# HYDROGEOLOGICAL MAPPING OF TREATED WASTE WATER INFILTRATION USING RESISTIVITY SURVEYS

## Hydrogeologisk kartläggning av infiltration av renat avloppsvatten genom resistivitetsmätningar

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## Abstract

This field study constitutes an evaluation of resistivity surveys as a method of following subsurface water transport. An ABEM Terrameter LS was used to detect chloride enriched infiltrating water. A resistivity profile was established at a field site in Omma outside of Sjöbo, Sweden. The profile followed a slope starting atop a glacifluvial sand deposit going towards a stream in a valley along a hydraulic gradient. A water treatment facility at the top of the glacifluvial deposits large volumes of chloride enriched water that is infiltrated through the soil surface. Resistivity measurements were made repeatedly with the Terrameter during a ten day time period. Inversion was used to create models of the resistivity distribution in a vertical cross section. The data sets were analyzed via time-lapse inversion in order to track change in resistivity due to the infiltration. Supported by existing documentation of the local geology, hydrogeological interpretations of the model results were made. The models indicate that the majority of the infiltration water's horizontal transport has taken place in the ground water zone. The method was capable of detecting the chloride-rich infiltration water and its progress through the profile stratigraphy during the measurement period. The results indicate that repeated resistivity surveys are a feasible method for tracking subsurface water transport in future projects.

*Key words* – Groundwater flow, resistivity, infiltration, wastewater, Omma, Sjöbo

## Sammanfattning

Fältstudien presenterad i denna artikel är ett försök att pröva resistivitetsundersökningar som en metod för att följa transport av infiltrationsvatten. En ABEM Terrameter LS användes för att detektera kloridhaltigt infiltrationsvatten. En resistivitetsprofil upprättades på en fältlokal i Omma utanför Sjöbo. Profilen löpte längs med en grundvattengradient, ned från en isälvsavlagring mot ett lokalt vattendrag. Stora mängder kloridberikat vatten från ett närliggande vattenreningsverk infiltrerades från en dammanläggning på toppen av isälvsavlagringen. Upprepade resistivitetsmätningar utfördes med Terrametern under en tiodagarsperiod och kombinerades till s.k. time-lapse sektioner för illustrera förändringar i profilen under mätperioden. Inversionsmodeller framställdes från mätdata genom programmet Red2dinv. Med befintlig dokumentation om lokalens geologi som underlag gjordes hydrogeologiska tolkningar av mätresultaten. I modellen går det att urskilja grundvattenzonen, och se att majoriteten av infiltrationsvattentransporten skett inom denna. Den tillämpade metoden har fungerat väl för att följa det kloridhaltiga vattnets transport genom marken. Resultaten är lovande för resistivitetsundersökningar som en metod för att följa vattentransport i framtida undersökningar.

## Introduction

The unsaturated zone, situated between the soil surface and the groundwater table, plays an important role in all ecosystems and is the base upon which the food chain is built. An important aspect of the unsaturated zone concerns the recharge of groundwater. Groundwater constitutes an important water supply component for several purposes, such as domestic, industrial, and agricultural use, and is often considered as a clean water resource. However, polluting solutes from the soil surface can be transported down through the soil contaminating the groundwater.

The capillary zone is situated between the saturated and unsaturated zones, it is defined as the thin zone above the water table with a water content close to saturation but with a lower air entry pressure than required to penetrate the water table (e.g., Bear, 1972). In more general terms the capillary zone is the transition zone between the mainly vertical flow in the unsaturated zone and the three dimensional flow (mainly horizontal) in the saturated zone. In coarse materials the capillary zone is only a few centimetres thick whereas in fine textured materials it can be several meters thick.

In 2011 a series of results were published in Pojmark et al. (2011), recording the transport of infiltrating water in laboratory experiments by i) photo documented dye tracing and ii) high resolution 3D resistivity imaging. The experiments show a large lateral transport in the capillary zone. Water transport in the capillary zone is dynamic, with an increased lateral transport as the pore saturation increases. The corresponding results of the two methods verified resistivity imaging as a viable method for field experiments (Pojmark et al., 2011).

