Fully Coupled Hydrogeophysical Inversion of Salt Tracer Experiments

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presented by
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Summary

Estimating subsurface hydraulic parameters, in particular hydraulic conductivity, is of major importance for predicting solute transport and managing groundwater resources. Hydraulic conductivity in natural aquifers is highly nonuniform, and estimating its spatial distribution with traditional intrusive hydrogeological methods is challenging and expensive. In hydrogeophysics, geophysical techniques are used to characterize the hydraulic properties of the subsurface. Particularly time-lapse monitoring of hydrogeological experiments appears promising. Within the latter, a large potential is represented by the monitoring of salt tracer tests by electrical resistivity tomography (ERT). The analysis is often performed in two separate steps, the first one consisting of a standard geophysical inversion to obtain the distribution of electrical conductivity (and by petrophysical relationships concentration) in the aquifer through time, the second one in a hydrological interpretation of the geophysical images. If hydraulic constraints are missing in the geophysical inversion, results which are in contradiction to the underlying physical laws of flow and transport in porous media might be obtained. To avoid this, I present an approach in which groundwater flow, solute transport and geoelectrics are considered as a coupled system. I characterize the electrical potential time curves measured during a tracer experiment by their temporal moments. These are related to temporal moments of concentration, which in turn depend on hydraulic conductivity. Using temporal moment-generating equations and a linearized form of the Poisson equation, I show that it is therefore possible to directly relate the temporal moments of potential perturbation to the hydraulic conductivity distribution.

I first test the developed method on a simple synthetic two-dimensional forward test case simulating the temporal moments of the electrical potential time curves for a tracer test in a homogeneous hydraulic conductivity field. I show that the linearization applied to the Poisson equation is valid for low concentrations, and that the ratio of the first over the zeroth temporal moments of potential perturbation is less affected by linearization error than the moments themselves. I also present an efficient method based on adjoint states to compute the sensitivities of the temporal moments on hydraulic conductivity.

In a second step, I implement the method in a geostatistical inversion framework and test it by inferring hydraulic conductivity from synthetic time-lapse ERT data in a two-dimensional synthetic test case mimicking a salt tracer experiment in a sandbox. The estimated hydraulic conductivity shows a good agreement with the true distribution, although small-scale variability
is lost. The transient behavior is also recovered satisfactorily. I also test the influence of different factors on the results, in particular the use of erroneous prior geostatistical parameters, the effect of measurement error, and the choice of electrode configurations, in particular a comparison between the results obtained by using only surface measurements and combining them with surface-to-borehole measurements. The latter allow to obtain a higher resolution and increase the variability at depth. A large measurement error has a significant impact on the results.

After the positive results obtained from the synthetic test case, I perform real laboratory salt tracer experiments in a quasi two-dimensional sandbox, which I fill with four different types of sand. I inject a sodium chloride solution at a constant flow rate through the left boundary of the sandbox and monitor the resulting changes in electrical potentials through time. I also add cochineal red to the solution and take photographs with a digital camera at regular intervals. This allows comparing the results obtained by the hydrogeophysical inversion with the actual tracer distribution at different times. The estimated hydraulic conductivity distribution obtained by inverting the temporal moments and a few hydraulic head measurements agrees reasonably with the filling pattern of the sandbox, although some differences can be noticed. Most importantly, however, the comparison of the estimated transient behavior of the salt tracer plume with the photographs shows an even better agreement, indicating that some small-scale variabilities not detectable by viewing the filling pattern are present in the sandbox.

Overall, the developed approach shows promising results and provides a useful contribution to the important field of hydrogeophysics. Further research will be necessary to assess how the approach can be used successfully in field applications.
Zusammenfassung


Zuerst teste ich die entwickelte Methode anhand eines einfachen zweidimensionalen synthetischen Beispiels, in dem ich die zeitlichen Momente der elektrischen Potentiale für einen Salztracerversuch in einem homogenen hydraulischen Leitfähigkeitsfeld simuliere. Ich zeige, dass die Linearisierung der Poisson-Gleichung für niedrige Konzentrationen zulässig ist und dass das Verhältnis zwischen dem ersten und nullten Moment weniger stark durch Linearisierungs-
fehler beeinflusst wird als die Momente selber. Ich entwickle auch eine effiziente Methode, die auf adjungierten Gleichungen beruht, um die Sensitivitäten der zeitlichen Momenten in Bezug auf die hydraulische Leitfähigkeit zu berechnen.


Zusammenfassend zeigt das entwickelte Verfahren vielversprechende Resultate und trägt zum wichtigen Forschungsfeld der Hydrogeophysik bei. Weitere Forschung ist notwendig, um das Verfahren auf dreidimensionale Feldstudien zu übertragen.