Geoelectrical monitoring of freshwater-saltwater interaction in physical model experiments

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INTRODUCTION

The availability of freshwater in coastal aquifers is endangered by saltwater intrusion (e.g. over-pumping, sea level rise, storm surge). As differences in the mineralization of groundwater affect the electrical conductivity, geoelectrical measurements are suitable for imaging saltwater distribution in aquifers. Monitoring the geoelectrical resistivity comes into widespread use for the characterization of the subsurface and reveals general information about the pore fluid and its temporal variability.

Typically, saltwater intrusion is the movement of the saltwater wedge into a coastal freshwater aquifer. The position of this wedge depends mainly on groundwater recharge rates and geological characteristics of the subsurface. The dynamics and rates of saltwater intrusion are further affected by climate change. In order to make quantitative predictions, we simulate a coastal aquifer in the laboratory using a transparent model tank and change recharge rate and sea level. Furthermore, saltwater inundation is simulated by short temporary slopover. Geo-electrical surface measurements are conducted during these experiments and time-lapse inversion of the data is done, revealing fluid conductivity and thus salt concentration.

EXPERIMENTS

A two dimensional physical experiment was conducted within a 200 cm long, 50 cm high and 5 cm wide acrylic tank. Using filter gravel (d ~ 0.7 to 1.2 mm), a cross-section of a coastal aquifer was simulated. After saturating the model with saltwater (density of 1025 $kg \cdot m^{-3}$ and electrical conductivity of about 6 $S \cdot m^{-1}$) to a height of 30 cm, three different experiments were conducted:

1. Freshwater (density of 1000 $kg \cdot m^{-3}$) was recharged to the onshore part of the model by drippers until equilibrium was reached and the saltwater-freshwater interface was in steady-state, forming a typical wedge.
2. The freshwater recharge rate was reduced causing a movement of the saltwater-freshwater interface into the aquifer.
3. The sea level was temporary increased slightly above the top of the aquifer for about 5 min, simulating saltwater inundation. After the saltwater front had moved through the aquifer steady-state was reached again.

By coloring the fresh- and saltwater with different tracer dyes (Uranin and Eosin), movements could be visualized and compared to hydraulic modeling and geophysical inversion results.

For geoelectrical measurements, 32 electrodes were distributed equidistantly with spacing of 6 cm. To enhance the resolution at the saltwater wedge, 7 electrodes were placed at the sloping beach face within the saltwater. We used the RESECS equipment with a Schlumberger configuration providing 225 measurements for each time in about 3 minutes each. In total 948 time frames were measured in a total experiment time of 2 days.

The electrical fields are three-dimensional and disturbed by the final dimensions of the tank. But the measurement scheme only allows for reconstructing a two-dimensional resistivity distribution. Therefore, a hybrid 2D/3D approach was used for data inversion: First a 2D triangle mesh was constructed using the dimensions of the tank, the shore and the sea level. The 3D mesh consists of triangle prism elements aligned across the y-axis. All cells belonging to one triangle face form a region with only one unknown and smoothness constrains between each other. Furthermore, all cells belonging to seawater were combined into one inversion region, which is decoupled from the aquifer and is represented by only one resistivity. The BERT package (Günther et al. 2006) was used for inversion. Forward modeling was achieved using a refined finite element mesh.

RESULTS

Experiment 1

The inversion result of the initial steady-state reveal resistivities of 0.76 and 0.16 Ωm for the aquifer and the sea, respectively. The latter agrees well with sampling. The homogeneous initial state allows to derive a formation factor of F = 5 that is used to compute fluid conductivity from the determined bulk resistivity using σ_w=F/r. The inversion results (right-hand-side column) and corresponding photos are depicted in Figure 1.

Shortly after starting the artificial precipitation, the freshwater starts to displace the saltwater in the aquifer. The process successively slows down since freshwater starts to discharge at the shoreline. However, as the freshwater is on top, it immediately leaves the tank and thus the sea resistivity remains constant.

