Reply to the comments of referee #2

We thank the reviewer for the thoughtful and constructive comments.

(1) This submission maybe a potentially valuable scientific contribution in the field of hydrogeophysics. Recent work (e.g., Lunt et al. 2005, Wollschlager & Roth, 2005) has clearly demonstrated that traveltime information from GPR reflection profiling can provide very useful water content information. [...]

The introduction of our work will be rephrased in a revised version of the paper. Our contribution is given explicitly as follows. "GPR methods are of great importance in soil hydrology due to the characteristics of non-invasiveness, good depth investigation and larger scale than point measurements. Monitoring wetting/drying front at natural and artificial conditions using GPR have been demonstrated in several studies [e.g., Binley et al., 2001; Stoffregen et al., 2002; Deiana et al., 2008; Haarder et al., 2011; Mangel et al., 2011]. Following this direction, the geophysical data are used to constrain unsaturated flow models. However, the accuracy of water-content estimates from GPR still challenges this as pointed out by Moysey (2010). One solution is using the coupled inversion schemes that use rock-physics relationships to link the hydrologic process model with a geophysical instrument model [e.g., Kowalsky et al., 2005; Lambot et al., 2006, Looms at al., 2008]. Another alternative approach presented in this study is to reduce the uncertainty of the estimated quantity, where the soil water volume obtained from the multi-channel GPR method provides the potential. Through investigating the natural drainage after a rainfall event at the study site, we could deduce the hydrologic processes based on the measured data with a good accuracy.

Another issue for the field-scale soil hydrology model is soil heterogeneity. For specific soil architectures, soil water flow regimes are different. Steelman et al. (2012) demonstrated the application of GPR to characterize vertical soil water dynamics in multi-layered soils over a complete annual cycle. In addition, to image rainfall drainage over a 2D area, Truss et al. (2007) have used a time-lapse GPR method and 2D surveys to obtain the preferential flow path geometry and quantitative changes in water content within a limestone site. Similar to this study, we demonstrated an application of the multi-channel GPR method to quantify the field-scale soil water dynamics at an agricultural land with dune structures. It shows the data with the multi-channel GPR method can be used in 3D soil hydrologic modelling. Moreover, considering the influences of the soil architecture on the soil water redistribution during the drainage, we can deduce its relationship with the agriculture. It provides a potential application of GPR in precision agriculture."

(2) The authors need to give details regarding the processing of the GPR data. What software package was used? What processing steps (e.g., dewow, gains, filters) were used? What were the values of processing parameters selected? Were the same processing steps, processing sequence and parameter values used for all the data sets? If not, why and what potential impact could this have on the results? [...]

We used PG, a software package developed in our group. For the data processing, only a dewow filter was applied, where the amplitudes were weighted and averaged within an interval of 5 ns. The same processing steps and parameter values were used for all the data sets.

(3) Figure #1: Indicate approximate location of top of saturated zone? Is there a significant capillary fringe (zone of tension saturation)? It should be remembered that the water table is a piezometric surface and may be well below the top of the capillary fringe (the boundary of interest for GPR). This information is important give the authors' statement that water salinity probably restricts depth of investigation. [...]

The wording in the revised paper is rephrased to read “groundwater including the capillary fringe” .

(4) The comparison between the TDR and GPR needs to be done in terms of dielectric permittivity or EM wave velocity; these are the basic properties that are being tested. The conversion of both measurements into water content and volume significantly obscures this comparison. [...]

Considering an n-layer medium orthogonal penetration, the total travel time is

$$t = \sum t_i = \sum d_i \sqrt{\epsilon_i}/c_0$$

where d_i and ε_i are thickness and dielectric number of layer i. With $t = d\sqrt{\varepsilon}/c_0$, we find

$$\sqrt{\epsilon} = \sum d_i \sqrt{\epsilon_i}/d.$$

Since, with the CRIM model, $\sqrt{\varepsilon} = \alpha + \beta\theta$ with α, β parameters and θ volumetric water content, we may either compare θ or ε, provided they are are both thickness-weighted. During the calculation from ε to θ, there would be a minor difference between GPR and TDR due to the different α_i, β_i. We agree that comparing the permittivity is conceptually the right way.

