Quantitative assessment of infiltration processes using ERT: more questions than answers

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Summary

3D ERT measurements of infiltration processes observe a transient process. Water content of the subsurface and, most probably, resistivity of the pore fluid vary concurrently. The relationship between water content and resistivity changes with time and this relationship with its changing characteristics is to be known in order to establish the quantitative interpretation.

Three experiments were carried out in sandy soil and the infiltration processes were observed using 3D ERT. Subsequently the test sites were excavated and TDR measurements were conducted. Samples were taken and the relationship between water content and resistivity was established in the laboratory. In order to achieve the quantitative interpretation the ERT data were inverted, time lapse inversions were applied, and the relationship between resistivity and water content from field and lab-measurements was used to quantify the process. The quantitative interpretation of the first experiment seems convincing. During the second experiments a tracer with higher conductivity was applied and for this experiment the quantitative assessment remains doubtful. The changing relationship between resistivity and water content can be calculated if the mixing between original pore water and tracer is continuous, but measurements seem to indicate that this is not the case.

Introduction

During recent years monitoring of infiltration processes by ERT has become popular. The advantage of the method is striking: minimal invasive, information on 1 – 100 m scale, well developed instruments and inversion schemes, a growing community for scientific discussion and, last but not least, wide applicability with regard to hydrology, hydrogeology, agriculture, soil science and geological hazards i.e. landslides. For many applications the information about the "location" of the water flow paths is already "enough", however, many themes require also a quantitative interpretation. Groundwater recharge is a prominent example; we would like to know how much water reaches the groundwater, how fast does it infiltrate, and dependent on which parameters. And, of course, once we have achieved a qualitative/quantitative interpretation of the infiltration process, we long for evidence. In the predominantly sandy soil of Fuhrberg, a township close to Hannover, Germany, during recent years different ERT monitoring experiments were carried out and some results are summarized below.

The experiments

In order to evaluate the applicability of ERT to observe the infiltration of water through the soil three sprinkling experiments were carried out and monitored using 3D ERT. In this text we will concentrate on two sprinkling experiments with low and high concentration of a conductive colour tracer (brilliant blue).

The soil in the Fuhrberg region where the experiments were conducted is podzol with fine to medium fluviatile sand. The area is partly under agricultural use and partly covered with pine trees. This area is well known for its productive aquifer and the Fuhrberg water works supply drinking water to the city of Hannover. Contamination of this aquifer from agricultural sources is a matter of concern and, therefore, the soil water system has been studied intensively since more than 30 years.

The sprinkling experiment with low brilliant blue concentration

During this experiment 110 l of water is sprinkled on an area of 1.6 x 0.4 m using a semi porous pipe, the infiltration rate is 37 mm/h. The infiltration process is observed using a 3D ERT array comprising 200 electrodes with distances of 20 cm, the lay out was 4.8 m long and 1.4 m wide (Figure 1). The ERT measurements are done before, during, and after the experiment. These measurements used dipole-dipole-configuration and each array measurement comprised 2047 single quadrupole measurements. Only 1.3% of these were obviously outliers and therefore later removed. The error of a quadrupole measurement is calculated by the measuring device as RMS of repeated measurements. No error exceeded 1%, even the error of the outliers did not. For inversion the data errors for all measurements were set to 3% and the 3D inversion is done using the code DC3DInvRes by GÜNTHER (2004). In advance several forward models were calculated in order to estimate the presumably optimal parameter setting for the inversion of these process data. From these calculations it was decided to use minimal length constraint and a small lambda of 5, the model cells were 10 cm in x and y direction, 10 layers were used with increasing layer thickness with a maximum depth of 1.7 m. During this experiment the groundwater table was at about 1.3 m as measured in a nearby borehole.

