Hydrology and Earth System Sciences Discussions

Interactive comment on "Identifying a soil hydraulic parameterisation from on-ground GPR time lapse measurements of a pumping experiment" *by* A. Dagenbach et al.

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We thank the three anonymous referees for their constructive comments and suggestions. Before we turn to answer reviewer specific comments, we first address questions brought forward by more than one reviewer.
All reviewers raised concerns about our usage of "pumping" or "infiltration" to describe the process of raising the water table in our experimental structure by adding water from below. We agree that this might have been misleading in this context and have consistently adapted the manuscript to use "imbibition" for water input and "drainage"

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for extracting water.
Also, our choice of reference system and the referral to height and depth gave rise to some confusion. For clarification, we now consistently refer to the z-coordinate with the origin at the surface as has been introduced in figure 1 for every statement regarding the experimental data. In all plots concerning simulations with stationary profiles we keep the ordinate as height over water table. It allows an easier understanding of the parameterisations and underlines the fact that there is no attempt to reproduce all experimental data but to show the basic characteristics concerning the parameterisation. Please find our answers directly at the corresponding comments below in italic letters.

Referee 1

The first reviewer mainly raises a question about the effect of noise on our capability to distinguish between the different functional forms of the soil water retention curve parameterisation:

"However, I would encourage the authors to consider the effect of noise on the capability of the approach to distinguish, in practice, between different capillary parameterization. In fact, the authors state in their conclusions that a "a sharp air entry with a transition zone above is required to reproduce the reflections". To what extent is the noise in the GPR field data expected to blur our capability to see such features?"

In our current understanding, there are three types of noise which need to be addressed in this context: (I) precision of the measurement equipment (i.e. the signal-to-noise ratio), (ii) practical aspects of moving the measurement equipment which might induce additional noise and (iii) inherent noise which is due to the subsurface structure (clutter and potentially interference with signals generated from layer boundaries). As already mentioned in the paper and visible in Fig. 2 and Fig. 4, (iii) is a significant aspect of disturbance. This is because clutter might have a comparable amplitude and make it impossible to detect a capillary fringe reflection in the case of a stationary water content distribution. This issue rises the necessity to conduct time-dependent experiments with a moving water table, allowing to clearly distinguish between the different reflections. The other two points (i) and (ii) are of interest if the noise level lies in the same range as the reflection amplitude of the capillary fringe. This might make the usage of the signal impossible. Nevertheless, a clearly detectable capillary fringe reflection during imbibition and drainage (to exclude effects of the hydraulic conductivity) will always allow use to distinguish between a water retention curve with a sharp air entry and a continuous air entry area. This is due to the fact that the characteristic reflections mainly differ in the main wavelength which will not be altered by random noise.

Reply to minor comments:
Why do the author refer to a "pumping" experiment? This is actually misleading, as the experiment consists of infiltration and drainage.
As has been addressed above, we changed the wording to "imbition".

line 76: the details of the dewow filter shall be presented (is it a median or a mean filter?).Such filtering may alter the wavelet shape.
The applied runmean filter is given as the remainder of a runmean hat-filter with a width of 5 ns. We adapted the text accordingly.

line 71: put "oscillation" after "the water table"
Done.

line 80: remove "Regarding nature" (not sure what it means)
Done.

line 208: change "extend" into "extent"
Done.

line 209: change "higher" into "longer"
Done.

Referee 2

Apart from issues already clarified above, referee 2 adds two further points:

Specify in line 23 that entire area was supplied with this amount of water, adding infiltration rate as mm/h or similar would also be useful for easier comparison with other experiments.
This issue was addressed by adding a more detailed explanation of the imbibition process as well as the imbibition and drainage rates.

