems in hard crystalline rock. (5) Permeable fracture zones. (Aaltonen, 1998a).

The success of the electrical measurements in locating plumes furthermore depends on the size and shape of the plume and the resistivity contrast between the indigenous groundwater and the invading fluid, as stated earlier. It is difficult to quantify the contrast needed, due to a wide range of site conditions and plume configurations, but some figures are reported in Table 3.

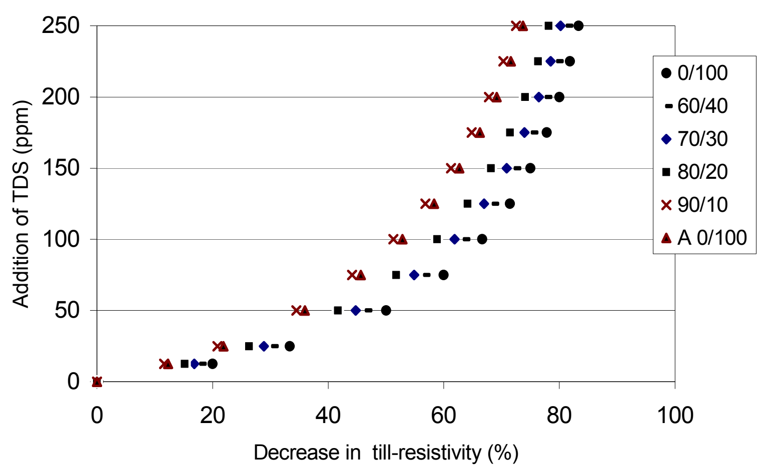
Table 3. Reported contrast or changes in electrical conductivity of groundwater needed to provide a reliable resistivity contrast

Reference	Comment
EPA, 1978	The contaminated groundwater should have a conductivity of 5 to 10 times that of the natural groundwater to give good resistivity results.
Greenhouse & Harris, 1983	Contamination easily mapped when conductivities were at least 3 times background levels.
White et al., 1984	A change of 20% or greater in the value of the ground conductivity may produce a good target.
Benson et al., 1988	Needed contrast between background and anomalous should be at least 1 to 1.5.
Buselli et al., 1990	A factor of 2 from non-contaminated to contaminated, but considers this as only slightly higher than the measured background spatial variation in formation resistivity.
Campanella & Weemes, 1990	5 - 10% electrical contrast, assuming that there are no lithological variations.
III	Conductivities should be at least 2 times background level (laboratory experiment)

Saksa and Korkealaakso (1987) state that the normal resistivity contrast between the leachate from a landfill and 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. This implies a dilution in concentration of 10 to 100. In an imaginary scenario, a 1/100 part of the saturated zone in a till aquifer (60% unsaturated zone and 40% saturated zone) is invaded by leachate of 1 Ωm. This will result in a decrease of 70% at the point of measurement for a dilution of 10, and a decrease of 20% for a dilution of 100. The corresponding figures for a clay environment would be a 20 % and a 0 % decrease respectively (IV). However, this assumes non-changing lithology.

McNeill (1990) reports that an addition of 25 ppm of TDS (Total Dissolved Solids) to the groundwater increases the groundwater conductivity by about 1 mS/m. The relationship between the decrease in normal resistivity of till and clay environments due to the addition of TDS is shown in Fig. 3 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 Meju (2000) and Patnode & Wyllie (1950).



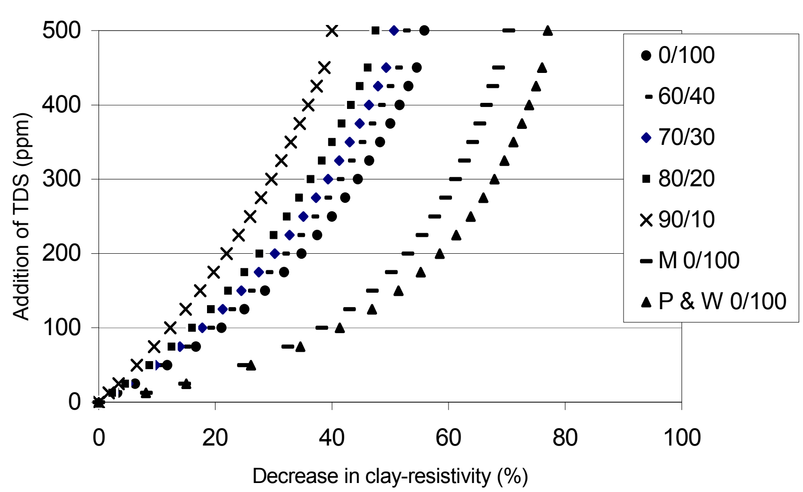


Fig 3. Decrease in normal resistivity based on McNeill's (1990) assumption that an addition of 25 ppm TDS increases the conductivity by 1 mS/m. The legend shows different ratios of percentage unsaturated ground to percentage saturated ground in the volume measured. The calculations assume that all TDS are moving in the saturated zone, while the unsaturated zone can be regarded as dry. A: Archie's Law (Parasnis, 1997). M: Meju (2000). P&W: Patnode and Wyllie (1950). (IV).

In addition, synthetic examples by Whiteley & Jewel (1992) show that the change in TDS would have to be greater than 20 to 50% to show a noticeable change in a sounding curve if the contaminated layer is sandwiched between two resistive layers. In the case of an intermediate conductive contaminated layer in-between a highly resistive surface and a conductive basement, the change in TDS should be close to 100% to cause a significant change in the shape of a sounding curve.

Type of contamination is also decisive for the success of detection. Table 4 presents a compilation of a number of different investigations relating to different sources of groundwater contamination. As most investigations reported are from predominately successful investigations, the table is by no means complete for chemicals non-detectable by resistivity measurements.

Table 4. A compilation of some resistivity investigations and the main chemical parameter outlined

	Reference	Comments
Landfills	Seitz et al., 1972	Correlation between landfill leachate (TDS content) and low resistivity areas.
	Benson et al., 1988	Correlation of geoelectrical measurements and groundwater chemical analyses has been as good as 0.96 at the 95% confidence level for organic contaminants.
	Benson et al., 1988	Correlation of resistivity with physical and chemical parameters of conductivity, ammonium, nitrogen, sodium and total organic content (TOC) of water samples ranged from 0.756 to 0.885 at the 95% confidence level. As might be expected, conductivity and sodium showed the greatest correlation.
	Barker, 1990	Landfill leachate outlined, Cl content 45-100 mg/l.
	Buselli et al., 1990	Landfill leachate outlined, where high Cl content and EC correlate with low resistivity.
	Buselli et al., 1992	The main solutes contributing to a detectable increase in conductivity are usually chloride, sulphate, bicarbonate and sodium ions.
	Whiteley & Jewell, 1992	Solid domestic waste normally produces a highly conductive leachate (1.5 to 10 Ωm), which may be outlined from natural non-saline groundwaters.
	Senos Matias et al., 1994	Correlation between landfill leachate (conductivity of groundwater) and low resistivity areas.
	Bernstone, 1998	Landfill leachate outlined. Mean resistivity of leachate water from 26 Swedish landfills was 2.9 Ωm.
	Kayabali et al., 1998	Landfill leachate outlined, Cl content 100-1600 mg/l, ΣFe 1- 23 mg/l, TDS 600-4600 mg/l.

Table 4. (Continuation from previous page)

	Reference	Comments
Mines	Aloa, 1985	Abandoned copper mine, leachate with high levels of $CaCO_3$, Ca and HCO_3 outlined.
	Knuth et al., 1990	Formation brine from gas wells, leachate with high levels of Cl and Br outlined.
	Benson, 1995	Acid mine drainage, leachate with high levels of SO_4, Fe, Pb and Zn outlined.
Storage tanks	Benson, 1992	Good correlation between lower resistivity values and high contamination values of benzene, toluene, ethyl benzene, xylenes and total petroleum hydrocarbons (TPH).
Oil pollution	Mazac et al., 1989	Oil pollution detected as increasing resistivity.
	Campanella & Wemees, 1990	Insulating organic NAPLs increase bulk resistivity by blocking paths of conduction through the pore space of the soil.
	Henderson, 1992	Organic contaminants are less easy to detect than inorganic types, being generally non-conductive. However, crude oils may contain salt and refined hydrocarbons may be anomalously resistive.
	Whiteley & Jewell, 1992	Contaminants which are naturally resistive and do not mix with groundwater, e.g. hydrocarbon compounds such as oil, may displace natural groundwater causing a local increase in resistivity where they pool.
	Atekwana et al., 2000	LNAPL from 50 years of leakage into glacio-fluvial geological settings was outlined as low resistivity zones.
	Sauck et al., 1998 and Sauck, 2000	Controlled spill experiments concur that high electrical resistivity and low relative permitivity are characteristic of geological media contaminated by hydrocarbon spills. However, many field investigations of LNAPL contaminated sites report results of a decreasing resistivity instead. An explanation can be the change with time of LNAPLs due to biodegradation.
Saltwater intrusion	Nowroozi et al., 1999	Resistivity (Ωm) – Geology – Salt content (mg/l) 0.5-10 – porous sand or saturated clay – 1500-20000 10-30 – sandy clay to clayey sand gravel – 700-5000 30-100 – sandy gravel – very small to 100
Tracer test	Gheith &Schwartz, 1998	2000 mg/l NaCl, provided a measurable conductivity contrast.
	Khair & Skokan, 1998	0.25 g/l NaCl reduced resistivity by about 30% and an increase from 0.75 to 1.75 g/l NaCl reduced the resistivity by about 40 %.