(5) The multi-channel analysis method in Gerhard et al. (2008) and Pan et al. (2012) implicitly assume straight ray paths. Large vertical velocity gradients are quite probable during transient hydrologic events due to variations in moisture profile. [...]

Vertical dielectric gradients indeed lead to deviations from the assumed straight ray paths. However, calculations of approximate ray paths, for different configurations of horizontal layers each with constant ε, the ensemble with the same mean value, reveals that the resulting errors in the volumetric water content are small, about 0.01. Nevertheless, we should pay more attention to this factor, and thank the reviewer for this correction.

(6) In the absence of independent observations (e.g., gravimetric soil moisture sampling) or supporting hydrologic modeling, I have very serious reservations about much of the details about soil moisture dynamics inferred from the GPR data presented in this paper. [...]

We agree with the reviewer that the temporal changes in the average dielectric properties between the surface and the stratigraphic reflector after the rainfall event is the most reliable information inferred from the data. Similar results have been demonstrated in several GPR studies [e.g., Moysey, 2010; Mangel et al., 2011]. In all these approaches, the key challenge is the rather small change of average or total water content within a layer during typical events. Hence, a stable measuring procedure is of key importance, together with a correct estimate of the measuring error. While we are very confident with the first issue, our approach to estimate the errors was not correct and indeed greatly overestimated the true values. The reason for this is, that we erroneously gave the uncertainty estimate for an individual measurement, while the quantities shown in Fig 10 are indeed averages over a rather large ensemble. The correct quantity to use would have been the standard error of the mean, which is by a factor of $\sqrt{n}$ smaller than the sample standard deviation, where n is the number statistically independent members in the averaged set. Estimating n in our case is somewhat difficult because the individual measurements are spatially correlated through the geometry of the measuring setup. Our approach was presume the fluctuations to be represented by an isotropic random field with a well-defined correlation length λ . With this, $n = N\lambda^2/A$, where A is the total area sampled with N single GPR measurements. For the estimation of λ , we first looked at the longest antenna separation (a = 1.94 m), which causes the correlation, and secondly at empirical autocorrelation functions estimated from the actual measurements (λ between 1 and 4 m). From these we chose $\lambda = 2$ m. With N = 24025 and A = 1728 m^2, this led to a reduction of the previously reported error by a factor of 0.09 (see modified figure below).

The small error bars indicate that the changes of θ and l over the calculated areas are significant and accurate. Therefore, this information makes us trust what we observed from the GPR measurements. Thus, two more results from our study also become reliable. One is the spatial changes in total water volume in the areas with clay inclusions, valleys and ridges in Fig. 5. The other one is the temporal changes in total water volume, which shows the hydrologic behavior of the soil infiltration through the dune structure. The spatial water content changes in Fig. 5c and the statistical analysis in Table 3 (in the submitted paper) further support our deductions. As we also pointed out in the paper, the verification of further details of our hypothesis for the soil water dynamics would require additional information either on soil hydraulic properties or long time series of hydraulic state variables at various depths together with the corresponding precipitation/evaporation record. This, unfortunately, is not available for the current experiment. Nevertheless, we are convinced that we could demonstrate the capability of multi-channel GPR to monitor the spatio-temporal soil water dynamics in a 3D heterogeneous soil during a short-duration infiltration event. This should eventually prove instrumental for a new approach towards estimation of spatially highly resolved hydraulic properties at larger scales. In addition, this study also reveals the reason for the patterned wheat at the study site through investigating the soil architecture and associated soil hydrologic processes during the short-duration infiltration event.

Reference cited in this reply that are not listed in the submitted paper:

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