In '5 Numerical simulations' a stationary water content profile was calculated for a 2m deep profile, why not the same as for the physical system? Likewise for the model domain.
Our interest lies on the effect of the shape of the capillary-fringe on the shape of the reflected wavelet. Hence, to represent the actual position of the water table and domain size given in the experiment is of minor importance or can even be disturbing. The latter fact arises from the investigation of different scenarios for the water retention curve, where the antennas have to be far enough from the water table to neglect the variation of the water content close to antenna with respect to the shape parameters of the retention curve. The extent of the domain was chosen on this basis and accordingly the domain size for the GPR simulations. For the latter, the domain was represented smaller than the domain of the experiment. This is possible since no additional reflections – especially from the side and bottom walls – are found in the measured data to interfere with the reflection signal of interest. To suppress artificial reflections from the domain boundaries in the simulated data, the perfectly matched layer boundary condition was employed.

In Figs 2 and 3 I suggest including depth/height references.
While this is common practice, it is not possible for the situation at hand. The reasons are (i) the water content in the layers above the reflecting interfaces changes over time and hence also the travel time to the reflections. A fixed conversion of travel time

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to depth would then lead to the conclusion that the depth of the interfaces changed, what is not the case. (ii) The signals which are reflected from the capillary fringe are composed of multiple reflections along a stretched water content profile. Hence to assign a "depth of reflection" is not necessarily uniquely defined. (iii) To convert travel time to depth would make detailed knowledge of the water content distribution necessary, especially at the capillary-fringe. This, however, is the objective of the study at least in a qualitative manner.

Referee 3

We thank referee 3 for taking his/her time and providing very detailed suggestions. However, we feel that there might have been some degree of misunderstanding as to the purpose of our study. In particular, this study does not aim at estimating values for hydraulic parameters, but only to decide on an appropriate formulation for the parameterization model. Hence, for clarifying the purpose of the paper, we have changed the title to "Identifying a parameterization of the soil water retention curve from on-ground GPR measurements". In the abstract this is now further specified by adding a statement "... to identify the parameterization of the soil water retention curve, i.e. its functional form,...".

1. Two big assumptions were made in this research. (a) Subsurface water flow in the unsaturated zone and in groundwater is governed by the Richards equation, which is a function of soil water content and hydraulic conductivity. In this manuscript numerical simulations for modeled GPR signal were performed for an unsaturated zone (50 cm above water table) without considering the effect of unsaturated hydraulic conductivity. *We agree that the dependence of the hydraulic conductivity on the water content cannot be neglected if the water dynamics is simulated by solving Richards equation. By analyzing the impact of the capillary-fringe shape on the wavelet shape using a hydrostatic water content profile, however, the water retention curve corresponds to the solution of Richards equation for this special case. Since equilibrium is assumed, no water flows and thus the unsaturated hydraulic conductivity has no impact. (b) Simulations were performed for one sand layer and the soil hydraulic parameters were estimated for a single layer, whereas experimental setup has three layers, top layer and bottom layer (uncompacted and compacted). Furthermore, the dimensions used in numerical simulation are not the same as in experimental setup. Please find a detailed comment to this issue as our reply to point 13.*

2. In this study, time-lapse GPR measurements showed qualitatively that enough information is contained in the radargram during injection and pumping of water. In the

quantitative analysis (numerical simulation), time-independent 1-D permittivity profile was used to generate the radar signal. Modeled time-lapse GPR data was not generated and compared to the measured time-lapse GPR signal. Therefore, title of the manuscript should be changed as time-lapse GPR data was not used to estimate soil hydraulic parameters.
We agree that the previous title was not focused enough on the key method of the study, hence we changed it to "Identifying a parameterization of the soil water retention curve from on-ground GPR measurements". Indeed the time-lapse data were used, but only to identify the reflection from the capillary fringe.

