An Investigation of Groundwater Flow on a Coastal Barrier Using Multi Electrode Profiling

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ABSTRACT
Preliminary geophysical and hydrogeological investigations indicate that multi-electrode profiling (MEP) can be used to monitor groundwater salinity on a coastal barrier where a shallow thin aquifer discharges to the North Sea. A monitoring system including five groups of piezometers and five MEP probes, having closely spaced electrodes from above the groundwater table to a depth of 5 m below sea level, have been installed and tested. Using this system we will monitor resistivity and thus groundwater salinity variations in space and time. Analyzing the measurements using density dependent groundwater modeling we hope to be able to quantify how time varying recharge, tides, and storms hitting the barrier affect groundwater flow and discharge to the sea. At the conference we will present monitoring results from the winter and spring 2008.

INTRODUCTION
In the end of the 1950's and the beginning of the 1960's chemical waste including pesticides were deposited in a dune repository at the Harboøre Barrier, a coastal barrier on the North Sea coast of Jutland, Denmark. Most waste was removed in the 70's and 80's but residual contamination has been slowly leaking to the sea since then. The aim of our project is to investigate the significance of the physical processes that influence the groundwater flow with which the pollutants are transported from the repository to the sea.

Contaminants reaching the ground water of coastal aquifers are transported to the sea by Submarine Groundwater Discharge (*SGD*). Li et al. (1999) proposed a model for calculating the different contributions of *SGD* in order to evaluate their individual impact on chemical transfer rates. The contributions to total *SGD* (*TSGD*) considered by Li et al. (1999) are discharge due to groundwater recharge from precipitation D_r, discharge due to tidal forcing D_t, and discharge due to wave activity D_w. On the actual coastal barrier we add the discharge caused by flooding of the beach during storms, D_s, so

$$TSGD = D_r + D_t + D_w + D_s$$

The timescale of the four contributing terms is seconds for waves, hours for tides, hours to days for storms, and weeks or months for recharge. Neglecting the variation of the latter may lead to wrong estimates of *TSGD* (Charette et al., 1999). Michael et al. (2005) summarizes a study of *SGD* for a thick aquifer in Waquoit Bay, Massachusetts. They examined the effects of temporal variations in recharge by monitoring piezometers during a winter period and by measuring the saline seepage directly using seepage meters. Large saline discharges were observed but sufficient seawater inflow was not observed to balance this outflow. A lag between the precipitation cycle and the *SGD* was observed which implies that the larger precipitation in the winter recharges the aquifer during the summertime as it takes several months for the water to percolate to the water table.

For the coastal barrier we study, mainly D_r, D_t, and D_s are expected to contribute significantly to *SGD*. In order to quantify the terms we will monitor with an adequate temporal resolution the spatial and temporal variation of groundwater salinity along a profile perpendicular to the coast, set up and calibrate a model of density dependent groundwater flow on basis of time series of salinity, recharge, and water table, and subsequently use the model to analyze how recharge, tides, and storm flooding induce groundwater discharge. In this paper we present the monitoring system.

GEOLOGY, WATER TABLE, AND GROUNDWATER SALINITY

Figure 1 shows the geology on the barrier near the repository as it can be described on basis of lithological samples from borings. The deeper stratigraphic sequence consists of sandy coastal deposits overlain by a 40 m layer of fine grained clay which has its top surface approximately 9 m below mean sea level (MSL). The clay is superimposed by a 6 m silty sequence that in the eastern part of the profile is topped by less than 0.5 m clay. In the western part the clay is missing. The fine grained deposits are overlain by a sandy sequence that extends to the surface.

Groups of piezometers have been installed on each of the five locations named E1 to E5 in Figure 1. Measurements show that the water table is highest under the dune (in E2 and E3), where it is approximately 1 m above MSL, and that it falls towards the coast as well as towards the lagoon area behind the dune (to the east). The chloride concentrations measured in water samples from the piezometers vary from about 200 mg/l near the water table under the dune to about 8000 mg/l just above the thin clay layer at E1. Deeper piezometers have recently been installed in order to analyze the chloride content in the deeper silty sequence.

The lower part of Figure 1 shows the electrical resistivity along the profile as estimated from surface multi-electrode profiling (MEP). The measurements have been inverted without any constraints (for example not constrained by information about the actual depths of the water table in the piezometers), so the fairly deep unsaturated zone distorts the interpretation somewhat which makes the water table (where resistivity in Figure 1 transitions from very high values to a value less than 150 ohm-m) appear to be deeper than it really is. Anyhow, the important thing to notice is that there is a transition of resistivity with depth from about 100 ohm-m, in saturated sand deposits with low groundwater salinity, to resistivities of just a few ohm-m. The low resistivities in depth can be caused by the clayey deposits, or by high groundwater salinity, or most likely by both. The transition zone appears to be about 5 m thick below the dune whereas it is just a few meters thick outside the dune. This picture has been confirmed by several other MEP profiles made in the area as well as by electric logging at a number of positions using an geoelectrical auger.

MEP PROBE MONITORING OF RESISTIVITY CHANGES IN TIME AND SPACE

In the fall of 2007 a MEP probe was installed at each of the five positions E1 to E5 (Figure 1). Each probe has 32 electrodes (or 28 electrodes at E1 and E5) with a spacing of 0.25 m, and it was installed in an open bore hole that was left to collapse naturally. Installation of the probe was done so the top electrode is positioned about 1 m above the groundwater table while the bottom electrode is positioned approximately 5 m below MSL.