Resistivity surveys investigate how well a material conducts electricity by inducing a current and measuring the voltage drop between two points. The resistivity of a soil is affected by factors such as grain size, porosity, pore saturation and the chloride concentration of pore fluids. By measuring ground resistivities at different depths and locations along a profile (CVES: Continuous Vertical Electrical Sounding) it is possible to construct and interpret geological stratigraphies and in some cases water table locations (Auken et al., 2006).

The present study was carried out as a B.Sc. thesis as a part of a research project headed by the departments Engineering Geology and Water Resources Engineering of Lund University, with funding from the Swedish Geological Survey. The project; "Water and Solute Transport Processes Across the Capillary Fringe" seeks to document the characteristics of water transport in the capillary zone.

The aim of the present study was to investigate the suitability of repeated resistivity surveys as a method for studying water transport in the capillary fringe. The goal was to follow the transport of infiltration water through a ground profile using resistivity surveying. Repeated measurements were made across one profile and gathered data were processed and analysed in order to follow the water activity in the ground during the measurement period. A hydrogeological interpretation of the stratigraphy was made.

## Materials and Methods

### Survey Area

The survey area is located 3 km west of Sjöbo, southernmost Sweden, in a birch forest in close proximity to a municipal water treatment plant (see figure 1). The area
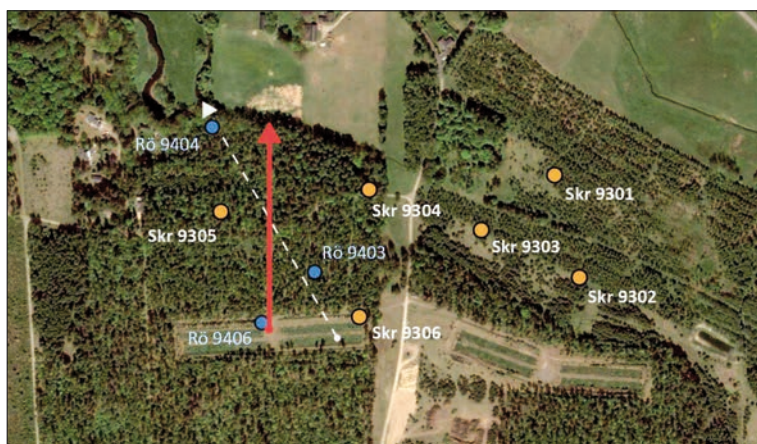


Figure 1. *Modified satellite image of the survey area (http://maps.google.se/). The red line marks the 250 m long measured profile. The profile's start point in the infiltration pond area is marked with a dot. The profile terminates in the valley east of the Björkaå stream which meanders northwards. The brown circles mark locations of borehole logs and groundwater observation wells. The blue circles mark the locations of three additional groundwater observation wells. The dashed grey line marks an earlier documented hydrogeological cross section by Sweco VIAK (figure 3) which is based on the information from the boreholes in the picture.*

Figure 2. *Photo of the infiltration pond area during active use. The water infiltrates through the gravel before it puddles.*

is located 46 m.a.m.s.l. on the northern edge of a terrace formation consisting of sand and gravel sediments sloping into a valley where the meandering stream Björkaån is located.

## Infiltration Ponds and Chloride Enriched Water

The infiltration ponds were originally erected as a pilot project in 1994 in an attempt to utilize the local geology for nitrogen removal of ammonium rich waste water (Hebrand, 1994). Since 2002 they are in permanent use and approximately one million m$^3$ waste water per year is infiltrated at the site (figure 2). Waste water is released through pumps at the edge of the terrace. Ammonium levels are heavily reduced in a fully natural two-step process as the water percolates through the coarse sandy slope towards the organic sediments of the valley (Hebrand, 1997; Hebrand and Vanek, 2003; Vanek, 2010).

