Author-Reply to Review Comments to ***„Quantitative high-resolution observations of soil water dynamics in a complicated architecture with time-lapse Ground-Penetrating Radar"***
by P. Klenk, S. Jaumann, and K. Roth

We sincerely thank both anonymous reviewers for their insights and their useful suggestions for improving our manuscript. In the following, we first address some major aspects and point out in which way we have revised the manuscript. At the end, we briefly reply to minor comments and smaller suggestions.

First, we agree with both reviewers that calculating the mass recovery would be a desirable result and that the precision of our method does suffice to do it. However, there remain uncertainties, most importantly the total volume of the tank with its somewhat irregular walls and the fact that we cannot measure right to the edges. Hence, we decided against doing this.

Secondly, both referees found it difficult at times to clearly recognize the observed dynamic evolution of the capillary fringe, namely:

> I find it difficult to see the three-featured wavelets and the distinct two-feature wavelet (observed on Page 12379, lines 1-2) in the small radargrams. Also the observation: "the CFR signal split into two distinct two-featured wavelets" (observed on Page 12379, lines 10-11) could nicely be documented with a figure similar to Figure 7.

(referee #1)

and

> Page 12383, Line 20-29. This is difficult to follow. Perhaps the reader should be guided better here, and the relevant features should be indicated in the figure.

(referee #2)

We realized that the observed dynamics is hard to represent in any static figure. Thus, we decided against including additional figures such as suggested by referee #1, but instead added a time-lapse movie for each experiment to the online supplementary material, which in our opinion clearly illustrate the phenomena we describe in the manuscript. In addition to showcasing the high temporal resolution of our measurements, the movies also display the evolution of the capillary fringe reflection along two selected traces which are plotted to the right of each corresponding radargram. Color-coded arrows in the radargrams mark the respective positions.

We thank referee #1 for pointing out some inconsistencies in the description of experiment 1, especially concerning the numbers for the imbibition and drainage rates:

First, I am very confused about the details of experiment 1. On page 12371 you write that 10 m3 of water is pumped into a well with a constant rate (23.4 cm/h) for 12 h. First of all, this is not in agreement with Figure 2, where the entire experiment time (including imbibition and drainage is approx. 12 hours). Second, if I divide 10 m3 over the 77.28 m2 area of the ASSESS site (18.4 m times 4.2 m) I get 0.129 m or 12.9 cm over the entire experiment time. How does this match up with the other data (23.4 cm/h) and the black line in Figure 2? Is it because one cannot expect that the water fills up the entire sand box, but only at a certain distance from the well? And why does the black curve on Figure 2 not increase at t=0 hours? The description of experiment 2 is also slightly unclear. I would suggest that you made a Figure 2a with experiment 1 and a Figure 2b with experiment 2. In these new figures you could include the timing of experimental changes with different background colors (i.e. one color for imbibition, drainage, infiltration, equilibrium time, etc.), but also you could include the timing of the collected radargrams presented in Figures 6 and 10.

Indeed, there has been a mix-up: The experiment description has been revised accordingly; now including the corrected values. Of course, the whole experiment took about 12h, not the imbibition phase itself. For calculating the mentioned infiltration rates, we use 79.94 m^2 for the surface area of the ASSESS-site, which was estimated from laser tracker measurements. Furthermore, we added additional information about the amount of infiltrated and imbibed water for the second experiment to the manuscript.

We decided against splitting figure #2 because we would like to keep the direct comparison of the induced water table dynamics for both experiments. Still, we did adjust figure #2, such that the start of both pictured curves now coincide with the acquisition of the first radargrams in Figures 6 and 10. The respective timing has been added to both Figures 6 and 10 as suggested: All times mentioned in these figures now refer to the timeline in figure 2.

The revised experimental overview now reads:

During experiment *1*, a series of imbibition, equilibration and drainage periods were monitored with GPR. At first, $10.0810 \pm 0.0001\ \text{m}^3$ water were pumped into the well at an approximately constant rate over the course of about 5.3 hours, which translates to an imbibition rate of 2.38 cm/h. After one hour of equilibration time, $9.5630 \pm 0.0001\ \text{m}^3$ water were pumped out again, at a drainage rate of 3.42 cm/h. Over the whole course of experiment *1*, four-channel GPR data have been acquired along a stretch of the site at a temporal resolution of approximately one radargram per minute.