Table 4. (Continuation from previous page)

	Reference	Comments
Tracer test	al Hagrey & Michaelsen, 1999	Resistivity decrease directly proportional to water salinity. The negative anomalies minima of 5%, 55, and 125% for salinities of 0.5 g/l (TDS of tap water), 5 g/l (KBr) and 10 g/l (KBr) respectively, with the corresponding water resistivities of 15, 1.5 and 0.75 Ωm.
Others	Tillman, 1981	Resistivity correlates well with groundwater data on mineral intrusion (NaCl and SO_4).
	Ringstad & Bugenig, 1984	Location of zones with acceptable levels of TDS in the groundwater (between 800 and 2000 mg/l).
	Stierman, 1984	Resistivity used for outlining areas with liquid wastes, including industrial solvents, acids containing salts and heavy metals, and organic residues from pesticide manufactures.
	White et al., 1984	Acids and chemicals that dissolve into ions are good electrical targets, by increasing the electrical conductivity. A decrease in pore fluid conductivity, such as occurs with a number of petroleum products, can also be a target. Certain contaminants, which themselves would not necessarily increase conductivity in pure water, may react with natural groundwater impurities and cause chemical reactions that increase the groundwater conductivity.
	Saksa & Korkealaakso, 1987	The increase in electrical conductivity correlates with the increase in concentration of chloride, dry solid content, and also permanganate ($KMnO_4$) and chlorinated hydrocarbon (1,2-dichloroethane), but not with phenols (C_6H_5OH).
	Mazac et al., 1989	Liquid wastes from a uranium-bearing cold scrap recovery plant outlined with decreasing resistivities.
	Cahyna et al., 1990	Cyanide outlined in laboratory experiments.
	Subbarao & Subbarao, 1994	Resistivity used for outlining areas with leachate from an alcohol distillery and from a zinc smelter plant.
	Bernstone & Dahlin, 1998a	High levels of metal contaminants (Cr up to 13800 mg/kg dry substance and Cu up to 11000 mg/kg dry substance) could not be correlated to the results of CVES measurements. One reason for this deficiency can be that the contaminants are predominantly found as adsorbed into clay and organic materials and the impact these particles have on the ohmic conductance is probably small.

The success in oil leachate mapping has been dependent on either increases or decreases in the resistivity. However, as Sauck (2000) expressed it, the old prevailing model of an increase in resistivity has mostly been achieved in laboratory environments, while decreases in resistivity are predominant in field investigations, where the oil spill has been exposed to chemical interactions.

Finally, it has to be stated that if a certain level of contamination can be detected with resistivity surveys in one aquifer type, then it is not at all certain that the same level of contamination would be detected in a different aquifer. This is due to different clay contents or high resistivity surroundings as pointed out by e.g. Buselli et al. (1990). The spatial variation in geology causes a variation in resistivity over several hundred decades.

3

Resistivity and Seasonal Variation

The resistivity of the ground varies due to factors such as variation in geology, temperature and water content of the ground, where the water saturation is considered to govern the resistivity response most (e.g. Benson et al., 1988; Clark, 1990 and Nobes, 1996). However, it can be difficult to determine the contribution of each of these factors on the measured resistivity when their effects are considered simultaneously and when the different factors also interact and depend on each other.

As resistivity reacts to the variation in seasonal factors, it can be used to investigate the same. Johansson & Dahlin (1996), for instance, combined temperature and resistivity measurements in embankment dams to study seepage. The resistivity method has been used to determine the soil water content in different investigations. As early as 1978, Constantino et al. used electrical soundings at time intervals to investigate the water content of the soil (calcarenites overlain by cultivated soil). Later, Goyal et al. (1996) used resistivity-sounding data acquired at different times to study the temporal variation in a soil moisture profile (both synthetical data and field data). Benderitter & Schott (1999) did a similar investigation in which repeated resistivity measurements were used for detailed studies of vertical water movement in the vadose zone (marly beds with sand) due to natural cycles of water saturation. The resistivity method can also be used to investigate the effect of ground frost. For instance, Ferguson and Desrosiers (1998) have used resistivity to determine the thickness of the frozen layer within different years and locations in Canada, to get information for instance for agricultural planning and for modelling run-off during snowmelt and spring rainfall. Similar investigations have also been made by Scott et al. (1990).

When using resistivity for monitoring purposes it is of great importance to separate natural variations in resistivity from variations caused by anthropogenic sources. However few investigations are done to take this variation into consideration. This chapter will show seasonal variation in resistivity in different Swedish soils, together with a discussion of two approaches for taking these seasonal variations into account.

Examples of resistivity and seasonal variation

Several investigations were carried out to investigate the extent of seasonal variation (Aaltonen, 1998b; II, III, V and VI). The investigations differed both in scale and in duration. However, all of the investigations carried out focused on the seasonal variation in the resistivity and not on its diurnal variation.

The range of variation in resistivity in different soils is presented in Figs. 4 and 5.

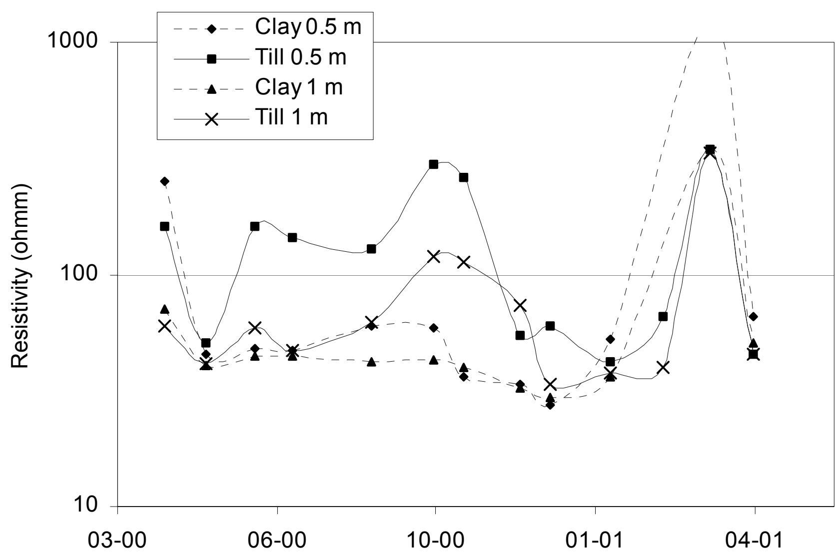


Fig 4. Comparison of resistivity variation versus time in clay and till soil, measured with a Wenner array (electrode spacing 0.5 and 1 m) at Högbytorp. Note that the measurements in April 2000 and March 2001 were affected by ground frost (see also VI).

In Fig. 4, the largest seasonal range occurs in till, 260 Ωm within an twelve month period for a Wenner array, with 0.5 m electrode spacing, compared to about 30 Ωm in the clay, if the measurements affected by ground frost are omitted. The corresponding figures for the electrode spacing of 1 m are 80 Ωm in till and about 10 Ωm in clay.

When looking to larger soil volumes using a 5 m electrode separation, the largest variation was found in an area with superficial gyttja clay, followed by a clayey till and a silty fine clay (Fig. 5).

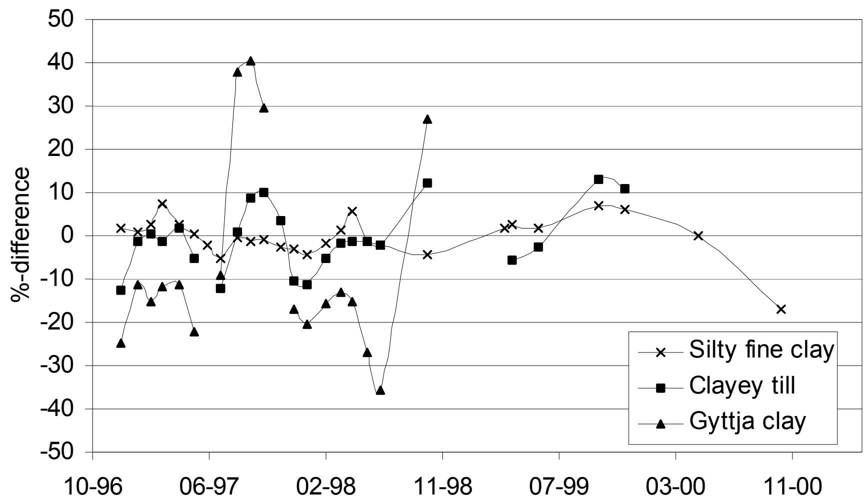


Fig. 5. Seasonal variation in resistivity of three different soil types in Högbytorp. The resistivity measurements were made with a Wenner array, 5 m electrode spacing (Aaltonen, 2001).

Consideration of seasonal variation

As the geology is non-changing in a monitoring programme for control of groundwater contaminant migration, the resistivity of the ground at each specific measuring point can be said to be dependent on simply the soil moisture, ground temperature and ion concentration, where soil moisture is in turn dependent on soil type, vegetation (transpiration), topography (drainage) and weather factors (precipitation, evaporation and temperature). The important challenge for monitoring of resistivity is to determine the variation in resistivity without including the effects of soil moisture and temperature variation. Another approach is to describe the total seasonal variation, independent of the factors affecting it, by long-time series and by that set limits for an acceptable variation in resistivity.

Here the two approaches are described, where the first is based on linear relationship giving the variation in soil moisture resistivity versus time and the other is based on long-time series of resistivity data, giving a resistivity variation span, showing the normal and acceptable levels of resistivity (III and VI).

The computation approach is based on a linear relationship between soil moisture and resistivity. Resistivity data from twelve months (Wenner array, 0.5 and 1 m electrode spacings) were used, and corrected for the change in soil temperature, to a resistivity at 6 ^{0}C (mean temperature). Thereafter, this resistivity was compared to a measured soil moisture content, showing a linear relationship (R^2=0.5 to 0.7) between the two factors, for both till and clay soils (Fig. 6). These results indicate a linear relationship between the soil moisture and ground resistivity, where the residual remaining represents the conductivity variations that are related to changes in ion concentration of the soil moisture.