3. The exact location of a pumping tube and a stationary GPR antenna installation is not mentioned in the text and also in Fig 1. It is important as the experimental setup has big dimensions (19m x 4m x1.9m) and if GPR antenna is close to pumping tube will have different signal response as compared to far away from pumping tube. What are the dimensions of a pumping tube (radius of pipe, open area per meter of slotted pipe)? Is a single pumping tube used to saturate such a big setup? If pipe of small radius and small area of opening are used than the water level may rise in the pipe above the water table and create a gradient of soil moisture in the top layer, which is not considered and discussed in this manuscript.
Our experimental structure features a saturated gravel layer at the lower boundary (compare Fig.1) with much higher conductivity than the lower sand layer. The imbibition flux is applied through only one pipe with a diameter of 0.47m. The pipe is only perforated over the extent of the gravel layer. Hence, the imbibition flux through the pipe is expected to be uniformly over the lower boundary. We added a sentence to the text which clarifies this points.

4. In the section 2, it is mentioned that after injecting water of 3800 L within 2 hrs, the system equilibrated for 2 hr. What was the criterion of equilibrium?It may take more time to stabilize as the water is injected through pipe, which may forms a gradient of water level above the water table. It would be great if the water level fluctuation data

can be provided during the system equilibrated for 2 hrs.

The criterion of equilibrium chosen was the change we see in the GPR data; hence we assume the system to be equilibrated, once the traces recorded do not change anymore within the measurement precision. Since we can assume an uniform imbibition flux over the whole lower boundary, we do not expect a changing gradient with distance from the pipe. The water level in the pipe did not change 90 min after stopping the imbibition. In addition to these aspects we would like to stress that the water dynamics was not considered for the final conclusions drawn in the paper. The discussion of the imbibition and drainage radargrams primarily aims at the identification of the signal which is used afterwards. This, in turn, is treated as-is by analyzing it employing water-retention-curves and focusing on the impact of its shape around the air-entry value.

5. What was the logic to compact part of the second layer and leave 20 cm uncompacted at depth 80-110 cm? It increases complexity and the two layer problem become three layer.

In fact, the compactions were carried out about every 30 cm in height. The position of compactions, which are relevant here, are given at 110 cm and at 80 cm (at the boundary of the different materials). The compactions were necessary to forestall an uncontrolled compaction of the materials by the their weight.

6. P-9098 L-14: "uniform infiltration" should be replaced with "uniform saturation".
We changed the formulation to "uniform imbibition".

7. Change the title 3.1 "Infiltration" to saturation. Infiltration is the process by which water on the surface of ground enters the soil. However, in this section GPR signal is discussed when water is injected through the pipe and the sand layer get more saturated (water level increases). Kindly replace infiltration with saturation.
We realize that our original wording was misleading and we now consistently use "imbibition" and "drainage" for the respective processes.

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8. In section 3.1 and 3.2, Fig 2 (a) and (b) are discussed in detail and the radargram is show from 16 ns to 26 ns. The radargram 0-16 ns should be provided and discussed as it would be great to see which type of reflections are recorded in the top layer as there may be a gradient of soil moisture in the top layer formed because injection and drainage has been done using a pipe.

We intentionally focus on the 16 ns to 26 ns part for showing the occurring dynamic changes with greatest possible detail. The omitted part of the radargram shows just the constant features of the direct ground wave and smaller constant reflections, not influenced by the dynamics induced in the lower layer. Hence, there is no significant gradient of soil moisture above; in fact the upper sand layer is largely dry with a residual volumetric water content of about 0.05 (measured with TDR).

9. Page 9098, L 23: "The pumping event was conducted by infiltrating a total amount of 3800 L within 2 h". In hydrology, pumping is used to take out water from well. Whereas, here water is injected into the system. Rephrase the sentence.
As above, this has been rephrased using "imbibition".

10. For Figure 4 please provide values for the extreme ends of the x-axis.
Done.

11. Page 9102, L 23: "full van Genuchten". Such an expression is never used in literature. I think it can be replaced with classical van Genuchten.
To our knowledge, "classical van Genuchten" is mostly used synonymously with the simplified version which is most often applied in literature. We thus use the term "full van Genuchten" to stress the fact that n and m are treated as fully independent parameters.