The aim of experiment *2* was to investigate the hydraulic dynamics during a period of infiltration followed by a period of imbibition. GPR observations were obtained at the same temporal resolution as during the previous experiment. Ten days prior to experiment *2*, a green house roof had been built above the ASSESS site, ensuring the absence of significant precipitation induced infiltration fronts in the top soil. The experiment started with infiltrating $0.2113 \pm 0.0001\ \text{m}^3$ water from above into the two-layered part of the structure with the infiltration device centered at 17 m over the course of 1.6 h. This leads to a highly localized infiltration pulse. The detailed spreading of this infiltration pulse in the subsurface is a 3D effect. In our case, we expect a well-defined infiltration front due to the coarse textured material and the imposed high infiltration flux. After 1.6 h, having reached a steady state of gravitational flow into the structure, the infiltration was stopped and immediately followed by a 5 h period of imbibition of $9.1661 \pm 0.0001\ \text{m}^3$ water. Afterwards, GPR measurements were continued at minute resolution for another 1.5 h followed by half hourly measurements for another 3 h in order to monitor the subsequent relaxation phase.

An overview of the water table position in the observation well during the different stages of both experiments can be found in figure 2. For periods of imbibition (between 0.3 and 5.6 h for experiment *1* and between 3.0 and 8.0 h for experiment *2*, respectively), the figure shows that the water table rise – as measured in the observation well – is not entirely constant, despite the approximately constant water flux into the well. In particular at times when the water table in the sand structure crosses major layer boundaries, we observe changes in the increase rate of the water table (e.g., between 2.2 and 2.6 h for experiment *1*, corresponding to the water table crossing the layer boundary in the two-layered region). This effect can be explained by the differing hydraulic properties of the respective materials and the corresponding adaptation of the transition zone above the capillary fringe. We have observed this effect in the GPR data as well and will discuss it in more detail below. The infiltration phase during experiment *2* which took place did not lead to a measurable change in the water table position.

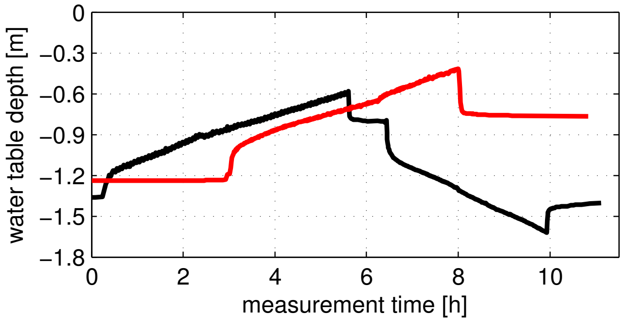

Figure 2. Variation of the water table depth below the surface over the course of experiments *1* (black line) and *2* (red line) as measured in the pumping well. The first radargrams in figures 6 and 10 have been acquired at time $t = 0$h.

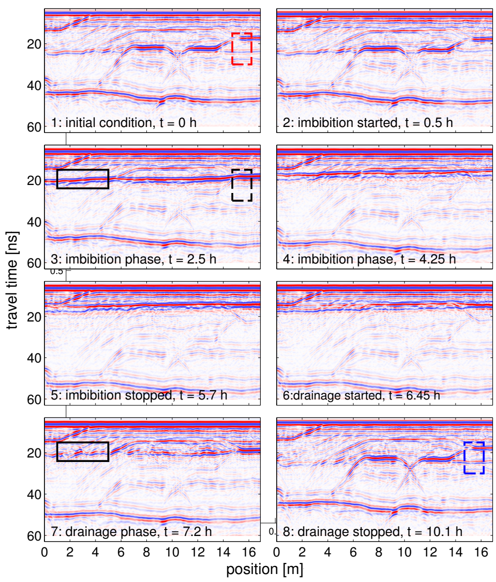

Figure 6. Common offset radargrams showing the hydraulic state during experiment *1* (imbibition/relaxation/drainage) at several characteristic times. The solid black rectangles in radargrams 3 and 7 mark the CFR at approximately the same position during imbibition and drainage, respectively. The dashed rectangles in radargrams 1, 3 and 8 denote the regions over which the traces shown in figure 7 are averaged.

