Overview of common field measurements

applicable in the research on freshwater lenses in coastal areas

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Knowledge for Climate Theme 2
Workpackage 2.2

Contents

1 Introduction

In many low-lying coastal areas, saline groundwater is present within the subsurface. So called 'freshwater lenses' float on top of this saline groundwater. They are recharged by the precipitation surplus. In the Netherlands these freshwater lenses vary in thickness from >50 m in the coastal dune areas, 5 to 20 m in fossil sandy creeks to <2 m in agricultural parcels in polder areas with prominent saline seepage (Figure 1.1). During summer time, the water demand is high due to large groundwater extractions and evapotranspiration. Freshwater supply from the larger freshwater lenses is limited due to governmental regulations, because overexploitation leads to salt water intrusion and abstraction well closure. Crop damage can therefore easily occur during periods of severe droughts, as freshwater supply cannot meet the irrigation demand. In addition, crops can suffer elevated salinities in their root zone in areas where the shallow freshwater lens is not well developed and subjected to prominent saline seepage.
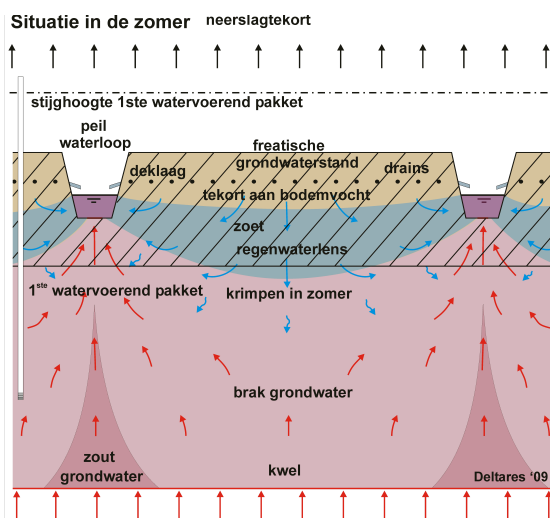

Figure 1.1: Sketch of a shallow freshwater lens in an agricultural (drained) area. (In Dutch)

Previous research has indicated that amongst others, recharge, seepage, hydrogeology and drainage characteristics influence the extent and spatial distribution of freshwater lenses. Climate change will probably influence precipitation and evapotranspiration both in quantity and seasonal distribution. Furthermore, freshwater lenses will be influenced by the time-varying regional groundwater flow system (Oude Essink et al., 2010). In the first place, this transient character of the groundwater flow system is caused by the ongoing land subsidence due to anthropogenic measures like poldering and drainage. As the controlled and low surface water level in polder areas will keep pace with the land subsidence, the seepage will increase in the future. The salinity will of this seepage will also rise since in most cases salinities increase with depth. Second, ongoing sealevel rise will lead to an increase of the hydraulic head in the aquifers near the coast. This will also contribute to higher seepage intensity.

It is clear that fresh groundwater lenses at different scales will be influenced by these changes. Future water management requires a quantification of this saltwater intrusion into freshwater reserves and possible countermeasure to increase their water supply function. Therefore, research has been initiated within the Knowledge for Climate (KfC) program theme 2. In this theme, the author will work on work package 2.2, in which different possible measures to mitigate the salinization due to climate change, sea level rise and increasing need for fresh water are

analyzed. The aim is to increase the availability of fresh water by creating a robust and flexible buffering capacity of fresh water stored in fresh water lenses. This report describes various field measurements that can be used in to determine the salinity of groundwater at different scales in the Netherlands. It provides KfC stakeholders a brief description of different measurement techniques and their advantages and disadvantages.

In this report, 'salinity' refers to the chloride content of the groundwater. Chloride is the major conservative anion in the Dutch Delta and is classified here as fresh ($Cl^- < 150$ mg/L), brackish (> 150 mg/L $Cl^- < 1000$ mg/L) or saline ($Cl^- > 1000$ mg/L).

2 Applied geophysics

Geophysical methods are non-destructive and especially effective in quick investigations of large areas at relatively low costs. Although 'applied geophysics' involves any physical method for investigations at and near the Earth's surface, this section will focus on geo-electric and electromagnetic methods. With both methods the apparent electric resistivity (or conductivity, which is its reciprocal) of the subsurface can be deduced. From this, empirical relationships are used to determine the electrical conductivity (EC) of the pore water. This will be further explained in section 2.1.3. From the pore water EC, the chloride content can be derived. At low chloride contents, other anions like sulphate (SO_4^{2-}), nitrate (NO_3^-) and especially bicarbonate (HCO_3^-, see Figure 2.1) contribute significantly to the EC of the fluid. Additional chemical concentration data is therefore needed if one wants to relate EC to chloride content of fresh to slightly brackish water.

The EC also depends on the temperature of the groundwater. The EC can be referenced to a standard temperature. Following the convention from McNeill (1980): $EC_{T=25^oC} = EC_{T=T^oC}$ (1+0.022(T-25)), where T is the temperature of the water, $EC_{T=25^oC}$ is the electrical conductivity of the water at 25^oC, $EC_{T=T^oC}$ is the electrical conductivity of the water at temperature T.
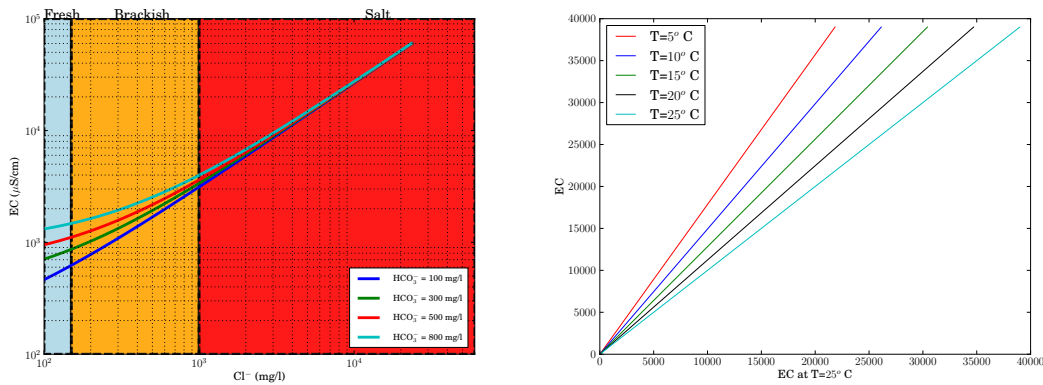
(a) EC-Cl at different HCO_3^- concentrations. (b) EC and temperature standardized EC.