12. Page 9103, L 10: How were θ_s and θ_r calculated?
The aim of this study is not to estimate the parameters but to make a decision about the type of parameterization. Therefore, plausible values have been chosen for θ_s and θ_r. As explained in the paper, the different characteristics result from the different shape

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around the air entry point which is not effected by these parameters.

13. (a) Page 9103, L11: For numerical simulation the sand profile is considered as a single layer and having 2 m depth. Whereas experimental setup has three layers (top sand layer, compacted and uncompacted sand layer) of 1.9 m tick. Furthermore, the simulation domain for FDTD is considered to be 2m x 2m x 2.7m whereas the experimental setup dimensions are 19m x4m x 1.9m. It is not possible to reproduce the measured GPR signal by using different dimensions and layer setting for numerical simulation. Repeat the numerical simulation with exact dimensions and layer thicknesses.

The key method of this paper is to study the effect of the shape of the capillary-fringe on the shape of the signal, which is reflected from the capillary fringe. If the parts of the capillary fringe which are relevant for this analysis can be considered to be located in only one material we think a representation of all layers would not introduce relevant information for the analysis. A detailed representation of the domain size might hinder the analysis since different scenarios for the water retention curve were investigated. Hence, the antennas have to be far enough from the water table to neglect the variation of the water content close to the antenna with respect to the shape parameters of the retention curve. The extent of the domain was chosen on this basis and accordingly the domain size for the GPR simulations. For the latter, the domain was represented smaller than the domain of the experiment since no additional reflections – especially from the side and bottom walls – are found to interfere with the reflection signal of interest, in the measured data. To suppress artificial reflections from the domain boundaries in the simulated data, the perfectly matched layer boundary condition was employed.

14. Page 9106, L 2: On which basis h_0 is fixed to 0.25 m?
α and h_0 have been chosen to lie in a realistic range considering the sand layer to be saturated approximately to the height of the compaction horizon. Furthermore, to allow a good comparison between α and h_0, they have been chosen to fulfill $h_0 = 1/\alpha$.

15. Page 9106, L 20: "This shows that a reflection from sands parameterized by the

Brooks-Corey paramerisation are suitable to reproduce the given experimental data." Why such data is not reproduced? This is the main objective of the manuscript that soil hydraulic parameters were estimated using time-lapse GPR data. Without generating a modeled time-lapse GPR data and comparing it with the measured GPR data the estimated soil hydraulic parameters are always questionable.

Although no estimation of the hydraulic parameters was carried out, we agree that the given sentence is misleading since no direct comparison of the data is given. We changed the sentence to "This shows that reflections from sands parameterized by the Brooks-Corey approach reproduce the characteristic signal changes observed in the experimental data."

16. Depth mentioned in experimental setup (1.9 m) does not match with figure 1 (180cm). Correct it and use same units "m" or "cm" throughout the manuscript.
This has been corrected.

17. There is no discussion in the paper regarding potential sources of error in the hydraulic property estimates obtained from the GPR data. I think that it needs to be more clear in the results and conclusions that there were a number of assumptions made that, in reality, could result in model errors that significantly bias hydraulic property estimates.

Since the method aims only at the identification of a parameterization of the soil water retention curve a quantitative discussion of error sources is not feasible. Nevertheless, we now included a qualitative discussion of the issue in the Numerical Simulation part: "...Although we are not able to make a quantitative statement this last point gives a hint on the limitations of the method. The reflection amplitudes in Fig. 7 suggest a high probability that a sand following the van Genuchten parameterisation with a continuous transition around the air entry might not have a satisfactory signal-to-noise ratio due to the small amplitudes of the reflection. This fact also gives the limitations concerning a quantitative estimation of hydraulic parameters. In all cases the reflection originating from the transition above the air entry has a very small amplitude, presumably in the

range of the deviations over time shown in Fig. 3b."

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