Author reply to 2nd round of reviews of „Form and function in hillslope hydrology: In situ identification and characterization of flow-relevant structures" (revised version) by C. Jackisch et al.

We are very grateful for the valuable and constructive comments from Christian Stamm, the anonymous second reviewer and the editor Ross Woods. Along the suggested lines, the manuscript has been revised carefully.

There has been some concern about the combination of the form-function framework and the overall experiments. In order to elucidate this, we addressed the distinction between form and function, and structure and heterogeneity more explicitly. Moreover, we position our experiments in the scale-dependent framework more clearly. This is now followed throughout the manuscript. Through this we also lift comprehension of the correspondence to the companion manuscript.

As suggested, the hypotheses and research questions have been restructured and reformulated. They do now follow the hierarchical learning process across the scales. Furthermore, this lead to a slight adaptation of the title, too.

Another concern related to confusion about the GPR-based attributes we employ. As the structural similarity attribute is central in the manuscript, we added explanation and the equation. For the semblance attribute supported picking of potential structures we added guidance to interpret figure 10.

To further underline the deviance of the observed vertical flow velocities from the expectations we added the Rosetta-based estimates as second reference (figures 4 and 9). Moreover, figures 5, 6 and 13 have been revised. The a priori model reference for the hillslope experiment has been shifted to the Appendix and is now explained with more detail in an additional figure.

Please see the following list for detailed replies to the reviewers' concerns. The original statements are given in black. Our replies are colored blue. Below the replies I added a comparison version of the MS tracking all changes.

Referee 2

Terminology: Much of the manuscript deals with the distinction between structure(s) and heterogeneity. However, the actual meaning of these notions is not precisely defined (see for example in the abstract L. 11 – 12, p. 24, L. 25 - 26). As I read the manuscript, structure refers to flow paths (for fast transmission of water (and potentially solutes)) that connect through a large fraction of the flow domain while overall heterogeneity is considered to have only local connectivity. To me it seems essential to distinguish explicitly between situations where such flow paths are caused either by specific pore structures that differ from the other parts of the pore space (e.g., root channels, worm burrows) or whether the flow paths emerge as a results of locally heterogeneity in macroscopically homogeneous soils (see for example (Roth 1995)). Only in the first case, there is in principle the possibility to detect flow structures by local measurements (e.g., on soil samples) because one can infer (potential) connectivity based on the type of pore structure that is identified (e.g. a worm burrow).

In the context of this field experiment, this distinction leads to question whether or not observed flow paths at the plot or hillslope scale can be related to the existence of types of pore structures that are different (at a local scale) from the rest of the pore space. If such structures existed this could help to potentially generalize the findings also for other locations.

If I am right with my view, the authors should make the differences between what they call structure and heterogeneity more explicit and be also more specific in what others have already published on this issue. If my interpretation was wrong, there would also be a need for clarification.

Thank you for this reflection. We fully agree with your comment and added clarification in sections 1.2 and 4.4. In the study at hand we so far neglected the second type (emerging structures) because of two reasons: The setting of periglacial cover beds creates a situation in which even at a macro-scale homogeneity is hardly declarable. Our experiments would have needed a different focus when the impact of antecedent soil moisture and irrigation intensity requires to be tested. Since one of the scopes of the MS is to present time-lapse GPR as a potent means to do such experiments, your concern is taken up in the outlook section 4.5.

With regard to structure identification across scales it was actually surprising that the Darcy scale pedo-physical analyses revealed very similar hydraulic conductivity as the apparent reactions at the plot and hillslope scale. Since the structures at larger scales require also sufficient supply to sustain flow, this may indeed turn out to be a base for generalization as long the structures are within related controlling factors. We address this topic by tracing the sub-scale identification of inter-aggregate pores across the scales in the revised MS.

Further details:

p. 2, L. 3 – 4: Sentence too generic.

I dropped the generic middle part of the sentence.

p. 2, L. 5 – 12: Too general, without insight into the topic of this paper. I cannot find the link between form and function in Wittgensteins Tractatus. So why to mention?

I agree to your concern that Wittgenstein's Tractatus may not be the best reference. Yet, it is one classic example of the reasoning about the relation of form and content. I mainly refer to points 2.033, 2.045 and 4.1241. In order to reduce to prominence of the citation I rephrased and shorted the reference. Moreover, I put more emphasis on the roots in system biology tracing back to Aristotele.

p. 2, L. 15: What needs to be revised?

The established relation of hydraulic conductivity and pore-size distribution. The sentence has been corrected.

p. 2, L. 16: Flurys experiments were not at the catchment scale but carried out in different soil types.

The formulation has been imprecise and states now: *…as has been observed at plots of different soil types (Flury et al., 1994) and in most catchments (Uhlenbrook, 2006).*

p. 2, L. 21 – 25: This paragraph is clear and helpful.

p. 4, L. 11: These responses are functions, not form, aren't they? If not, what do you actually mean by functions as compared to form?

We derive form by the footprint of function. This has been introduced in the brief reviews in section 1.2. To avoid confusion, I reworded the question slightly with clear focus on stains and patterns rather than response in general. The issue is taken up in the discussion section, too.

p. 5, L. 31: Why is it not Fig. 2?

In order to avoid emphasis on case-study related elements we transferred some of the details to the Appendix. This is also the case for the arrangement of samples at the surrounding of the plot-scale experiments. However, the results are comprised in fig. 9, too.

p. 7, L. 15: Provide the dates of the experiments.

The dates have been added.

p. 7, L. 28: Sentence is not clear.

I revised the sentence and rephrased it.

p. 7, L. 29: Why should this time be only depend on the duration of the input signal and be independent of the size of flow domain (imagine the same input duration for a small system where the input leads to steady-state across the entire system as compared to a large one where most of system has not yet been influenced by the input at the time of ending the input)?

I agree that the scale is of importance and rephrased the reference for clarity. The discussion you raise is very worthwhile but not of scope in the MS.

p. 8, L. 2: Provide details of the quick sampler.

I added a description in the appendix.

p. 8, L. 14 – 15: Skip it if you don't use it for the paper.

The data is given as additional reference to the Bromide data. Although this is just a minor side track it supports the validity of the data.

p. 10, L. 12: Give the date of the experiment.

Done.

p. 10, L. 15: What is facilitated?

I added the explanation.

p. 10, L. 18: Before or after the natural rainfall? Please provide a schedule where all relevant events are clearly indicated.

The survey has been conducted prior to the natural rain events. Because the precise timings are of main concern for the overall process analysis (function), which is given in the companion MS, I find it more disturbing than helpful to provide a full schedule or time series in the MS at hand, which is focusing on the structures in the subsurface (form).

p. 10, L. 29: The modeling was not introduced earlier nor is it mentioned later on. I suggest that you briefly compare the prior predictions (based on your prior knowledge of the system) to the actual results. Please also describe the prior assumption about the flow structure you implemented. This provides a very nice opportunity to demonstrate how you gained insight from the experimental work. You should do so even in case that the prior predictions were rather different from the actual outcomes – this would not be interpreted as a weakness (see for example (Holländer, Blume et al. 2009)). Did you consider the natural rainfall for the modeling?

Thank you for pointing this out. Obviously, employing a model for the identification of experimental parameters is often demanded but so far rarely done. I prepared a table with the used soil parameters and a figure showing the domain and some snapshots of the results. In order to keep the focus of the manuscript I shifted the section to the appendix. There I also briefly discuss the deviation between the model and experimental results. Moreover, I added a brief outlook on how the insights from the measurements and experiments should be used to enhance the model in the new methods discussion section 4.3.

p. 12, L. 27: How was the grid generated?

The grid is simply a regular matrix for computation.

p. 13, L. 19: Why is this rainfall event only mentioned here?

You are right. I moved the sentence to section 2.4.3 Experimental design.

p. 13, L. 26: According to Fig. 3 in the companion paper the irrigation is indicated after the runoff event. Please clarify.

The formulation has been misleading. It is clarified now.

p. 13, L. 29 – 31: The procedure is not clear. How can two similarity attributes show increasing similarity? Why is a decrease in similarity attributed to the irrigation? This part is essential to this paper but is rather obscure. It might help to have a figure in this manuscript where all relevant events are depicted on a time line and all relevant comparisons for this similarity calculations are demonstrated. Mathematical notations/equations might also facilitate the understanding.

I added details and the equation how the similarity attribute is calculated. Low similarity points to changes in soil water content. As such a decrease in similarity is attributed to newly arriving water. Increasing similarity can only appear after a more dissimilar state. As the reference state is assumed to be in quasi-steady state (at least with regard to the time-scales under study), any free water would be seen as low similarity attribute.

p. 14, L. 5: I do not fully agree with this statement. Upon inspection, it seems to me that the Ks range is clearly the largest in the topsoil with a pronounced range decrease with depth. The data suggest that at the surface there are samples with very high and with very low values (e.g., due to macropores on the one hand, and due compaction on the other hand, respectively). A similar range decline seems to be related to texture.

Arguably, the given figures may not be the best to fully analyze trends with depth. Since the MS is about the spatial organization of flow paths, I still prefer this set of figures over layer-wise histograms or kdes. They present sufficient deviation from the normal perception of decreasing conductivity and increasing bulk density with depth. They also reveal only at the Holtz site a profound pattern reflecting the first layer of periglacial deposits.

p. 14, L. 27: Sentence not clear.

Rephrased for clarity.

p. 16, Fig. 5: The profiles of the T and B locations seem to differ with regard to gravel content and depth of the periglacial material: what are the implications?

I would not say so in general. The situation is highly heterogeneous and the insight from soil core profiles is limited. One aspect to notice is the lower bound of the drillings to range around the same depth. In order to highlight that this is due to large stones or bedrock I added the notation for this to the bars. Moreover, I exchanged one of the profiles for sake of spatial proximity to the experimental sites.

p. 16, L. 7: what is the positive bias in the analyses?

I clarified the statement to relate to the observed hydraulic capacity deviating from expected/literature values.

p. 17, L. 2: Please mention the recovery explicitly. It is almost hidden in Fig. 7.

Done as suggested.

p. 19, L. 1: What is inconsistent about the distributions?

They are not matching each other. I rephrased the sentence accordingly.

p. 20, Fig. 9: I like these figures. The right panel indicates that the response of water content is faster than that of solute transport pointing to the displacement of pre-event water. This aspect should be explicitly discussed in the manuscript.

This is an interesting point but also speculative. Since the derived velocity distribution of the solutes highly depends on the estimated time of fixation (t_fix) a slightly reduced value would result in a better fit. Moreover, the depth of the TDR and GPR response measurement is to be seen in the margin of the measurement precision of about 10 cm. Hence the right panel is more an argument that the parameter t_fix is critical (as addressed in section 3.2.5) and maybe even below the suggested 1.5-times of the irrigation. Having explained this, I would see the raised discussion to be worthwhile but only weakly supportable by our data.

p. 20, L. 6: Does this remain unclear at that stage or after considering all of the results. Please clarify.

This refers to the stage of having conducted a static survey only. I added the explanation accordingly.

p. 20, 3.3.2: This section is difficult to follow all of the temporal comparisons. A figure with the time line would help.

As explained earlier, the overall temporal comparisons are intentionally left to the companion MS. Including a time line in the existing figures would overload them. That is why we clarified the dates and times in the text but refrain from adding a specific time line.

p. 21, L. 1 – 2: Why should be a difference between connected flow paths and the irregular network of inter-aggregate pores (see (Roth 1995))?