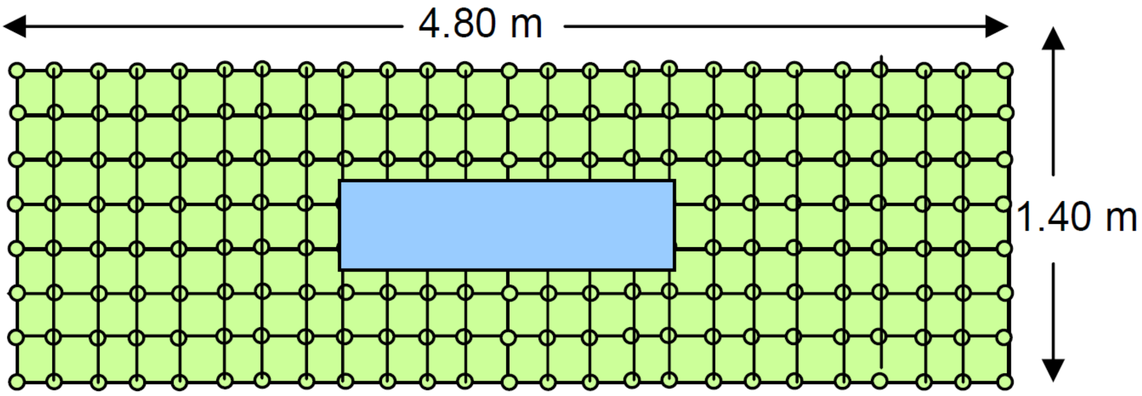

Fig. 1: Sketch of the experimental setup for the infiltration experiment. The infiltration area is located at the centre of the observation area.

The inversion result revealed a bath-tube like infiltration plume with only very minor hints for preferential flow during the early times of the experiment. Two days after the experiment the central part of the area was excavated and along three vertical sections the water content was measured using TDR devices. These measurements revealed a relative strong heterogeneity with regard to water content and, surprisingly, no hint for the blue colour, and no indication that the infiltrated water still remained in this zone except, presumably, in the upper 10 cm which were not included in the TDR measurements. The only explanation seemed to be that the water had already flown through the soil and reached the groundwater.

From later analysis it became clear that the brilliant blue concentration was much to low to actually colour the soil and the conductivity of the infiltrated water was 586 µS/cm (ρ_w.= 17 Ωm) However, this relatively low conductivity had the advantage that the change in pore water conductivity during the experiment was negligible.

In order to calculate the infiltration process quantitatively using ERT the relationship between water content and resistivity is established. This is done using a combination of laboratory measurements and the results of the TDR measurements from the excavation. Firstly the ERT inversion result from the edge of the area where surely no water penetrated into is compared to the TDR results of the excavated section at exactly the same position. The result is a cross plot resistivity vs. water content as shown in Figure 2.

From the scatter in the cross plot (Figure 2) it is evident that for the field data no clear parameter fit for any Archie function can be done with certainty. Therefore, samples of the soil were taken in the field and the Archie function was measured in the laboratory. For these measurements the soil was stepwise saturated with artificial rain water and the resistivity was measured for every single saturation step. From these data the Archie parameter were calculated.