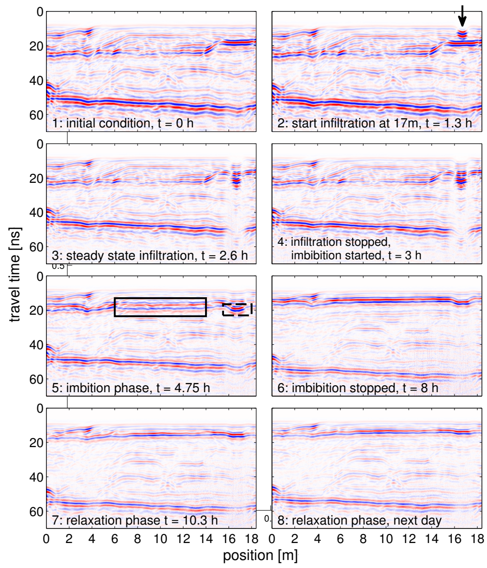

Figure 10. Common offset radargrams showing the hydraulic state of experiment *2* at several characteristic times: Localized infiltration at 17 m (denoted by the black arrow in radargram 2) followed by imbibition and a period of relaxation. The dashed (solid) black rectangle in radargram 5 highlights the CFR at a (non) pre-wetted position during the imbibition phase.

Referee #2 raised concerns about an insufficient differentiation of the current study from the aims and results of Dagenbach et al. (2013):

> 1. I feel that the introduction can be significantly improved. Although it provides an overview of what has been achieved, it does not really become clear what is missing in previous work, and how the present study addresses this. Although it is perhaps a matter of taste, I would also like to see the formulation of a clear aim in the last part of the introduction. As the introduction is written now, it gives the impression that this manuscript makes a small contribution here and there but only in an incremental manner. It also seems that the main message of this manuscript is close to that of Dagenbach et al. (2013). The authors should make it much clearer how this paper is different from their previous paper that also dealt with the shape of the capillary fringe reflection. Finally, it may be worth to motivate why looking at the capillary fringe reflection is interesting. In many instances in the field we do not clearly see this reflection because shallow groundwater is not likely to occur in soils amenable to GPR.
>
> 2. Along the same lines as outlined above, I found that it is also not so clear from the presentation of the results what the main findings are. What have we learned from this study, and how can this bring us forward with GPR?

We now address these concerns and some other points in a revised introduction. In particular, we clarify that the previous work by Dagenbach et al. (2013) solely discussed the identification of a hydraulic parameterization for correctly describing the GPR response of the capillary fringe. Although that study was based on data from a limited range imbibition experiment, the induced dynamics were never large enough to effect a clear variation in the corresponding capillary fringe reflection. In contrast, we here observe, discuss and simulate the dynamic evolution of the shape of the capillary fringe reflection for transient conditions. To the best of our knowledge, this is a first. Furthermore addressing the question about where we can actually find such a case, this part of the manuscript now reads:

> this permittivity profile. The shape of this transition zone is essentially determined by the specific soil hydraulic properties, and hence is in turn the shape of the resulting GPR reflection. Therefore, studying the transition zone reflection with GPR can give access to soil hydraulic properties of sandy soils which feature a shallow groundwater table such as river plains, sea and lake shores, as well as permafrost and periglacial environments. Following this line, Dagenbach et al. (2013) have reported on time-lapse observations of the transition zone reflection during an imbibition and drainage experiment. In that study, due to the limited range of the induced hydraulic dynamics, no significant variations of the static transition zone signal were observed. Nevertheless, the shape of the measured GPR response already allowed deciding for an appropriate parameterization for the corresponding soil water characteristic function through a joint approach of hydraulic and electromagnetic modeling. More recently, Bradford et al. (2014) have explored the estimation of hydraulic properties from monitoring an aquifer water table during a pumping test with GPR, noting the requirement for observing sufficiently large dynamical changes.

With respect to the aims of our study, our introduction was intended to develop three main aspects:

> under transient conditions, single-instant in time measurements of seemingly clear reflections can prove difficult to interpret, as shall be briefly touched upon in this paper.

(page 12368 lines 1-2)

ductivity, which includes an explicit optimization of the source wavelet. Demonstrating the attainable relative precision of monitoring soil water dynamics based on an on-ground common offset GPR measurement setup without a similarly involved evaluation scheme will be another aspect of this paper.

(page 12369 lines 17-20)

The observation of the transition zone above a water table through multi-temporal GPR measurements of deliberately imposed soil water dynamics and the interpretation of these observations will be the main focus of this paper.