The water released through the infiltration ponds comes from a nearby sewage water treatment plant. By-products of the treatment processes are increased salt levels in the water, among others chloride (Hebrand, 1997). The Chloride content is a major factor influenc-

ing water resistivity when measuring the electrical conductivity of soils (Palacky, 1987). In the case of the study site, the treated sewage water released from the infiltration ponds has a measured resistivity of 8 Ωm, compared to the 22 Ωm resistivity of the natural groundwater (Hebrand, 1995). This resistivity contrast would make it possible to distinguish the infiltration water in the measured data.

Several previous surveys of the area performed by the consultant company SWECO on behalf of Sjöbo Municipality were used as a fundament for planning the field procedure. The available data comprised; i) borehole logs analyses and stratigraphies ii) a hydrogeological model of the terrace slope iii) sampled conductivity values for the natural water as well as for the infiltrated sewage treatment plant infiltration water (Hebrand, 1994; 1995).

## Field measurements

The infiltration ponds are distributed across some hundred meters along the slope towards Björkaån's valley. The measurements were made along a 250 m long northbound profile originating next to an infiltration
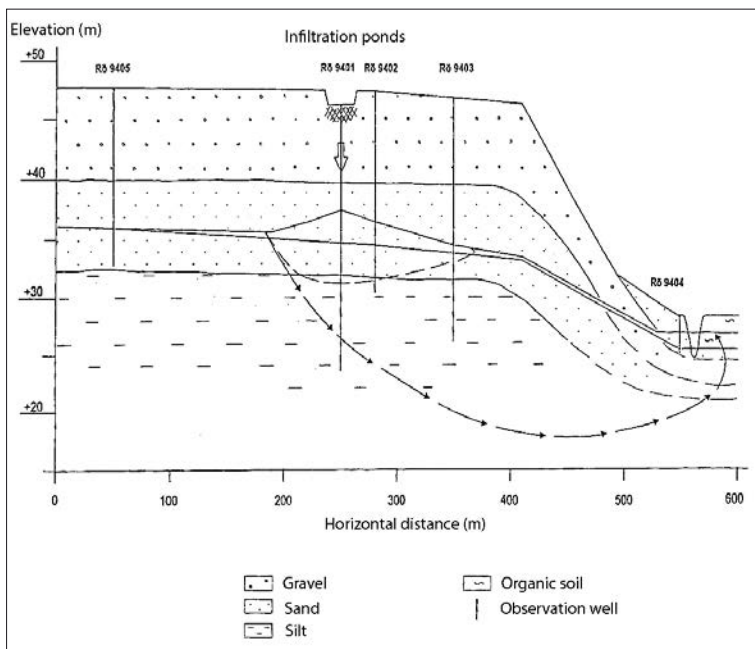
Figure 3. *Geological stratigraphy of the ice age deposits along the terrace formation's northern slope towards Björkaån's valley, along with measured ground water tables from observation wells (modified from Hebrand, 1995). This profile is marked as a dashed grey line in figure 1.*

pond running towards a valley stream (figure 1). Measurements were made between 2012-04-11 and 2012-04-21.

The 2nd of April, 8 days before the field work began, Sjöbo Municipality shut down the operation of the infiltration ponds. This was done under the presumption that the bulk of the existing sewage water would, after this time period, have drained from the system. This would cause a greater conductivity contrast between the infiltrating chloride rich water and the natural ground water. After obtaining the first dataset on the 11th, intended as a reference set, the infiltration ponds were restarted. In the results section the days are renumbered, with day 0 being 11th of April when the first measurement was taken and the infiltration of treated wastewater started.

Continuous Vertical Electrical Sounding (CVES) measurements were made using an ABEM Terrameter LS instrument along a 250 m long profile. Cable reels100 m long with a 5 m electrode spacing (21 electrodes per reel) were used. These were configured in a parallel-displaced two line set up giving an electrode distance of 2.5 m (2x21 electrodes per 100 m). At the first established measurement station the Terrameter plus relay switch with power source were connected to a reel pair in each direction thus covered 200 m. To cover the remaining 50 m distance, a roll-along procedure was implemented. The groundwater observation well Rö 9406

(figure 1) was located 18 m from the start of the profile. The water table was measured using a plummet to 8.25 below ground on 2012-04-21.