The resulting conductivity images agree very well with the photographs at the same time. However the interface is blurred indicating the limited resolution. After about 12 hours there is only a thin layer of saltwater at the bottom of the tank, but in the inversion result it appears thicker. The final steady-state is again very well reproduced.

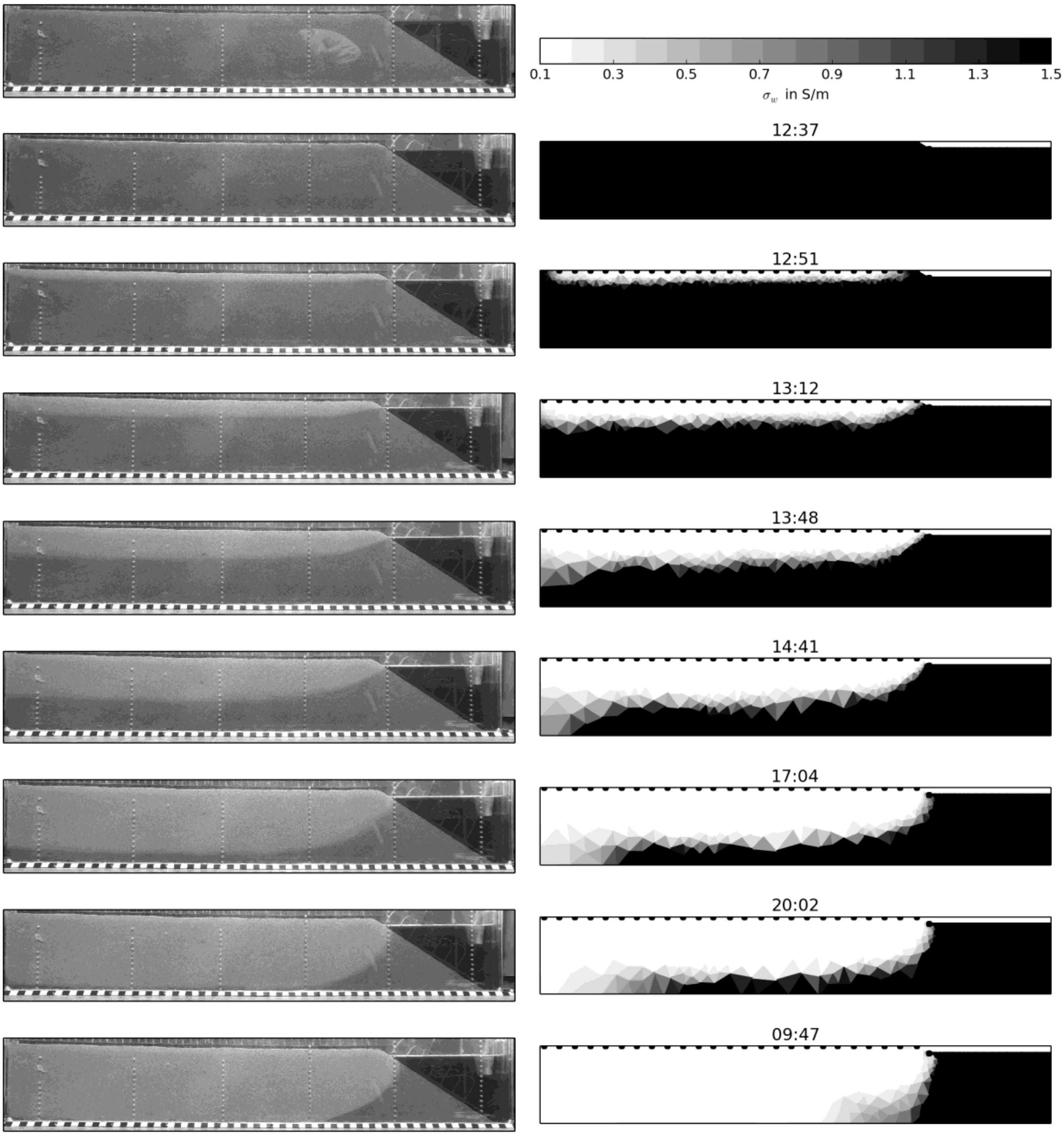

Figure 1. Photographs (left) and retrieved fluid conductivity distribution for experiment 1 (displacement of saltwater by freshwater recharge).