(page 12370 lines 1-3)

Further aims of this study are: (i) to demonstrate the experimental observation capabilities of hydraulic dynamics with our GPR setup, and (ii) to show that we can consistently reproduce the observed transient phenomena with our numerical simulations. We have expanded the last paragraph of the introduction to reflect this and to summarize the previously already formulated goals more clearly:

> This study continues the path towards estimating hydraulic parameters from high-resolution monitoring of soil water dynamics and in particular time-lapse measurements of the dynamic shape of the transition zone signal by on-ground GPR. Our main objective here is to analyze and interpret from an experimental point of view the dynamic evolution of the transition zone above a water table as measured through multi-temporal GPR measurements over a large range of dynamic conditions. In particular, we will assess the experimental capabilities our GPR setup with respect to detailed observations of deliberately induced transition zone dynamics and show that we can consistently reproduce the observed transient phenomena with numerical simulations.

Eventually, the goal of our work is to estimate hydraulic properties from these datasets. Based on our experiments, we agree with referee #2 that there should be sufficient information contained in our observations for estimating hydraulic properties, especially in our high-resolution datasets. However, this is not a matter of simply running a quick inversion. It is thus beyond the scope of this experimental study.

Referee #2 furthermore raised concerns about our comment on the relationship of this study to full-waveform methods:

> Page 12367, Line 19. It is not so clear to me why you try to introduce a contrast here between what has been achieved with full-wave inversion and what you are doing. Could you provide a better motivation?
>
> Page 12369, Line 2. Although the cited work indeed assumed horizontal layering, I do not think that the methods are fundamentally limited to layered media. Therefore, I find this not a very strong argument.

We did not intend to introduce a dichotomy between our method and full-waveform inversion, and the respective comment has been removed. Full-waveform inversion for GPR signals monitoring water dynamics in arbitrary soil architectures is certainly the desirable goal. However, this still demands a massive computational effort that we are currently not capable of. We furthermore do not have the required detailed antenna representation at our disposal. In our assessment, both these restrictions typically lead to the constraint to special cases such as (planar) layered media.

Both referees commented on our interpretation of the compaction layer reflection (figure 7):

> Page 12379, lines 23-28: I am not sure I understand why you conclude that the reflection at 23 ns is porosity variation. Did you not state that the wavelet at 23 ns was caused by the CFR on lines 2-3? Is it not the same reflection you are discussing?

(referee #1)

and

> Page 12380, Line 4. If it is porosity only, I would expect that the permittivity difference is largest at saturation. Could you clarify your argumentation here? Is it not the effect of different porosity on the other soil hydraulic parameters that we are seeing here?
>
> Page 12380, Line 12. Why misinterpreted? Since the porosity is different, I think that this is a different material.

(referee #2)

In the new manuscript, our original discussion has been revised. We agree that tracing the emergence of the compaction layer reflection solely to porosity variation has been too superficial and formulate our hypothesis in the manuscript now more precisely:

> dashed rectangles in figure 6. The additional reflection is drawn as thick red and blue lines in figure 7 for the two cases in which it is clearly discernible. This reflection does not arise at a conventional layer boundary between different kinds of sand but is due the building process of our site during which the sands had to be compacted in regular intervals. This compactification process of the sand material altered the pore geometry below each compaction horizon. The associated reorganization of the grains leads to a local porosity variation and concomitantly to a higher capillary rise within the material just below such a compaction horizon. Hence, whenever the water table position is just below a compaction horizon, there is a significant dielectric contrast over this horizon leading to the observed reflected signal. Here, this is the case for the hydrologic states observed both before (trace

As argued by referee #2, at saturation the remaining contrast is solely due to the porosity variation, which in this case is not enough to produce a notable reflection by itself. Still we maintain, that such a local variation within the same material does not constitute a conventional layer boundary between different materials and it could be easily misinterpreted as such, depending on the specific hydraulic situation.

Further replies to small comments from referee #1:

> Title: I would change "with time-lapse Ground-penetrating Radar" to "using time-lapse Ground-penetrating Radar"

→ OK. Changed the title.

> Page 12367, line 5: The reason soil moisture can be estimated is due to the large difference in permittivity between water and air, and not between water and soil.

→ revised: "Such variations are foremost connected to differences in soil water content due to the large permittivity difference between water and air."

Some of the following references could be included in the introduction:

Trinks et al., 2001. Monitoring water flow in the unsaturated zone using georadar. First Break 19:679–684.

Truss et al., 2007. Imaging rainfall drainage within the Miami oolithic limestone using high-resolution time-lapse ground-penetrating radar. Water Resour. Res. 43:W03405, doi:10.1029/2005WR004395.

