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Influence of natural time-dependent variations of electrical conductivity on DC resistivity measurements

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Abstract

Long-term direct current (DC) resistivity monitoring surveys are carried out to investigate structures and processes in the subsurface which are coupled to changes in electrical conductivity. Examples would be leaching tests in the unsaturated zone or the observation of a salt tracer spreading in the saturated zone. As these investigations usually take some hours to weeks, natural time-dependent background variations of electrical conductivity have to be considered.

Parameters influencing the electrical conductivity are temperature changes, variable water contents in soil due to precipitation or changing groundwater levels, and natural fluctuations of the ionic content in groundwater. Measurements over different time periods (one month to one year) at different test sites demonstrated daily and seasonal trends of electrical conductivity and temperature of groundwater, surface temperatures and groundwater levels. Variable water saturation and changing soil temperatures (in the uppermost soil) are estimated to influence the electrical conductivity most significantly, followed by changing water temperatures and varying ionic content.

To verify these conclusions, multi-electrode DC resistivity monitoring has been performed at two test sites for 16 and 22 days. The results reflect natural characteristics and processes in the subsurface. With mean values and standard deviations of apparent resistivities plotted in pseudosections, different areas of the subsurface with different ranges of resistivity variations have been specified. In the area of variable groundwater level (varying water saturation) and in the uppermost soil (strong temperature and moisture changes), especially high resistivity variations are obvious (up to 26%). In the saturated zone, variations are low (predominately below 1%).

Concerning resistivity measurements, we conclude that electrodes positioned below the groundwater level (e.g. for salt tracer tests) or between the uppermost meter of subsurface and the area of variable groundwater level (e.g. for leaching tests in the unsaturated zone) should be used to avoid strong influences of background variations.

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1. Introduction

Geoelectrical surveys are performed to investigate subsurface structures and processes, which are coupled to spatial or temporal variations of electric

conductivity. For the investigation of hydrogeological features, long-term monitoring measurements are carried out. An important problem is that measurement results do not depend on desired effects only (e.g. a salt tracer movement) but also on natural background variations of electrical conductivity.

Objectives of geoelectrical monitoring surveys are, e.g. the dynamic of moisture migration in the unsaturated zone, or groundwater flow directions and velocities. For processes in the unsaturated zone, both natural recharge and forced loading (following a tracer input) conditions have been studied recently, e.g. using cross-borehole tomography (e.g. Daily et al., 1992; Slater et al., 2000; Binley et al., 2001).

To determine groundwater flow directions and velocities, geoelectrical measurements in combination with salt tracer injections have been used for many years. First applications have been carried out with the *mise à la masse*-method originally developed for ore explorations (e.g. Nesterov et al., 1938; Gorelik, 1951; Dachnov, 1953). With one current electrode placed in the area of the salt plume, this method is restricted to the area near the borehole.

For the investigation of shallow aquifers, direct current (DC) resistivity measurements at the surface allow a monitoring of a salt tracer spreading over large areas (e.g. Fried, 1975; White, 1988, 1994; Kollmann et al., 1992; Morris et al., 1996). Due to dilution processes, observation time for a salt tracer spreading is restricted to several days or some weeks (e.g. Patton, 2001). When planning a salt tracer test, knowledge on background variations of electrical conductivity is helpful to specify the amount of salt to be injected or to place the electrodes for the monitoring measurements.

In this paper, natural time-dependent background variations of electrical conductivity are analysed. Natural variations of electrical conductivity in the subsurface are induced by several factors, such as varying conductivity of the groundwater, changing soil moisture, variations of the groundwater level or changing temperatures.

To discuss the reasons for these variations, several parameters have been measured. Data on the electrical conductivity and temperature of groundwater and on groundwater level variations (test sites Lauswiesen and Safira, see Fig. 1), and on surface temperatures (weather observatory station at Rottenburg-



Fig. 1. Location of the test sites.

Kiebingen, about 15 km west of Tübingen, Germany) have been analysed. These data regard different observation periods (ranging from one month to about one year) and different measurement frequencies (one measurement per hour to one measurement per day). Furthermore, the influence of different ionic contents on fluid conductivity has been approximated. From the evaluated parameter variations, estimations have been made concerning maximum effects on electrical conductivity of the subsurface.

To verify the conclusions, DC resistivity monitoring measurements have been performed for 16 days (test site Lauswiesen) and for 22 days (test site Safira). This time period has been chosen because geoelectrical surveys, e.g. for the monitoring of salt tracer plume commonly are performed over a period of some hours to days. The results are discussed concerning natural variations of electrical conductivity specific to different parts of the subsurface. Finally, recommendations are given for the performance of DC resistivity investigations.

2. Reasons for the variation of electrical conductivity in the subsurface

Factors inducing variations of electrical conductivity in the subsurface are:

- changing soil moisture
- variation of groundwater level

- changing temperatures
- varying concentrations of ions in groundwater.

In the following, these factors are described and measurements of certain parameters are discussed.

2.1. Changing soil moisture and variation of the groundwater level

Soil moisture content depends on the rate of precipitation and evaporation. It can be quantified by the degree of water saturation. There are subsurface areas completely water saturated (saturated zone) and areas with spatially and temporally variable water saturation (vadose zone). Large time-dependent variations of water saturation can be expected in the upper part of the vadose zone and in the area of variable groundwater level. This assumption is confirmed by cross-borehole tomographic measurements with ground penetrating radar, carried out by Binley et al. (2001) to characterise the dynamics of moisture migration in the vadose zone. Vertical profiling clearly shows large temporal variability of moisture in the upper parts of the vadose zone and near the groundwater level and low variations in middle positions.

Electrical conductivity of the subsurface depends to a great extent on the water saturation. An equation to estimate the electrical resistivity of partly saturated rocks is given by Archie (1942), Dahnov (1959) (assuming that the electrical conductivity of the matrix is negligible):

$$\sigma_{ps} = \sigma_f P^m S_w^n \quad (1)$$

- σ_{ps} electrical conductivity of partly saturated rocks
- σ_f electrical conductivity of the fluid
- S_w degree of water saturation
- n exponent of saturation; range depends on rock type (Worthington and Pallatt, 1989) or succession of previous saturation conditions (Keller and Frischknecht, 1966; Worthington et al., 1990; Knight, 1991); often assumed: $n = 2$ (e.g. Archie, 1942; Schlumberger, 1989).
- P porosity

- m exponent of cementation; $m = 1.3$ for unconsolidated sediments (Dahnov, 1962, 1975, in Schön (1983)).

The electrical conductivity of the subsurface σ , influenced by changing water content can be calculated by:

$$\sigma = \sigma_0 f(S_w) \quad (2)$$

- σ_0 electrical conductivity, reference
- $f(S_w)$ factor of changing water saturation

with

$$f(S_w) = \left(\frac{S_w}{S_{w0}} \right)^n \quad (3)$$

- S_{w0} water saturation, reference value
- n exponent of saturation (see Eq. (1))

Large variations of electrical conductivity can be expected in the upper part of the vadose zone and in the area of varying groundwater level, e.g. changes in water saturation from 30 to 20% result in a resistivity decrease of about 56%, water saturation changed from 100 to 90% in a resistivity decrease of about 19% (calculations with Eqs. (2) and (3)).

In this work, ground water levels have been monitored at two test sites to determine the area of rapidly changing water content. Results of measurements at the test sites Safira and Lauswiesen reveal different rates of groundwater level variations during day, month and year. Fig. 2 shows results of data logger measurements at the test site Safira (one measurement per hour over a period of 10 months). At the test site Lauswiesen, observed groundwater level variations (manual measurements at 11 wells) are higher (45 cm per month (late autumn 2000), max. 29 cm per day).