We agree that there is quite some self-similarity between the inter-aggregate pores at the smaller scales (Darcy to plot) and the flow paths at the hillslope scale. The sentence aims at explaining this. We revised the discussion section to clarify this.

p. 22, Fig. 9: How can one understand this figure without considering the natural rainfall?

We failed in clarifying that the shown changes in soil moisture are relative to the pre-irrigation state, when the observed system apparently was already back in local equilibrium. As such figure 11 indeed is looking at the irrigation-induced reactions and specifically their positioning in the subsurface. This is explained in the revised MS.

p. 22, L. 1: What’s the overall response here?

Additional guidance is added.

p. 24, L. 4 – 5, 10: You say the properties were not expected for this soil texture but you provide an explanation, which is not very peculiar (network of inter-aggregate pores). So, is this pore network different from that of soils of similar texture?

I agree that inter-aggregate pores should commonly be expected. However, they are heavily underrepresented in currently available soil-physical concepts and models. This implies quite substantial opposition to the common hypothesis that we can derive soil-water-retention properties from texture and bulk density. And thus yes, the Rosetta-derived ksat of 10^-5.2 m/s given the mean texture (15.7,47.9,36.4 %S,Sl,C) and bulk density (1.1 g/cm3) is two orders of magnitude below the observed responses.
We added this reference in fig. 4 and 9 and referred to it in section 4.2.

p. 24, L. 13 – 14: Sentence not clear.

There appears to be some confusion about the capability of dye staining experiments. It is out of debate that the revealed dye patterns are the result of the soil water redistribution processes (thus relating to function). However, if dye is retained at a specific location this can have many reasons (high retention capacity, long contact time, high supply, etc.). In addition, there is no information about the time of fixation in the dye stains. Lacking the temporal dimension, dye stains do not reveal much information about function but can exhibit the potential pathways – and hence form, given sufficient supply and dye. We altered the sentence accordingly.

p. 24, L. 18: Why should all flow paths identified by their soil moisture response be stained? It seems that you confuse water flow and solute transport (see comment above on Fig. 9).

I see the point in distinguishing water flow and solute transport. One methodological hypothesis in tracer hydrology is that within the scope of the experiment the tracer is somewhat mapping the flow path – the travel depth of the center of mass reflects average flow velocities, while the width of the tracer profiles reflects dispersion due to sub-scale variability of flow velocities. Thus solute transport is deviating only slightly from actual water flow. When it comes to diffusive flow in the matrix, I fully agree that this assumption collapses. However, in the scope of the MS regarding flow-relevant structures non-stained voids link to a lack of connectivity (or retention capacity e.g. at stone surfaces). Ultimately, this means that identifying all potential structures, inter-aggregate voids, channels etc. will simply shift the question of reaction to an event to the issue of connectivity and interaction. This supports our arguments of the interconnectedness of form and function and to use time-lapse GPR as 2D and 3D visualization means of subsurface flow processes.

p. 24, L. 20: What are the point-sampling related issues?

We have shown that point samples or point-scale monitoring is insufficient to unambiguously characterize the structured and heterogeneous subsurface. The sentence has been clarified

p. 24, L. 22: Sentence not clear.
p. 24, L. 25 – 26: See comment above on terminology.

p. 24, L. 28 – 29: This sentence is rather obscure.

The paragraph has been revised accordingly.

p. 25, L. 4 – 6: It would be useful to refer to some literature.

p. 25, L. 10: Which threshold?

We refer to the threshold separating noise from signal in soil moisture changes. I added this specification to the sentence.

p. 25, L. 17: Where can one see these discrepancies?

Figure 10 presents another example of the difficulty to infer subsurface structures from static conditions. We derived potential subsurface structures using a semblance attribute supported picking in data of a 3D GPR survey. The dynamic records in the TDR and GPR profiles draw a different picture of flow relevant structures, which could not be anticipated from the static survey. This can be seen by the reactions not aligning with the potential structures. I added this information to the figure caption.

p. 25, L. 25: This is actually one of the essential questions here: are the flow paths due to structures which differ from other parts of the pore space in their properties. You suggest that they actually do, however such flow path may also emerge from local heterogeneity (see comment above).

I totally agree that flow paths can emerge from heterogeneity and that this is an issue to address in hydrological research. However, it is not exactly the essential question of this study as the flow paths we identified (at the plot and hillslope scale) clearly point to existing voids. Moreover, we argue that there is a difference between heterogeneity and structure when the physical processes cannot be lumped as in the case of advection and diffusion.

p. 27, L. 30 – 31: What are these new ways?

Continuous, non-invasive in situ observation of changes in soil moisture in the subsurface.

p. 28, L. 4: As mentioned above, I have serious doubts that Wittgensteins work on formal logic really helps in the context of this manuscript.

There appears to be few literature on the theoretical concerns of form and function. In many cases, it is treated rather implicitly or case specific. I agree that Wittgenstein might not be the best reference but he shaped a general reasoning to that point. I eased the link to his Tractatus in the MS accordingly to avoid it being stressed too heavily.

p. 28, L. 5: This sentence is actually at the heart of the issue and I suggest you bring this aspect up already in the Introduction. Furthermore, there are ramification to what you conclude that should be discussed in more detail. You criticize – based on your findings - the concept of investigating separately relevant soil structures and their hydrological functions/responses. You suggest that irrigation experiments and time-lapse GPR measurements could solve this problem. While this holds true locally, your argument suggests a major problem for (hillslope) hydrology, which is that of generalization and spatial extrapolation. The rational why to investigate structure and functions at least partially separately is that (physical) structures are generally much more stable in time and relatively easy to observe as compared to hydrological functions. Hence, observations of structures allow for estimates about hydrological responses without carrying out for example irrigation experiments at all sites. If you claim that such a separation does not make sense your claim also entails the message that flow experiments are necessary everywhere to make statements about hydrological functions. I suggest that you discuss this aspect in more depth.

Thank you for highlighting the lack of discussion of this aspect. Actually, I do not see extrapolation in space and time to be necessarily such a “ramification”. The consequence should be a much more rigor test of the hypotheses we usually apply implicitly: Is the functional reaction persisting in time, space and across different events? Do we monitor the system adequately by a couple of sensors at pre-defined points? It could turn out that the transfer-storage-release-system can be described by a much more general set of parameters than heterogeneous soil matrix definitions.
Your comment motivated me to add a new discussion section setting the efforts and gains of all applied methods into perspective (4.3). I would disagree that irrigation experiments are the only means to base statements about hydrological function on. However, if we consider eco-hydrological system to be highly structured in general, it may be worthwhile to revise the rather ad-hoc monitoring based on point observations. Furthermore, we argue that time-lapse GPR is an easy to employ system, which reduces ambiguity about the system’s form and function, and which could guide the selection of adequate monitoring setups.
I revised the introduction and discussion section accordingly and added this aspect.

p. 29, L. 20: Conclusive with regard to what?

Conclusive to represent the system. We clarified this in the revised MS

Conclusion:

I think the manuscript has the potential for an interesting contribution to HESS but still needs to address a number of issues as listed above. Some of them actually got only visibly because the current version is much more readable than the original one.

Thank you again for your very constructive comments.

References:

Holländer, H. M., T. Blume, H. Bormann, W. Buytaert, G. B. Chirico, J.-F. Exbrayat, D. Gustafsson, H. Hölzel, P. Kraft, C. Stamm, S. Stoll, G. Blöschl and H. Flühler (2009). "Comparative predictions of discharge from an artificial catchment (Chicken Creek) using sparse data." Hydrology and Earth System Sciences 13: 2069-2094.

Roth, K. (1995). "Steady state flow in unsaturated, two-dimensional, macroscopically homogeneous Miller-similar medium." Water Resources Research 31: 2127 - 2140.

Referee 4

The revised version of the manuscript of Jackisch et al. (2016) investigates the identification of structures relevant for subsurface flow processes in the context of form and function based on soil samples, Ks measurements, TDR, GPR and tracers (KCl and brilliant blue). The revised manuscript is now a very nice study, which would be very helpful for the community to shed light into subsurface flow processes in periglacial cover beds. The idea of form and function is hereby an interesting perspective on the hydrological system and could be extended to many other processes.

The content is relevant for the journal but the modalities still need additional revision, especially in the coordination to the other manuscript of Angermann et al. In the here presented modified version the authors integrated the comments of the reviewers. Structure and story line are getting form. The author's introduction is plausible and taken the relevant literature into account. They developed the theory of form and function in a very nice way. The materials block is shortened reasonable and most of the unimportant technical details are removed. The benefit of all these measurements to understand subsurface flow patterns is now recognisable.

Thank you for this comment. The confusion about some of the main aspects in the manuscript and the coordination with the companion study are interrelated. Based on your suggestion, I streamlined the arguments of this MS and related to the companion study where appropriate.

The description of the results is in the presented form much better except the GPR part.

Section 2.3.5 and the related result sections have been revised for clarity. Specifically I added details about the calculation of the structural similarity attribute. Moreover, more guidance to read the respective figures is provided.

But the benefit of their experimental design in the view of the presented theory of form and function compared to other experimental studies is still unclear. Their experiments compared to other studies are similar. The same hypotheses are postulated without direct knowledge what is exactly is the reason for the observation.

I revised the formulated hypotheses based on the raised concerns and clarified the research questions by aligning them with the story line across the three scale levels. In order to focus on the identification and characterization of flow-relevant structures in this MS, concerns related to overall process understanding was largely shifted to the companion MS. The two MS overlap in the hillslope experiment to some degree which is in line with our conclusion that form and function need to addressed as conjugated pairs. This poses significant concern about hydrological and soil physical surveys and monitoring relying on point observations and implicit assumption about the internal structures of the soil.

Form and function is scale dependent. At the hillslope scale or at larger scales it is hard to identify. That is different to the plot scale, where the water-retention curve and the relationship of hydraulic conductivity to pressure head is available from lab experiments because of clear boundary conditions. The authors start to formulate an answer for the next scale, similar to Reggiani (1999, 2000, 2001) on the model level, whit his REW model concept. And at that point the authors give no answer how to solve the problem. Maybe only setup like the experimental hillslopes of Japan or the Biosphere 2 experiments of the Troch group are able to give therefore an answer and should be cited and discussed in the introduction.

Thank you for raising this concern. I agree that scale dependency is part of the form-function relation as much it is generic for hydrological processes. We raise this concern in the introduction section and throughout the MS. However, I disagree that it is generally easier to be identified at the plot- and Darcy-scale. Despite all admiration of the REW concept, I also do not quite follow your argument. In our study we focus on the identification and characterization of flow-relevant structures at the plot and hillslope scale. Our findings can say little about the generalization of the form-function relationship in models across scales so far. With regard to the REW-concept our findings could ultimately lead to references to define a fast flow zone. In more general terms, we hope that our findings contribute arguments and a novel method to advance our understanding of subsurface flow processes. Since the flow-relevant structures are the results of soil genesis I would actually see it as a counter argument against artificial hillslopes without a clear reference of their system properties (across scales). We suggest that in situ investigations are possible and should be done with different intensities, antecedent moisture states and at different locations/scales.

The hypotheses are not well formulated. Where is the new direction to understand form and function at the hillslope scale? Here they just add different methodologies and have still many assumptions to be taken into account. The difference between Q2 and Q3 is not strong. From my perspective they can combine them to one. There is still potential for much clearer aims.

The in situ visualization of subsurface flow response patterns is regarded as a novel approach to understand form and function at the plot and hillslope scale. On the one hand this allows for spatially continuous, undisturbed observations. On the other hand it is employed complementary to more traditional methods. As explained, the research questions have been revised.