Figure 2.1: EC-Chloride/ HCO_3^- and EC-T relationships.

Electromagnetic and geoelectric methods will be described briefly in the following sections. First, a little background on the basic principles of electricity, magnetism and electromagnetism is provided. These concepts are then used to describe some examples of techniques and instruments which are known by the author.

2.1 Basic principles of geoelectric methods

2.1.1 Electrostatics and electric potential

Consider the concept of an immobile electrical charge. Charged matter is either positive or negative (Figure 2.2). The unit of charge is Coulomb (C)[1]. Matter will experience a force when it comes in the sphere of influence (more on that further on) of charged 'source' matter. It both matter are positively or negatively charged , both matter will experience a repulsive force. If they

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[1]Charge is quantized; each electron carries the same amount of charge, about -1.6022 10^{-19} Coulomb

have an opposite charge, they will experience an attractive force. The mathematical expression of the relation between forces on charges is known as Coulomb's law:

$$F = k_e \frac{q_1 \, q_2}{r^2} \qquad (2.1)$$

where F is the simultaneous force on both matter, k_e is a proportionality constant (known as Coulomb's constant), q_1 and q_2 are the charges of matter 1 and 2 and r denotes their distance. If the force is positive, q_1 and q_2 will both experience a repulsive force. In case of a negative force, the force will be attractive.

The 'sphere of influence' of a charge is usually denoted by its electrical field E. The electrical field of a charged matter can be defined as the force experienced by matter due to electrical charge of other matter and is mathematically expressed as:

$$E = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \qquad (2.2)$$

ε_0 is called the electrical constant and has units of $C^2 N^{-1} m^2$. E must therefore have the units force (F) per charge (C). A very useful property of electric fields is that fields can be super-positioned. The total electric field is therefore the sum of each individual charged matter. The work that is required to displace a charged matter in this electric field is called the electric potential, and has the units of electric potential energy W per unit charge U (Nm C^{-1} or Joule (J) per Coulomb), better known as a Volt (V). Using a water flow analogy, electric potential would be the same as the hydraulic head[2]. A change in hydraulic head will give rise to water flow, a change in electric potential energy (δV) to an electric current.
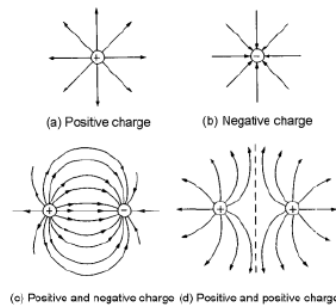

Figure 2.2: Electric charge and electric fields.

2.1.2   Electric current

Electric current due to an electrical potential difference is possible only if the medium has conductive properties. A distinction can be made between a direct current (DC), where charge moves in one direction, and a alternating current (AC) where the direction of charge is changing (opposing) over time. In this section, DC is concerned, because this is used in geoelectric surveys. AC comes in play in the section on electromagnetic methods.

The well known Ohm's law relates the current through a conductive medium as being proportional to the electric potential difference and inversely proportional to the electrical resistance (R; unit Ω) between two points (Figure 2.3):

$$I = \frac{\delta V}{R} \qquad (2.3)$$

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[2]The hydraulic head expressed in units of length is the potential energy of groundwater per unit weight.

The resistance is a property of the conducting medium, and is the main interest in geo-electric and electromagnetic surveys.

2.1.3   Subsurface electrical resistivity

Figure 2.3 depicts a sketch of a direct current through a wire. The resistance of the wire can be determined from the applied electric current and the electric potential difference.
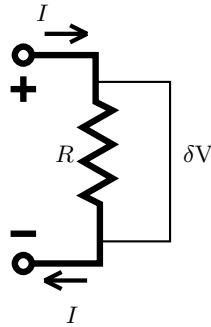

Figure 2.3: Current, resistance and the electric potential difference across a wire.

An electric current can also be conducted through rock and sediment, so the resistance of the subsurface can be deduced. There is however a difference in the distribution of the current, denoted by the current density J. In a (electrically) homogeneous subsurface, the total current is distributed over a hemisphere (because air acts like an insulator). In a configuration as is shown in Figure 2.4, the resistivity of the subsurface can be calculated from:

$$\rho = \frac{2\pi\delta V}{I}K \tag{2.4}$$

where K (unit; m) is the geometrical factor, defined as (see Figure 2.4):

$$2\pi\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} - \frac{1}{NB}\right]^{-1} \tag{2.5}$$

The SI unit of subsurface resistivity is Ω m. Subsurface electrical conductivity is expressed in Siemens (S) per meter. As was explained in section 2, the pore water EC influences the electrical resistivity of the subsurface. In addition, the subsurface resistivity depends on:

- The constituents of the sediment grains or rock; clay is a good conductor, old metamorphic rocks are often not.

- The moisture content of the subsurface.

- The porosity.