2.2. Soil and groundwater temperature

Surface temperatures are controlled by the influx of solar energy and depend on geographical position and

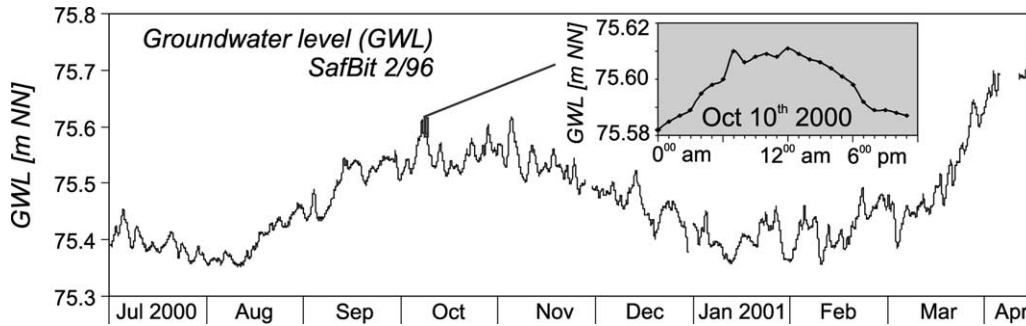


Fig. 2. Groundwater level (test site Safira, well SafBit 2/96).

topographical elevation (Militzer and Weber, 1985). Variations of these temperatures rapidly decrease with depth but are significant in the upper part of the subsurface. Surface temperatures measured at the weather observatory station near Rottenburg-Kiebingen show high daily and yearly variations. Temperatures in 14 months, measured three times a day (7:30 a.m., 2:30 p.m. and 9:30 p.m.) are ranging from -14.3 to 33.5 °C (see Fig. 3).

From surface temperature variations, amplitudes at different depths in the subsurface can be estimated (Militzer and Weber, 1985):

$$T_{\text{air}}(z) = T_{\text{air,s}} e^{-z\sqrt{\pi/t_0k}} \quad (4)$$

$T_{\text{air}}(z)$ amplitude of air temperature at depth z
 $T_{\text{air,s}}$ amplitude of air temperature at the surface

t_0 period of air temperature wave
 k temperature conductivity

In the following, daily temperature waves are discussed. For temperature conductivity k , extreme values for wet sand and for loose sediments in general have been regarded (calculated from heat conductivity values presented by Militzer and Weber (1985), according to Rzevskij and Novik (1973)).

As Fig. 4 shows, daily air temperature variations decrease rapidly with depth (shown for single amplitudes, relative to surface amplitudes). With the above-simplified assumptions, daily variations of surface air temperatures seem to influence only the uppermost meter of subsurface. In this region, temperature variations have to be considered for

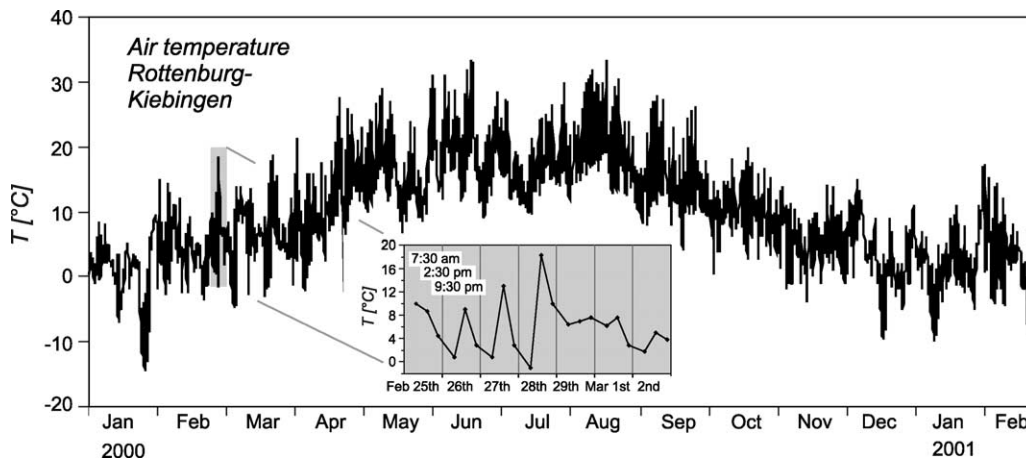


Fig. 3. Air temperatures (weather observatory station in Rottenburg-Kiebingen).

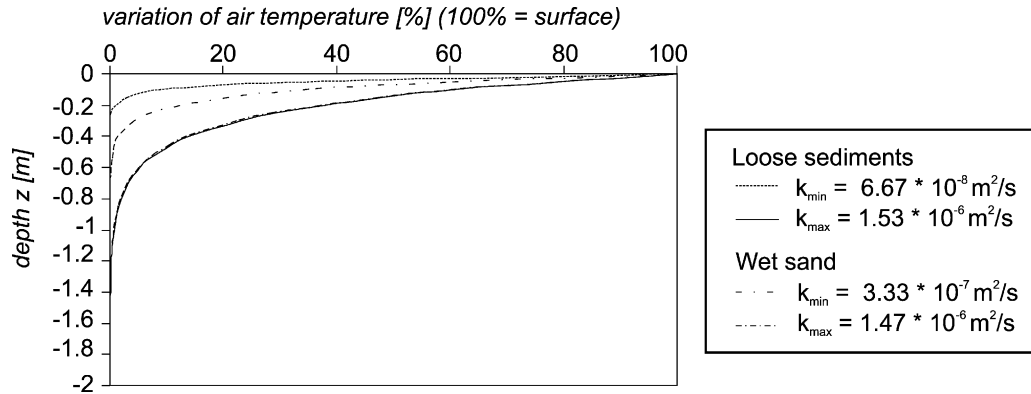


Fig. 4. Relative decrease of air temperature amplitudes (daily waves) with depth.

geolectrical investigations, e.g. for the evaluation of landfill sealings.

Beside the above described processes in the upper part of the subsurface, there are noticeable temperature variations in deeper parts, i.e. in the saturated zone. Groundwater temperature variations have to be considered when salt tracer tests are performed.

Results of data logger measurements at the test site Safira show groundwater temperatures between 12.6 and 14.2 °C in 11 months (see Fig. 5). The data logger at well SafBit 2/96 was placed at a depth of 5.30 m below the surface (1.35–1.75 m below the groundwater level). During days, observed variations of groundwater temperatures are about 0.1 °C at maximum.

At the test site Lauswiesen, manual measurements have been made at groundwater samples pumped out

of a horizontal borehole (4.30–5 m below the surface, and 0.10–1.25 m below the groundwater level, see Fig. 11). Groundwater temperatures have been lower compared to the test site Safira (7.7–11.4 °C), with higher variations (3.7 °C per month, max. 2.2 °C per day).

Temperature variations result in changing ionar mobility, which influences the electrical conductivity. Conductivity changes due to temperature variations can be approximated according to an equation presented by Dachnov (1962):

$$\sigma = \sigma_0 f(T) \tag{5}$$

- T_0, T fluid temperature at time t_0, t_1
- σ, σ_0 electrical conductivity of the fluid
- $f(T)$ factor of changing fluid temperature

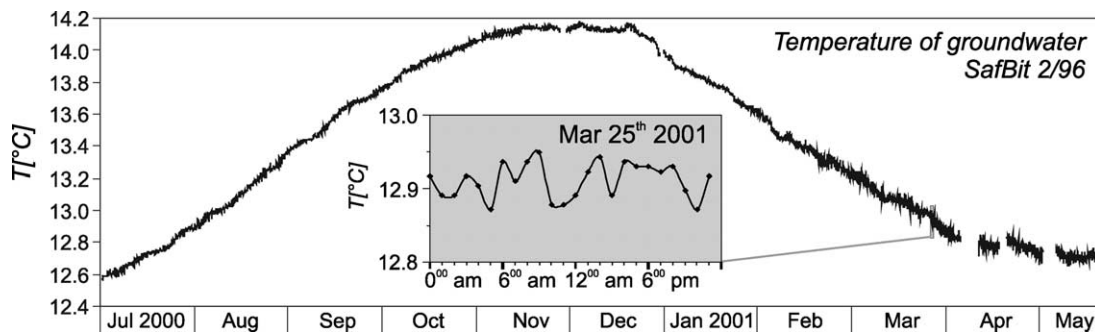


Fig. 5. Groundwater temperature (test site Safira, well SafBit 2/96).