A figure, which guide through the manuscript would be nice. Which experiments have which aim on which time scale and with which spatial footprint, etc. . And here is the point where the authors should present, what the difference is between the two studies. Currently Jackisch et al. and Angermann et al. have many similarities, whereby the second study has better structure and is clearer formulated compared to the first. The titles sounds too similar. Jackisch is investigating the flow relevant structures and Angermann the subsurface. But are these two topics spreadable, to investigate structures the flow is has to be known and vies versa?

We see the necessity to well-align the two companion MS. The given overlap in the hillslope experiment is intended and supports our reasoning to show how form and function are acting as conjugated pairs. The imaging and quantification of subsurface flow structures from the point to hillslope scale is complementary to the inference on hillslope reaction in a top-down manner. As these require rather different methods, this justifies the spreading of these two aspects into two companion papers.

The block of the models (page 10 line 30- page11 line 1) is still not that what I would expect in an experimental study without presenting any simulation results. If they have proven the boundary conditions of the experimental setup with a physical hydrological model, how have they parameterised the entire unknown structures of the hillslope to extract the required irrigation amount and estimated the response time of the system. Why have they not proven their findings of these structures with the model with the observation data in a third step? Here they could have presented a form and function based on observations and virtual experiments (Weiler and McDonnell, 2004) with all its structural uncertainties.

Despite being advocated in several papers, a priori modeling of experiments for tuning the respective limits seems to be done rather rarely. However, the model was set up based on findings from the measurements presented in in Appendix C (earlier section 3.1). Although the concrete subsurface structure was unknown, we had sufficient data to parameterize the model. Moreover, one has to be clear about the purpose of the model: It was employed to define the necessary irrigation amount and intensity plus the spacing of our TDR and GPR monitoring network. This was done by analyzing different scenarios towards the observable soil moisture change without explicit structures. We ease the confusion by adding the parameters and model results to the description.
Virtual experiments have been intended in an earlier state of the MS preparation. To keep the focus on the exploratory aspects of subsurface structures (and processes) we consider them out of scope for this study. However, I added a brief outlook on this in the new discussion section 4.3.

In the materials and method block a short description of the estimation of structural similarity and its mean is missing. A very clear description can be found in the manuscript of Angermann et al. The presented description is hardly understandable.

The equation and some more details to calculate the similarity attribute after Allroggen and Tronicke 2016 is now included.

Most of the plots are still hardly comprehensible and need simplification. Two plots (11 and 12) are used by both manuscripts. Explanation has to be given.

I revised the figures and added more guidance to their interpretation.
The figures 11 and 12 are presented complementary in the sense that they point out form and function. While Angermann et al. uses the full set of monitoring observations from the hillslope experiment, the MS at hand points out the structural information about flow-relevant pathways – e.g. in figure 12 the regions of such structures are excerpted.

Figure 1: I am wondering how they could be using soil samples and Ks measurements of the wider surrounding area in case of these complex periglacial cover beds and not observations only from the direct surrounding area. The analysis could be completely wrong.

I fully agree and also argue in the MS that taking point-scale soil samples, measurements and monitoring in a “complex” environment is prone to bias. However, I find results from 63 undisturbed ring samples, 40 hood infiltration points and 32 boreholes for ksat measurements not a small number of references for a relative small headwater. In many catchments reasoning is based on far less and more dispersed observations.

Abstract still needs revision, because they are not able to present form and function.

The abstract has been slightly revised. However, more details about the form function relation is added in the introduction, discussion and conclusion sections.

They have moved many parts to the appendix, but that needs linking to the main manuscript and not only the moving.

I carefully revised the Appendix and the linkages to it. In the current, revised form it underlines the arguments of the main part of the MS by providing additional details which otherwise would remain unclear.

Discussion has to be shortened with more linkage to form and function and to model approaches for the larger scale, which could have the potential to investigate the specific problem.

By clarifying the definition of structures more clearly and by restructuring and rewriting the discussion we aim to substantiate the main findings and to complement the concerns raised in the companion MS. Model approaches for the larger scale are not directly topic of the MS. With regard to model approaches at larger scales I added the REW outlook as suggested. With the methodological discussion, I hope to provide more details about possible implications also for model approaches.

Writing still needs modification and proving.

I revised the MS and rephrased passages which deserved clarification. Final copy editing will be done in the production process.

Abbreviations (Two Way Travel time) have to be defined.

Sorry. The definition has been added to the caption.

Specific comments:

P3L2: That should be questionable if double peaks are driven by macropore networks. The phenomenon is very special and has not a fast response in the sense of subsurface storm flow. It is slower. But of cause their assumption would be able to investigate the phenomenon. A link to it would need an extra point.

This point is left to the companion MS.

P39-10: That's not clear; dye tracers are used to understand the interactions between macroporosity and matrix. What do they mean with the requirement of strong assumptions to that topic?

The formulation has been eased and the discussion is taken up in the appropriate section 4.1.

P5L2: change "large number of methods", they present GPR, dye and salt tracer, soil samples and Ks measurements and irrigation data, that is not large.

We combine hydrological, pedological and geo-physical methods at point, plot and hillslope scale in situ and in the laboratory. The formulation has been adapted.

P5L13: Add English name to the botanical. Are the conifers important? I just saw deciduous plots.

English names were added as suggested. Most of the measurements and all experiments took place in beech forest. Beeches are known to have a strong impact on the community of shrubs and soil biota which is different to spruces. Although we did not specifically investigate this impact, we think it is important to point to this fact.

P7L13: Figure 13 is still hard to understand but important. I would move a simplified version back to the main manuscript. Add in figure 1 station E. It is not clear where it is located.

The location of the plot experiments is explicitly given in fig. 1. I also changed the overall location reference to gauge Weierbach 2 for clarity. A simplified version of the presented data is given as fig. 9. Fig. 13 has been updated accordingly.

P7L15: What kind of return period for the specific area are these values?

The irrigation amount is chosen relatively high to activate the flow paths. An event of 40 mm/d has a return period of about 15 years in the catchment. The plots have been irrigated once each. I added the dates to the description.

P8L2: check spelling, is that important? A fast sampling design is obvious for that kind of experiments.

I am not aware of many study which sample the excavated faces of irrigation experiments with accurate to volume samples in such a resolution. I added further description to the sampler in Appendix A.

P8L11: The neglecting of lateral flow is common practice in tracer analysis in soil profiles. But by looking in a new direction of form and function should it not be critical discussed? The authors could not just criticise the old studies and then do it exactly the same way.

This method requires this assumption. And this is exactly why we propose time-lapse GPR as an alternative or complementary technique as it can observe the full 3D flow field. Your point is taken up in the discussion section in the revised manuscript.

P8L15: Link to Angermann et al. and remove the isotopes from the appendix. The appendix is not the area, where all not presented material should be moved to.

This is a misunderstanding. The isotopic references in Angermann et al. refer to the hillslope experiment and the stream flow reaction. The isotopic data we present here complement the Bromide tracer analysis in the soil cores. It is shown to corroborate the tracer findings on the one hand and to critically highlight the assumption of tracer techniques on the other hand. With this we address exactly the point raised by you with regard to P8L11.

P9L10: check spelling

Done.

P10: Shorten that block

The blocks have been revised.

P10L30: Why are the plot sites not proven with the physical model? I am wondering of the intensity of 30 mm in comparison to the plot sites.

For the plot-scale experiments we used the intensities which have been applied to other sites of the overall catchment. Here the estimation of intensities and observation setup was less critical as we monitored the full 3D field and one soil moisture profile. 30 mm was selected as low-intensity reference.

P11L8: How have they removed shrubs without disturbing the soil, with chain saw and disc cutter?

We manually cut the shrubs with a bypass lopper. Shrubs of larger diameter were cut with a manual saw. One fallen tree and its roots had to be chain sawed to be removed. The area of the irrigation was specifically chosen to require minimal shrub removal to avoid any impact on the soil.

P12L1: The presented irrigation is completely different to the plot experiments. Explain the reason and how these experiments still could be comparable. Are the antecedent conditions similar?

The argument is given in Appendix A (section 2.4.2 in the earlier version) based on the a priori modeling. Since we compare the flow-relevant pathways for lateral hillslope reaction (which needs more intensity to be observed as the irrigated area is very small compared to the whole hillslope) and vertical plot reaction, the assumptions are justified. The antecedent conditions are similar with regard to pre-initialized structures by natural rainfall but dissimilar with regard to the overall system state.

P12L26-30: Block has to be rewritten. In that form it is not clear.

We checked the paragraph and hope that it is more comprehensible through the modified introduction and discussion of the topic.

P13L25: add duration of the rainfall events and intensities.

The temporal dynamics are intentionally left for the companion MS where details about the natural storm events include timing, intensity and isotopic composition. I added an introductory sentence naming the total amount of the events.

Figure 5: Where are these profiles? A link in the figures 2 and 3 would be important to understand the spatial distribution; maybe an arrangement in a catena for the hillslope experiment.

The positions of the profiles are given in fig. 3 and 13. I included a reference to these figures accordingly and changed their flags.

P16L7: What did they mean with a positive bias in the soil data?

I regret the confusion caused by the formulation. The intention of the statement was to comprise the deviance of the expected/literature properties with the observed ones (fig. 4). The sentence is revised and states now: *This explains the much higher values of the observed hydraulic capacity compared to expected/literature values (figure 4).*

P16L11: Where is B7? A signature (line or an arrow to the layer) should be added to the base layer in figure 6.

Thank you for pointing to this. I exchanged one of the B-profiles in fig. 5, revised their nomenclature and added their positions in fig. 13. Moreover, I added markers for the deposit layers in figure 6.

P17L14: The differences in the figures 6, 15 and 16 are hardly identifiable. The intention of radargrams is unclear.

A visual inspection of the radargrams in fig. 8, 15 and 16 is not expected to reveal the recorded shifts. This is why we calculated the structural similarity attribute. However, for sake of scientific transparency and rigor we expect the radargrams to be necessary to understand the methodological capabilities and limits.

P17L12-P18L9: Block is hard to follow.

We revised the paragraph.

Figure 9: Add abbreviation of the three CHP's to the caption. Explain the three differences.

Added as proposed.

P18L4: Where is T7, is it the 7 in figure10 and 3? Then add the T and add a comment to the captions.

This has been addressed. The nomenclature has been revised to be consistent and more easy to follow.

Figure 10 needs simplification. The main focus is on 1.5 m depth, figure should highlight that region.

I see your point. However, I do not find any more simple way to aggregate the 3D data (plus response) more clearly. It has been shown in the plot experiments that the deposit layer is not restricted to one precise depth level. The picking of this horizon resulted in the presented patches between 1.2 and 1.9 m depth (white to orange). As the picking was guided by the semblance attribute which highlights areas of high spatial contrast, we also want to show this (white to black). Where more than one horizon exists, the top one is plotted. I added further explanation to the caption to clarify this intention.

Figure 11: Why have they not selected the same TDR profiles in the temporal development plots and in the distribution functions of the TDR profiles for the apparent velocity? Angermann (figure 8) used the same plot, but here two time steps more are presented, why?

The temporal development denoted to function is the focus of the companion MS. The MS at hand shares the hillslope experiment but analyses the data with regard to identification and characterization of the flow-relevant structures. That is why we extended the shown observation period (the structures react and return to their antecedent state) and that is why we do not use the full set of profiles here.