In water saturated sediments, the pore fluid acts as an electrolyte[3]. The grains contribute very little to the resistivity of the sediment, except when they are good conductors themselves (like

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[3]An electrolyte is any substance containing free ions that make the substance electrically conductive. Pure water can barely conduct charge, but free ions are generally present in pore fluids.

clay). In absence of clay in the subsurface, the specific resistivity of an formation (aquifer) (ρ_s) can be calculated by an empirical law developed by Archie (1942):

$$\rho_s = a\phi^{-m}\rho_w \tag{2.6}$$

ϕ is the porosity of the formation and a, m and n are constants. This group can be lumped into a single factor which is known as the formation factor. This formation factor ranges from 2 - 6, mainly depending on the porosity. Using Archies law, the pore water EC can be deduced from the specific resistivity of a formation.
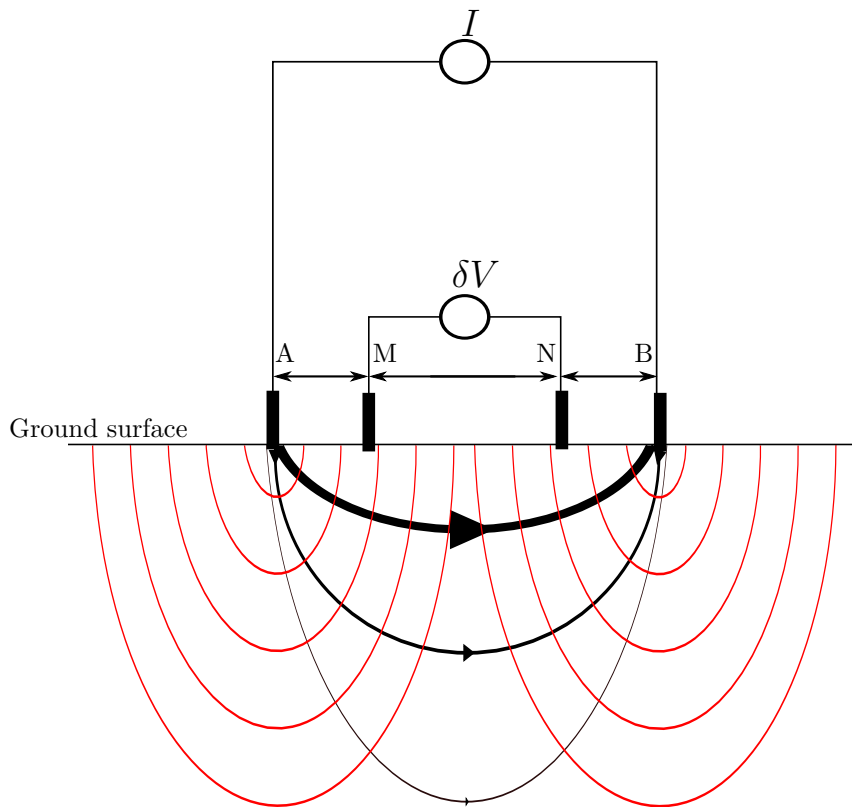
Figure 2.4: Current, resistance and the electric potential lines (or electric field) in a homogeneous subsurface. In red are the equipotential lines and in black are the current flow lines, which intersect the equipotential lines at right angles. Notice that the contour intervals are not equal. Increasing thickness of the current lines denote increasing current.

2.2   Electrical resistivity; methods of deployment

2.2.1   Vertical electrical sounding (VES)

In many cases the subsurface is heterogeneous. Therefore, the measured resistivity of the subsurface is an apparent resistivity (ρ_a), composed of multiple units having a specific resistivity (ρ_s). A vertical electrical sounding (VES) measurement can be performed to obtain a layer model, where each layer has its own specific resistivity. First, the resistivity is measured with a small current electrode distance. Upon an increase of the current electrodes, the bulk of the current will be distributed over a larger (vertical) extend. Different electrode configurations exist, but the most appropriate and most generally applied one is the Schlumberger configuration. For more information on other configurations see for example Reynolds (1997). In the Schlumberger configuration, the distance of the potential electrodes (MN) is no more than one fifth of the half the distance of the current electrodes (AB). A so called sounding curve, where the apparent resistivity values are plotted as a function of half the current electrode separation (AB) on a double log scale, can then be constructed from the different electrode distance measurements. From this sounding curve, a layer model can be derived. This is generally done by computer models, which can construct an n-layered model where each model layer has a thickness and an specific resistivity. This however, introduces equivalence problems as the signal can be the result different combinations of layer depth and specific resistance.

2.2.2   Constant Separation Traversing (CST)

In a CST measurement, also four electrodes are used, but their distance inner distance is kept fixed. This configuration is moved, usually along a profile, to detect lateral changes of the apparent resistivity. The Wenner configuration is generally used in CST, where the distance of the potential electrodes (MN in Figure 2.4) is always 1/3 of the distance between the current electrodes. As the electrode distance is kept fixed, one has to determine the electrode spacing before a CST measurement is performed. This is generally done by VES measurements.

2.2.3   Continuous vertical electrical sounding (CVES)

In a CVES (Figure 2.7) measurement, multiple electrodes are used which are connected by multi-core cables to a microprocessor. The electrodes can serve as current or potential electrodes. With this microprocessor and appropriate software, numerous electrode combinations can be used to calculate the apparent resistivity of the subsurface. One can chose between many but the Wenner (faster) and Schlumberger (slightly better resolution) configurations are most often used. Inversion software is used to obtain a two-dimensional image of the apparent resistivity of the subsurface. Equivalence problems are reduced (though not removed) due to the large numbers of electrode combinations.

2.2.4   Normal resistivity borehole logging

In normal resistivity borehole logging, a cable is lowered into a borehole. At the end of the cable, three electrodes are present. The outer electrode functions as a current electrode. One of the two electrodes higher on the cable functions as a potential electrode. Measurements are taken at discrete points in a borehole as the cable is pulled up.