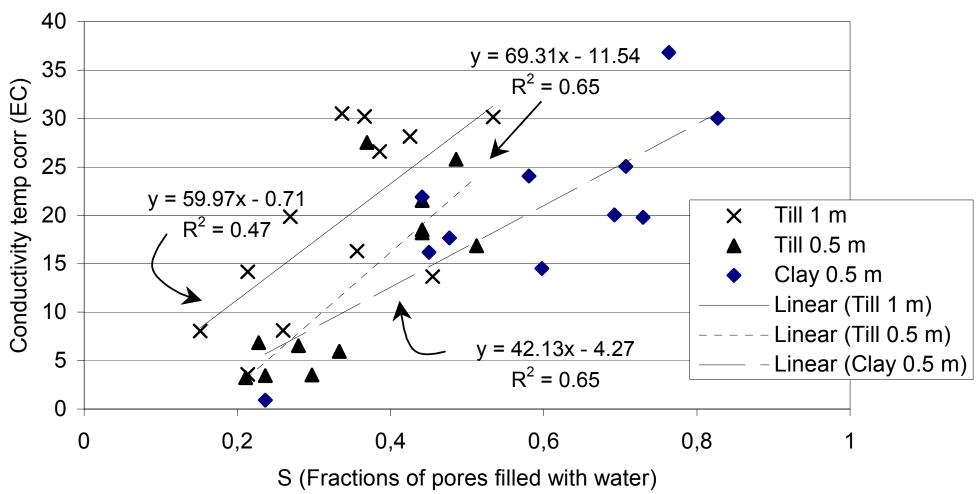


Fig. 6. Temperature corrected conductivity values versus fractional soil moisture content measured with TDR, for the two soils (0.5 and 1 m electrode spacing) (VI).

The long-time series approach preferably supposes initial conditions that represent unaffected ground. The presented example is based on intense (monthly or more) resistivity measurements over a period of four years. The mean of these measurements was used as a baseline year, while the maximum and minimum established the limits of variation. These limits, of course, differ due to the geology of the area monitored as seasonal variation also differs due to geology. The measured profiles, categorised both according to the geology and to the variation due to season, were then applied as the base for a resistivity variation span (maximum to minimum resistivity).

In Fig. 7, the example is illustrated with a baseline composed of the mean resistivity of monthly measurements from the existing landfill at Högbytorp (III and IV). When measurements fall below the minimum acceptable variation, measures have to be taken as this indicates a non-normal low resistivity in that particular area, compared to the baseline, which should represent a normal climatological year. This is further discussed, with respect to monitoring, in Chapter 4.

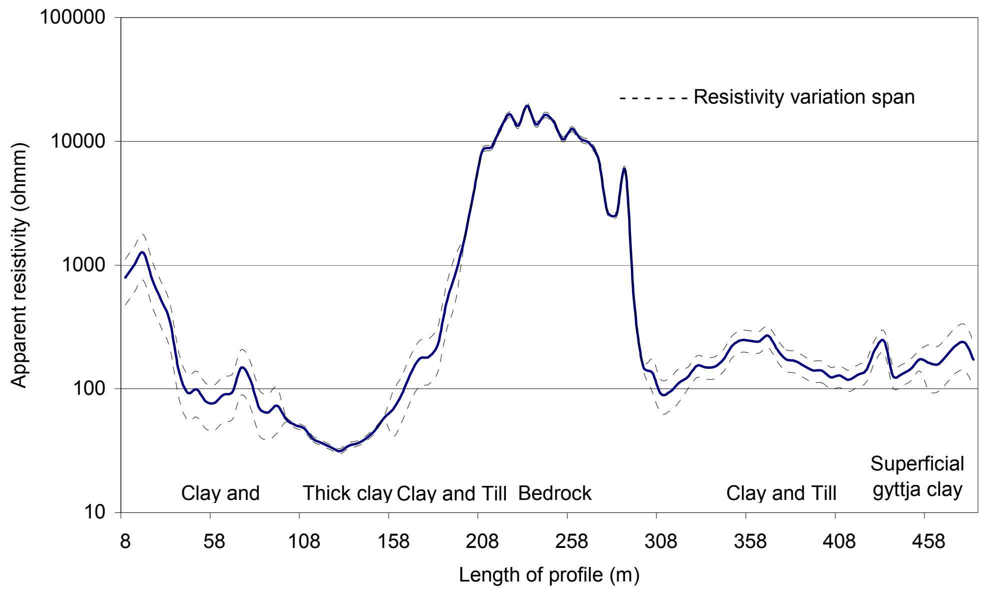


Fig 7. Example of a resistivity variation span, where the lower limit will be decisive for acceptable resistivity values. Measurements from the Högbytorp landfill (IV).

Discussion on seasonal variation

The seasonal variation in resistivity can sometimes be considerable, and dependent on several interacting factors. For instance during the summer/autumn season, high temperatures coincide with lower water content of the ground, while during spring low ground temperatures are combined with snowmelt, giving high soil moisture contents. The seasonal variation in resistivity is of course also dependent on the depth of investigation. This can be seen in Aaltonen (1997) and VI. Similar results were also reported by Buselli et al. (1992), where strong seasonal responses were seen for small current electrode spacings (AB/2 = 10 m Schlumberger).

The seasonal variation investigated and consideration of the approaches suggested are discussed in the following:

Soil moisture

- Soil moisture variations did not fully explain the variation in measured resistivity, probably because a seasonal variation also occurs in concentration of ions in the soil moisture (III and VI). In clay soil another explanation can be the so-called double layer of exchange ions. This double layer consists of a fixed layer immediately adjacent to the clay surface and an outer diffuse layer. Ions in the diffuse layer are free to move under the influence of an applied electric field, resulting in an increased surface conductivity (Ward, 1990).

Groundwater table

- The variation in resistivity was only explained by the variation in groundwater table in a few cases. One explanation may be the depth to the groundwater in the investigation areas (III). The variation in groundwater table is to a large extent governed by the size of the aquifer, the effective porosity and by the topographical location (recharge or discharge area) and to a lesser extent by the seasonal variation. However, in till the seasonal variation can be extensive. Another explanation is that the groundwater level was only measured in few points, not representing all of the different geologies investigated with resistivity measurements.

Precipitation

- Even if it can be hard to obtain a good direct relationship between the ground resistivity and the precipitation due to a lag between the occasions of rainfall and its effect in the soil matrix (see also Al Chalabi & Rees, 1962 and Nobes, 1996), precipitation data may be valuable for assessing ground moisture conditions and by that normalising the resistivity variation from annual series (Fig. 8).

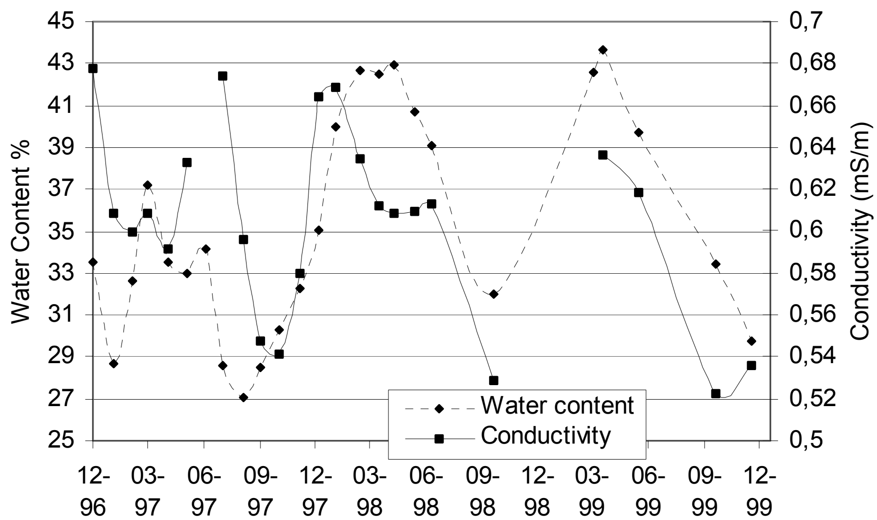


Fig. 8. A comparison between a simulated soil moisture content and measured resistivity in till soil (5 m electrode spacing, Wenner array). The soil moisture was modelled with CoupModel (Jansson & Moon, 2001) using climatological information (precipitation, air temperature, cloudiness and groundwater table) from the investigation site as input data (III).

Consideration of seasonal variation

- The computation approach suggested for till and clay soils provide the possibility to consider variation in temperature and soil moisture, and to calculate a normalised variation in resistivity. However, input data are needed on soil moisture and temperature, which can be hard to achieve for larger areas. But as shown in III and Fig. 8, the temporal dynamics in soil moisture can be simulated, based on general precipitation-, groundwater fluctuation- and temperature data.

- The suggested way of dealing with seasonal variation in resistivity results by a long-time series approach may under certain circumstances be lacking in precision. The suggested period of baseline measurements, 1-2 years, will be too short in certain hydrogeological and climatological environments, and by that give a baseline which cannot be considered normal. One way of dealing with this problem of short periods of baseline measurements is to put the resistivity results in relation to long-time series of weather data, such as for instance precipitation and groundwater table, and by that calculate the variation in the normal resistivity year for the area in question, together with return times. However, this has to be further investigated.

- For projects with a more short-term perspective Nobes (1996) for instance have recommended that the survey should be conducted within a limited period of time, and the ground conditions can be regarded as consistent for the entire survey period. Al Chalabi and Rees (1962) and Clark (1990) are of the opinion that resistivity measurements for shallow purposes, such as archaeological studies, should be made during seasons with lower amounts of rain, that is May to September in England. In Sweden the period with lowest amount of rain extends from April to June.

4

Resistivity and Monitoring

As stated already in the Introduction, resistivity measurements for monitoring purposes can overcome limitations of water chemical analyses from scattered observation wells around contaminated areas. However, relatively few examples of long-term monitoring programmes around landfill areas or other larger contaminated environments are to be found in the literature (Benson et al., 1988; Osiensky, 1995; Kayabali et al., 1998; Aristodemeou & Thomas-Batt, 2000), compared to examples concerning mapping of groundwater contaminants. Most current work concentrates on automatic early warning leak detection systems under impermeable layers in pond construction (Parra, 1988; Parra & Owen, 1988; Van et al., 1991; Kalinski et al., 1993a and b; Binley et al., 1997; Frangos, 1997; Taylor et al., 1997) and on monitoring using borehole resistivity measurements (Benson et al. 1988; Karous et al., 1994; Bernstone et al., 1996).