Figure 12 is also in Angermann (figure 9) but there much better explained. What is the reason for the duplication?

For the identification of the structures we refer to the plot experiments in this MS. Fig 12 is a subset of fig 9 in the companion MS as we do not need all transects and time steps to identify the reacting subsurface structures. In addition to the companion MS I calculated regions of flow-relevant structures based on the standard deviation of the structural similarity attribute over time (given as bottom row). I agree that in this the two MS are very closely related. But it is also reflecting the conjugated nature of the form-function relation which we argue exactly at this point.

P24L5: But that cannot be the aim of an experiment that there is still the need of more data to have representative sample size or to have a perfect conversion. Is not the better solution to understand the process with less sampling by using an intelligent strategy, which they have? Later, in the discussion they even discuss that less effort is possible.

Our experiments tried to push the limits of what is possible in experimental hydrology (within the given financial and personnel limits). In most studies we need to rely on the assumption that the sampling is ergodic without further reference. Just because we applied different methods at different scales, the capability of the pedo-physical approaches has become apparent. Your suggestion to understand the processes with less sampling is exactly what we propose: A revision of the hydrological approaches to avoid the assumptions of isotropic conditions and well-behaved diffusive flow in the subsurface. Using time-lapse GPR could be one means to do so with comparably little effort.

P25L28-31: Here a link to form and function to model approaches and to Reggiani could be an important step.

As mentioned earlier, the modelling part is intentionally kept very general. Adding reference to one kind of model concept can easily be lopsided. One could think of applications in the MIPs model (Davies et al. 2013, 10.1002/wrcr.20377) much more straight forwardly. However, we took up your suggestion as surrogate for large scale models in general and added REWs. In case REV have been confused with REW we also clarified the section by largely dropping the issue.

P26-27: shorten

The discussion has been restructured and largely rewritten.

P28L1-3: I miss models which would be able to take larger scales into account (Weiler and McDonnell, 2004; Lee, Zehe, Sivapalan, 2005ac) and not only the soil core and hillslope scale.

I agree that more large-scale approaches are lacking and that relation our findings to such models is very worthwhile. However, the models are not of focus in this MS. Hence I leave it to forthcoming studies to convey our findings to models at the catchment scale and above.

Thank you again, for your review.

Form and function in ~~hillslope~~ hydrology: In situ ~~identification~~ imaging and characterization of flow-relevant structures from point to hillslope scale.

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Abstract. The study deals with the identification and characterization of rapid subsurface flow structures through pedo- and geo-physical measurements and irrigation experiments at the point, plot and hillslope scale. Our investigation of flow-relevant structures and hydrological responses refers to the general interplay of form and function, respectively.

To obtain a holistic picture of the subsurface a large set of different laboratory, exploratory and experimental methods was used at the different scales. For exploration these methods included drilled soil core profiles, in situ measurements of infiltration capacity and saturated hydraulic conductivity, and laboratory analyses of soil water retention and saturated hydraulic conductivity. The irrigation experiments at the plot scale were monitored through a combination of dye tracer, salt tracer, soil moisture dynamics, and 3D time-lapse ground penetrating radar (GPR) methods. At the hillslope scale the subsurface was explored by a 3D GPR survey. A natural storm event and an irrigation experiment were monitored by a dense network of soil moisture observations and a cascade of 2D time-lapse GPR "trenches".

We show that the shift between activated and non-activated state of the flow paths is needed to distinguish structures from overall heterogeneity. ~~2D and~~ Pedo-physical analyses of point scale samples are the basis for sub-scale structure inference. At the plot and hillslope scale 3D and 2D time-lapse GPR applications are successfully employed as non-invasive means to image subsurface response patterns and to identify flow-relevant paths. Tracer recovery and soil water responses from irrigation experiments deliver a consistent estimate of response velocities. The combined observation of form and function under active conditions provides the means to localize and characterize the structures (this study) and the hydrological processes (companion study Angermann et al., 2017, this issue).

1 Introduction

1.1 Form-function relationship in hydrological sciences

From a general perspective the interplay of processes and spatial structures (Grayson and Blöschl, 2001) lies at the core of our understanding, exploration and modeling. It manifests itself as patterns in dynamics (Sivapalan, 2005) and self-organization (Zehe et al., 2013). This interplay can be expressed as form-function relationship, which is addressed in many disciplines. Especially in systems biology the form-function relations are deeply rooted (e.g. Thompson, 1917) (e.g. Aristotele in Blits, 1999; Thompson, 1917 under debate until today (e.g. Mugler et al., 2011). In logical and philosophical terms the separation abstract terms the relation of form and function is fundamental for the concept that we can predict the a behavior of a system under different forcing by knowing its constructive properties (e.g. Wittgenstein, 1922). In this respect we understand form as the shape and material property of the soil domain, whereas function refers to the dynamic behavior of water within the same. Already Wittgenstein (1922) highlighted that it is form and content which make up the substance configuring the world and that form exhibits the possibility of structure. Although it is generally agreed on the existence and importance of form-function relationships, it is not clear to what extent form follows or reveals function and vice versa.

In a soil-hydrological context of soil-water-interactions the retention curve relates the pores size distribution and their covariance structure to storage of water against gravity and root water uptake. The hydraulic conductivity curve relates the pores pore size distribution and the interconnectedness of the pores to the conductance/release function of water depending on the wetting state. These are classic examples of form-function relations at the Darcy-scaleDarcy scale. However, this requires revision the established relation does not directly translate to water displacement and contact angles at the actual pore-scale (Armstrong et al., 2016). When we scale-up, pore scale (Armstrong et al., 2016). At larger scales, accepted form-function relations turn out incomplete when preferential flow paths become important as has been observed observed at plots of different soil types (Flury et al., 1994) and in most catchments (Flury et al., 1994; Uhlenbrook, 2006). Also here the Darcy-scale form-function relations become of limited use when macropore density , connectivity , (Uhlenbrook, 2006). Form-function relations for plots and hillslopes should reflect how macropore density and connectivity in conjunction with the rainfall forcing and initial state control initiation and interaction of macropore flow with the soil matrix are main controls of flow and redistributionand thus ultimately export and redistribution of water from or within the control volume. In either case determining topology and connectivity (form) and understanding their implication on soil water transport (function) is seen as "forefront of multiphase flow research" (Armstrong et al., 2016).

It is a long-standing vision in eco-hydrology to observe and characterize form and function of all possible different flow paths in the subsurface. However, this is hindered by a lack of observation techniques which are capable to measure and visualize flow paths across the relevant range of scales in a continuous manner. In this study, we address the challenge of in situ observation, identification and characterization of flow-relevant structures through a series of complementary methods at the pedon-, plot- and hillslope-scalepoint, plot and hillslope scale.

1.2 Identification and characterization of flow-relevant structures in the subsurface

~~Preferential or rapid subsurface flow takes place through structures that add directed drainage paths to the already often highly heterogeneous setting of the soil . Channelled through biogenic structures, such as~~ While heterogeneity is seen as purely random variation of soil properties, organized heterogeneity implies a spatial covariance of these properties and connected flow paths. As such we define structure based on their functional implication in line with Gerke (2012) and others. While such structures can be classical macropores like earthworm burrows (Palm et al., 2012; Blouin et al., 2013; van Schaik et al., 2014)~~and plant roots (Nadezhdina et al., 2010), ~~, decayed root channels (Nadezhdina et al., 2010) or cracks and geogenic structures like voids in periglacial cover beds (Heller, 2012), ~~it is~~ we also attribute connected inter-aggregate pores to structure. They have in common that gravity induced preferential subsurface flow is facilitated through the directed drainage paths, partially bypassing large sections of the soil. Beven and Germann (1982) initiated a discussion about macropores and preferential flow and more recently resumed that the topic is still not given the attention appropriate to its significance in all areas of soil and catchment hydrology (Beven and Germann, 2013).

Despite observation of fast responses through such macroporous networks e.g. as tracer breakthrough (Schotanus et al., 2012; Klaus et al., 2013) or in ~~double peak~~ multi modal reactions (Martínez-Carreras et al., 2016), it was shown that quick responses of catchments are often fed by pre-event water (Neal and Rosier, 1990; Jones et al., 2006) which is known as "old water paradox" (Kirchner, 2003). ~~Analyses of the integral responses inspired a multitude of studies in experimental basins around the globe and studies based on models.~~

Due to limited direct observability of subsurface flow, most evidence is either inferred from integral responses or derived from model applications: In the field, a large spectrum of methods is applied to investigate subsurface connectivity (Bishop et al., 2015; Blume and van Meerveld, 2015) and to quantify preferential flow (Allaire et al., 2009). Dye staining has evolved as common practice since its first applications (presumably Bouma and Dekker, 1978) for a retrospective imaging of preferential flow paths. ~~This technique provides valuable information but requires strong assumptions about macropore-matrix interaction, time of fixation and recoverability.~~ Even though Anderson et al. (2009) extended dye staining to the ~~hillslope-scale~~hillslope scale, the technique is usually limited to ~~plot-scale~~ plot scale applications. Another drawback is the requirement to excavate and thereby destroy the system, which prohibits analyses of function under variable forcing. Application of salt tracers in the vadose zone adds a quantitative measure, but at lower spatial resolution than dye staining. It also suffers from the a posteriori inference about the retention of the solutes.

Furthermore, breakthrough curves of precipitation or irrigation events at trenches or springs are commonly used (e.g. McDonnell et al., 1996; Tromp-van Meerveld and McDonnell, 2006; Bachmair and Weiler, 2014). In combination with fluorescent~~and salt~~, salt and natural tracers they can ~~also~~ provide quantitative information over the course of rapid flow events at this scale (e.g. Wienhöfer et al., 2009). However, ~~also~~ such measurements can only capture spatially integral signals and require to infer the form by the observed function.

So far, relatively few studies managed to actually ~~observe the internal, spatially distributed flow paths~~in situ image spatially distributed subsurface flow paths at larger scales. On the one hand, applicability is also often technically limited to very small scales: Schlüter et al. (2016) examined multiphase flow with time-lapse X-ray microtomography in a sample of ~~4.2 ml~~4.2 mL.

Koestel and Larsbo (2014) presented an X-ray tomography study with a sample of ~~258 ml~~ 258 mL undisturbed soil. Gerke (2012) analyzed the pore fractions in two samples of ~~785 ml~~ 785 mL undisturbed soil through a medical CT X-ray scanner. Wehrer and Slater (2015) report findings from tracer breakthrough experiments in laboratory lysimeters accompanied by 3D time-lapse electrical resistivity tomography (ERT). Guo et al. (2014) conducted a multi-2D time-lapse ground penetrating radar (GPR) survey to identify preferential flow structures in situ in a $2\,\mathrm{m}^2$ section of a hillslope.

On the other hand, the lack of a unified theory of advective and diffusive soil water redistribution, mixing, storage and release (Beven and Germann, 2013) adds to unclearness about appropriate observation strategies.

Hydrological "standard approaches" attempt to explore parameters like soil layer depth, porosity and hydraulic conductivity based on distributed ~~point-scale~~ point scale measurements. Also state and flux monitoring most often consists of a set of point observations e.g. of hydro-meteorological conditions and soil moisture. An appropriate sampling design is substantial for the statistical inference (e.g. de Gruijter et al., 2006). Thus there is also a conceptual issue arising from the fact that such samples necessarily integrate over ~~structured entities.~~ sub-scale structures, such as inter-aggregate pore networks. At the same time such an integral may not necessarily allow inference about structures at the larger scale exceeding the support of the observation. When the respective sampled set and the subsurface setting is basically unknown, spatial scaling of soil moisture (Western and Blöschl, 1999) and other observed variables becomes problematic. In a "Special Section" on preferential flow Gerke et al. (2010) ~~highlight~~ highlighted that further analyses need to focus on the quantification of flow-relevant structures. They continue that experimentally non-invasive and imaging techniques are needed for research and model testing. We will take up these issues in the discussion section.