Experiment 2

Starting at steady-state after the first experiment, the flow rate of freshwater was reduced. Within approximately four hours the saltwater wedge was moving about 50 cm in onshore direction. As the movement of the wedge is quite slow, only four different time-steps are depicted in Figure 2. Compared to the photos taken, the movement is generally observable in the inversion result. However, the coarse mesh at the bottom of the tank does not allow a better localization of the wedge. Still, these small resistivity changes are resolvable.

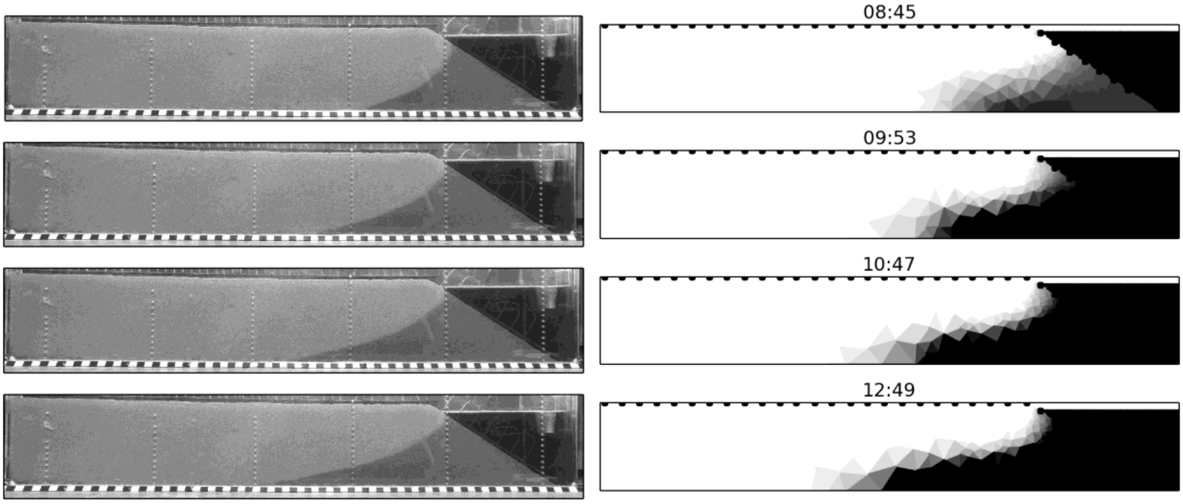

Figure 2. Photographs (left) and retrieved fluid conductivity distribution for experiment 3 (increased recharge rate and interface movement).

DISCUSSION AND CONCLUSIONS

Using a hybrid 2D/3D inversion for geoelectric data on a laboratory scale was mostly successful. The third experiment (sea water inundation) could not be fitted correctly, because of the changing model-geometry at the beginning of the experiment. This leads to artifacts that influence the whole time-lapse inversion. By using the predecessor-model as base line model these artifacts can be removed for later time-steps.

The position of the freshwater-saltwater interface in the aquifer could be determined by electrical resistivity tomography (ERT) based on surface measurements. It images the dynamics of the interface with high temporal resolution. The spatial resolution decreases with depth. The reconstructed fluid conductivity agrees well with the photographs of the dye tracer. Up to this point artifacts near the slope could not be removed. The possibility of removing affected electrodes is under investigation. Sometimes there is a slight discrepancy that might be within the equivalency of models. Moreover, there might be a separation between dye and saltwater due to dispersion.

REFERENCES

Günther, T., Rücker, C. & Spitzer, K. (2006): 3-d modeling and inversion of DC resistivity data incorporating topography - Part II: Inversion. Geophys. J. Int., 166 (2), 506-517.

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