This chapter will discuss the characteristics of measurements for long-term monitoring, together with a suggestion for a permanent or semi-permanent monitoring system, which would be suitable around operational sites as a complement to existing observation wells.

A major concern in groundwater sampling for mapping and monitoring of contaminants is the design of the sampling network. Important considerations in design include the need for close interval point sampling and sample location that take into account the character and complexity of flow (Domenico & Schwartz, 1990). Today, the following recommendations are stipulated when designing a groundwater-sampling programme in Sweden (SEPA, 1994 and 1996):

For investigation of known leachate or spill

- Groundwater wells should be installed to define the source strength and to delimit the contamination. This means at least one well should be placed in the most contaminated area. Furthermore, wells are placed to define the border between contaminated and non-contaminated areas. At least one well should also be placed up-stream from the contaminated area to give a reference value. At least three additional wells have to be installed to decide the major groundwater flow direction.

For monitoring leachates

- Sampling should be carried out in at least one point in the inflow region and two points in the outflow region of the contaminated area. The number of points should be decided on the basis of hydrogeological investigations and how quickly the leachate migration has to be determined.

Both types of sampling are done at different times during the year, hence the seasonal variation in the groundwater composition can be described. Some examples from Sweden (SEPA, 1989) show that each of four landfills (10-13 ha) had only 2 to 10 groundwater sampling points. Although leachate migration was present, nothing was seen in the observation wells within three of the areas.

It is important to remember that many of the constraints of resistivity methods reviewed in Chapter 2 are of course also limiting in the case of monitoring. Furthermore, the following advantages and disadvantages can be found with resistivity measurements for monitoring purposes:

Advantages

- Measures the properties of larger soil volumes, which gives a more volumetric covering monitoring, compared to single observation wells (e.g. Benson et al., 1988).
- Gives relative measurements, which are relatively easy to interpret since the variation in results due to a spatial variation in geology can be neglected (e.g. Van et al., 1991; Bernstone et al., 1996).
- Can easily be combined with water sampling from observation wells (e.g. Benson et al., 1988).
- Can be arranged in simple measurement system without large need of maintenance.
- Can be varied in infinity, for example in spacing between electrodes (depth of investigation).
- Can be automated (e.g. Henderson, 1992; Dahlin, 1993).
- Can easily be run by landfill personnel, if limits of acceptable resistivity variation are set by experts.

Disadvantages	▪	Does not directly give an answer on which contaminant and in which concentration.
	▪	Can be hard to detect contaminants occurring in single fractures.
	▪	Can be difficult to decide an appropriate electrode spacing in order to determine in which horizon the contamination will move (this problem may be overcome by measuring several electrode spacings with for instance CVES).
	▪	Gives less resolution when performing deeper investigations which will comprise larger volumes of ground. A high contrast between the affected and unaffected ground will, however, make the measurements feasible.

Example of resistivity monitoring

A simple, low-cost monitoring system was developed and used from December 1996 and onwards, around parts of an operational landfill at Högbytorp, north-west of Stockholm (II to IV). The system set-up is based on fixed electrodes that are spaced 5 m apart in a Wenner array. Measurements are made using two electrode spacings, measuring volumes of soil down to two depths, approximately 2.5 and 5 m (Fig. 9). The time needed for one person to measure both electrode spacings is approximately 150 - 200 m/hour.

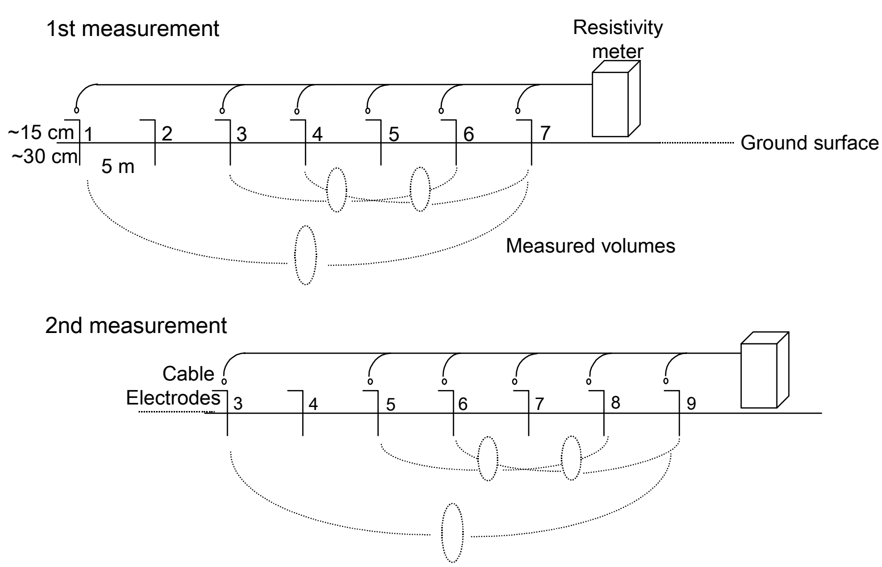


Fig. 9. System layout, with fixed electrodes, cable and measurement course. The dotted lines indicate the measured ground volumes at each set-up. The cable is free and connected for each measurement occasion.

The system in Fig. 9 was cheap and simple to install. The cost of stainless steel electrodes (~50 cm long, of which 30 cm is buried in the ground) was approximately USD 260 per km. Electrical wire for the cable used (5 and 10 m Wenner configuration) cost only approximately USD 25.

The monitoring was performed from December 1996 and roughly once a month until December 1999, in order to obtain a picture of the natural seasonal variation. During 2000 measurements were made in late spring (May) and late autumn (October/November).

Fig. 10 shows the resistivity of one part of the monitoring system during the first years. The lateral resistivity variation in the area is considerable and clearly reflects the strongly different geological conditions (Fig. 11), whereas the variation over time is approximately 15 % (with a range of 2 to 35 %) from the mean value at each specific point. This mainly reflects the seasonal variation, such as the soil moisture and the groundwater level.

The large variation coefficient for +10 to +50 m is due to a transfer of the profile in 1998. Otherwise, larger variation coefficients are seen for the areas with till, which generally shows a larger seasonal variation than more fine-grained soils (Chapter 3).

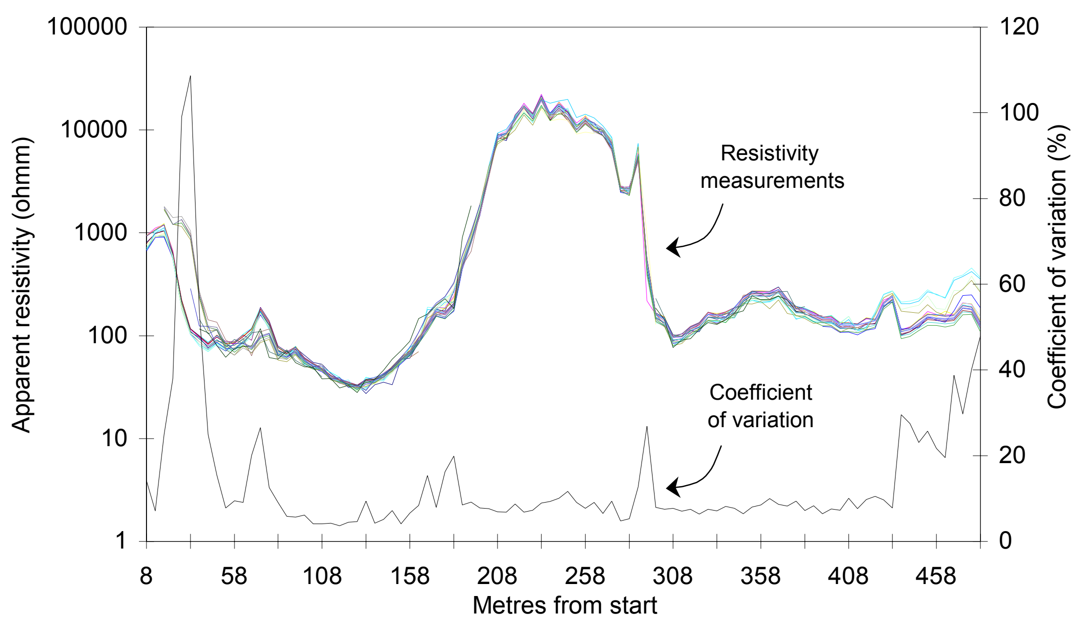


Fig. 10. Apparent resistivity along a resistivity monitoring transect at Högbytorp for 26 measurement occasions. The bottom curve gives a rough picture of the variation during the years of measurement (IV).

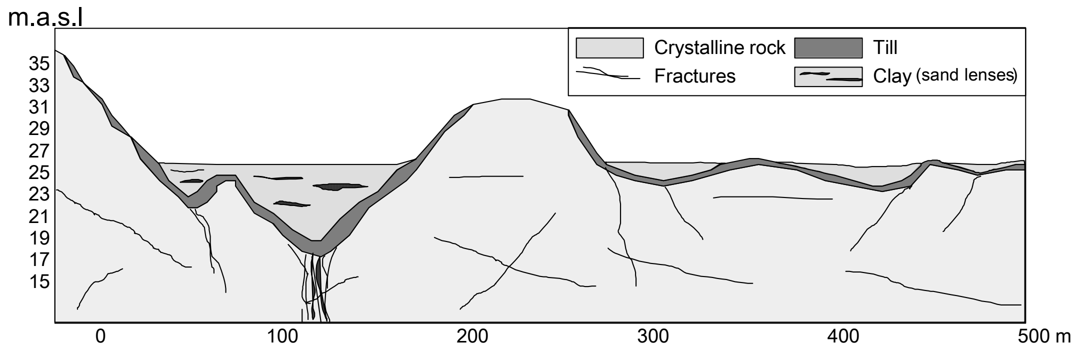


Fig. 11. A generalized geological section of the transect in Fig. 10. The section is compiled from geological surface mapping, subsurface radar measurements and manual sounding (IV).