In the long normal configuration, the distance between the potential and the current electrode is usually 64 inch, while in short normal configuration this distance is usually 16 inch. The other current and potential electrode are located in the soil at the surface. The measurement of the apparent resistivity is comparable with the methods described above. The short normal

Figure 2.5: Set up of a VES measurement at the beach. Four reels of wire are used to connect the measurement unit (the orange device) to the current and potential electrodes.

configuration gives information near the borehole, while the long normal configuration covers a larger area which provides information about the formation resistivity. A major drawback of this method is that an uncased well is required. In unconsolidated sediment, as is often encountered in deltaic areas, wells are always cased. A new borehole therefore has to be made, which is collapsed when the cable is installed.

2.2.5   Cross borehole electrical resistivity tomography (ERT)

ERT comprises every electrical resistivity method whereby a two- or three-dimensional image (tomography) of the subsurface resistivity is obtained, such as a CVES. In this document however, ERT refers to resistivity tomography from cross borehole resistivity measurements. In ERT measurements, two or more boreholes are used to lower multi-electrode cables. Like in CVES measurements, an electrode selector is used to measure multiple combinations of current and potential electrodes. A different electrode configuration (bipole-bipole) is generally used in ERT.
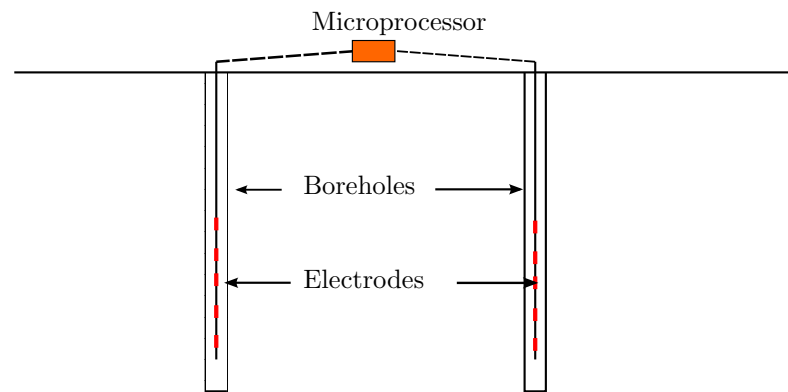
Figure 2.6: Sketch of an ERT measurement using two boreholes.

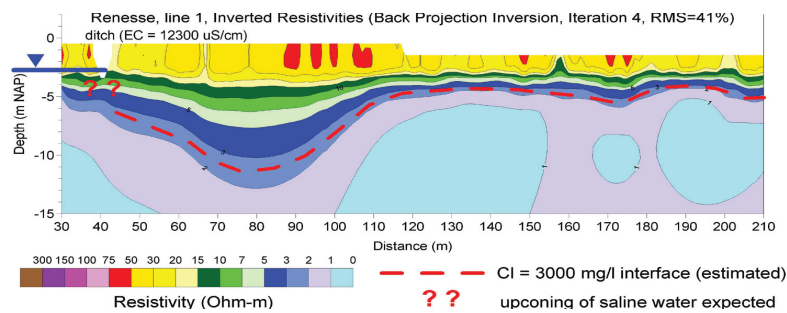Figure 2.7: Set up of a CVES measurement at the beach.

Figure 2.8: Inversion interpretation result of a CVES measurement in the province of Zeeland (Goes et al., 2009).

By inversion, a two- or three-dimensional resistivity image is obtained. One recently developed application of this method is a system whereby the ERT measurements are taken over time and that data acquisition takes place by telemetry (Kuras et al., 2009) Using this method, a much higher temporal resolution can be obtained compared to manually repeated measurements.

2.2.6   Electric cone penetration tests (CPT)

With a CTP, a cone is pushed at a controlled rate into the subsurface using a heavy truck. The site should therefore allow heavy truck access. The resistance to penetration (pressure) at the tip of the cone and and the friction on a surface sleeve above the cone gives information about the soil properties (clay or sand). With an electrical CPT, also the electrical resistance of the subsurface can be determined using electrodes.

2.2.7   The temperature-electrical conductivity (T-EC) probe

The T-EC probe is constructed for the measurement of temperature and electrical conductivity of soft soils down to a depth of 6 m. The electrical conductivity is measured with a two-electrode system.   The temperature is measured right in the tip of the probe, whereas the electrical conductivity is measured between the two stainless steel rings on the tip (Figure 2.9). Generally, temperature and EC measurements at 10 cm intervals are measured. The probe has to equilibrate at each subsequent measurement. This takes about 1 to 3 minutes.

A T-EC probe consists of a metal stick with two sensor at the tip (Fig. 2.2), which is pushed into soft (wet clay, peat) soils by means of human force up to a maximum depth of 4 meters. The electrical conductivity is measured between the two sensors (stainless ring), whereas the temperature is measured in the tip of the probe. This unconfined cell is totally surrounded by the soil and connected to a standard pocket EC meter (section 3.1).