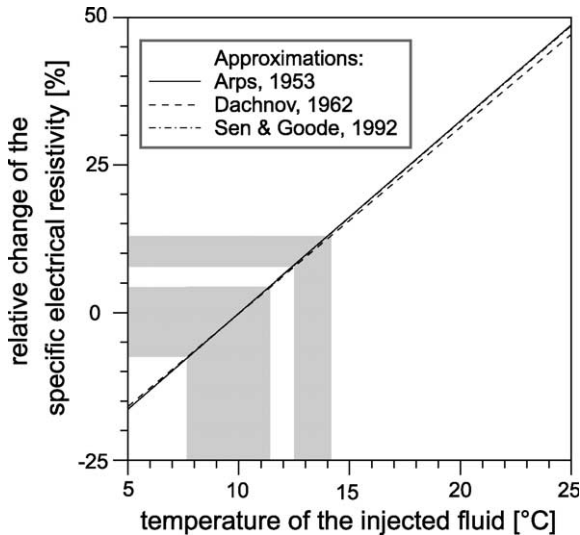


Fig. 6. Relative change of electrical resistivity due to temperature variations. —; Arps, 1953; Dachnov, 1962: - - - -; Sen & Goode, 1992.

with

$$f(T) = \frac{1 + \alpha_T(T - 18)}{1 + \alpha_T(T_0 - 18)} \quad (6)$$

α_T , temperature coefficient; decreasing with T, α_T [± 18 °C] ≈ 0.025 °C⁻¹.

Dachnov's equation got developed for temperatures around 18 °C. As groundwater temperatures are lower, this is just a rough approximation.

In Fig. 6, results calculated with the equation of Dachnov are plotted. The diagram shows relative changes of the electrical resistivity due to temperature

changes. As it can be seen, temperature variations in the range of those observed at the test site Safira (1.6 °C, 11 months) result in resistivity changes of approximately 5%. During days (temperature variations of max. 0.1 °C), resistivity changes are very low (0.8%). At the test site Lauswiesen, temperature induced resistivity changes are higher (12% per month, max. 7% per day).

2.3. Varying concentrations of ions in groundwater

The composition of ions dissolved in groundwater depends on the geological background. Ionar contents can vary for different reasons, e.g. varying of dissolved components in precipitation water, leaching processes in the vadose zone and processes in the saturated zone. These processes depend on climatic conditions, intensity of biological degradation, residence time of the water in the subsurface and flow conditions in the groundwater. Biological degradation results in the production of carbonic and humic acids, which may dissolve ions from soil material (e.g. Sauck, 1998).

Looking at the results of groundwater conductivity measurements, daily and yearly trends are obvious (see Fig. 7). At the test site Safira, evaluated relative groundwater conductivity variations are about 3% in 11 months, and about 0.6% maximum per day (absolute value of variation referred to the respective mean value; temperature corrected measurements with the data logger at well SafBit 2/96, see Section 2.2). At the test site Lauswiesen, a lower range of

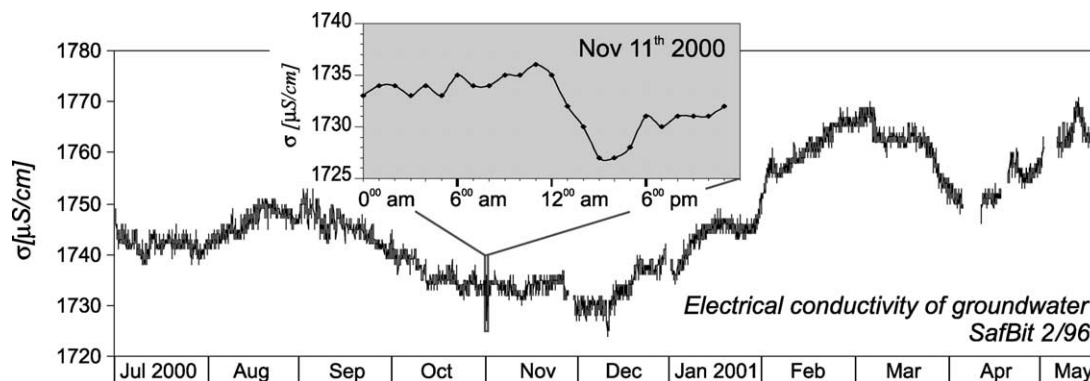


Fig. 7. Electrical conductivity of groundwater (temperature corrected hourly measurements at the test site Safira, well SafBit 2/96).

electrical conductivity is measured (910–955 $\mu\text{S}/\text{cm}$) with higher variations (4–5% per month and max. 3% per day; temperature corrected manual measurements at samples pumped out of the horizontal borehole, see Section 2.2).

Besides the natural factors, anthropogenic sources may also contribute to the ionar composition of the subsurface and groundwater, such as sewage spills, contaminated sites or areas of intensive agricultural production. Many efforts have been undertaken to investigate contaminant plumes with geoelectrical methods (e.g. Tamburi et al., 1985; Wexler and Mandel, 1985; Sauck, 1998; Schütze et al., 2002). In this paper, potential influences of inorganic substances dissolved in groundwater on electrical conductivity are discussed. Our objective is to roughly evaluate the usefulness of DC resistivity measurements for the detection of inorganic contaminants dissolved in groundwater. Several ions relevant in drinking water have been studied. The evaluated ions have been regarded as completely dissolved. For this simplified approximation, which is neglecting ionar interactions, an equation developed for low salt concentrations has been applied. With given values of ionar mobility, electrical fluid conductivities can be calculated from ionar concentrations (Keller and Frischknecht, 1966):

$$\sigma_f = Fa \sum_{i=1}^{N_i} C_i^{\text{eq}} \nu_i \quad (7)$$

σ_f	electrical conductivity of the fluid
Fa	Faraday Constant, $Fa = 9.64845 \times 10^4 \text{ A s/mol}$
C_i^{eq}	equivalent concentration of ion i , $C_i^{\text{eq}} =$ concentration of ion $i \times$ valency of ion i
ν_i	mobility of ion i in the solution (temperature-dependent).

With Eq. (7), fluid conductivities depending on varying ionar contents can be estimated by:

$$\sigma = \sigma_0 f(C) \quad (8)$$

σ_0	electrical conductivity, reference
$f(C)$	factor of changing ionar concentration

with

$$f(C) = \frac{\sigma_{f,1}}{\sigma_{f,0}} \quad (9)$$

$\sigma_{f,0}$, $\sigma_{f,1}$: electrical conductivity of the fluid (reference, time $t = 1$).

Using Eq. (7), for different values of electrical conductivity (1, 10, 50 and 100 $\mu\text{S}/\text{cm}$), concentrations specific to single ions dissolved in water have been calculated (see Fig. 8a). In Fig. 8b, the calculated concentrations are compared with guideline concentrations, derived from different legislations on drinking water.

To cause significantly enhanced conductivities, many of the studied components have to show much higher concentrations than those stated in guidelines for drinking water (see Fig. 8b). Under natural conditions, interactions even reduce the influence of specific ionar components on the electrical groundwater conductivity. So, for geoelectrical monitoring measurements and for the studied components, only bold printed substances in Fig. 8b seem to potentially provide contributions at a measurable magnitude.