1.3 Hypotheses and overall aims of the study

The rationale of this study is to ~~infer~~ analyse insights on flow-relevant subsurface structures ~~in a~~ based on qualitative and quantitative ~~sense~~measurements at the point, plot and hillslope scale. Specifically, we hypothesize that a combination of quantitative field methods and in situ imaging of subsurface response patterns with dye staining and time-lapse GPR ~~at three scale levels provides~~ provide the missing link between form ~~and function of flow paths and~~ of the flow-structures and how their interactions determine rapid subsurface flow and thus function.

We test this hypothesis by addressing three main research questions:

Q1 What kind of information on sub-scale flow-relevant structures, their characteristics and their distribution can be inferred from ~~direct measurements using~~ a large set of ~~soil core profiles, soil core samples, permeameter measurements and a GPR survey?~~ direct point scale measurements of soil hydraulic properties?

Q2 How do salt tracer data, dye tracer ~~patterns, and soil moisture responses from plot- and hillslope-scale irrigation experiments compare with localized imaging with 2D and~~ stains, soil moisture response patterns, and 3D time-lapse GPR ~~?~~ compare with respect to inference on vertical flow channels and apparent flow velocities at the plot scale?

Q3 How do ~~identified flow-relevant structures and estimates of vertical response velocities compare between the different methods?~~ methods and identified structures convey to the hillslope scale?

The study is approaching the topic from identification and characterization of flow-relevant subsurface structures as the aspect of *form*while the . The alternative starting point *function* towards hillslope process understanding is taken in the companion study by (Angermann et al., 2017, this issue)Angermann et al. (2017, this issue) with the aspect of *function*.

2 Experimental approaches and study methods

The study at hand approached the topic on three complementary scales with a large number of range of different methods: As standard reference, results from auger exploration and in-situ measurements of hydraulic conductivity and infiltration capacity were collected. They were extended with pedo-physical laboratory examination of 250 ml 250 mL undisturbed ring samples for bulk density, porosity, texture, soil water retention characteristics, and saturated hydraulic conductivity. We then broadened the perspective to the plot-scale plot scale with irrigation experiments accompanied by TDR (time domain reflectometry) measurements of soil moisture dynamics in a 1D profile, 3D time-lapse GPR imaging, and tracer recovery of dye, salt and stable isotopes. At the hillslope-scalehillslope scale, 3D GPR was used to identify flow-relevant structures in a static survey. For dynamic investigation, an irrigation experiment specifically designed to identify lateral flow structures was observed by a dense network of TDR soil moisture profiles and a series of trench-like 2D time-lapse GPR transects.

2.1 Study site description

The study is situated in the headwaters of the Colpach riverwhich is , a tributary of the Attert which has been investigated by several studies before (Pfister and Hoffmann, 2002; Hellebrand et al., 2011; Jackisch, 2015). Located at the southern edge of the schistose Ardennes Massif the soils are characterised by eolian loess deposits and weathered schist debris. The hydrological setting of quick catchment reaction to precipitation especially during the non-vegetated season has been subject to some process hypotheses related to the periglacial deposit layers and flow at the bedrock interface (van den Bos et al., 2006; Fenicia et al., 2014; Wrede et a
Our measurements and experiments focus on two forested hillslopes (mostly managed stands of beech, *Fagus sylvatica*, with mixed shrubs, ; some measurements took place in stands of spruce, *Picea abies*). The agriculturally used plateaus at the hilltops are not examined here. Figure 1 presents a map of the area and the location of the respective measurements and experiments.

2.2 Pedo-physical exploration

The soil physical exploration addressed our research question Q1 using an intentionally large set of hydrological and geophysical methods to survey the subsurfaceat three hillslopes. The sampling is guided by a network of hydro-meteorological monitoring stations measuring all relevant fluxes and states in the atmospheric boundary layer and the subsurface (research project "Catchments As Organized Systems" (Zehe et al., 2014)).

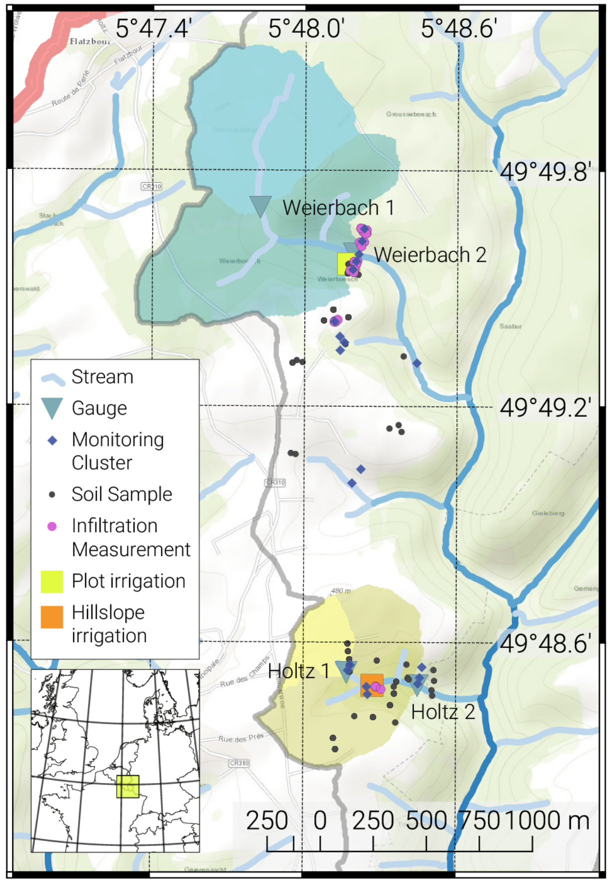

Figure 1. Map of the study sites in the upper Attert basin, Luxembourg.

2.2.1 Sampling design

Aligned with the ~~sensor clusters~~ monitoring stations infiltration capacity and saturated hydraulic conductivity was measured. In order to address ~~plot-scale~~ plot scale (few meters) and ~~hillslope-scale~~ hillslope scale (few 100 meters) heterogeneity, the design consisted of clustered sets of point measurements along two catenas plus one set at the site of the hillslope irrigation experiment presented in section 2.4. A detailed map is included in appendix figure 13.

The distance between the clustered sets was 80 m to 200 m. In each, three nested sets with a lag distance of 10 m to 20 m along and perpendicular to the contour line were defined. In such a nested set at least one measurement of infiltration capacity and two profiles (laterally spaced 1 m) of saturated hydraulic conductivity in different depth levels were conducted. To complete the scale triplet (Bloschl and Sivapalan, 1995) the respective support is given in the description of each technique.

In addition to the point measurements a series of percussion drilled profiles (drill head diameter of 4 cm) as 1D profiles were drawn and 250 mL ring samples were taken within the top 0.6 m for laboratory analyses.

2.2.2 Exploration techniques

Infiltration capacity was measured at 40 points with a Hood Tension-Infiltrometer (IL-2700, UGT GmbH). It employs a tension chamber (12.4 cm radius) as infiltration water supply. Inside the chamber, a defined low negative pressure head is established, which allows a precise measurement of infiltration capacity at different tensions. 3 to 5 tension levels between 0 and 5.5 cm water column were applied at each spot.

In addition to infiltration capacity at the surface we used a Compact Constant Head Permeameter (CHP, Ksat Inc.) for determination of saturated hydraulic conductivity in 32 borehole profiles with 3 to 7 depth levels of about 20 cm increments with the lowest level at a depth where further hand-drilling was inhibited by stones. The permeameter establishes a constant water level (10.5 cm in our cases) above the bottom of a borehole (here 5 cm diameter). The outflow is measured to calculate saturated hydraulic conductivity ~~(k_{sat})~~ (Amoozegar, 1989).

The 63 undisturbed soil ring samples were analyzed for bulk density, porosity (assumed to be equal to saturated soil water content), soil water retention properties (Hyprop, UMS GmbH and WP4C Decagon Devices Inc.), saturated hydraulic conductivity (Ksat, UMS GmbH), and soil texture (ISO 11277, wet sieving and pipette method sedimentation).

2.3 Imaging and quantification of rapid flow in ~~plot-scale~~ plot scale irrigation experiments

In order to explore the network of flow-relevant structures and patterns of rapid subsurface flow we conducted three ~~plot-scale~~ plot scale irrigation experiments. This relates to our second research question Q2. The general setup is very similar to the one described by Allroggen et al. (2015b), van Schaik (2009), Öhrström et al. (2004) and Kasteel et al. (2002). Marked on the map in figure 1 the three plots are located on a forested mid slope ~~in direct vicinity of observation station E~~ near gauge Weierbach 2 (see also appendix figure 13).

2.3.1 Experimental design and multi-method approach

Three plots of $1\,\mathrm{m}^2$ size were irrigated each for 1 h with an intensity of $50\,\mathrm{mm\,h^{-1}}$, $30\,\mathrm{mm\,h^{-1}}$ and $50\,\mathrm{mm\,h^{-1}}$ ~~.~~ on Oct. 30, Nov. 1 and Nov. 2, 2013 respectively. The relatively high rates were chosen to activate all potential flow paths and thereby establishing connectivity. A layout of the experiment is presented in figure 2.

The irrigation was accomplished by spray irrigation (full-cone nozzle Spraying Systems Co.) using a wind-protection tent. Brilliant Blue dye tracer ($4\,\mathrm{g\,L^{-1}}$) and Bromide salt ($5\,\mathrm{g\,L^{-1}}$ Potassium bromide) were used for qualitative and quantitative reference, respectively.

In addition, temporal dynamics of soil moisture along a selected profile was monitored throughout the experiments through continuous TDR measurements in an access tube (Pico IPH, IMKO GmbH) down to 1.5 m depth and with a diameter of 4.2 cm. This technique is chosen to minimize the impact of sensor installation (percussion drilling and installation of the tubes from the surface) and to avoid interference with the GPR (sensor probe was removed during GPR measurements). The sensor measured an integral of about ~~1.05L~~ 1 L (depth increment of 18 cm, mean signal penetration of 5.5 cm). It was manually lowered in the tube to the respective depth for each reading. Each measurement took about 10 seconds. Hence the whole procedure added

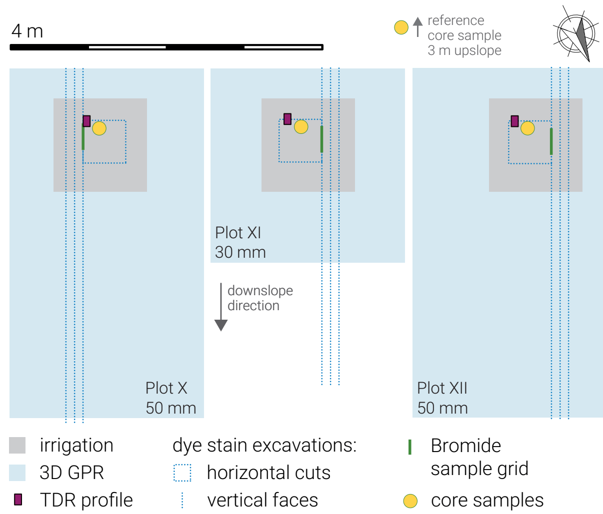

Figure 2. Plan view layout of the ~~plot-scale~~ plot scale irrigation experiments. Three irrigation plots (1 m^2, gray squares) are monitored by 3D time-lapse GPR (blue rectangles) and TDR (soil moisture tube probe, red box). The plots are sampled for tracer recovery by percussion drilled core samples (yellow dot) and in a grid on the last of three vertical faces (dashed blue line). Moreover, dye stains are excavated at horizontal cuts in the center of the irrigation area (dashed blue square). A pre-irrigation reference for pore water stable isotope composition is sampled as fourth core 3 m upslope.

up to 4 min to 10 min per profile record. The procedure was continuously repeated until 1.5 h after irrigation onset in line with the findings of Germann and al Hagrey (2008) and Germann and Karlen (2016). They propose that film flow in soil structures ~~equilibrates gravity and thus the main fraction of advective flow is dispersed~~ disperses into the matrix after 1.5 times the duration of a constant ~~input rate~~plot irrigation.