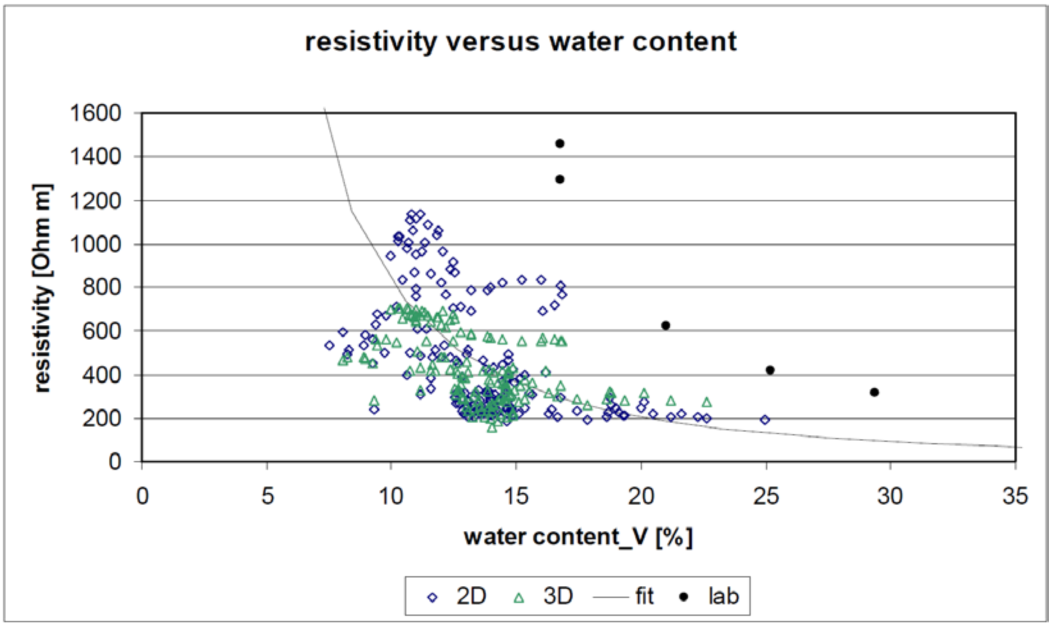

Fig. 2: Resistivity versus volumetric water content; lab-measurements, inversion results and fitting line (n=2, m=1.3, ρ_w = 15 Ωm).

The scatter plot (Figure 2) raises several questions: Why are the results of the 2D inversion and the 3D inversion that different and what are the reasons for the deviation between the laboratory and the "field" measurements? The latter is caused by the different pore water conductivities of the laboratory measurements and the field situation, respectively. The different inversion results are not only due to the ill posed inversion problem leading to ambiguous results but as well to the heterogeneity of the soil and different inversion parameters.

Using the Archie function presented in Figure 2

$$\rho_f = \rho_w * S^{-n} * \Phi^{-m} \tag{1}$$

n = 2 = Saturation (S) exponent
m= 1.3 = cementation factor
ρ_f, ρ_w = bulk resistivity, pore water resistivity (15 Ωm)
Φ = porosity

the infiltration process is quantified. Firstly the original saturation at the site is calculated

$$S_0 = \left(\left({\rho_w}/{\rho_{f(t0)}}\right) * \Phi^{-m}\right)^{\frac{1}{n}} \tag{2}$$

from the inversion result of the array measurement before infiltration (t0).
Then, by using time lapse inversion strategies, the saturation change is calculated by

$$\Delta S_{tx} = S_0 * \left(\left(\frac{\rho_{f(tx)}}{\rho_{f(t0)}}\right)^{-\frac{1}{n}} - 1\right) \tag{3}$$

For this equation no change in pore water conductivity during the infiltration process is assumed. In this particular case this assumption seems to be justified since the resistivity of the infiltrated water (17 Ωm) is similar to the assumed pore water resistivity of 15 Ωm.

The results of the quantitative calculation are surprisingly close to the infiltrated amount of water (Figure 3).