Organic contaminations may affect the electrical conductivity of the subsurface as well, e.g. Sauck (1998) describes a geoelectrical model of sites contaminated with LNAPLs. According to this model, there are areas with reduced electrical conductivity (free or mobile and residual product) and others with increased electrical conductivity (dissolved plume). At the latter, carbonic and humic acids are produced by several biological and geochemical processes and ionar components are dissolved from the sediment, enhancing the electrical conductivity.

2.4. Summary—factors of conductivity variation

The above described investigations demonstrate that different factors are responsible for the variation of electrical conductivity in the subsurface. Differences between the different test sites are obvious. The factors show specific variation ranges at different parts of the subsurface.

Eq. (10) summarises the studied factors, highlighting their multiplicative character. At specific regions of the subsurface, some of the factors have to be concerned, others can be neglected. The electrical

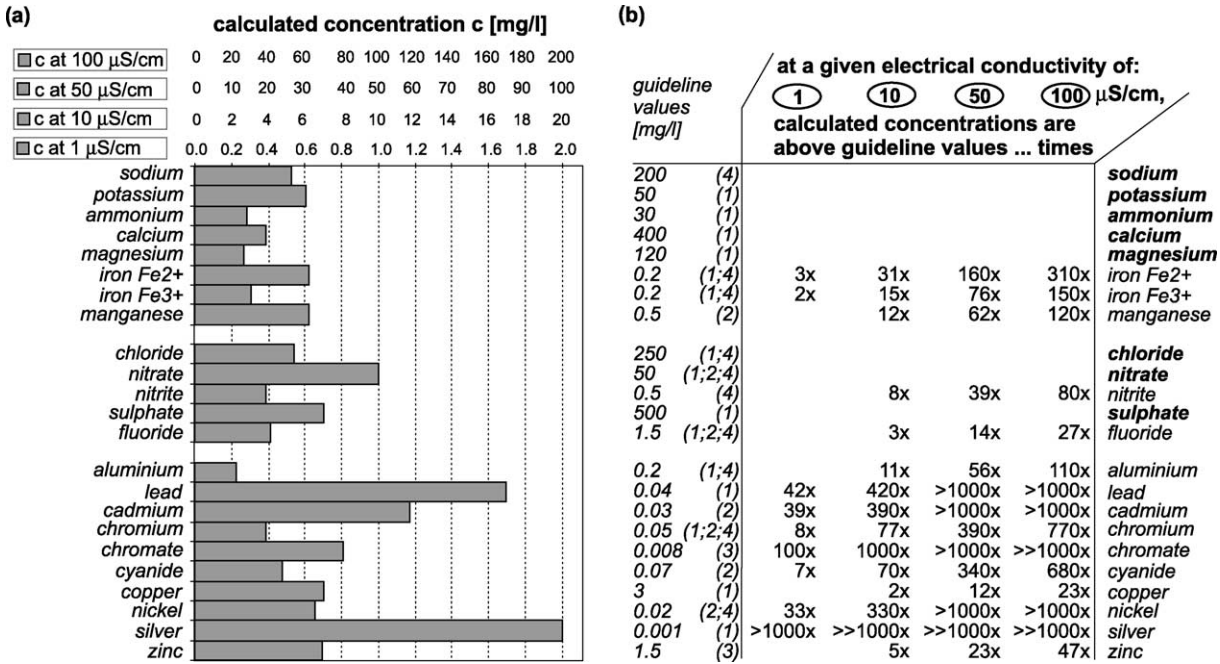


Fig. 8. (a) Calculated concentrations of ions dissolved in water at four given values of electrical conductivity, (b) comparison of the calculated concentrations with guideline concentrations for drinking water ((1) German federal regulation on drinking water, December 12th 1990; (2) World Health Organization, Guidelines for Drinking Water Quality, 1996; (3) Administrative regulation of Baden-Württemberg, September 16th 1993; (4) EU directive on drinking water, directive No. 98/83/EG, November 3rd 1998).

conductivity σ referred to the reference σ_0 is

$$\frac{\sigma}{\sigma_0} = f(S_w)f(T)f(C) \tag{10}$$

$f(S_w)$ factor of changing water saturation (see Eq. (3)), to be considered in the area of variable groundwater level and in upper parts of the vadose zone

$f(T)$ factor of changing temperature (see Eq. (6)), upper parts of the subsurface and groundwater

$f(C)$ factor of changing ionar concentration (see Eq. (9))

Table 1 summarises some conductivity variations determined in this study specific to the different factors. They are given as relative values to enable comparisons. Changes in water saturation and changing temperatures in the upper soils are of high influence, whereas the influences of variable

Table 1
Relative variations of electrical conductivity due to different factors

Relative variations of electrical conductivity		
(1) Due to changing water saturation, $f(S_w)$	(a) From 30 to 20% S_w : 56%	(b) From 100 to 90% S_w : 19%
(2) Due to changing temperatures in upper soil (max. daily variations), $f(T, \text{soil})$	(a) At a depth of -0.25 m: 20%	(b) At a depth of -0.5 m: 5%
(3) Due to changing GW temperatures (max. values), $f(T, gw)$	(a) Test site Lauswiesen Month: 12% Day: 7%	(b) Test site Safira Year: 5% Day: 0.8%
(4) Due to changing ionar concentrations in GW (max. values), $f(C)$	Test site Lauswiesen Month: 5% Day: 3%	Test site Safira Year: 3% Day: 0.6%

groundwater temperatures and ionic contents are comparably low.

To calculate the total effect, the different contributions to conductivity variation have been regarded in terms of an error propagation. The error of this function has been approximated by Bronshtein and Semendyayev (1998)

$$\frac{\Delta(a_1^n a_2 a_3)}{|a_1 a_2 a_3|} \approx |n| \frac{\Delta a_1}{|a_1|} + \frac{\Delta a_2}{|a_2|} + \frac{\Delta a_3}{|a_3|} \quad (11)$$

- $\Delta a/|a|$ relative error
- Δa error bound
- a approximate value for true value z $a - \Delta a \leq z \leq a + \Delta a$

With this approximation, the total conductivity variation $\Delta\sigma_{\text{total}}$ is given by the sum of the single contributions. For the term of conductivity variation due to changing water saturation ($\Delta\sigma_{f(Sw)}$), the exponent of saturation has to be considered

$$\Delta\sigma_{\text{total}} = n\Delta\sigma_{f(Sw)} + \Delta\sigma_{f(T)} + \Delta\sigma_{f(C)} \quad (12)$$

n , exponent of saturation, s . (Eq. (1)) with:

$$\Delta\sigma_{f(Sw)} = |\sigma_0 f(Sw) - \sigma_0| \quad (13)$$

$$\Delta\sigma_{f(T)} = |\sigma_0 f(T) - \sigma_0| \quad (14)$$

$$\Delta\sigma_{f(C)} = |\sigma_0 f(C) - \sigma_0| \quad (15)$$

Table 2 presents calculated results at some parts of the subsurface. According to the parameter measurements and further evaluations described in this chapter, largest natural variations of electrical conductivity are associated with the upper vadose zone

and the area of variable groundwater level, lowest variations with the saturated zone.

3. DC resistivity measurements

To verify the conclusions made in the previous chapter, DC resistivity measurements have been performed at the test sites Safira and Lauswiesen. The measurements described in this paper took place over 16 days in autumn 2000 (test site Lauswiesen) and over 22 days in winter/spring 2001 (test site Safira).

3.1. Data acquisition and processing

The DC resistivity data have been acquired with the computer controlled multi-electrode system Resecs 960. Main parts of this equipment are a resistivity meter, a multi-channel relay matrix switching unit, a portable PC-type computer and different electrode cables with distribution boxes.