Measured data were reviewed as pseudosections where apparent resistivity is plotted. The inversion software Res2dinv was used in order to generate possible models of the section's actual resistivity distribution. When a credible resistivity model has been obtained it can be used as a basis for a hydrogeological interpretation of the inverted section. The robust inversion method was used for the inverse modelling (Loke et al., 2003), with a cell width of 1.25 m which is half the actual electrode distance. Topographical data for the profile were measured and included in the inverted model sections. So called time-lapse inversion was used in which a constrain between the different time steps is used in order to reduce artefacts and focus the results on actual change (e.g. Sjödahl et al., 2008).

## Results

### Pseudosections

Figure 4 and 5 are time-lapse pseudosections showing the apparent resistivity change during the field measurement periods. They are indicative of mean resistivity changes but cannot be used for detailed analysis. The colour gradient shows resistivity change in the range of +/–10%.
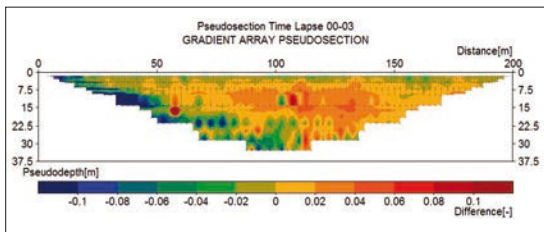
Figure 4. *Pseudosection time-lapse of measurement data from day 0 and day 3.*



Figure 5. *Pseudosection time-lapse of measurement data from day 2 and day 10.*

Figure 4 shows the change between day 0–3. The is a distinct trend of strongly reduced resistivity (over 10 %) spreading out over a pseudodepth of ca. 7.5–22.5 m along the profile direction across a distance of approximately 30 m during the 4 day time period. In the right half of the profile there has been a minor reduction of resistivity of between 0–6 %. Figure 5 shows the change between day 2–10. There is now a major, broad decrease in apparent resistivity across more than 100 m of the profile.

### Inversion model

Figure 6 is an inversion model based on the pseudosection measured day 10. The section shows estimated real resistivity as function of depth and can be used for hydrogeological interpretation. The model can be divided into three distinct sections. The red section has a very high resistivity – over 2500 Ωm. The blue section has a low resistivity – under 270 Ωm. Between these extremes there is a yellow-green section with a gradually decreasing intermediate resistivity range of around 1500–500 Ωm. The red section has a relatively even depth of 7.5 m which increases at the profile's borders, while the yellow-green section's depth fluctuates more heavily with the underlying blue border.

Figure 7 shows a time-lapse inversion model of the change in resistivity of the profile between day 2 and 10 after infiltration was resumed. There is a thick red horizontal path of increased resistivity between 7.5–15 m
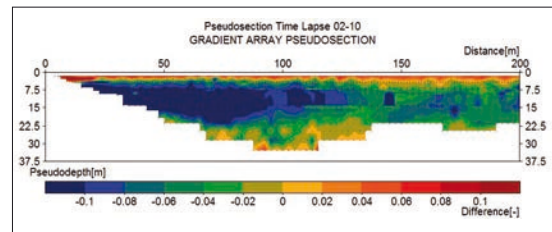
depth. Above this there is a very thin band of reduced resistivity. Below 15 m depth there is a widely spread plume of decreased resistivity concentrated to the first 125 m of the profile.

## Interpretation

A soil stratigraphy of two facies has been interpreted from the inversion model (figure 6). The red section in figure 6 is likely coarse grained glacial deposits situated above the water table. The fractions have been described to vary in local stratigraphies from borehole logs but generally contain gravelly sand.