The leachate from the landfill has a resistivity of about 1 Ωm (corresponding to an EC of 1000 mS/m), which together with the moderate seasonal variation and the stretch of monitoring lines close to the landfill (< 100 m) favour the detectability of contaminants. During the four years, however, no sign of leakage was detected along the measured profiles or in groundwater samples collected from tubes along the same transect.

Discussion on design and operation

The design of a resistivity monitoring programme is dependent on the present situation (geological and climatological), the object (type of deposit, size) and type of plume being monitored, the hydrogeological environment and the required accuracy. Three main groups of systems can be outlined (Aaltonen, 2000; IV) and the characteristics of the three different monitoring systems are summarized in Table 5 below.

- Permanent system: Permanently installed electrodes and cables around or beneath a contaminated area or construction.
- Semi-permanent system: Electrodes permanently installed, cable connected while measuring (see example above).
- Fully mobile system: All equipment needed is arranged at approximately the same locations for each measurement occasion.

Table 5. Three example of resistivity monitoring systems (Aaltonen, 1998b)

System type	Advantages	Disadvantages
Permanent	Permits fast and easy measurements to be made automatically. Measurements can be made throughout the year if the electrodes reach below the ground frost layer. Can also be installed beneath a landfill. Measurements can be made to several depths depending on the cable used.	Expensive. The cost of cable will be high for larger sites. Requires construction work to protect the cable.
Semi-permanent	Cheap to install and easily applied at landfills in operation. Measurements can be made throughout the year if the electrodes reach below the ground frost layer. Measurements can be made to several depths depending on the cable used.	More time consuming during measuring, due to reconnection of cables. Cannot be used beneath a landfill or leachate dam.
Mobile	Cheapest as no installation efforts are needed. The most adjustable system to different depths. Measurements can be made down to several depths depending on the cable used.	Higher measurement scatter, due to difficulties in placing the electrodes at similar positions. Most time consuming. Difficulties in measuring during winter, due to ground frost. Cannot be used beneath a landfill or leachate dam.

Permanently installed systems are most advisable, but due to costs it can be recommended to use them primarily for new establishments and around smaller sites, for instance around or under pond constructions where extensive measuring can be needed. Semi-permanent systems are again advisable for larger areas or around existing constructions where permanent installation can be difficult. Fully mobile systems should only be applied in cases where there is no possibility for grounding permanent electrodes or where monitoring is seldom needed. However in, for example, homogeneous peat and clay areas with minor natural variations, a mobile system can be used.

The resistivity measurements can be made with any suitable measurement method such as VES, profiling or CVES measurements. High-density measurements are achieved with CVES systems, which give a large number of electrode spacings and, hence, several investigation depths at one time, while low-density measurements are characterised by more simple systems, giving for instance 1 to 3 different electrode spacings (see example in Fig. 9).

It is advantageous if the monitoring system can be constructed before the establishment of a landfill or other hazardous site, in order to determine the pre-contaminated status. However, if the aim is to construct a monitoring system around an operational site, the lack of pre-contamination measurements can to some extent be overcome with a more thorough groundwater sampling in those parts where the resistivity from the start appears to be unusually low.

The most critical part of development of any long-term groundwater-monitoring programme is in eliminating, or at least minimizing, the errors made in the assessment of the overall site conditions (Benson et al., 1988). This means that a site investigation (modified after IV) should include the following parts:

- Review of old investigation material, such as geological maps and borings.
- Complementary geophysical and geotechnical investigations in order to define groundwater and bedrock levels, clay zones etc. The definition of a correct groundwater level is important, so that the optimal electrode spacing is chosen, especially for low-density measurements (if only using some different electrode spacings). If CVES is used this problem is to a large extent overcome.
- Establishment of a conceptual hydrogeological model of the area in question, as a basis for the identification of possible groundwater flow paths.
- Decision on other parameters to measure, such as the seasonal variation in soil moisture and soil temperature, which may affect the variation in resistivity.
- Decision if, where and when complementary drilling and water sampling should be carried out.

Furthermore, the following should be considered, for installation and maintenance (IV):

- The location of measuring lines is often limited by existing constructions such as cables, fences and other interfering objects.
- Fixed electrodes may disappear, due to animal or human activities. This problem can be overcome if the measuring lines are placed inside fencing of the area or if the system is permanently installed and covered.
- Electrodes may be hard to locate (if a semi-permanent system is used), due to high grass and snow cover.
- Agreement with landowners about land use recommendations, since changes of land use may affect the results.

The equipment needed for a resistivity monitoring system is listed in Table 6.

Table 6. Equipment needed for a resistivity monitoring system

Equipment	Recommendations
Electrodes	▪ Stainless steel, or other material with low impedance. ▪ Robust. ▪ At least 20 cm below ground surface, in dry areas even deeper. ▪ Visible above ground surface, even with dense vegetation cover (not needed if a permanent system is used). ▪ For more coarse-grained soil, some type of stainless steel screw is more suitable than ordinary rods, as these tend to shake loose and can be hard to ground deep enough.
Cable	▪ Multi-conductor cable (length depends on need). ▪ Robust (if buried directly in the ground). ▪ Robust connection (non-rusting and durable).
Resistivity meter	▪ Weather proof. ▪ Easy to operate. ▪ Large data storage capacity.
Other	▪ Marking poles.

One example of localisation of a monitoring system is shown in Fig 12, where the resistivity profile stretches from an outcrop area and crosses a valley in order to cut off the prevailing groundwater flow. The profile is also located so that it passes by existing observation wells for a direct correlation between groundwater chemical analyses and resistivity measurements.

It is important to have a reliable and easy handled evaluation tool for all data collected. As the seasonal variation in both soil moisture and temperature affects the resistivity results, data should be normalised according to Chapter 3 and VI. A resistivity variation span can also be applied. However, this is more uncertain as values affected by contamination can fall inside the span if it is set too wide. This is especially the case in environments where the natural variation of, for example, soil moisture is large.

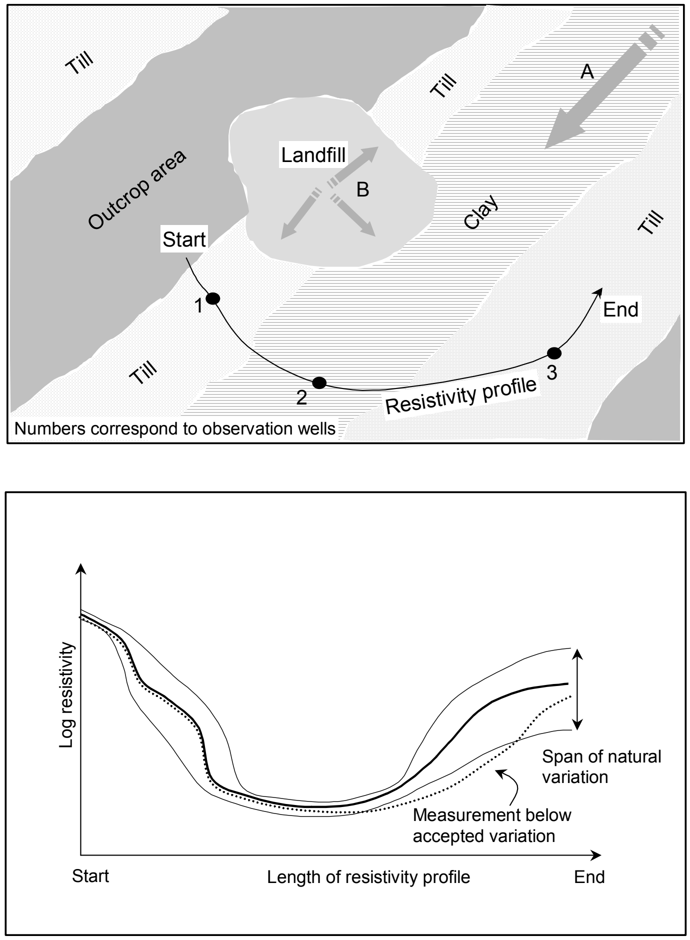


Fig. 12. Example of a resistivity profile for monitoring purposes around parts of a landfill area. The top figure shows the localisation and the bottom figure the baseline resistivity with a normalised resistivity span. The grey arrows in the top figure represent A) natural groundwater flow direction and B) local groundwater flow.

An example of an evaluation tool is given in IV, with an especially developed PC-programme for comparison of large numbers of time series. The main function of the programme is to compare one set of data to former data series by statistics, including automatic alarm functions if resistivity decreases to a value lower than fixed limits. Such operations are sufficient if the seasonal variation in the investigation area is low and the contrast between unaffected and affected ground can be considered high in every geological environment present. For more complicated environments the evaluation tools are complemented with Modified Double Mass calculations, which can distinguish even minor trends in the data sets, to differentiate between effects of natural variations and those of contamination (Fig. 13).

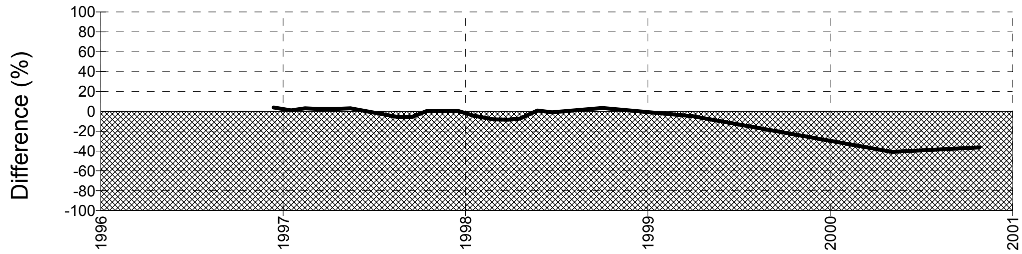


Fig. 13. Differences calculated by Modified Double Mass, between resistivity at the test positions of 350 m at the transect presented in Figs. 10 and 11, and a synthetic site based on mean values of 5 sites along the same transect. A decrease in resistivity amounting to 15 % of original values was introduced after May 1999 (IV).