2 h after the end of each irrigation, a percussion drilled soil core was taken (drill head diameter of 8 cm) and sampled in 5 cm depth increments down to 1 m. The plot was excavated 24 h after irrigation for vertical and horizontal recovery of Brilliant Blue stains. This was done by successive digging of 3 vertical faces into the plot (aligned with the slope line, 0.1 m distance starting from the lateral edge) and 5-7 horizontal cuts in different depth levels down to the first deposit layer (0.5×0.5 m^2 in the center of the plot). On the third vertical face in the center of the plot ~~mini~~ core samples of 66 mL soil were taken in a 5 cm grid with 5 columns and 14 to 21 rows. In order to minimize time lags in the 70 to 105 individual samples a ~~quick sampler~~ quick-sampler (see Appendix A) was developed allowing for precise and nearly undisturbed ~~core~~ sampling.

2.3.2 Bromide recovery and stable isotope analysis

All samples were analyzed for Bromide (Br^-). This was done by oven drying the samples and consecutively suspending them in 150 mL de-ionised water (72 h in overhead shaker at 9 rotations per minute). The samples were then left 4 days for sedimentation to exfiltrate the excess through a) filtration paper (5 µm to 13 µm) and b) 0.45 µm PP micro-filter. The extracts were analyzed in an Ion Chromatograph (Metrohm 790 Personal IC) with an anion separation column (Metrosep A Supp 4 - 250/4.0) for Br^- concentration.

A recovery coefficient (RC) is calculated as proportion of recovered mass of Br^- in the soil samples scaled to the total irrigated area times the depth of the lowest sample. Through this we neglect lateral flow from the irrigation spot and further percolation in the calculation. We also assume the samples to be representative for the whole affected soil volume.

Prior to the Bromide analysis, the percussion drilled soil core samples were also analyzed for their stable isotopic composition (δ^{18}O and δ^{2}H) of the pore water. See appendix D for details and results, which are given in comparison to the Bromide recovery.

2.3.3 Calculation of apparent vertical flow velocity

The quantitative measurements allow to infer apparent vertical flow velocity along the profiles. For Bromide we employ a cumulative curve method (Leibundgut et al., 2011). The distribution of the advective velocity v_{advect} is set to the depth distribution of the tracer concentration at the time of fixation t_{fix}. For the profile we assume apparent velocities:

$$v = z/t_{\text{fix}}, \tag{1}$$

Relating to our third research question Q3, they are projected to the recovered distribution of tracer concentration:

$$\Phi(v_{\text{advect},z}) = c_{\text{tracer},z} / \sum_{z=0}^{z_{\max}} c_{\text{tracer}}, \tag{2}$$

where z is depth and Φ is the cumulative distribution function. Obviously, the estimated travel velocity distribution depends strongly on the selection of t_{fix} somewhere between irrigation and excavation. This can scale v several orders of magnitude. Again, the reference of 1.5 times the irrigation duration is chosen (Germann and Karlen, 2016). For Br^- in the sampled grids each column was treated as individual 1D profile. The calculation further assumes full tracer recovery.

2.3.4 Analysis of soil moisture responses

The individual TDR soil moisture measurements (θ) were projected to a regular grid of $0.1\,\text{m}$ depth increments and $10\,\text{min}$ time increments for visualization of changes compared to the initial records. As an alternative and independent estimate of vertical response velocities (research question Q3), we calculated the distribution of first exceedance of soil moisture by $\geq$2vol$\%$ in each depth level z:

$$v_{\text{response}} = z/t_{\Delta\theta \geq 0.02} \tag{3}$$

For this the un-interpolated measurements were used.

2.3.5 3D time-lapse GPR

GPR is known as geophysical imaging technique with high spatial resolution (Huisman et al., 2003; Binley et al., 2015). Applied at the shallow subsurface it has been proven as potential means to locate and characterize soil layers and subsurface structures (Holden, 2004; Gormally et al., 2011; Steelman et al., 2012; Klenk et al., 2015). GPR is also capable to monitor subsurface fluid migration in time-lapse approaches (Birken and Versteeg, 2000; Trinks et al., 2001). Our experiments were monitored by 3D time-lapse GPR measurements as described by Allroggen et al. (2015b). We employed a PulseEKKO Pro GPR system (Sensors and Software Inc.) equipped with $500\,\mathrm{MHz}$ shielded antennas with constant offset of $0.18\,\mathrm{m}$. Sampling interval was set to $0.1\,\mathrm{ns}$, recording a total trace length of $100\,\mathrm{ns}$ in 8 internal stacks. Since precise positioning and accurate repeatability are key requirements, we used a kinematic survey approach relying on an automatic-tracking total station (Leica Geosystems AG, providing sub-centimeter coordinates) in combination with a portable measuring platform (Allroggen et al., 2015b).

Using this setup, we acquired one 3D GPR data cube before irrigation, one directly after the end of irrigation, and a last one about $20\,\mathrm{h}$ after irrigation for each plot. One survey took about $45\,\mathrm{min}$. Allroggen and Tronicke (2016) have shown, that a pixel-to-pixel comparison alone of the radar amplitudes (A) is not suitable for analyzing time-lapse GPR data in the presence of limited repeatability and noisy data. They propose a structural similarity attribute , which basically calculates the crosscorrelation inspired by (Wang et al., 2004) calculated in a moving window. It normalizes the crosscorrelation $c_{x,y}$ of the residuals normalized ($A-\mu_A$) of two different acquisition times (x,y) by the product of the standard deviations of two moving windows at the same positions and different acquisition times. their standard deviations (σ_A). They further introduced a as 10% of the maximum amplitude to avoid numerical instabilities with near-zero σ values:

$$S_{\text{struct}}(x,y) = \frac{c_{x,y}+a}{\sigma_{A_x}\sigma_{A_y}+a} \tag{4}$$

In our study we calculate the structural similarity attribute S_{struct} of the pre-irrigation reference and the two post-irrigation records using a local Gaussian window of $2.5\,\mathrm{ns}$ along the vertical axis and $0.1\,\mathrm{m}$ along the horizontal axes. The attribute ranges between 1 and -1 -1 with 1 being highly similar and -1 referring to most dissimilar. Points of low similarity indicate deviations that arise from changes in dielectric permittivity which likely reflect changes in local soil water content.

As additional estimate of vertical response velocities the same approach as for the soil moisture responses (section 2.3.4) was employed with a threshold of the similarity attribute of zero between pre- and post-irrigation records.

2.4 Lateral subsurface flow paths in the hillslope

In order to examine the characteristics of flow-relevant structures and the periglacial deposit layers at the hillslope scale we conducted an experiment on June 21, 2013 at a close-by hillslope. The experiment was specifically designed to explore the response in lateral preferential flow paths and to replicate the plot-scale plot scale experiments without tracer application. The site had to be chosen for facilitation reasons (permissions, accessibility, collaboration within the CAOS research project). With reference to its hydrological responses (companion paper Angermann et al., 2017, this issue), vegetation, slope, soils and hydraulic properties we consider the hillslopes to be very similar.

2.4.1 3D GPR survey of the hillslope

As additional reference to the soil core profiles a 3D GPR survey of the hillslope was conducted prior to the natural event and the irrigation. The GPR data processing relies on a standard processing scheme including bandpass filtering, zero time correction, ~~envelope based~~ envelope-based automatic scaling, gridding to a regular $0.03\,\mathrm{m}$ by $0.1\,\mathrm{m}$ grid, inline fk-filtering and a 3D topographic migration approach as presented by Allroggen et al. (2015a), using an appropriate constant velocity of $0.07\,\mathrm{m\,ns^{-1}}$.

For structural analysis, the processed data are imported into the OpenDtect software (dGB Earth Sciences). Under heterogenous soil conditions the derived data cube is dominated by complex reflection patterns which prohibit a classical structural analysis based on picking reflectors (as done in a study with a similar cope but different setting by Gormally et al., 2011). Therefore, we support our interpretation of the 3D GPR data and picking of potential flow-relevant horizons by a dip-corrected semblance attribute. The attribute calculates the spatial coherency and highlights areas of coherent reflections (Marfurt et al., 1998). Low semblance indicates more complex reflection patterns caused by high internal heterogeneity, possibly influencing the subsurface flow regime.

2.4.2 ~~A priori model reference~~

~~Based on the findings of the pedo-physical exploration, we setup the 2D process model CATFLOW (Zehe et al., 2001) as representative hillslope for hypothetical *a priori* simulation of the experiment in order to determine the required irrigation intensity, the spatial extent of the observation network, the temporal resolution, and the duration of the monitoring. The model domain was set up assuming periglacial deposit layers as conductive layers in the hillslope. In a series of scenarios, the one with $30\,\mathrm{mm\,h^{-1}}$ irrigation for $4\,\mathrm{h}$ turned out to be well balanced with respect to anticipated hillslope reaction given a limited source area. Fast soil water redistribution was modeled to last for $12\,\mathrm{h}$.~~

2.4.2 Experimental design

The experimental site is located at the lower part of a north facing hillslope. Vegetation is dominated by mixed beech forest. However, the experimental site is placed in an area with no major trees. Except for few young trees at the downhill monitoring area, all shrubs were carefully removed from the experimental site to accomplish GPR measurements and allow for undisturbed and homogeneous irrigation. The topographic gradient is about $14°$.