The electrical conductivity that is measured by the T-EC probe deviates from EC measurements with an EC meter. A correction factor must therefore be used, which slightly depends on the salinity of the groundwater. The correction factor can be determined by measuring comparing EC values of an EC meter and the T-EC probe simultaneously, e.g., in a bucket, with several water salinities. The average correction factor is around 0.4. This value increases to about 0.5 for EC's of 16 mS/cm and higher. The measured electrical conductivity by the T-EC probe is the apparent resistivity of the subsurface. A formation factor should therefore also be used to convert the apparent resistivity to the porewater EC.
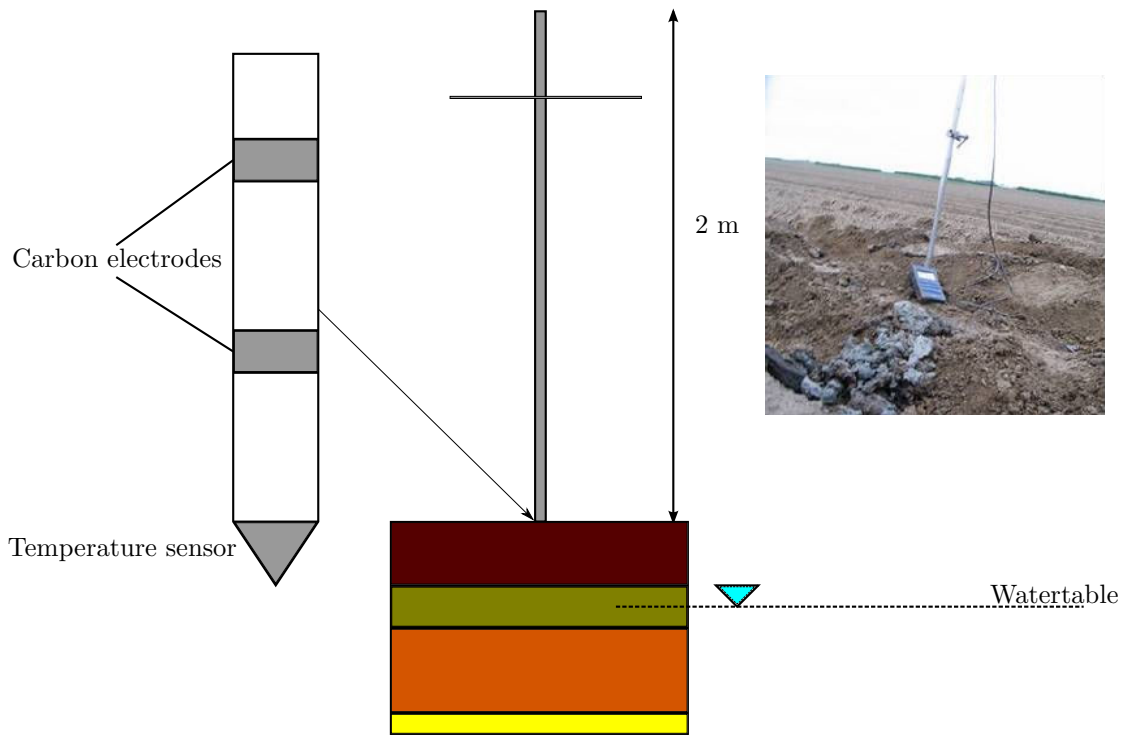
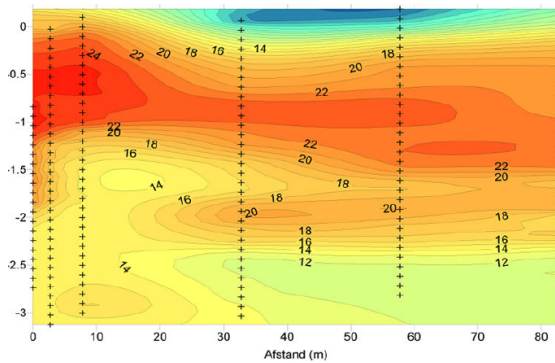Figure 2.9: Sketch of a TEC probe.

Figure 2.10: Vertical cross section of interpolation of T-EC probe measurements. A shallow freshwater lens is present (indicated in blue). Contour lines of EC have also been indicated (Oude Essink et al., 2009).

2.3   Basic principles of electromagnetic methods

A wide range of instruments exists which are based on electromagnetic techniques. They are used in many different field studies, e.g., mineral exploration, landfill surveys, permafrost mapping and geological mapping. Even in groundwater surveys concerning fresh and saline groundwater, the variation of instruments is large, so the user can often choose the most appropriate tool. Electromagnetic methods do not need direct contact with the ground surface. Measurements can therefore be taken from airplanes, ships, boreholes and near the ground.

The theory behind electromagnetism is complex and briefly described here, by starting with the concept of magnetism. Magnetism is related to electricity. This was discovered by Hans Christian Oersted in 1891 when he observed that a changing electric current in a wire affected the needle of a compass. A few years later, Michael Faraday showed that an electric current can be induced by a changing magnetic field. It is now known that magnetism is always accompanied by an electric current or by time changing electric fields. The magnetic property of an apparently 'static appealing' bar magnet arises from small currents[4] within the metal. A magnet always has two opposing poles, denoted by a north and a south pole [5]. Opposing poles attract each other, while equal poles repel. The concept of a magnetic field is comparable with an electric field, except that a magnetic field is a dipole field (is has a magnitude and a direction). This is depicted in Figure 2.11.
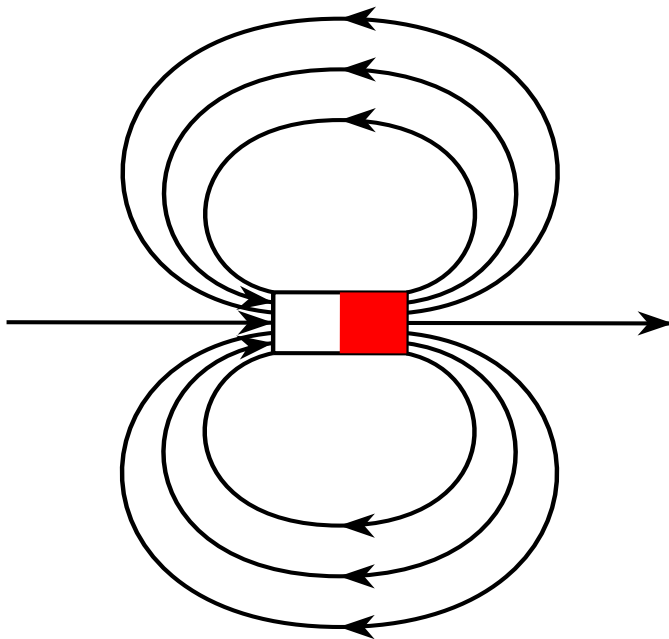
Figure 2.11: The magnetic dipole field, with a north (in red) and south pole (in white).