The yellow-green section is interpreted as finer sediments, likely fine sand deposited as glacial lake sediments which are common below the coarser sediments in the region (Daniel, 1992). The section has a gradually increasing resistivity which would be due to the fact that glacial lake sediments become gradually finer with depth. After around 120 m the resistivity of the sections drops somewhat to a range of 700–1300 Ωm. When the resistivity decreases to below 250 Ωm (blue zone) it most likely represents the groundwater table, water saturated pores can be expected to dramatically lower the resistivity (e.g., Ewing and Hunt, 2006). This is vital since it is mainly along this gradient that the chloride rich infiltration water would be causing a resistivity change.
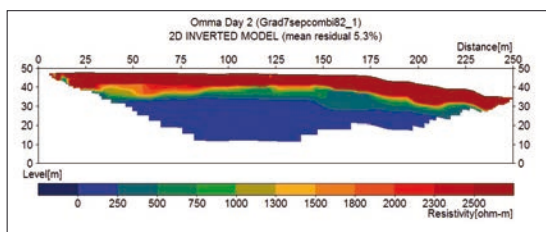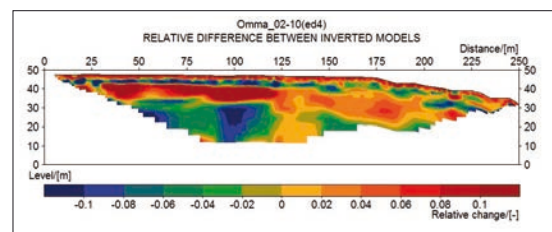


Figure 6. *Inversion model.*



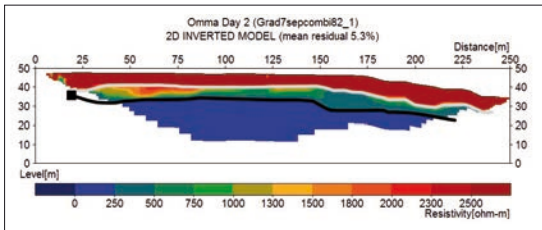Figure 7. *Inversion model time-lapse of measurement data from day 2 and day 10.*

Figure 8. *Interpreted inversion model, outlining a stratigraphic boundary (grey) and the groundwater table (black). The square marks the measured groundwater table in groundwater observation well Rö 9406, see figure 1.*



Figure 9. *Interpreted model time-lapse (day 2 and day 10), outlining a stratigraphic boundary (grey) and the groundwater table (black). The square marks the measured groundwater table in groundwater observation well Rö 9406, see figure 1.*

The grey line in figure 8 shows the interpreted border between coarse glacial and finer ice-lake deposits. The black line shows the position of the interpreted water table (the square is the level measured in the groundwater observation well).

Figure 5 shows a strong net decrease of resistivity in the left side of the profile after the infiltration has been active for 10 days (over 10 % in dark blue areas). Comparing figure 4 and 5, it can be deduced that the resistivity has decreased with time in the direction of the terrace slope and groundwater gradient, towards the local stream, causing a major resistivity decrease. This is likely due to the infiltration water moving along the water table.

Figure 9 shows the change in resistivity (day 2–10) with the interpreted hydrogeological model superimposed. The thick band of increased resistivity above the groundwater table is most likely due to the drainage of rainwater from the unsaturated zone during the field measurement period (figure 10). The wide plume of decreased resistivity beneath the water table correlates well with the development observed in the pseudoplots. This could be an effect of the water released in the ponds at
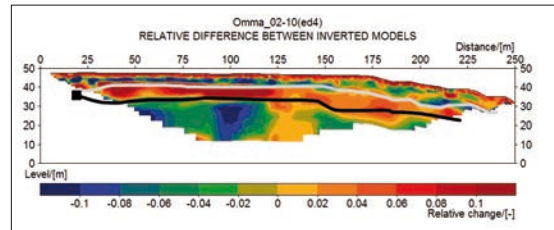
the start of the profile infiltrating down through the coarse sediments, and then travelling along the groundwater gradient through the profile. Reversely, the increase in resistivity at the right side of the profile could then be the result of pre-hiatus, remaining infiltrated water leaving the system. The thin blue-green horizon at 5 m depth describes a sharp decrease of resistivity just at border between the two facies. If this shift is related to the infiltration water it would indicate a second lateral transport zone of water.