To minimise influences of disturbing signals, the intervals of the introduced rectangular currents have been chosen as a multiple of both public and railway electricity supply (Fig. 9). With an interval of 480 ms, the introduced frequency was 24-fold of the public electricity supply (20 ms or 50 Hz), and the eight-fold of the railway electricity supply (60 ms or 16 2/3 Hz). So, these disturbing signals have been eliminated to a large extent by destructive superposition (concept of the geoelectrical trace, according to Dietrich and Fechner (1998)).

To evaluate both lateral and vertical resistivity variations, measurements along a profile and with expanding electrode configurations have been

Table 2
Total conductivity variations ($\Delta\sigma_{\text{total}}$) for different parts of the subsurface, calculated from single contributions ($\Delta\sigma, f(Sw)$, etc. according to Table 1)

	Upper vadose zone	Area of variable groundwater level				Saturated zone			
$2\Delta\sigma, f(Sw)$	$2 \times 56\%$	$2 \times 19\%$							
$+\Delta\sigma, f(T, \text{soil})$	20%								
$+\Delta\sigma, f(T, \text{gw})$		12%	7%	5%	0.8%	12%	7%	5%	0.8%
$+\Delta\sigma, f(C)$		5%	3%	3%	0.6%	5%	3%	3%	0.6%
$\Sigma, \Delta\sigma_{\text{total}}$	132%	55% month	48% day	46% year	39.4% day	17% month	10% day	8% year	1.4 day
		Lauswiesen		Safira		Lauswiesen		Safira	

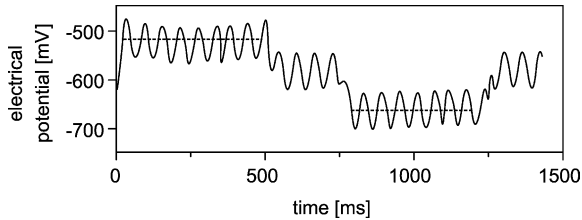


Fig. 9. Rectangular signal, influenced by railway electricity supply. Dotted line: averaged values.

performed (combined electric profiling and sounding according to Sharma (1997)). In this paper, measurements with Wenner and dipole–dipole arrays (Lauswiesen), and with Schlumberger arrays (Safira) are discussed. Table 3 summarises the respective electrode geometries. Measurements with further configurations are described by Rein (2001).

For the interpretation of the data, mean values and standard deviations of apparent resistivity have been calculated and plotted in pseudosections. The mean values are supposed to represent lateral and vertical resistivity variations in the subsurface, whereas the standard deviations indicate temporal resistivity variations at each position of the pseudosection. The standard deviations are given as percentage values to enable comparisons between different data sets:

$$s (\%) = \sqrt{\frac{\sum_{i=1}^n (\rho_{a,i} - \rho_{a,\text{mean}})^2}{n}} \cdot \frac{100}{\rho_{a,\text{mean}}} \quad (16)$$

- s standard deviation
- $\rho_{a,i}$ apparent resistivity, value i
- $\rho_{a,\text{mean}}$ apparent resistivity, mean value
- n number of values

The mean values and standard deviations have been calculated from 49 values (test site Lauswiesen) and 224 values (test site Safira).

3.2. Site description and measurement setup

3.2.1. Test site Safira

The test site Safira is situated in the south eastern downstream area of a large estate of former chemical industry in Bitterfeld, Germany. It was established in 1996/97 by the UFZ Leipzig and several research partners as a study area to develop and test passive groundwater remediation techniques (Weiß et al., 1997; Merkel et al., 2000). In contrast to the test site Lauswiesen, the test site Safira is located in an urban area with a long history of brown coal mining and chemical industry. Soils and groundwater are heavily contaminated in a complex way.

Fig. 10 shows a cross-section through the area of the test site. Geological data is derived from a detailed geological and hydrogeological survey (Ruske et al., 1997) and from well logs (see eg. Fig. 13, profile of well SafBit 11/97). In the area of the test site, there are mainly Quaternary and Tertiary sediments. Under a coverage of artificial landfills, there are sands and gravels, structured by silt horizons. These terrace gravellas of the nearby river Mulde were deposited during the Weichsel ice age. In their deeper parts, they

Table 3
Electrode geometries for Schlumberger, Wenner and dipole–dipole measurements

test site	Safira	Lauswiesen	Lauswiesen
array	Schlumberger	Wenner	dipole-dipole
electrode geometries	$a = 1$ $n \cdot a = 1, 2, \dots, 18$	$a = 1, 2, \dots, 16$	$a = 1, n = 1-5$ $a = 2, n = 2-5$ $a = 3, n = 3-5$ $a = 4, n = 3-5$ $a = 5, n = 3-5$

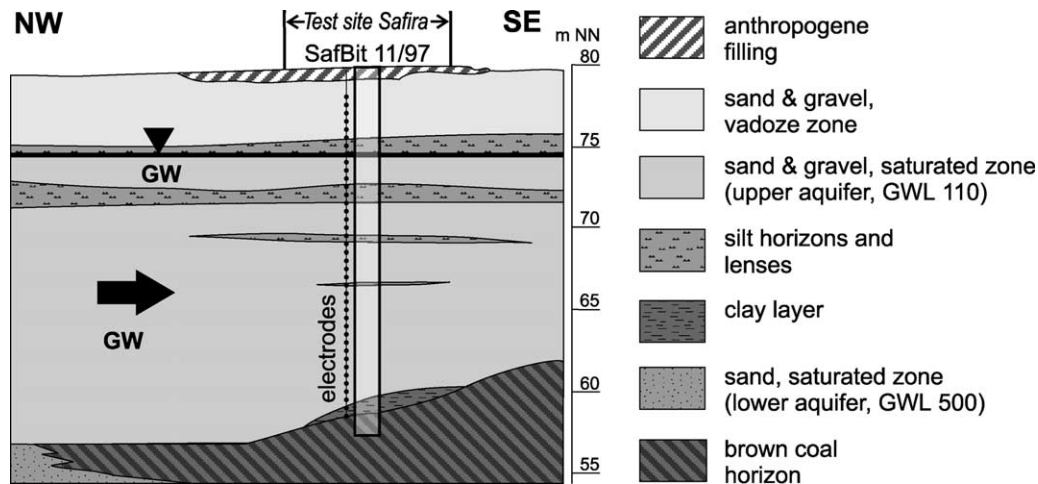


Fig. 10. Cross-section through the area of the test site Safira.

are water saturated (aquifer GWL 110). Below that follows a brown coal horizon (Bitterfelder Flöz) of Tertiary age which is presumed to be discontinuous. Further below, there are mica sands (Bitterfelder Glimmersande), forming a second aquifer (GWL 500).

Due to drawdown activities at open pits and landfills, groundwater flow directions vary between SE and E (Ruske et al., 1997). There are low flow gradients. Both aquifers are confined and there seems to be a regional hydrogeological connection between them.

At the test site Safira, DC resistivity measurements described in this paper have been performed at the well SafBit 11/97 (see Fig. 10) during 22 days in winter/spring 2001. The well contains an electrode chain with 40 electrodes, which are arranged in distances of 0.5 m (see Figs. 10 and 13). The deepest electrode is located at a depth of 21 m below surface so that the electrode chain is crossing the vadose zone and the saturated zone (upper aquifer GWL 110), reaching a clay layer at the top of the brown coal horizon (see Figs. 10 and 13).

3.2.2. Test site Lauswiesen

The test site Lauswiesen was established in 1996 at the former site of a pumping station. In 1998, a horizontal borehole was installed at the site

(see Fig. 11). Geological data for the cross-section of Fig. 11 is derived from nearby boreholes, described by Sack-Kühner (1996). The test site is located in the valley of the river Neckar, which is filled with gravels containing silt and clay horizons and covered by floodplain loam. The valley filling is framed by mesozoic rocks. The uppermost gravels are part of the unsaturated zone. In deeper parts there is an aquifer. At about 10 m of depth, the aquifer is based on clay stones of Keuper age. Main flow direction of groundwater is NW, with effluent conditions towards the nearby river Neckar (Sack-Kühner, 1996). Looking at hydrogeochemical conditions in the area of the test site Lauswiesen, there are hydrogen carbonatic–sulphatic groundwaters (Schollenberger, 1998).