The experimental layout is given in figure 3. ~~The irrigation~~ Irrigation intensity, the duration of the experiment and the spacing of the observation profiles have been decided based on a priori modeling scenarios as described in Appendix C. The experiment was preceded by two strong storm events of $43\,\mathrm{mm}$ in total on June 20. The events ended $20\,\mathrm{h}$ before irrigation onset. The irrigation of $141\,\mathrm{mm}$ in $4.5\,\mathrm{h}$ was fed from stream water and was realized by four circular sprinklers (Wobbler, Senninger Irrigation Inc.) arranged to overlap at a $5\,\mathrm{m}$ by $5\,\mathrm{m}$ core area with relatively homogeneous intensity. While boundary effects were mitigated by an irrigated buffer zone of about $4\,\mathrm{m}$ at the uphill and lateral borders of the core area, the downhill boundary was defined by a rain shield. This established a sharp transition to the non-irrigated area below. Water collected by

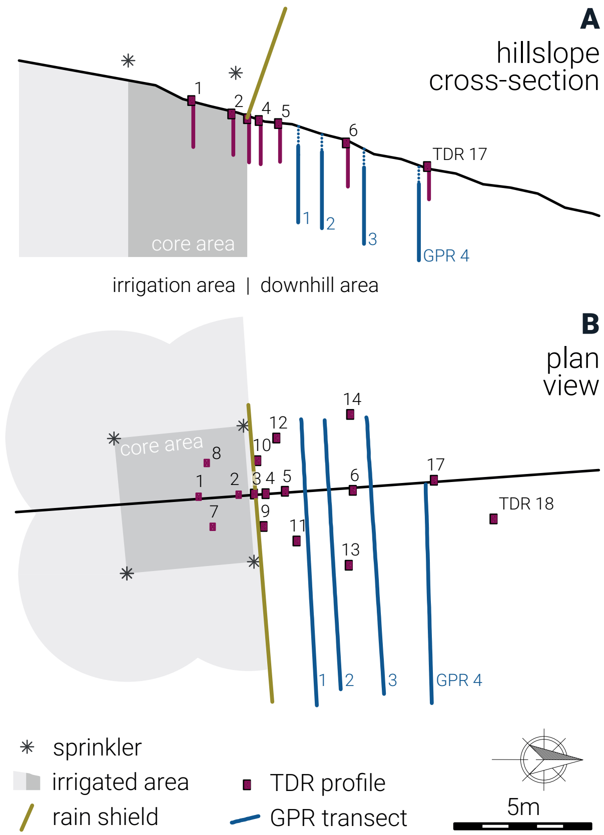

Figure 3. Layout of hillslope-scale hillslope scale irrigation experiment as vertical view (A) and plan view (B). The hillslope is divided into an irrigation area and a downhill area by a rain shield. 16 access tubes for TDR measurements of soil moisture profiles are arranged in 3 diverting transects. Parallel to the contour lines 4 transects of 2D time-lapse GPR are recorded.

the rain shield was routed off the experimental site. Irrigation was monitored by a flow meter to measure the absolute water input, one tipping bucket to monitor the temporal variability, and 42 mini rain collectors evenly distributed across the core area to check spatial heterogeneity of the intensity.

Moreover, a surface runoff collector was installed across 2 m of the lower boundary of the core area. It was built from a plastic sheet installed approximately 1 cm below the interface between litter layer and Ah horizon of the soil profile. At the downhill end of the sheet, the water was captured by a buried and covered gutter. An in-ground tube was attached to the deepest point of the gutter to conduct the water to a tipping bucket downhill of the investigated area. The tube had been filled with water prior to the experiment to ensure an immediate reaction to the occurrence of surface runoff.

We monitored soil moisture dynamics in a setup of 16 access tubes with 3 TDR sensors manual TDR probes like in the plot scale experiments (Imko GmbH, two with 12 cm integration depth and one with 18 cm). Measurements required manual positioning of the sensor probes for each reading. We continuously recorded the states in all tubes in 10 cm depth increments realizing revisiting intervals of 5 min to 20 min. The tubes were installed to reach to a depth of about 1.7 m. The layout consisted of three diverging transects with four TDR profiles in the lower half of the core area, the highest density of profiles just downslope of the rain shield, and the furthest profile about 9 m downhill.

Four 2D time-lapse GPR transects were treated as *GPR-inferred, non-invasive trenches* parallel to the contour lines located 2 m, 3 m, 5 m and 7 m downslope of the rain shield. Here, the GPR acquisition unit was equipped with shielded 250 MHz antennas. The data were recorded using a constant offset of 0.38 m, a sampling interval of 0.2 ns and a time-window of 250 ns. Wooden guides and the automatic tracking total station guaranteed accurate and repeatable positioning.

2.4.3 Analysis of TDR data

In order to synchronize the almost 5000 individual TDR soil moisture records to a regular grid in time and depth interpolation and resampling was required. To do so, we generated an intermediate grid of high data density onto which linearly interpolated versions of the time series of each profile were projected. We then resampled from this intermediate grid to derive a synchronised version of the records in 0.1 m depth and 15 min time increments. With this the spatial aggregation remains below the integration length of the TDR probes. The temporal resampling and the therefore necessary linear interpolation is close to the acquisition timing of one profile (4 min to 10 min each). Since the correlation length of distributed soil moisture observations is rather short and because we explicitly aim to analyze the responses of preferential flow structures, the issue of interpolation needs special attention and will be discussed in section 4.2.1.

All soil moisture measurements are converted to changes in soil moisture referenced to the state previous to irrigation onset to identify activated flow paths. Lateral interpolation between different TDR profiles over distances of about 1 m and above is unfeasible. Soil moisture as extensive state variable is discontinuous at interfaces. The found subsurface setting does not exhibit any isotropic continuum required for such interpolations.

As in the plot irrigation experiments, vertical response velocities are calculated for the TDR profiles at the core area. The calculation of lateral response velocities is given in the companion study (Angermann et al., 2017, this issue).

2.4.4 GPR transects and structural similarity attribute interpretation

The 2D time-lapse GPR data is derived from 9 repeated recordings along the four vertical GPR transects. Each record is processed after a standard processing scheme of bandpass filtering, zero time correction, exponential amplitude preserving scaling, inline fk-filtering, topographic migration with constant velocity ($0.07\,\mathrm{m\,ns^{-1}}$), and consecutive gridding to a 2D transect with regular trace-spacing of 0.02 m.

Most time-lapse GPR data analyses are based on calculating trace-to-trace differences (Birken and Versteeg, 2000; Trinks et al., 2001) or picking and comparison of selected reflection events in the individual time-lapse transects (Allroggen et al., 2015b; Haarder et al., 2011; Truss et al., 2007). Like in the 3D time-lapse GPR applications, the radargrams in the young, highly heterogeneous soils do not exhibit explicit reflectors as suitable references. In addition, the limited repeatability of the measurements and the desired identification of lateral flow structures require an alternative approach.

Like for the plot scale experiments, we use the time-lapse structural similarity attribute ~~presented by Allroggen and Tronicke (2016)~~(Allrog
It is calculated using a local Gaussian window of 2 ns along the vertical axis and 0.06 m along the horizontal axis.

Due to the presence of remaining event water from the preceding storm event (Angermann et al., 2017, this issue), all measurements are referenced to the last acquisition time approximately 23 h after irrigation start and about 19 h after irrigation. The resulting structural similarity attribute images are used as a qualitative indicator for relative deviations from the reference state. ~~Points of low similarity indicate deviations that arise from changes in dielectric permittivity which likely reflect changes in local soil water content.~~

2.4.5 Discriminating the natural storm event and the irrigation experiment

The experiment was preceded by two strong storm events of 43 mm in total on June 20, 2013. In reference to the gauge reaction the experiment was conducted shortly before the ~~major~~ second peak of the ~~resulting runoff reaction (Please see figure 5 in Angermann et al., 2~~ reaction to the preceding storm events (see figure 5 in Angermann et al., 2017, for details). Accordingly, the structural similarity attributes, which compare the distributed states at the respective acquisition time to the last record, identify responses to both drivers, the natural storm event and the irrigation experiment. To discriminate the signals we analyze the dynamics of each pixel in the GPR transects over time. The first two structural similarity attribute transects 7.5 h before and directly at irrigation start are attributed to the natural event and show an increasing structural similarity (towards accordance with the reference state). Once the attribute value of a pixel decreases again (~~lower structural similarity~~increasing deviation from the reference state) it is attributed to the irrigation. For stability reasons, a threshold of 0.15 was introduced ~~, which~~ for the attribute to be exceeded to detect changes. This is discussed in appendix F.

3 Results

3.1 Soil physical exploration

3.1.1 Point samples show high heterogeneity

~~The *in situ*~~ The in situ point measurements of infiltration capacity and saturated hydraulic conductivity showed high variability without clear relationships to simple morphological descriptors like depth, hillslope position or topographic flow gradient (details given in the appendix figure 13). Infiltration capacity ranged between $5 \times 10^{-5}\,\mathrm{m\,s^{-1}}$ to $5 \times 10^{-3}\,\mathrm{m\,s^{-1}}$. The values for saturated hydraulic conductivity ranged from $1 \times 10^{-8}\,\mathrm{m\,s^{-1}}$ to $1 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ and even exceeded the measuring range of the constant head permeameter. Only at the site of the hillslope scale experiment a pattern of elevated conductivity in about 0.6 m depth was found. The strong heterogeneity and large spread of values was also depicted in the analyses of undisturbed soil samples (figure 4).

On average the area is dominated by silty soils (see also Juilleret et al., 2011). This was corroborated by texture analyses and the mean retention characteristics. However, the measurements of saturated hydraulic conductivity ~~showed a strong positive bias with respect to reported literature and text book values~~are on average two orders of magnitude larger than what might be expected for these soils given their texture (Schaap et al., 2001). Also porosity exceeds clearly the expected values, while bulk density is smaller than expected (compare figure 4 middle row of panels). ~~Accordingly, the range of porosity was positively biased and the range of bulk density lies below literature references.~~ All measurements exhibited a large spread of values which does not correlate well with simple morphological variables like depth or hillslope position ~~.~~ (figure 4, bottom row). The high hydraulic conductivity and large porosity maybe explained by aggregation of fine silty material in conjunction with a network of rapidly draining inter-aggregate pores.

3.1.2 Soil core profile snapshots

The soil core profiles (figure 5) generally confirmed the presence of the periglacial slope deposits by gravel bands but also showed a high degree of heterogeneity. The thickness of the horizons was variable, with a humidified mineral A-horizon of up to 0.3 m. The gravel content gradually increased over depth in the Bw-horizon and further increased in the C-horizon, starting between 0.4 m and 1.1 m depth. Below the depth of 0.5 m scattered layers of weathered rock with usually horizontal orientation were found in some soil cores. Percussion drilling was often inhibited at a depth between 1.5 m and 2.0 m (lower end of the bars in figure 5) due to even higher stone content with a more and more vertical orientation of the weathered rocks. In core ~~T7~~7, concretions of iron and manganese oxides were found in the depth between 1.6 m and 1.9 m below ground, indicating hydromorphic conditions.

Based on these standard techniques the overall setting of a heterogeneous silty soil deviating from expected low hydraulic conductivity was revealed. So far gained insight is limited to the general existence of periglacial deposit layers (high gravel content in soil profiles), rapid flow paths (hydraulic conductivity several orders of magnitude above literature references), and some integral retention properties~~could be derived~~. However, details about its spatial organization and the detection of specific and potentially continuous structures remained obscured by high heterogeneity.

3.2 Plot scale flow path activation and vertical velocities

3.2.1 Irregular patterns of dye stains

In the ~~plot-scale~~ plot scale tracer experiments the Brilliant Blue dye stains identified patchy infiltration patterns partially bypassing large sections of the soil without clear traces of the actual flow path (figure 6). For all experiments stained patches were found down to the periglacial deposit layer in 0.6 m to 0.8 m depth. During the excavation apparently isolated dye traces were recovered even several meters downhill the irrigation spot (4 m downslope, 1 m deep). The stains did not reveal a network of large macropores but an irregular mesh of connected inter-aggregate voids. This ~~explains the positive bias in the soil physical analyses~~is in line with the observed hydraulic capacity (figure 4).