## Discussion

The correlation between the general indications of the pseudosections and the resisitivity changes in of the inversion model, and the development shown in the time lapse sections indicate a transport along the interpreted groundwater gradient. The measured groundwater level in the well at the far left of the profile appears somewhat raised. This is likely due to a very local rise in the direct vicinity of the infiltration ponds during active periods that have been observed in previous studies (Hebrand, 1997).

It was not possible to identify a capillary fringe based on the model, which would probably be small in the relatively coarse geology of the profile. In a laboratory test with soil collected at the site (at 1 m depth) the capillary rise was found to be around 0,7 m.

The interpretation correlates with the measured groundwater level and local borehole logs, but ideally a direct correlation between measured resistivities and a profile borehole should be made to verify the model and the interpretation. Further sampling would also be required to investigate the nature of the shallow thin horizon with decrease in resistivity (blue). It is possible that it is a horizontal impermeable fine textured layer creating a hanging aquifer, forming a secondary transport way for the infiltration water. It might also be an artefact arising in the inverse modelling from to the very large
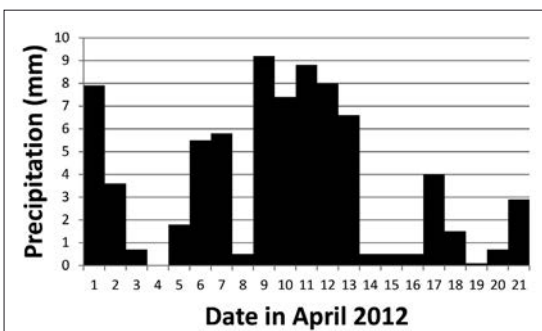


Figure 10. *Recorded precipitation in Sjöbo during the measurement periods i) 2012-04-11 to 2012-04-14 and ii) 2012-04-21 (Klart.se, 2012).*

resistivity gradient between the two facies, although this should presumably be taken care of by the time-lapse constrains used in the inversion. It is also possible that draining rainwater has accumulated at the bottom of the coarse top sediment, briefly saturating the finer lower sediment at the facies boundary and causing the resistivity decrease.

## Conclusions

From the results of the pseudosections (figures 4 and 5) it is possible to conclude that the infiltration water has travelled through the soil in the expected flow direction and lowered the resistivity. A geological stratigraphy based on the measurements has been interpreted from the inversion models, which correlates with the previously conducted drillings and surveys of the site shows how the flow of water causes resistivity changes in different depths and soil facies. The goal of the study has thus been accomplished. It has been possible to measure how much the resistivity of the ground has changed, and to estimate the general speed and expanse along the profile (about 110 meters after 10 days).

## Acknowledgements

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På morgonen den 14 juni vaknade byrådirektör Anders Ljungren av att ha förvandlats till en blåval. Han fick snabbt simma ut från lägenheten till havet. Flera av hans planerade möten ajournerades medan han slog med stjärtfenan utanför Århus. Livet är märkligt, tänkte han. Man vet aldrig vad morgondagen har i sköte. Mobiltäckningen var dålig över Nordatlanten så Ljunggren besvarade aldrig de samtal hans chef ringde. På myndigheten hyrdes en personal in från Rent-a-job AB veckan efter för att täcka upp efter byrådirektören. Ljunggren stannade i vattnet.

*Kenneth M Persson*

## DELA MED DIG AV DINA KÄNSLOR OCH TANKAR KRING VATTEN

Vi inbjuder dig som läser VATTEN att dela med dig av dina personliga reflektioner kring vatten. Skicka oss text och/eller bild med fri association till vatten. Formatet är fritt, men utrymmet begränsas till en sida. Redaktionen förbehåller sig rätten att fritt utforma layouten av sidan och att eventuellt kombinera olika bidrag på samma sida. Ingen ekonomisk ersättning utgår.