At the test site Lauswiesen, measurements with electrodes at the surface and in the horizontal borehole have been performed during 16 days in autumn 2000. The electrode array at the surface, which was installed in autumn 2000, contained 51 electrodes with a spacing of 1.50 m. The horizontal borehole contains an electrode chain with 41 electrodes positioned at distances of 1 m each (see Fig. 11). At certain distances in the borehole, plastic tubes are placed reaching the surface to take groundwater samples or to inject a salt tracer. During the study time, six of these tubes were permanently below the groundwater level and therefore, enabled groundwater sampling.

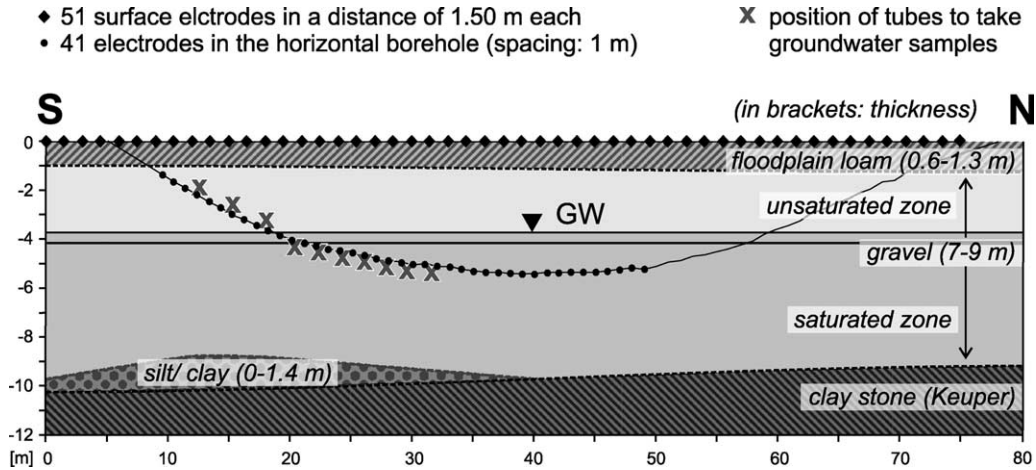


Fig. 11. Test site Lauswiesen, cross-section near the electrode chains.

4. Results and discussion

Fig. 12 shows apparent resistivities measured with two dipole arrays in the horizontal borehole at the test site Lauswiesen. Measurements with electrodes in the area of variable groundwater level reveal high resistivity variations during the whole period and during some days (Fig. 12a). Measurements with electrodes below the groundwater level show much lower variations (Fig. 12b).

By plotting resistivity values versus time, the characteristics of temporal variations can be analysed specific to single measurements. A disadvantage of this procedure is that an overview on temporal resistivity variations specific to different parts of the subsurface is difficult to achieve. To correlate temporal resistivity variations to specific parts of the subsurface, standard deviations of apparent resistivity have been calculated for each single measurement and plotted in pseudosections. Afterwards, pseudosections

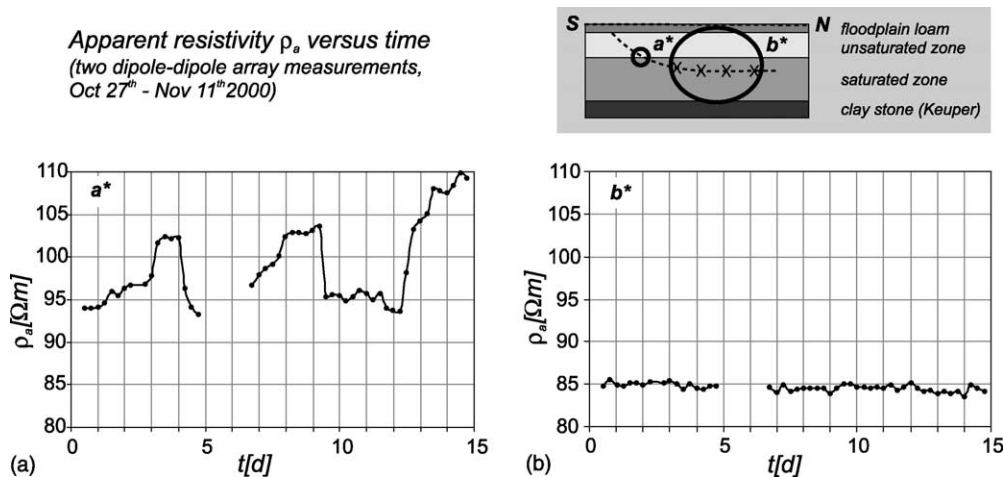


Fig. 12. Apparent resistivities versus time (dipole-dipole measurements, test site Lauswiesen, horizontal borehole). (a) Electrodes in the area of variable groundwater level, distances: 12 (A), 13 (B), 14 (M), 15 (N) m from the southern end of the horizontal borehole (compare with a* in Fig. 15), (b) electrodes below the groundwater table, distances: 15 (A), 19 (B), 35 (M), 39 (N) m (compare with b* in Fig. 15).

of both standard deviations and mean values of apparent resistivity have been studied, which is discussed in Section 4.1 and 4.2.

4.1. Test site Safira

In this section, results of Schlumberger measurements are discussed (see Fig. 13).

4.1.1. Mean values of apparent resistivity

At the upper edge of the pseudosection (see Fig. 13a, area a1), high apparent resistivities

can be recognised. This can be assigned to a low water content in the unsaturated sand and gravel zone.

Below the measured groundwater level (areas a2 and a3), low values are predominant. This corresponds to electrodes positioned in the saturated zone. Parts of the increased resistivities in the pseudosection reflect measurements with at least one electrode located in the unsaturated zone. Other increased values are difficult to explain, maybe they are influenced by inhomogeneities of lithology.

At the bottom of the pseudosection (area a3), low resistivity values result from the fact that