Finally, if measurements fall below the minimum acceptable level, as in Figs. 12 and 13, further investigations can be required as listed below. However, it should be remembered that the minimum acceptable level should be set according to seasonal variations but also according to current regulations, which may state that some leachate is acceptable in an operational phase.

- More frequent measurements in the area in question during a limited time, to see if the result was due to an occasional measuring error or a real event.
- A more detailed investigation, with for instance denser spaced electrodes and CVES or soundings to see at which depth the divergence occurs.
- If the difference continues to be too large, an additional observation well may need to be installed, to enable water chemical analyses.

5

Resistivity and Tracer tests

Resistivity measurements used as a complement in tracer tests are much like resistivity used for monitoring purposes. In both cases the aim is to map and monitor a conductive tracer with time, the contaminant itself or an injected tracer solution. However, tracer tests are usually carried out within a quite limited period of time. The difficulty with tracer tests today is most often the limited number of observation wells available. These wells should be open throughout the whole groundwater zone, or at several depths, to catch the injected tracer. The advantage with resistivity is that due to the larger volume of ground measured, a better picture of the flow patterns can be achieved, with less risk of losing the tracer. Tracer tests with an injection of a conductive solution have been utilised for vertical and horizontal flow pattern investigations (White, 1988; White, 1994; Osiensky, 1995; Gheith & Schwartz, 1998; Park, 1998; alHagrey & Michaelsen, 1999; Slater & Sandberg, 2000) and groundwater flow velocity determination (Rønning et al., 1995; Lile et al., 1997). Observe that the investigations referred to have used a number of different geoelectrical methods and not specifically surface resistivity measurements. Most of the above-mentioned applications could also be combined, as for lateral measurements, which can comprise an analysis of both flow patterns and travel time.

This chapter will discuss how resistivity measurements can be used in tracer tests investigating the groundwater flux and patterns, especially in areas with few observation wells.

Example of resistivity measurements for tracer tests

In Table 7, five different experiments with resistivity and tracer tests are shown. The experiments comprise one laboratory experiment and four field set-ups. The field experiments were carried out in different geological environments in the vicinity of Stockholm, mid-Sweden. All measurements were carried out with a Wenner configuration, and with a CVES-system for the field set-ups.

The small amount of injected tracer solution led to small changes in baseline resistivities, only around 10 %. However, a decrease, a minimum and a starting recovery phase were observed, reflecting the passage of a NaCl solution, in the laboratory, Löten and Rydbo experiments. At Högbytorp the measurement period was limited to four days, and only minor effects could be seen closest to the injection point. In the case of Katrineholm, no decrease at all could be seen with the resistivity method in the profile closest to injection (only 20 m away), as it was disturbed by numerous underground cables and constructions. However information about the major flow paths in the area was obtained from the second profile.

Table 7. Characteristics and results of some DC measurements in tracer tests (V).

Location	Soil	Ground-water table beneath ground surface	Aquifer thickness (m)	Hydraulic gradient	Distance between injection point and last profile (m)	NaCl-tracer (l and g/l)	Ground-water pumping (l/min)	Electrode array	Minimum resistivity reached after (h)	Maximum decrease (%)**	Calculated groundwater velocity (m/s)	Calculated change in electrical conductivity (Archie's Law) (mS/m)
Labora-tory	Sand	- 1.5 cm	0.1	Not measured	0.45	1 l and 1 g/l	Flow 0.04 l/min	Wenner, electrode spacing 5 cm, length 20 cm	80 min	11 %	$7.8 * 10^{-5}$	3
Löten	Sandy gravel	-1.2 m	~10	0.02	16 (3 lines)	80 l and 125 g/l	9 l/min	CVES Wenner, electrode spacing 1 m, length 20 m	20 h	7 %	$1.3 * 10^{-4}$	2
Rydbo	Boulders, gravelly sand and silty filling	-0.9 m	~1	0.006	16 (3 lines)	80 l and 250 g/l	Not measured	CVES Wenner, electrode spacing 1 m, length 20 m	23 h	7 %	$1.8 * 10^{-4}$	1
Högby-torp	Clay and till	-0.4 m	~4	0.03	17 (3 lines)	110 l and 270 g/l	-	CVES Wenner, electrode spacing 1 m, length 20 m	-	-	-	-
Katrine-holm*	Sand and gravelly sand	-9.5 m	~5	0.01	300 (2 lines)	10000 l and 0.2 g/l	~2400 l/min	CVES Wenner, electrode spacing 2 m, length 40 m	-	-	-	-

* Unpublished consultant's report.

** Calculated as the maximum decrease in the mid-line.

The groundwater velocities were estimated by using an approach suggested in V, which considers the reciprocal of the change in ion resistivity as an ordinary break-through curve, see Fig. 14. Observe that this is only one of several break-through curves that can be constructed from CVES measurements.

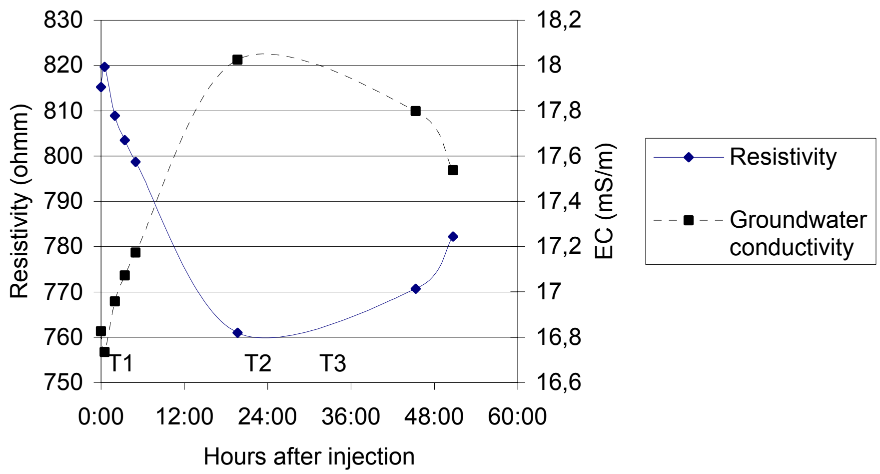


Fig 14. Example of a break-through curve, measured with resistivity during a tracer test in the Löten gravel pit, outside Stockholm. The groundwater conductivity was estimated using Archie's Law (V).

Time T1 in Fig. 14 is the shortest time for some parts of the tracer to move from the injection point to the observation point. Time T2 expresses the maximum concentration of the tracer in the aquifer at the observation point. Time T3 gives the time when 50 % of the tracer has passed, and thereby represents the average residence time. Finally, Time T4 was not reached for the case presented (except for the laboratory case), but gives the time for the last detectable concentration, showing how long a tracer/contaminant can stay in the investigated aquifer. In the examples from laboratory, Löten gravel pit and Rydbo quarry, the velocity values were all within the range given in the literature reviewed (V).

To see if all the injected tracer has been recovered, and by that the whole plume, Fig. 17 can be used as an approach. In the case of Löten, the ground volume showing a decrease in resistivity, together with estimates of how much NaCl this corresponds to, were used to estimate the amount of passed tracer. This calculation gave 7 kg of NaCl compared to the 10 kg used. In Rydbo, this estimate only recovered 4 of 20 kg, mostly depending on uncertainty in determination of porosity.

Finally, at Löten, where the conductivity of the pumped groundwater was measured, the difference between baseline and maximum conductivity was approximately 3 mS/m. Using Archie's Law, the maximum difference was estimated to 2 mS/m. In the laboratory case, the measured difference was 10 mS/m compared to the estimated difference of 3 mS/m (V).

Discussion on design and operation

When setting up a tracer test based on resistivity measurements the applicability, set-up and accomplishment should be considered (V), together with a careful site characterisation as suggested in Chapter 4:

Applicability

- Which aquifer thickness? According to White (1988), the resistivity measurements are limited to velocity tracer tests in aquifers within 10 to 20 m below the ground surface. This restriction is due to the loss of resolution by depth, since an increased electrode spacing leads to an increased soil volume measured. However, as in the case of Löten (see Table 7) where the aquifer thickness was considerable, the tracer could be followed due to the superficial groundwater level, the shallow application of tracer and the short distance between injection point and measured profiles. This limitation in thickness is of course also dependent on the present geology, where superficial conductive layers may further decrease the depth.

- What natural resistivity does the investigation area have? Resistivity measurements are not suitable in areas which from the beginning are low resistive (< 10 Ωm), as in areas with saline groundwater or very conductive surface layers (White, 1988). Maybe freshwater can be used as a tracer, but there is to my knowledge no experience of this.

- What disturbance factors can be found in the investigation area? Resistivity measurements can be disturbed by man-made installations, such as underground power lines or other constructions. Investigation areas in urban environments may also have a large share of hard surface cover, such as asphalt, which limits the possible installation of electrodes.

- What is the expected shape and dimension of the injected tracer plume? If a very thin plume is expected due to for instance geological conditions, this may be undetectable by resistivity (e.g. Whiteley & Jewell, 1992).

Set-up

- How to design resistivity profile locations? Some examples are shown in Fig. 15, but almost any type will cover a tracer injected in the injection point. However, the spacing between the profiles is decisive if the moving plume is very narrow (B and D). A grid net could be applicable with profiles measured in different directions or where the electrodes could be connected as square arrays (E). Example C is suitable when there is no knowledge of the prevailing groundwater flow direction.

- What electrode configuration to choose? The level of knowledge regarding tracer tests is relatively weak. White (1994) has carried out some investigations in this area, although the results are stated as uncertain. The resistivity rectangle had the maximum percentage decrease in resistivity due to tracer injection, followed by downhole electrode, Schlumberger sounding, Wenner profiling, Wenner sounding and mis-a-la-masse. Results from the tracer tests presented using a Wenner array, with CVES profiles perpendicular to the expected groundwater flow direction, proved usable in following injected tracers.