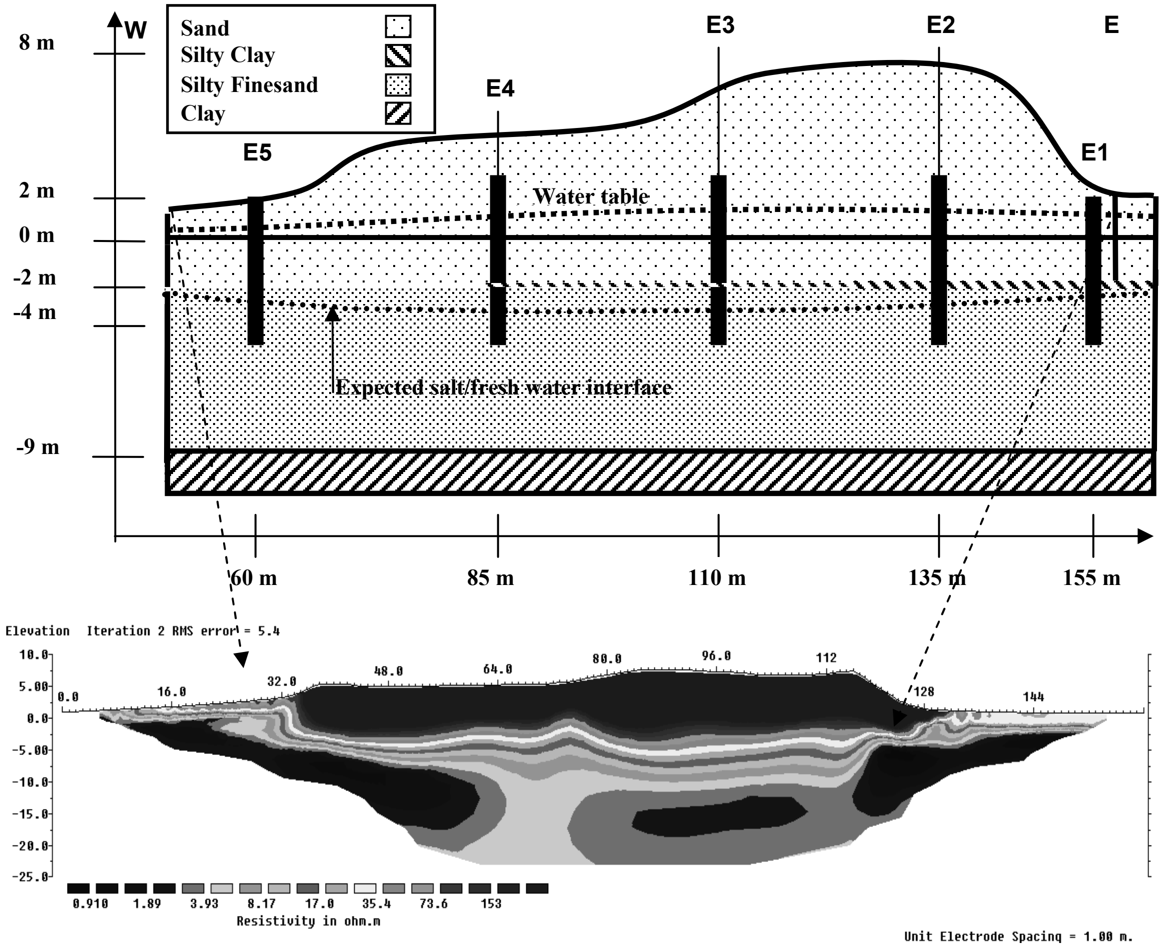

Figure 1: a) Schematic overview of the profile with MEP-probes E1-E5. X-axis: approximate distance the coastline [M]. Y-axis: Elevation DNN [m]. b) Interpretation of a horizontal MEP profile along the E1-E5. The North Sea is to the west, the lagoon area is to the east.

The purpose of installing the probes is to make it possible to make detailed vertical resistivity mapping at the five positions at any time we may wish to do so, and hopefully we can also obtain sufficiently accurate measurements of the induced polarization (IP) response using the time domain method. By interpreting the probe measurements together with water table measurements and salinity measurements in the nearby piezometers we expect to obtain good and detailed estimates of the variation in salinity with depth at the sampled times at the five positions. If the IP response can be measured by sufficient accuracy this will provide information about the clay content of the sediment surrounding the probes.

Two pilot series of measurement have been performed in order to check the probes, the geophysical equipment, and the measurement protocols (dipole-dipole as well as gradient protocols), and all seems to work properly. Rough preliminary inversions of the probe measurements give resistivity results that make sense when compared with the surface MEP results and with the salinity measurements made on groundwater samples.

CONCLUSIONS

The discharge of ground water to the sea is studied on a coastal barrier. Because the aquifer is shallow and thin it is expected that variations in recharge, tide, and beach flooding during storms have significant, time varying effects on the discharge and salinity of ground water. Geoelectric augering, Surface MEP measurements, and chemical analysis of groundwater samples have shown that salinity can be mapped by using geoelectrical resistivity measurements. Multi-electrode probes have therefore been installed at five positions along a profile perpendicular to the coast from near the shore to behind the barrier. The probes, measurement protocols, and equipment have been tested and work. It is hereby possible to make detailed vertical resistivity mapping at the five positions. By interpreting these measurements together with water table and groundwater salinity data we expect to obtain detailed information about temporal and spatial salinity variations that can be used to quantify by modeling how recharge, tide, and flooding contributes to the time varying discharge of ground water to the sea.

At the time of submission of this paper the coastal barrier is hit by the first winter storm in 2008. MEP probe and MEP surface measurements are being made during and following the storm so soon the first interpreted measurements will show to what extent beach flooding affects groundwater flow and salinity under and behind the barrier. On basis of this experience we will decide on how and how frequent to monitor the probe system in the years to come.

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