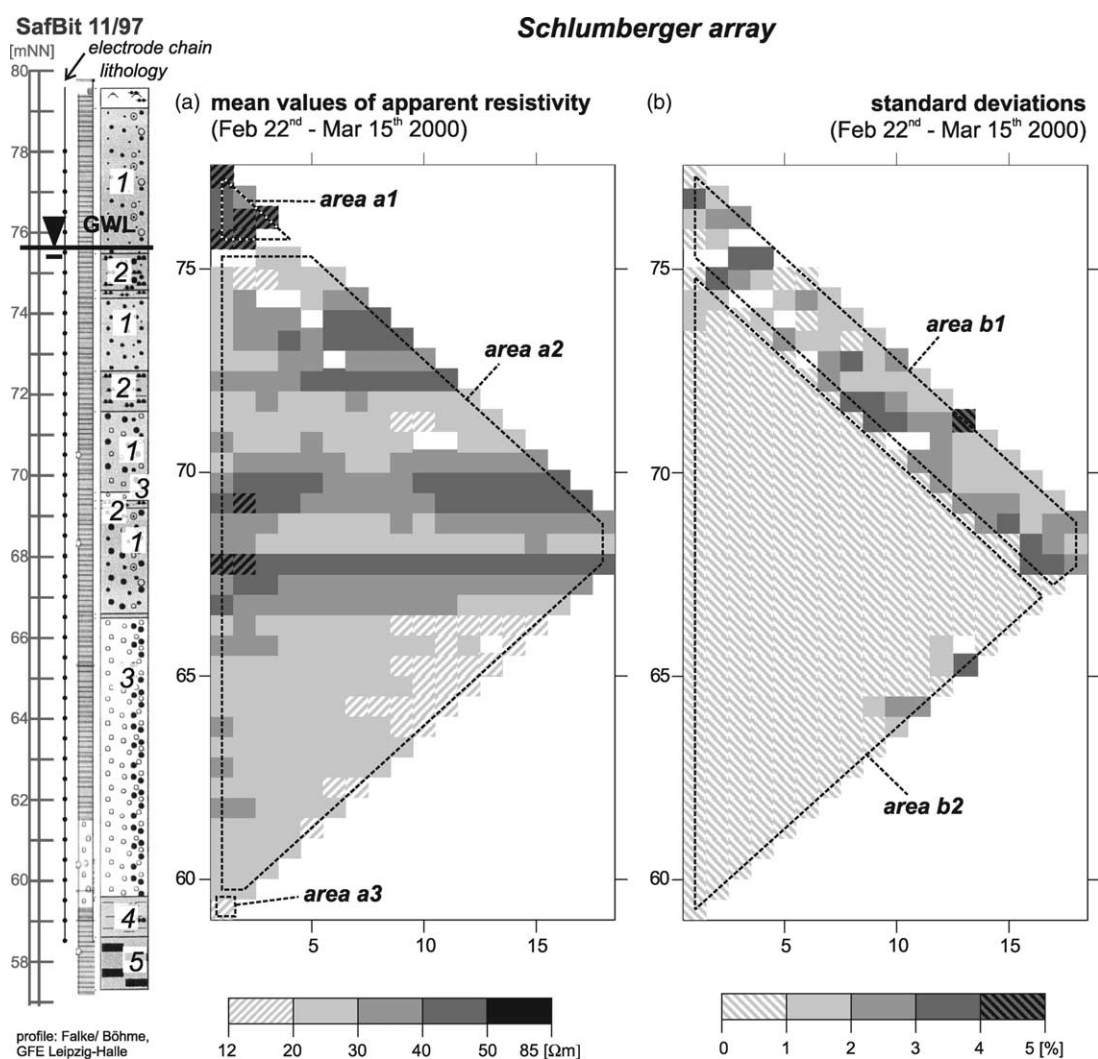


Fig. 13. Pseudosections of DC resistivity measurements at the test site Safira. (a) Mean values of apparent resistivity, (b) standard deviations; lithology: predominant components: 1 sand, 2 silt, 3 gravel, 4 clay, 5 brown coal; GWL: groundwater level, Feb 22nd 2000.

the concerned electrodes are positioned in clays (zone 4 at the well profile in Fig. 13).

4.1.2. Standard deviations

At the right upper margin of Fig. 13b (area b1), high standard deviations are predominant. At least one of the electrodes of the concerned configuration is placed in the zone of variable groundwater level. The large resistivity variations can be explained by variable water saturation (see descriptions in Section 2.1).

In the lower part (area b2), which covers most of the pseudosection, standard deviations are low with electrodes located in the saturated zone. Groundwater temperature variation and natural fluctuation of ionic content seems to cause low resistivity variations (see Section 2.2).

4.2. Test site Lauswiesen

In the following, results of Wenner and dipole-dipole configuration measurements are discussed.

4.2.1. Measurements with surface electrodes

Looking at Fig. 14, the pseudosections can roughly be divided into three areas. Fig. 14a and b shows mean values, Fig. 14c and d shows standard deviations of the apparent resistivities.

4.2.1.1. Mean values of apparent resistivity. In the uppermost parts of the pseudosections (area a1 and b1 in Fig. 14a and b, there are low apparent resistivities, correlating with the highly conductive floodplain loam and residual water.

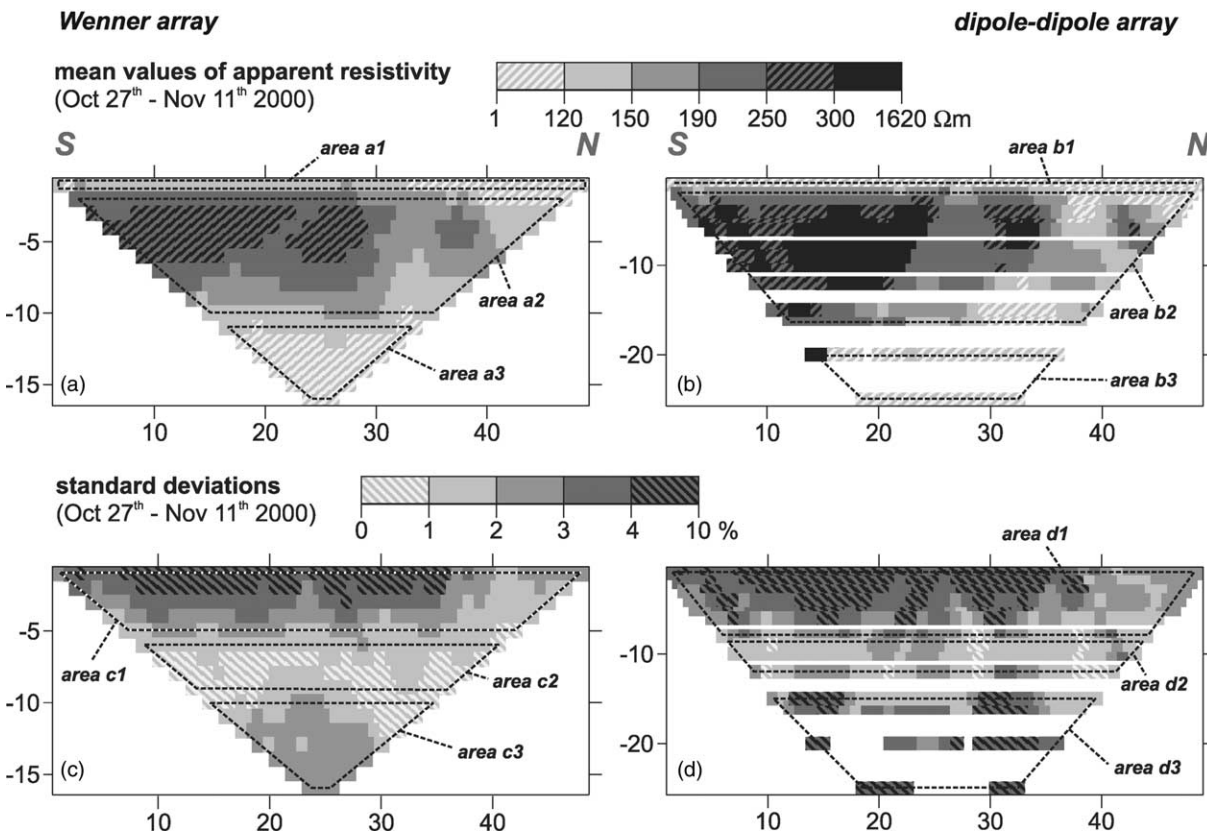


Fig. 14. Pseudosections of DC resistivity measurements with surface electrodes at the test site Lauswiesen, (a) and (b): mean values of apparent resistivity, (c) and (d): standard deviations.

At the mid positions (area a2 and b2), high apparent resistivities are visible, assumed to result from low water contents in the unsaturated zone.

The lower areas (area a3 and b3) again show low values, associated with the saturated zone.

4.2.1.2. Standard deviations. In their upper parts, the pseudosections of Fig. 14c and d show high standard deviations (area c1 and d1, respectively). This can be related to the conditions in the floodplain loam and the upper unsaturated zone, where soil moisture and temperature is changing rapidly. According to the evaluations of chapter 2, large resistivity variations are caused by variable water saturation (see Section 2.1) and soil temperature (see Section 2.2, Figs. 4 and 5).

In the middle of the pseudosections (area c2 and d2), standard deviations are low. This is associated

with the conditions of most parts of the unsaturated zone with little changes in soil moisture and strongly damped temperature amplitudes.