- Spacing between electrodes? The spacing between the current electrodes determines the sensitivity of the measurement to the passage of a tracer injection. The optimum spacing is best estimated by initial VES measurements (e.g. Kelly & Acse, 1977; White, 1988), from which the depths of different geological structures and groundwater level can be interpreted. The current electrode spacing should enable measurements in which a large enough part comprises the saturated zone and by that the tracer flow. This can be determined by modelling the effect of a tracer on the apparent resistivity at each current electrode spacing in a VES (White, 1988). Today the possibility of using CVES systems to a large part overcomes this problem, since it enables measurements using several electrode spacings.

- Distance between profiles? The distance between profiles is given by the investigation area (size, distance between injection point and last profile, disturbing constructions and the possible locations of the resistivity arrays). Of course densely situated profiles give best results but the amount of available equipment can be decisive.

- Which tracer to use? The main function of the tracer is to change the prevailing resistivity of the aquifer in a measurable way. Examples of tracers used are NaCl (White, 1988 and 1994), KBr (al Hagrey & Michaelsen, 1999) and $CaCl_2$ (Cahyna, 1990), where NaCl is the most common. NaCl is also a well-known tracer in ordinary tracer tests, as it is considered reliable, cheap, easy to access, easy to analyse and is not considered to bring about environmental or health hazards (Tilly et al., 1999).

- Which tracer concentration to use? A sufficient contrast is needed (see Chapter 2), but this can be hard to decide, due to dilution and change in geological conditions within the investigation area. The use of a too high concentration can cause a sinking of the tracer to the lower parts of the aquifer due to density differences, and thereby give an incorrect picture of the natural groundwater flow and velocity. If the tracer test is applied in aquifers used for drinking water, the taste limit of 300 mg Cl/l should not be exceeded. The amount of tracer and concentration of tracer should be based on calculations of aquifer size, hydraulic conductivity etc.

Accomplishment

- Instant or continuous application of tracer? A tracer can be added instantaneously or over a period of time. The method is chosen according to the aim of the investigation. For traditional groundwater sampling, an instantaneous addition is preferred during investigations of hydraulic connections, flow paths and velocities, together with dispersion parameters, while addition over a longer period is preferred if the aim is to investigate mixture parameters (Tilly et al., 1999). In the field investigations presented here (V), instantaneous injections were used in order to get a maximum contrast of resistivity.

- Groundwater pumping or not? This is dependent on the time available for the experiment. The need for pumping can be quite obvious, especially in till, where the hydraulic conductivity can be as low as 10^{-6} to 10^{-10} m/s. One example is shown in V, where a tracer test was carried out with injected NaCl-solution and without pumping in a till (approx. 3 m to bedrock). The hydraulic gradient was about 0.03 and within 4 days only a minor influence was seen in the resistivity profile located 4 m from the infiltration pit. However, it should be realised that pumping also influences the flow pattern and should not be used if the aim is to investigate natural groundwater conditions.

- Measurement interval? The measurements interval should be defined as for traditional tracer tests, by estimates of possible residence times. Because of the great uncertainty that is coupled to the residence time, dense measurements should be employed at the beginning of the test, with a successive decrease later on (Tilly et al., 1999). Resistivity measurement can be applied to measure automatically, and by that a continuous picture with time can be achieved. However, this is most often impracticable due to lack of instrumentation and unwillingness to leave instrumentation at the investigation area for longer periods. In the cases presented, it was simplest to leave the electrodes in the measurement profiles and move the cable and instrument between the profiles.

- Total investigation time? This depends on the aim of the investigation. If a complete break-through curve is wanted, for analyses of how long a contaminant can stay in the aquifer, the measurements have to continue until a complete recession is reached for the resistivity.

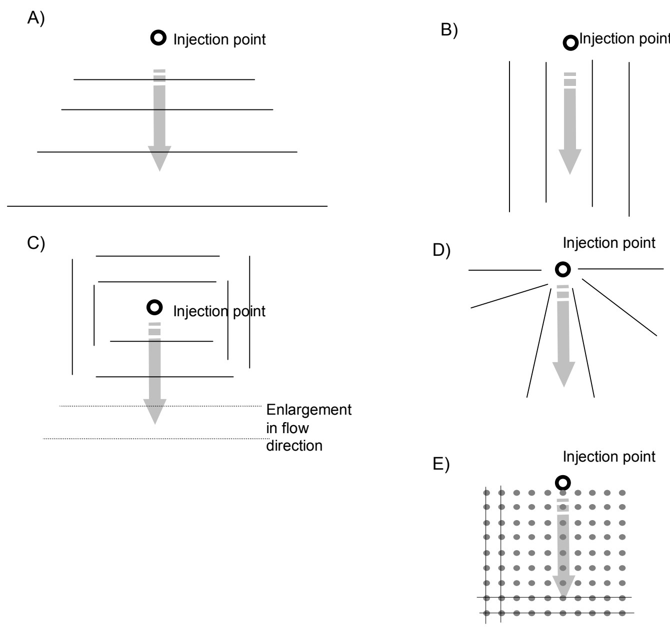


Fig. 15. Different electrode patterns (modified after White, 1988). The lines in A to D represent resistivity profiles (profiling, sounding or CVES) and the points in E the electrodes. The grey arrows represent the groundwater flow direction. Observe that the volume a resistivity measurement comprises is much larger than the line of measurements.

The interpretation of resistivity results from a tracer test can be divided into three different aims: To determine the groundwater flow pattern, to decide the groundwater flow velocity and to investigate the chemical composition of the groundwater. The results for the two first aims can be presented as in Fig. 16 where the measured resistivity profiles are presented as cross-sections or as a lateral picture of the resistivity distribution using specific electrode spacings and finally as a resistivity versus time graph. The result can easily be arranged to show the change by time at each measured point (see V). A combination of the presentations of A and B in Fig. 16 or using example E in Fig. 15 as a measurement technique could give a 3-D picture of the investigation area, as suggested by e.g. Bernstone et al. (1997) and Dahlin et al. (1997).

If the measuring period for tracer test is relatively short (< some weeks), the natural variations are assumed to be minor, hence, a decrease of around 15 % of the baseline resistivity should provide a detectable result. However, extended tracer test, may need a correction of seasonal variation as suggested in Chapter 3 or parallel reference measurements in an unaffected but similar hydrogeological environment.

It should also be possible to use the Modified Double Mass approach suggested in Chapter 4 and IV to see when the tracer is approaching and where in the measured cross-section.

The last aim of investigation is the chemical composition of the groundwater, a topic further discussed to some extent in Chapter 1 and V.

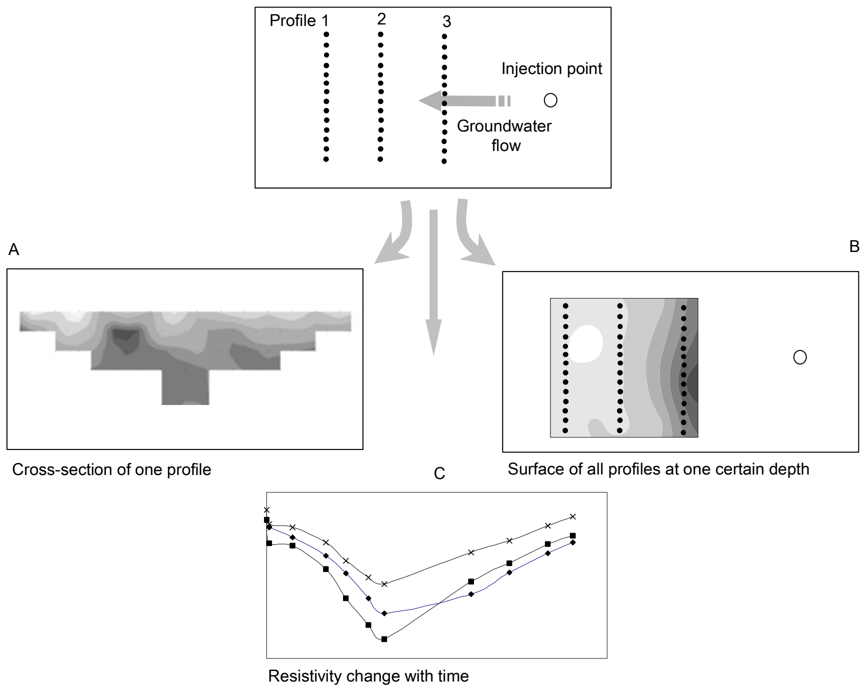


Fig. 16. Examples of the presentation of results from resistivity measurements in tracer tests. A) Cross-section of each profile. B) Surface picture of all profiles for a certain electrode spacing C) Graph of the resistivity for some measurement volumes by time (V).

Finally, in Fig. 17 an approach is suggested for how the recovery of the injected tracer can be estimated. The recovery will show the success of the tracer tests, in means of catching the whole plume with the measured resistivity profiles. The parallel CVES profiles will give a tracer plume with different volumes (depending on the migration pattern and porosity of the soil) and with different resistivities by time. This change in resistivity can be expressed in conductivity and by this also as concentration of chloride (V). Together with the change in volume this gives the amount of chloride for each measurement occasion.