The magnetic field creates a magnetic force on other objects with magnetic properties, just like and electric charge experiences an force due to an electrical field. A magnetic force however only acts on moving charges. The theory of a magnetic field is somewhat more complex and will not be discussed further here. For a conceptual understanding, it is sufficient to state that electric and magnetic field are closely related. For example, if a current is transmitted in a loop

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[4]These currents are known as 'Amperian currents' and arise from spinning electrons.
[5]This opposed to the electrical property of matter, which can either be negatively or positively charged.

(such as in a coil), a magnetic field is created. The orientation (strike) of this is field depends on the direction of flow, but is perpendicular to the plane of the loop. When the current is changing direction through time (an AC current with a frequency f in Hz), both electric field and magnetic field change through time, and electromagnetic (EM) waves develop (see Figure 2.12) and an EM field is created, composed of the related electric and magnetic fields.
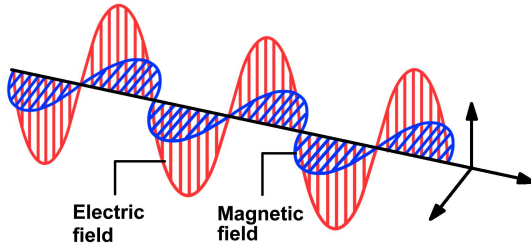

Figure 2.12: Electromagnetic wave composed of an electric E and an magnetic H field component.

The EM waves travel through the air and the subsurface. In the subsurface, the EM waves are modified slightly relative to the EM waves in the air. If a conducting medium is present within the subsurface, the magnetic field component of an (EM) wave induces alternating currents within this medium. Of course, these alternating currents are associated with magnetic field components, giving rise to a another EM field. This alternated EM field is called the secondary field, while the (nearly) undisturbed EM field is called the primary field. The waves of the secondary EM field differ in both phase an amplitude relative to the waves of the primary EM field. Electromagnetic methods make use of this principle. Among the various methods, a distinction is made between frequency domain electromagnetic methods (FDEM) and time domain electromagnetic methods (TDEM), which will be briefly explained in the following examples.

2.4   FDEM; methods of deployment

FDEM instruments consist of a transmitting and a receiving device. The primary EM field is generated using an AC with a certain frequency f. The frequency of the EM waves and the conductivity of the media (because the secondary electromagnetic field weakens the primary electromagnetic field) through which the electromagnetic waves travel determine the depth of penetration. The skin depth δ, which is the depth at which the amplitude of a plane wave has decreased to $1/e$ or 37% of its original amplitude, is commonly used as an indicator of the penetration depth:

$$\delta = 503\sqrt{\frac{1}{(f\sigma)}} \tag{2.7}$$

where f is the frequency of the electromagnetic wave and σ is the apparent conductivity in S/m. The receiving device detects both the primary and secondary EM field. As the conductance of the subsurface depends on the resistive properties of the subsurface and thus on the secondary EM field, the primary EM field has to be filtered from the signal. From the response of the primary and secondary EM signal, the apparent conductivity of the subsurface can be calculated.

FDEM instruments manufactured by GEONICS Ltd. calculate and provide a direct read out of the apparent conductivity of the subsurface. This only holds for subsurface media where the apparent conductivity < 100 mS/m (low induction numbers), because then the amplitude of

Table 2.1: Penetration depth and coil distance and orientation of the EM 34 instrument.

Coil spacing	Horizontal dipole	Vertical dipole
10	7.5	15
20	15	30
40	30	60

the EM wave is linearly proportional to the terrain apparent conductivity. Therefore, for high conductivities (such a sediment saturated with seawater) the equipment can indicate incorrect values and the measurements should treated qualitatively or should be corrected. Some examples of FDEM systems and their application are given in the following sections.

2.4.1   GEONICS EM 31

The EM 31 instrument is operated by one person. The instrument consists of a (extend-able) tube having a transmitting and a receiving coil at an inner distance of 3.6 m (Figure 2.13) . The effective exploration depth is about 6 m. The instrument is used for a quick investigation of the lateral variability of the subsurface bulk conductivity.

Figure 2.13: EM 31 instrument in an agricultural field.

2.4.2   GEONICS EM 34

The EM 34 instrument consists of a receiving and transmitting coil which are connected by cables. Three inter coil spacings can be used (10 m, 20 m and 40 m) using two coil orientations. When the horizontal dipole configuration is used, the coils are placed vertically on the ground (Figure 2.15). In the vertical dipole configuration, the coils are placed horizontally on the ground. Table 2.1 lists the penetration depths of each combination. The horizontal dipole configuration is less susceptible to measurement errors due to misalignment of the coils then the vertical dipole configuration, and is therefore used most often.

Although a sounding curve could be derived from the different penetration depths of the EM 34 instrument, the instrument is generally used for lateral variations in subsurface conductivity.

Figure 2.14: EM 34 instrument in the horizontal dipole configuration.

2.4.3   GEONICS EM 39

Although the EM 39 instrument is conceptually not very different then the EM 31 and EM 34 instruments, its application is. The EM 39 can only be used in boreholes. Measurements are taken at different depths as the probe is lowered in a borehole by a cable. The measurement is unaffected by the presence of plastic casing and conductive borehole fluid, as opposed to normal resistivity borehole logging. The peak response occurs at approximately 30 cm from the probe. It provides an effective radius of exploration of 1.5 m from the center of the borehole. As such, a much higher vertical resolution can be obtained than with the EM 31 and EM 34 instruments.

Figure 2.15: EM 39 instrument lowered in a borehole.

2.4.4   Airborne TDEM; HEM system by BGR

Helicopter-borne frequency-domain electromagnetic (HEM) systems use a towed installation with small transmitter and receiver coils (about 50 cm). The system RESOLVE (Fugro Airborne surveys) operated by BGR[6] (Siemon, 2009) serves as an example here. This system makes use of five pairs of transmitting and receiving coil and frequency combinations. In this way, the electrical conductivity of the subsurface in three dimensions can be measured by application of inversion techniques. The exploration depth depends on the resistivity of the subsurface. In relatively resistive terrain, up to 150 m can be detected, while this is much lower in conductive terrain. Large areas can be covered through times; a sampling distance of 4 m can be performed at a flight velocity of 140 km/h.