The lower areas (area c3 and d3) show high standard deviations. A possible explanation for these large resistivity variations are changing groundwater levels resulting in different degrees of water saturation.

Besides the above described structures in each pseudosection, differences between the arrays are obvious. In the pseudosections, the values show the same systematics of arrangement but differences in details. This is due to the fact, that both arrays have specific sensitivities and react differently on variations of resistivity (Dietrich, 1999). Dipole–dipole configurations react more sensitive to variations than Wenner configurations do.

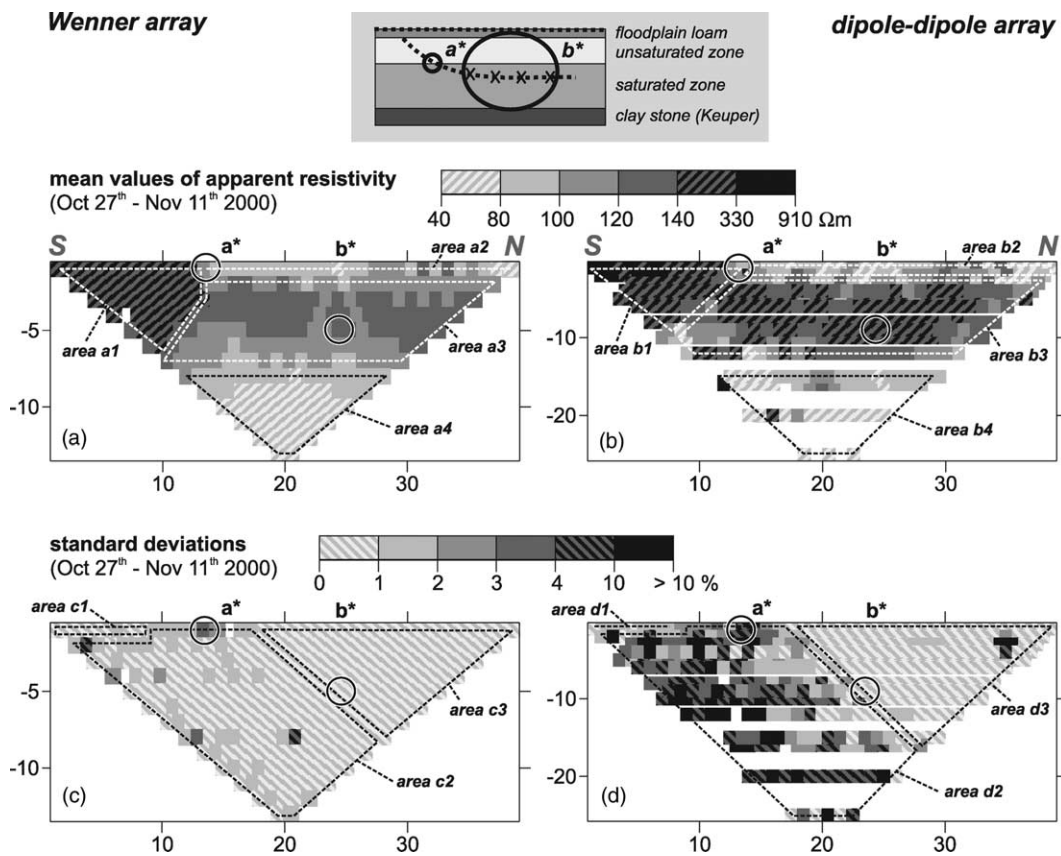


Fig. 15. Pseudosections of DC resistivity measurements with electrodes in the horizontal borehole at the test site Lauswiesen. (a) and (b): mean values of apparent resistivity, (c) and (d): standard deviations.

4.2.2. Measurements with electrodes in the horizontal borehole

As it can be seen in Fig. 15, measurements with electrodes in the horizontal borehole show different results compared to measurements with surface electrodes.

4.2.2.1. Mean values of apparent resistivity. In the left area of the pseudosections (area a1 and b1, Fig. 15a and 15b), high mean values of apparent resistivities are obvious. The electrodes are positioned in the unsaturated zone, which is characterised by low water contents.

Areas a2 and b2 show low apparent resistivities, as the electrodes are situated below the groundwater level. At areas a3 and b3, the values are elevated because measurements with the associated electrodes assume to integrate parts of the unsaturated zone.

At the bottom (area a4 and b4), apparent resistivities are lower again, caused by influences of conductive clay stones.

4.2.2.2. Standard deviations. In the left upper edge of the pseudosections (areas c1 and d1), standard deviations are low. The electrodes used for the respective measurements are located in the unsaturated zone. In areas c2 and d2, there are predominantly high standard deviations with at least one electrode positioned in the area of groundwater level variations (see a* in Figs. 12 and 15).

In areas c3 and d3, low standard deviations are visible with the responsible electrodes positioned in the saturated zone (see b* in Figs. 12 and 15). Changing groundwater conductivity and variable temperatures seem to cause resistivity variations at a very low scale (compare to Sections 2.2 and 2.3)

At the test site Safira, both mean values and standard deviations of apparent resistivity are lower compared to the results of measurements at the test site Lauswiesen. This can be assigned to different characteristics of the subsurface and different ranges of resistivity variation at both test sites. Among others in the subsurface of the test site Safira, there are more conductive components such as silt and clay.

5. Summary and conclusions

The investigations described in this paper show that there are variations of electrical conductivity in the subsurface specific to different zones. They depend on many different parameters which are spatially and temporally variable.

The factors influencing the electrical conductivity vary over different ranges at different parts of the subsurface. Monitoring measurements of electrical conductivity and temperature of groundwater, surface temperature and groundwater levels revealed daily and seasonal trends of variation with differences between the investigated test sites. For different areas of the subsurface, different factors have to be considered.

Generally, variable water saturation and soil temperature (uppermost soil) are reported to have the most significant influence, followed by changing groundwater temperatures and varying groundwater conductivities due to natural fluctuations in ionic content. Many of the considered contaminants are expected to have very limited influence.

The results of the DC resistivity measurements reflect natural processes and characteristics of the subsurface. With mean values and standard deviations of apparent resistivities plotted in pseudosections, different subsurface areas can be specified and for each area, a range of resistivity variations can be determined. For the same area, different results are achieved when measured with different electrode configurations or with electrodes located in different positions. This can be explained by the fact, that each configuration shows a specific sensitivity on spatial and temporal variations of resistivity, and that the sensitivities are highest in the area next to each used electrode. To avoid impacts of natural resistivity variations, every electrode used for measurement should be located in a zone of low variability.

Due to the integrative effects of DC resistivity measurements, results show lower variations compared to approximations based on parameter evaluations. Parameter-based approximations are more locally bound with parameters varying extremely.

Variations of electrical conductivity differ from site to site. Generally, high variations are found in the uppermost soil and in particular, in the area of variable ground water level (evaluated standard deviations up to 26%). Measurements with electrodes

positioned below the groundwater level show the lowest observed resistivity variations (standard deviations predominantly less than 1%).

Therefore, for DC resistivity monitoring of a salt tracer spreading in the saturated zone, it is recommended to use electrodes positioned below the groundwater level. For leaching tests in the vadose zone, the area below the uppermost meter of subsurface and above the area of variable groundwater level is supposed to show low natural variations of electrical conductivity. In the uppermost soil, influences of varying temperatures sometimes are stronger than those of changing water saturation and therefore, may cause difficulties for the observation of natural recharge or salt tracer transport in this area.

If high background variations of electrical conductivity are expected at a certain site (e.g. due to rapidly changing surface temperatures or to extended rain falls), it is useful to perform accompanying measurements at areas which are not influenced by the induced signal (e.g. salt tracer).

In this work, estimations have been made, concerning maximum effects of different parameters on electrical conductivity of the subsurface. In further work, more thorough investigation should be carried out concerning temperature influences in the subsurface and groundwater and the conditions of water saturation.

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