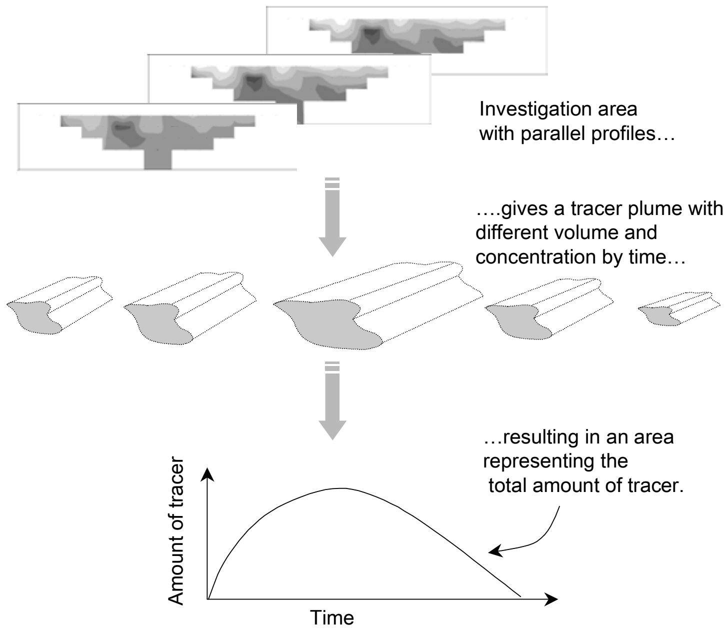


Fig. 17. Approach to estimate the recovery of used tracer, from CVES profiles.

6

Conclusions

First of all, it can be concluded that resistivity measurements can supply valuable information, both in the case of mapping and of monitoring conductive groundwater contaminants, in accordance with both reviewed and achieved experiences. However, although this thesis has concentrated on resistivity methods, it cannot be emphasized enough that resistivity should not be used as the sole investigation method, but should be complemented with, for instance, groundwater sampling and chemical analyses.

Based on the discussions within the three main chapters of this thesis, the following can be concluded:

Resistivity and Seasonal Variation

- The values for seasonal variation in resistivity, obtained for a Swedish forest with till and clay, varied from 2% to 35 % (15 % in mean), compared to a mean resistivity from 1 ½ years (5 m electrode spacing, Wenner array). For shallow investigations (1 m electrode spacing, Wenner array) the seasonal variation is more extensive (around 30 % compared to a mean).
- A variation in resistivity of 15 % compared to a mean is within the range of what is considered to be the requisite contrast between natural resistivity and that which can be regarded as anomalous resistivity (Table 3) and by that indicating that the seasonal variation may conceal the presence of minor amounts of groundwater contaminants if not adjusted.
- The computation approach developed to take temperature and soil moisture variation into account in till and clay soils explained 47 to 65 % of the variation. It was shown to be a feasible way of describing the residual or, in other words, a normalised variation in soil moisture resistivity.
- The long-time series approach with resistivity measurements carried out over a period of time provided an overview of the natural seasonal variation in resistivity in different soils, but lack in reliability as regards distinguishing low concentrations of contaminants within the resistivity variation span.

Resistivity and Monitoring

- Resistivity monitoring with a semi-permanent, low-density measurement system proved to be an easy and low-cost way of establishing a more laterally covering groundwater monitoring around an operational landfill area.
- The resistivity measurements required an initial time of measuring under natural, undisturbed conditions in order to obtain a reliable baseline.
- The suggested evaluation tool showed that a decrease of 15 % in the mean value at a specific site was possible to detect using Modified Double Mass calculations between resistivity time series and time series at a reference site with a comparable seasonal variation.

Resistivity and Tracer Tests

- Resistivity measurements proved to be a valuable complement to groundwater sampling in tracer tests. A decrease in resistivity, a minimum and a recovery phase reflected the passage of a NaCl-solution.
- The results of the resistivity measurements can be used to estimate flow velocity and flow patterns of the aquifers investigated and provide information on subsurface geological conditions.
- A recovery of 20 to 70 % of the tracer was achieved by calculating the change in affected ground volume and change in concentration due to a passing tracer.

Concluding remarks

- The measurement system for long-term monitoring or tracer tests, to be chosen considering layout and frequency, depends on the intended purpose and on site-specific conditions and therefore no standard system can be proposed.
- For monitoring purposes, high-density systems should be applied in areas with a complex hydrogeology and a very fluctuating groundwater table, as the system gives a vertical cross-section of the area in question. Low-density systems are usually adequate in hydrogeological environments with few layers and a shallow and stable groundwater table, or when less detailed information is needed (both in time and space).
- For tracer tests, the use of CVES-systems (Continuous Vertical Electrical Sounding) is recommended, both due to the density of measurements achieved and to the capability to measure automatically.
- Before using resistivity measurements within tracer tests, estimations of the required amount of tracer based on the depth and size of the aquifer, together with estimated groundwater flow, are necessary. A high concentration will give detectable resistivity changes even in deep aquifers, but too high a concentration may cause unwanted differential flows.

Future research

Finally, some thoughts on future research. Research should continue on the modelling of both monitoring and tracer test results in 3-D and 4-D, to give a full picture of the course of events due to contaminant migration. Research should also continue on normalising resistivity due to seasonal variation both by empirical relationships and by climatological return times.

In addition, more practical experience is needed on the detectability of different types of contaminants, in different concentrations and in different types of geological environments. A comparison could also be made between traditional point sampling and geophysical investigations (also integration of different methods) considering accuracy compared to lateral coverage. For example, it could be valuable to determine the number of wells needed to describe the hydrogeology in different aquifer types and then to establish the density of geophysical investigation to which this is comparable.

7

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8

Abbreviations and Definitions

Most of the following abbreviations and definitions, with some modifications, are found in:

1. Glossary of Waste Management. Swedish Centre of Technical Terminology Publication, TNC 62, 1977.
2. Nordic Glossary of Hydrology. Almqvist & Wiksell International, Stockholm, 1984.
3. Chambers Science and Technology Dictionary. Chambers and Cambridge, 1988.
4. Glossary of Geology. Swedish Centre of Technical Terminology Publication, TNC 86, 1988.

In the text the glossaries are referred to by their number.

ABEM Lund Imaging System:	Automatic system for resistivity and induced polarization imaging, working with a roll-along system, allowing long vertical cross-sections. Manufactured by ABEM Instrument AB, Sweden.
Anisotropy:	The quality of variation of a physical property with the direction in a body at which it is measured (2).
Anthropogenic:	Change, resulting from or influenced by man's activities (3).
Apparent resistivity:	A measured value and a function of the true layer resistivities, their boundaries and the location of the electrodes. In a homogeneous substratum, the apparent resistivity is a good approximation of the resistivity.
Aquifer:	A body of geological material, which can yield water in significant amounts (2).
Array:	Set of electrodes, placed in a fixed order.
Baseline:	Undisturbed measurements made before a tracer test, construction of a hazardous area etc.
Bedrock:	The solid rock underlaying soils or weathered surface rock (2).
Capillary fringe:	Belt of subsurface water held intermediately above the zone of saturation by capillary action (2).
Configuration:	The spatial arrangement of electrodes in a resistivity array.

Conceptual model: Simplified representation, often mathematical, of some or all processes in the hydrological cycle by a set of hydrogeological concepts (2).

Contaminant: An unwanted component added to a system from an external source.

CVES: Continuous Vertical Electrical Sounding also called multi-electrode system.

DC: Direct Current.

Double Mass: Successive accumulated values of one variable against the contemporaneous accumulated values of another variable (2).

EC: Electrical Conductivity. Ratio of current density to applied electric fields (3). Measured in siemens per metre. The direct inverse reciprocal of resistivity.

Geophysics: The application of the principles of physics to the study of the Earth. The subject includes meteorology, atmosphere electricity and ionosphere physics. In this thesis, geophysics is defined as the study of the physical characteristics of the Earth's outer layers.

Glaciated terrain: Terrain formed by glaciers in the past (2).

High-density measurements: Resistivity profiling with a high number of measurements with several different electrode spacings, giving a cross-section of the resistivity distribution.

Landfill: Site for deposition of waste as well as the contents of the same, also called waste deposits (1).

Leachate: Polluted water from accumulated waste at a landfill site, compost etc. (1). Consists of precipitation-, surface- or groundwater, which leaves after passing through the deposited material or by surface run-off leaving the deposited material.

Low-density measurements: Resistivity profiling with a few number of measurements, with one or two electrode spacings.

Mapping: Measurements made to determine the lateral and/or vertical situation at a particular time.

Monitoring: Measurements made at fixed locations as a function of time.

Moisture content: The quantity of water per unit volume or unit dry weight of soil (2).

Moraine: Deposit or landform of glacial till.

Ohm's Law: The current I flowing through a material is proportional to the potential difference V, the constant of proportionality being the conductance of the material. $I=V/R$ or $V=I*R$, where R is the resistance of the material (3).

Profiling: Lateral measurements using constant electrode spacing.

Pseudosection: Apparent resistivity systematically plotted versus profile position and corresponding electrode spacing. Gives an approximate picture of the apparent resistivity in a vertical cross-section.

Regression analysis:	Mathematical method of studying the correlation between variables (2).
Resistivity:	Physical property of a material, which indicates the in-situ resistance that a material has to the passage of an electrical current. Measured in Ωm. Resistivity is also the inverse of conductivity.
SAS300/SAS4000:	Resistivity meters manufactured by ABEM Instrument AB, Sweden.
Saturated zone:	That part of the lithosphere where the soil pores are completely filled with water (2).
Schlumberger:	A common array, mostly used for sounding. The inner potential electrodes are close together, while the outer current electrodes are more dispersed.
Soil:	The loose geological deposit of the Earth.
Sounding:	Vertical measurements made at a single location at increasing depth.
Surveying:	Investigation.
TDR:	Time-Domain Reflectometry. An instrument which detects the transmission properties of wideband systems, components and lines by feeding in a voltage step and displaying the pulses reflected from any discontinuities on a suitable oscilloscope (3).
TDS:	Total Dissolved Solids, a measure of the total ion content of a fluid.
Till:	Non-stratified glacial drift deposited directly by the ice and consisting of clay, sand, gravel and boulders intermingled in any proportion (2).
Tracer test (or method):	The use of dye, salt or other substances to trace the movements of water (2).
Unsaturated zone:	Upper part of the soil water zone where water is held under negative pressure and where the pores contain some air (2).
VES:	Vertical Electrical Sounding, see also Sounding.
Wenner:	Symmetric, straight-line array, with equal distance between the electrodes.