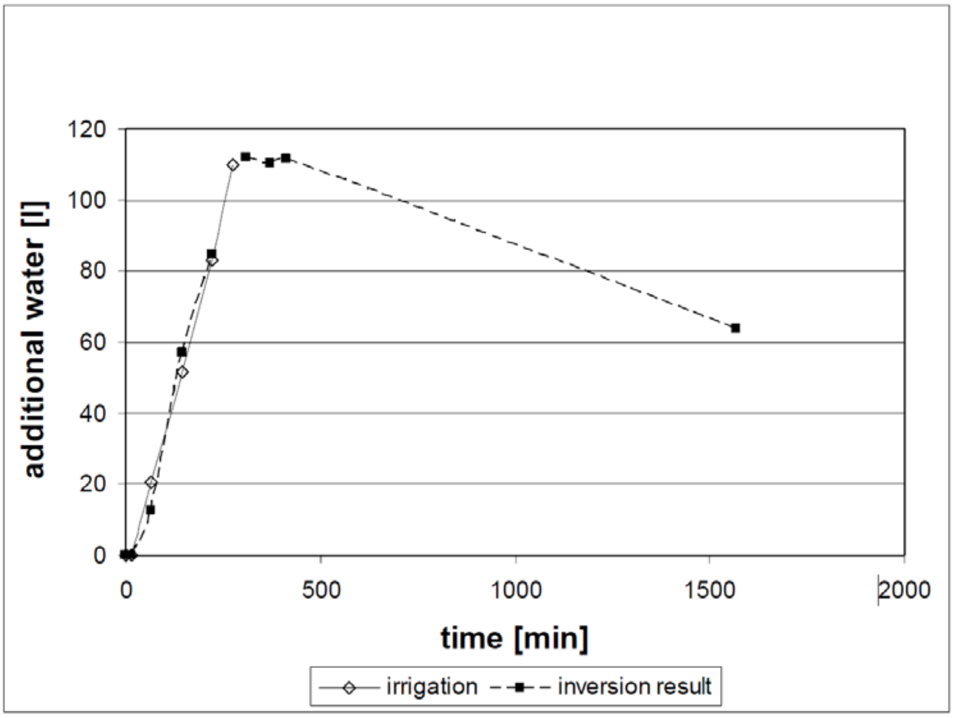

Fig. 3: Result of quantification as calculated from the timelapse inversion using the Archie function (1).

These results indicate that one day after infiltration already about 45% of the infiltrated water reached the groundwater. This coincides with the results of the TDR measurements showing two days after infiltration no increased water content in the central section of the experiment, where the water was irrigated onto.

By applying the error propagation law on formula 3 the error of the quantitative assessment can roughly be calculated. For this experiment it is in the range of 25 to 40 l. Most critical is the original pore water resistivity and it has to be taken into account that this might differ throughout the area depending on original saturation, soil type, and content of soluble matter.

The experiment with high brilliant blue concentration

For this experiment 80 l of water with a conductivity of 1213 µS/cm (ρ_{winf}= 8.2 Ωm) was sprinkled on an area of 0.4 x 1.0 m within 8 hours slightly off centre. In the excavated sections the deep blue colour marked the flow pathways which resembled a bath-tube rather than small preferential flow pathways (Figure 4). The soil at this site was similar to the first site although the TDR measurements showed lesser heterogeneity in terms of original water content.

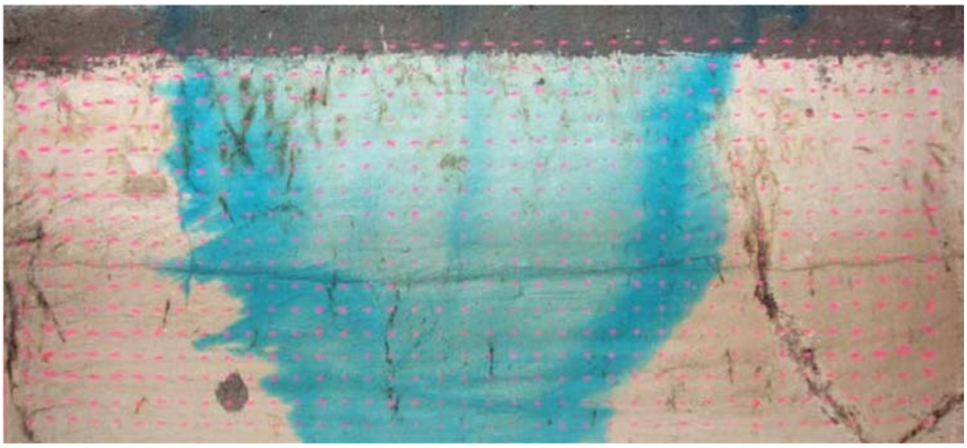

Fig. 4: Picture of the central section with blue infiltration plume

On account of the high pore water conductivity contrast between the original and the irrigated water the resistivity decreased enormously during infiltration. This called for the use of the FE-inversion code BERT (GÜNTHER et al. 2006) for inversion of the time lapse data. The FD code used for inversion of the data of the first experiment achieved no adequate data fit.