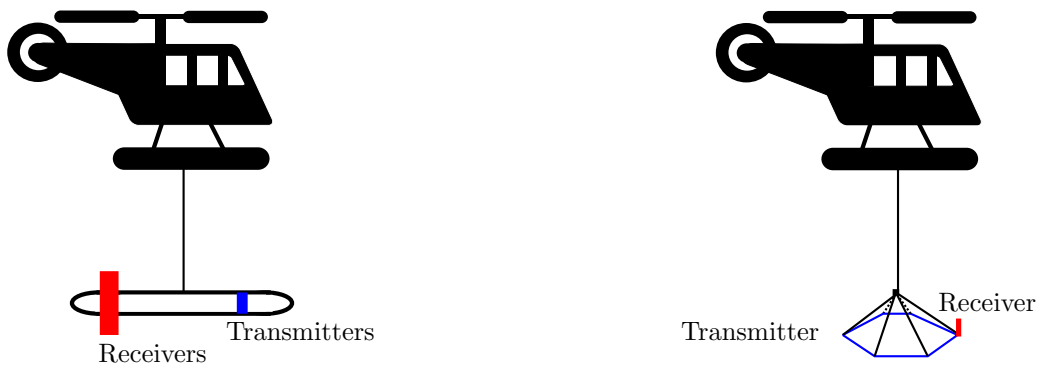[6]Federal Institute for Geosciences and Natural Resources

Figure 2.16: Sketch of HEM (left) and SkyTEM (right) set up (not on scale).

2.5   TDEM; methods of deployment

In time domain methods, a DC is transmitted through a large loop of wire. The flow of current will create a primary magnetic field. When the current is sharply (though controlled) switched off, the change in magnetic field will create currents within the subsurface. These currents dissipate due to the resistance of the subsurface, and create a secondary magnetic field which thus changes over time. In a receiving coil, this change (decay) in magnetic field in measured over time. The change depends of the resistivity distribution of the subsurface. An advantage of the method is that the transmitting loop can be used as a receiving loop.

2.5.1   NanoTEM (Zonge)

With the NanoTEM system by Zonge, TEM soundings can be performed using an outer transmitter loop and an inner receiver loop, which are placed in a square and ungrounded at the surface (see Figure 2.17). The size of transmitter and receiver loop can be changed, so the NanoTEM can be used for a variety of different targets (subsurface resistivity distributions). Inversion techniques are used to derive an resistivity layer model of the subsurface.
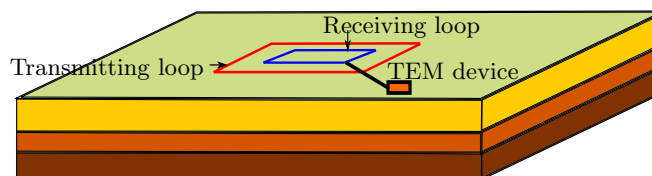
Figure 2.17: Sketch of NanoTEM measurement.

2.5.2   Airborne FDEM; SkyTEM

The SkyTEM system is a helicopter-borne TEM system (Viezzoli et al., 2010). The system is conceptually similar to the NanoTEM system. The transmitting loop consists of a hexagonal frame (see Figure 2.16) of about 24 m wide, present at about 30 m from the surface. A receiving loop is present at 2 m above the frame. The system is slower than the RESOLVE system by BGR (flight speed about 20 km / h), but has a larger exploration depth.

2.6   Discussion

Geophysical methods are indirect methods. They all measure the bulk resistivity or conductivity of the subsurface, so a conversion is needed which always introduces uncertainties due to equivalence problems. An advantage is that they are relatively cheap, and that large areas can be covered with less effort.

Electrical resistivity methods are simple in concept. A VES provides a 1d resistivity profile of the subsurface. A VES is better at detecting a conductive medium below a resistive medium than the other way around. CST is more suitable to detect lateral changes in subsurface resistivity. A CVES yields a continuous image of the subsurface resistivity distribution. In the inversion techniques, known parameters (such as a measured EC at a certain depth) can improve the result of the measurement. All these techniques require a relatively sharp contrast between conductive and resistive subsurface regions, because of the relatively low resolution.

Short normal and long normal borehole resistivity measurements provide a better vertical resolution than a VES, CST and CVES, but an uncased well is needed. In an unconsolidated subsurface this leads to extra efforts. ERT measurements can be performed in cased wells, and a 2d or even 3d image of the subsurface resistivity is yielded. Recent developments have made it possible to remotely yield ERT measurements over time.

An electrical CPT provides a fast, continuous measurement of the lithological properties of the subsurface, as well as the apparent conductivity with depth. The penetration depth depends on the lithology, but is usually restricted to the top 20-30 meters. The terrain should be suitable for heavy truck access.

Most resistivity methods are less susceptible to small conductors in and above the subsurface than EM methods. A major drawback is that they are generally labor intensive and that contact problems (between the electrode and subsurface) can arise. The major drawback of EM methods is that they are susceptible to surface conductors, such as barbed wire or subsurface cables. Large conductors can lead to unreliable measurements.

Advantages above electrical resistivity measurements are that they don't need direct contact with the ground surface and that larger areas can be covered with less effort than resistivity measurements.

The NanoTEM instrument can be used to derive a vertical 1d resistivity sounding just like a VES. This method introduces less equivalence uncertainties. Because the cover area (the area of the outer loop) is relatively small, the influence of lateral heterogeneities is less. In the upper 10 m of the subsurface however, a VES has a larger resolution.