Moysey, 2010. Hydrologic trajectories in transient ground-penetrating-radar reflection data. Geophysics 75(4): WA211-WA219

Haarder et al., 2011. Visualizing unsaturated flow phenomena using high-resolution reflection ground penetrating radar. Vadose Zone Journal 10, 84–97. doi:10.2136/vzj2009.0188

Mangel et al., 2012. Multi-offset ground-penetrating radar imaging of a lab-scale infiltration test. Hydrology and Earth System Sciences 16(11): 4009-4022

→ In the introduction, Truss et al (2007) has been added to the list of studies concerned with high-resolution monitoring of near-surface soil water variations. The Moysey et al (2010) study has received a mentioning as another approach to estimate soil hydraulic parameters:

> on-ground GPR (Busch et al., 2013). Following a different approach, Moysey (2010) estimated soil hydraulic properties based on hydrologic trajectories derived from fixed-offset time-lapse monitoring of an infiltration experiment by on-ground GPR.

The three studies by Trinks et al (2001), Haarder et al (2011) and Mangel et al (2012) mainly deal with the specifics of imaging and evaluating infiltration processes and as such certainly warrant mentioning wherever monitoring infiltration processes is the main focus. However, although we do use an infiltration pulse to pre-wet our soil, our focus here is solely on the impact of the pre-wetted soil on the observed shape of the capillary fringe reflection. Since we do not put any emphasis on the details of the actual infiltration process in this paper, we decided to not discuss in detail previous approaches focused on monitoring infiltration processes with GPR in our introduction (which would then also include mentioning studies such as Saintenoy et al, VZJ 2008, as well as a range of studies based on cross-borehole GPR such as Deiana et al, VZJ 2008), unless the aim was on parameter estimation such as the mentioned study by Rucker and Ferré (2004).

Page 12371, line 2: Is there a reference to this work?

→ this has not been published as of yet.

Figure 1a and Figure 4: Is there not a mix-up in the labelling of the sand types? According to Figure 1a there is more sand C at the surface (depth=0m) than sand A, and in Figure 4 this is reversed.

→ Yes indeed, and thank you very much for this keen observation: Revised in the corresponding plot

Figure 6: What does the time t1 correspond to? (i.e. in subplot 5). Please add the exact time of each radargram. Page 12379, line 22 & Page 12380 line 20: Is there missing some text? Or what is meant by “14 . . . 16 m”?

Page 12381, line 1 & Page 12382, line 2: Again there is a strange “. . .”.

→ The timings have been added as described above. We are used to denoting a range by these dots, hence 14 … 15 m would signify "between 14 and 16 m". Realizing that this might be misunderstood, we replaced the dots by respective wording wherever they were used before.

Page 12382, line 18: How did you calculate 0.70?

→We calculated the 0.70 as the ratio of the imbibition (2.38cm/h) and the drainage (3.42 cm/h) rates. This should be clear now that the correct numbers for the infiltration rates are part of the experimental overview.

Figure 10: I think it would be nice with the exact time of each radargrams in this figure. It could be supplemented by adding this information in Figure 2 as discussed above.

→ see above.

Figure 12: I think you should include a non-shifted travel time plot as well as the shifted travel time plot. And why does the time axis not start at 0 ns?

→ The time axis does not start at 0 ns since the direct waves and the additional wetting front reflection in the pre-wetted case have been intentionally clipped for clarity, as stated now explicitly in the figure caption. The largely different water contents are also the reason for not including a non-shifted travel time plot, since in such a plot the relevant features are barely discernible.

Further replies to small comments from referee #2:

Page 12367, Line 9. Please evaluate the use of acknowledged throughout the manuscript. I feel that you use it in an inappropriate manner on several occasions. Here 'recognized' seems more appropriate.

→ changed accordingly.

Page 12367, Line 6. Something is missing here. It is not the radar that needs quantification.

→ changed to "However, quantification of *results derived from* surface-based methods….

Page 12371, Line 17. Figures should be referred to in the presented order. Here, you jump from figure 1 to figure 4.

→ revised, exchanging figures #3 and #4.

Page 12371, Line 25. Not clear what you mean with infiltration curtain here and also later in the manuscript.

→ using "infiltration curtain" in describing our infiltration process was intended to stress the quasi-2D nature of the infiltration. In order to avoid confusion, we changed it now to "infiltration front" in the manuscript.

Page 12371, Line 22. I propose to only discuss the GPR measurements that will be analyzed later in the manuscript. No need to mention here what other GPR measurements were made simultaneously.