For the quantitative interpretation the same Archie parameters m, n and $\rho_{w(t0)}$ are used as for the first experiment. At this time the calculation of the saturation change has to take the change of pore water conductivity (ρ_w) during the infiltration process into account.

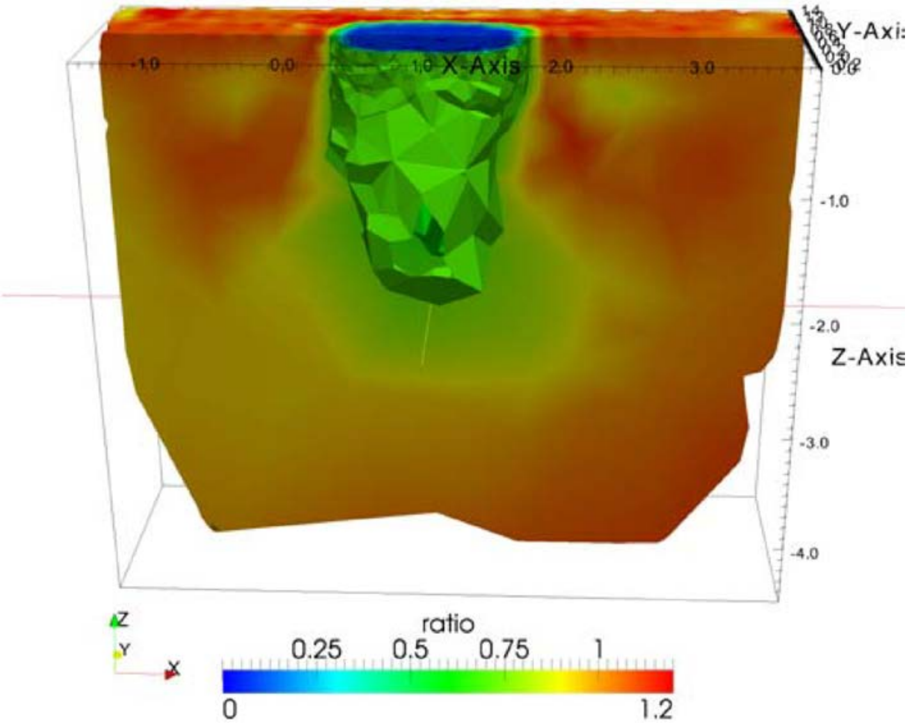

Fig. 5: Time lapse inversion result 21 h after start of infiltration.
Contour line marks the ratio = $\rho_{f(tx)}/\rho_{f(t0)}$ = 0.7.

$$\Delta S_{tx} = S_0 * \left(\left(\frac{\rho_{f(tx)}}{\rho_{f(t0)}} * \frac{\rho_{w(t0)}}{\rho_{w(tx)}} \right)^{-\frac{1}{n}} - 1 \right) \tag{5}$$

The calculation of $\rho_{w(tx)}$ for every time tx during a transient process needs either direct measurements of $\rho_{w(tx)}$ or a valid assumption. It is possible, however, to calculate a higher und lower limit of *ΔS*. The **higher limit** is given by the assumption that during infiltration no change in pore water conductivity takes place, consequently, the decrease in resistivity is caused by increased water content only. The **lower limit** can be calculated by the assumption that the pore water conductivity at time tx ($\rho S\Delta_{w(tx)}$) equals the value of the infiltrated water ρ_{winf}.

Conclusions and outlook

The infiltration experiments in sandy soil showed convincingly that the infiltration process can be observed by 3D ERT and that time lapse inversion permits not only a qualitative but as well a quantitative interpretation of the process if the change in pore water conductivity during the process is negligible. If a conducting tracer fluid is used the consecutive change in pore water conductivity during the infiltration process hampers the quantitative interpretation.

To achieve a reliable quantitative assessment of the infiltration process the measurement of the actual pore water resistivity seems indispensable although it will give only local information. Measurements of the pore water conductivity during the experiments are needed in order to formulate and test mixing laws to be applied for the quantification. The heterogeneity of the soil could complicate the situation and different mixing laws might be necessary.

References

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