Airborne EM methods can either be in the time or frequency domain and are able to cover large areas in few time. The penetration depth in the time domain (SkyTEM) is larger, but the operation speed is much lower. In the frequency domain, the penetration depth is less. This is especially the case in conductive terrain.

3   Direct methods

Direct methods do not need the conversion (formation factor) from formation resistivity to fluid resistivity. They are therefore more reliable, as this conversion is usually attended with uncertainties.

3.1   EC meter

An EC meter measures the electrical resistivity or conductivity of a groundwater sample, depending on the type of instrument. By convention every EC meters does give a read out of the electrical conductivity. Field EC meters make use of electrical resistivity techniques, using either two or four electrodes and an AC. Because temperature is also measured, the user can often choose to display the specific EC (compensated to 25°C) or the field EC. Other types of EC meters make us of an electromagnetic method (section 2.3), but this will not be discussed here. EC meters should be calibrated regularly using electrolytes of known conductivity.

3.2   CTD divers

A CTD diver is a small instrument (size is about 18×2 cm, see Figure 3.1), which is installed into a (water saturated) borehole or piezometer. Continuous measurements of the pressure, temperature and electrical are automatically taken over time and internally saved. The user specifies the frequency of the measurements before installation. The memory of most CTD divers allows for 16000 measurements. Again, electrodes are used to measure the fluid conductivity. The temperature sensors allows for specific EC read outs.

Figure 3.1: CTD diver.

3.3   Hydrochemical analysis

3.3.1   Cation exchange

The dominant ions in groundwater of fresh water lenses are often Ca^{2+} and HCO_3^-, as a result of calcite dissolution. Na^+ and Cl^- dominante in saline or brackish groundwater. When these water types mix, cation exchange processes take place. Hydrochemical data therefore can reveal whether a fresh water lens is freshened of salinized. Upon freshening, Ca will displace Na from the exchanger[7], denoted by X:

$$Ca^{2+} + 2Na{-}X \rightarrow Ca{-}X_2 + 2Na^+ \tag{3.1}$$

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[7]The sediment where the cation is adsorbed on. Sediment with a larger specific surface area (i.e. clay) will adsorb more cations. The adsorption capacity is expressed in the cation exchange capacity (CEC) in milli-equivalents (meq) per kg sediment.

which results in a water quality change from a NaCl to a CaCl$_2$-type of water. Saline of brackish intrusion will result in a NaHCO$_3$ water type, as the reverse reaction takes place:

$$2Na^+ + 2Ca-X_2 \rightarrow 2Na-X + Ca^{2+} \tag{3.2}$$

A usefull indicator for intrusion of salt or fresh groundwater is the Base Exchange Index (BEX) (Stuyfzand, 1993), which is the meq-sum of the typically marine ions Na$^+$, K$^+$ and Mg$^+$ corrected for the contribution of sea salt:

$$BEX = \left[Na^+ + K^+ + Mg^+\right]_{measured} - 1.0716\ Cl^- \tag{3.3}$$

where a positive BEX indicates freshening, a negative BEX indicates salt water intrusion.

### 3.3.2 Taking groundwater samples

A groundwater sample is usually taken from an observation well. Here it is assumed that the well is properly installed and problems such as short circuiting are not encountered. An overview of such well installation problems can be found in Stuyfzand (1993). The manual installation of (shallow) observation wells won't be discussed here either.

The representativity of the sample depends on the screen length. A depth specific sample can be obtained using a short well screen. The use of a longer well screen results in a more depth integrated sample. In general, short well screens are preferred in hydrochemical analysis, because variations in groundwater composition over depth results in mixing during sampling. This may induce chemical reactions. Moreover, permeability variations along the well screen can influence the depth integrated sample. Minifilters can be used for detailed depth specific sampling. The filter can consist of glass, ceramic material, stainless steel or nylon. Small tubes make retrieval possible. As the diameter of the tube is small, multiple minifilters can be installed in one well.

The (often) small diameter of a piezometer makes pumping the most appropriate method for sample retrieval. A vacuum pump is the easiest method but has disadvantages. As this pump creates an under-pressure, degassing of the volatile compounds in the sample may occur which can lead to changes in the pH. A vacuum pump can also not retrieve water from more than 10 m depth. Especially because of the first reason, the use of this pump is not recommended. Alternatives are a peristaltic pump, as it creates much smaller suction forces. The peristaltic pump can safely be used if the water table is less than a few meters below surface. For greater depths, pumps which apply an overpressure (using an inert gas like Ar of N$_2$) can be used.

When a sample is taken from a well, it is important that the stagnant water in the well is removed first. Standing water has a different chemical composition than the aquifer as evaporation and oxidation may have occurred. To evaluate the flushing demand, easily measured field parameters such as the Electrical Conductivity (EC) could be sampled over time until a stable value is obtained.

The retrieved sample may contain suspended solids, which need to be removed before the laboratory analysis. Generally, samples are therefore filtered using a 0.45 μm membrane filter. Contact with the atmosphere should be avoided as much as possible. Degassing of CO$_2$ may occur, changing the pH and alkalinity. When atmospheric oxygen enters the sample, redox reactions take place, especially when the sample is anoxic. An example is the oxidation of Fe^{2+} and the subsequent alkalinity change:

$$4Fe^{2+} + 8HCO_3^- + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H_2CO_3 \tag{3.4}$$
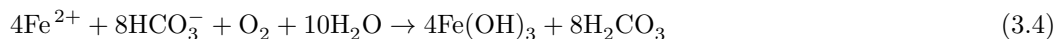
As a result, calcite may precipitate.

In order to avoid sampling errors, direct field measurements of the pH, temperature, EC and alkalinity should be performed. These parameters are easily determined with electrodes (except for alkalinity). One can also take measures for better conservation of the samples by adding acid to the sample until the pH is <2. This will stop bacterial growth, most redox reactions, and prevents adsorption or precipitation of cations.

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