→ Originally the high-resolution data were mentioned mainly to illustrate the measurement capabilities. Naturally not all radargrams could be displayed in the paper. However, all data mentioned have now been used in the respective movies.

Page 12373, Line 17. David Robinson did some really nice work on the determination of the solid phase dielectric permittivity. I propose that this paper is a better citation: Robinson, D.A. 2004. Measurement of the solid dielectric permittivity of clay minerals and granular samples using a time domain reflectometry immersion method. Vadose Zone J. 3:705–713.

→ We agree that this is nice study which we were previously not aware of and changed the citation accordingly.

Page 12374, Line 9. Simplify presentation here? I do not see a real need to introduce the soil matric potential here.

→ The soil matric potential is briefly mentioned here so that we can define the matric head in terms of this more fundamental quantity in case a reader is more familiar with a matric potential.

Page 12374, Line 9. This is true for static equilibrium only.

→ assuming that this comment was intended for Page 12374, Line 11, we added "In *static* equilibrium, the matric head describes…."

Page 12375, Line 10-25. Is it necessary to introduce the van Genuchten model here? For me, it is sufficient to say that previous work by Dagenbach et al. (2013) has shown that the Brooks-Corey model better represents the capillary fringe and thus the GPR reflection.

→ As suggested, we shortened the discussion of parameterizations and removed the formulae for the van Genuchten models. However, for reference and to stress the need for a parameterization displaying a sharp air entry value, we still mention its existence and maintain the comparison in what was previously figure #3. This revised section now reads:

so-called the soil water characteristic. The most widely employed models for these two functional relationships are the Mualem-van Genuchten and the Mualem-Brooks-Corey model, which are most conveniently formulated in terms of the water saturation Θ [–]. For the soil water characteristic, the most commonly applied models are the Brooks-Corey parameterization (Brooks, 1966), the van Genuchten parameterization and a simplified version of the latter (Van Genuchten, 1980). The Brooks-Corey parameterization, for example, is given by:

$$\Theta(h_m) = \begin{cases} \left[-\frac{h_m}{h_0}\right]^{-\lambda}; & -h_m > h_0 \\ 1; & -h_m < h_0 \end{cases} \tag{3}$$

with the air entry value $h_0 > 0$ [m] and the shape parameter λ [–]. The left plot in figure 4 pictures its inverse function, which is defined for $\Theta < 1$ as:

$$h_m(\Theta) = -h_0\Theta^{-\frac{1}{\lambda}}, \tag{4}$$

under equilibrium conditions in terms of the height above a water table for a generic coarse sand (see table 1). In particular, the figure shows the capillary fringe (which we define in this context as the region in which the soil stays completely saturated due to capillary forces, despite an already negative potential) and its associated transition zone from saturated water content θ_s to residual water content θ_r above a water table. For comparison, figure 4 also contains the soil water characteristic for the same sand using the corresponding simplified van Genuchten parameterization. For both parameterizations, the soil water characteristic describes a smooth water content transition above a water table for a certain hydraulic state in a homogeneous material. Such a water content transition corresponds to a gradual dielectric permittivity variation with depth (the corresponding permittivity profile can be calculated by employing an appropriate petrophysical relationship such as the CRIM, see equation 1). Hence, we can expect a corresponding GPR response from these permittivity variations, as has been shown by Dagenbach et al. (2013). For simplicity, we will denote this GPR response as the capillary fringe reflection (CFR), noting that this reflection in fact comprises the coherent superposition of all infinitesimal contributions along the whole transition zone above the water table. As an interference phenomenon, the resulting CFR will be sensitive to the specific shape of this transition zone. Hence, information about both the hydraulic state and the hydraulic properties can be gained from observing the CFR with GPR.

As can be seen from figure 4, Brooks-Corey and van Genuchten parameterizations differ most significantly close to saturation, where the simplified van Genuchten parameterization is smooth without a well-defined capillary fringe, while the Brooks-Corey formulation has a sharp air entry value. Following Dagenbach et al. (2013), a Brooks-Corey-type parameterization with respect to this sharp air entry value is needed for describing the shape of the transition zone in materials with a narrow pore size distribution in order to reproduce the characteristics of the measured GPR response. In the framework of this study, we will therefore directly employ a Brooks-Corey parameterization for the soil water characteristic, noting in passing that a sharp air entry value could also be realized using an appropriate full van Genuchten formulation.