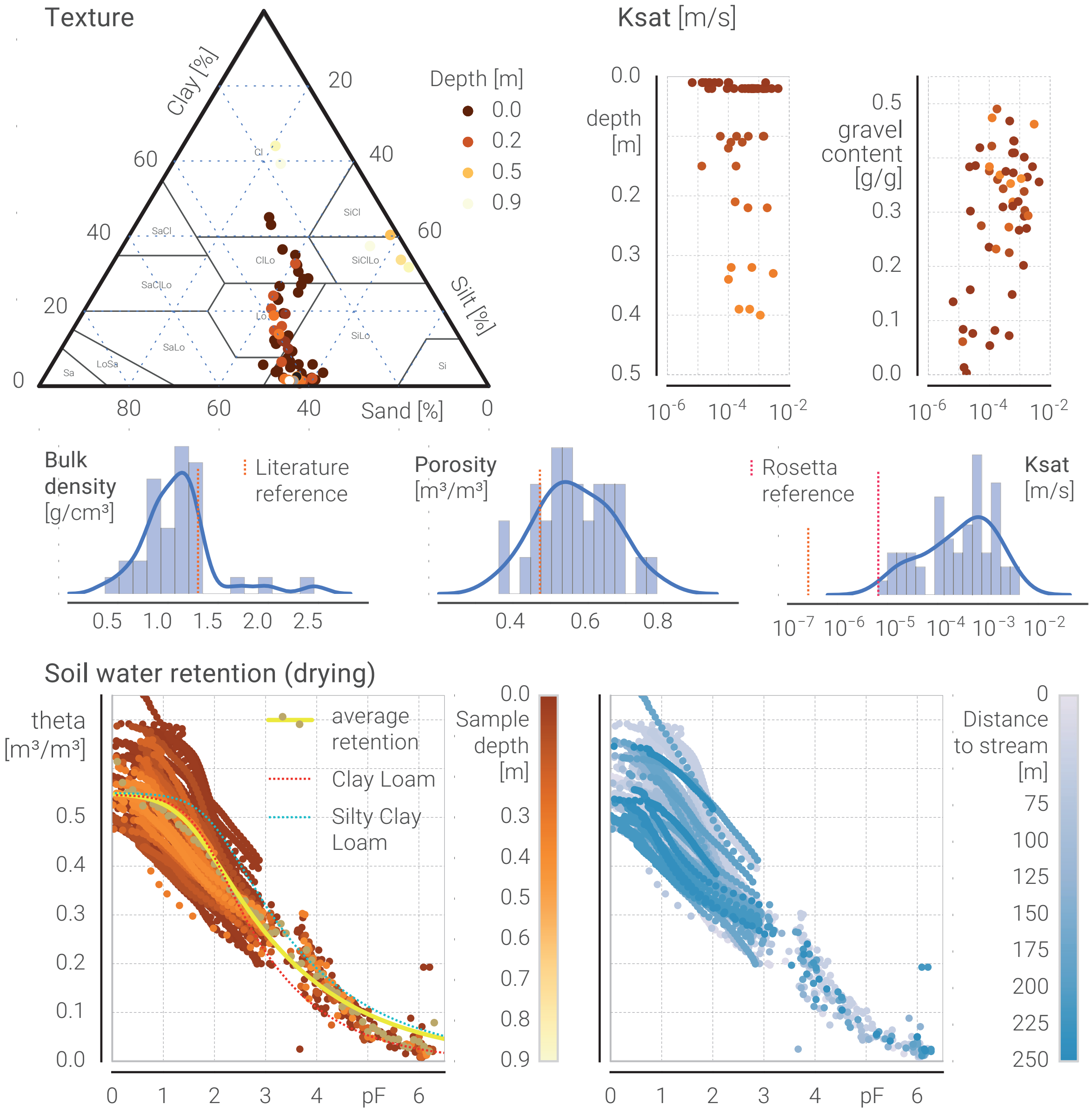

Figure 4. Results of laboratory analyses of 63 undisturbed ~~250 ml~~ 250 mL ring samples. **Top row:** Soil texture analysed with wet sieving and sedimentation (pipette method). Saturated hydraulic conductivity (Ksat) measured with the Ksat apparatus and plotted against sample depth and gravel content. **Mid row:** Histograms and kernel density estimate of measured bulk density, porosity and Ksat. Reference as mean silty loam value from literature ~~(Hillel, 1980; Rawls et al., 1982; Carsel and Parrish, 1988; Schaap et al., 2001)~~(Hillel, 1980; Rawls et al., 1982; Carsel and Parrish, 1988). Rosetta (Schaap et al., 2001) reference based on mean values of samples (15.7, 47.9, 36.4 % sand, silt, clay and BD 1.1 gcm^{-3}) **Bottom row:** Soil water retention relation measured with the Hyprop and the WP4C apparatus with average retention estimate (respective mean of each 0.05pF-bin and fitted van Genuchten model) and literature references (Carsel and Parrish, 1988) scaled to measured average θ_s and θ_r.

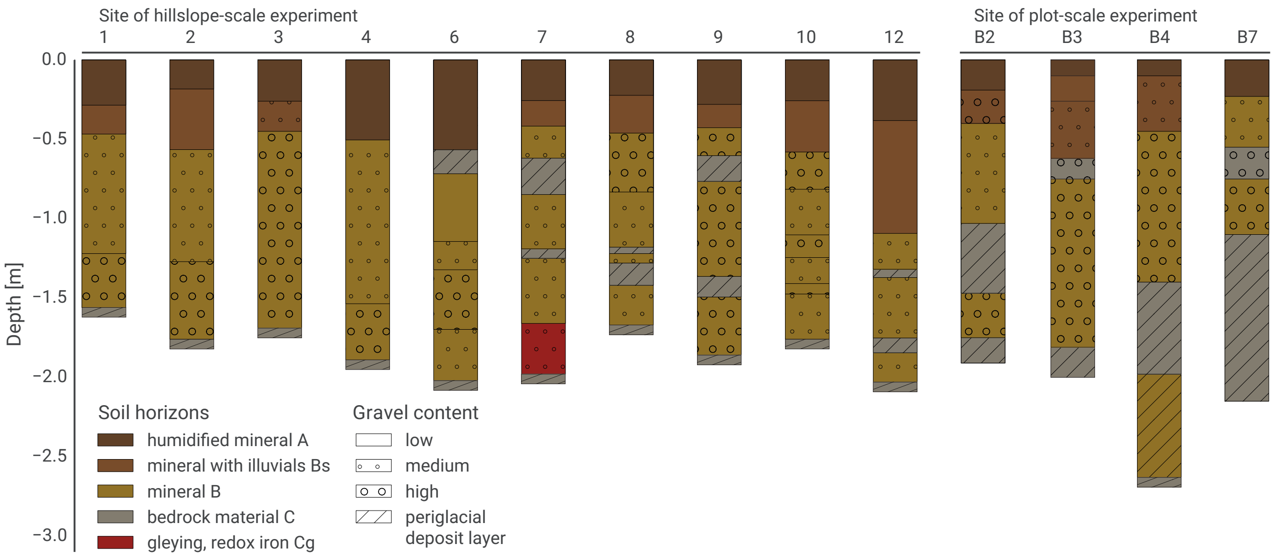

Figure 5. Soil core profiles from the upper Colpach River basin. ~~The T-nomenclature indicates cores from the installation of the TDR access tubes at the Holtz hillslope experiment~~See figures 3 and 13 for positions. ~~B corresponds to examples at the catena of the plot experiments.~~ Bar depth is the maximum drilling depth of the cores restricted by large stones or bedrock.

3.2.2 Bromide breakthrough to the periglacial deposit layer

The connectedness and large transport capacity of this network of inter-aggregate pores is corroborated by the distributions of Bromide tracer recovery (figure 7, top row). All plots suggested a relatively strong response in the depth of approximately 0.6 m. This depth correlates with the upper boundary of the first layer of periglacial deposits found in core profile ~~B7~~ B3 (figure 5) and in the excavated soil profiles. This response is contrasted by low Bromide concentration in shallower depth. Even plot XI, where only 30 mm were applied, showed the same pattern with a clear breakthrough to the periglacial deposit layer.

At plot XII we found a stronger interaction with the soil matrix, which led to more dye staining and a higher Bromide recovery. Overall, tracer recovery was ~~very low and even decreased~~ incomplete (0.45, 0.38, 0.83 for plot X to XII, respectively) and even declined when including the core samples (0.24, 0.3, 0.63) once more pointing to ~~heterogeneity~~strongly irregular soil water redistribution.

3.2.3 Quick soil moisture response in greater depth

The observed soil moisture changes (figure 7, bottom row) corroborated the results from the ~~tracers~~tracer data. Especially at plot X and XII we found a relatively quick and strong response in 0.7 m and 0.5 m depth, respectively. This even preceded soil moisture changes in shallower layers in plot X. Hence the records highlighted an important characteristic of the identified flow-relevant structures, although the signal had a much lower spatial resolution than the tracer results. In contrast to the recovered

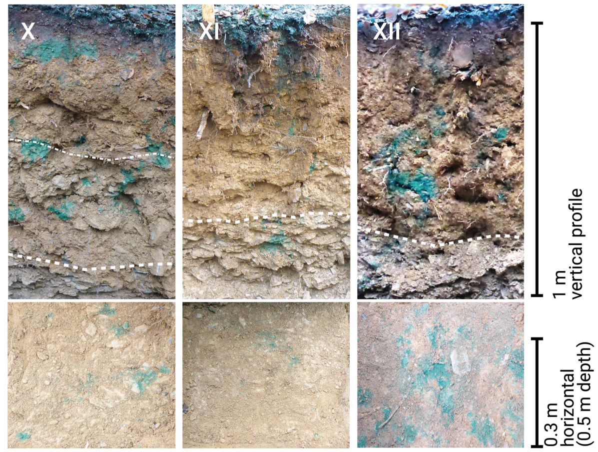

Figure 6. Recovered dye patterns in plot irrigation experiments. Top row excavated vertical faces, bottom row horizontal cuts in 0.5 m depth. Dashed lines indicate level of periglacial deposit layer.

tracers, we did not observe significant changes in soil moisture in plot XI. This can be explained by its position off set from the main flow field (figure 16 in appendix E).

3.2.4 3D view on soil water redistribution

The structural similarity attribute of the 3D time-lapse GPR measurements provided qualitative information of changes in soil moisture in a spatial context. At all plots the response patterns of low structural similarity pointed out quick vertical flow to a depth of 80 ns or about 1.4 m within 1.5 h after irrigation start (figure 8, and figure 16 and 17 in appendix E). Also here, strongest deviations were recorded in the mid horizon between 40 and 60 ns two way travel time (TWT) corresponding to approximately 0.7 to 1 m depth. The top horizon between 20 and 40 ns (0.35 to 0.7 m) had comparably high similarity. Measurements above that depth were technically not possible. Patches of low structural similarity until 20.5 h after irrigation start suggested further lateral redistribution in the later course of the experiment at plot X. At plot XI with 30 mm irrigation further vertical transport with a slight lateral component was recorded. Plot XII had very high similarity between first and third acquisition. ~~Thus~~ This is a sign for stronger macropore-matrix interaction and dispersive redistribution~~is corroborated~~.

The contrasting attribute distributions over time and comparing plots X and XII did not only reveal ~~heterogeneity~~diverse patterns. It also highlighted the qualitative nature of the analytical method of the GPR data. Although visual interpretation of the radargrams (top row in figures 8, 16 and 17) is very difficult, they show how the structural similarity attribute highlighted areas where radar patterns changed. Due to the complex reflection energy patterns it is not suitable to trace individual reflectors. This prevents a quantitative interpretation as shown by Allroggen et al. (2015b).

For the identification of structures, the results did not exhibit specific macropores like the dye stains but areas of response to the irrigation. Nevertheless, the patchy characteristic of the found response patterns was very similar to that of Brilliant Blue.

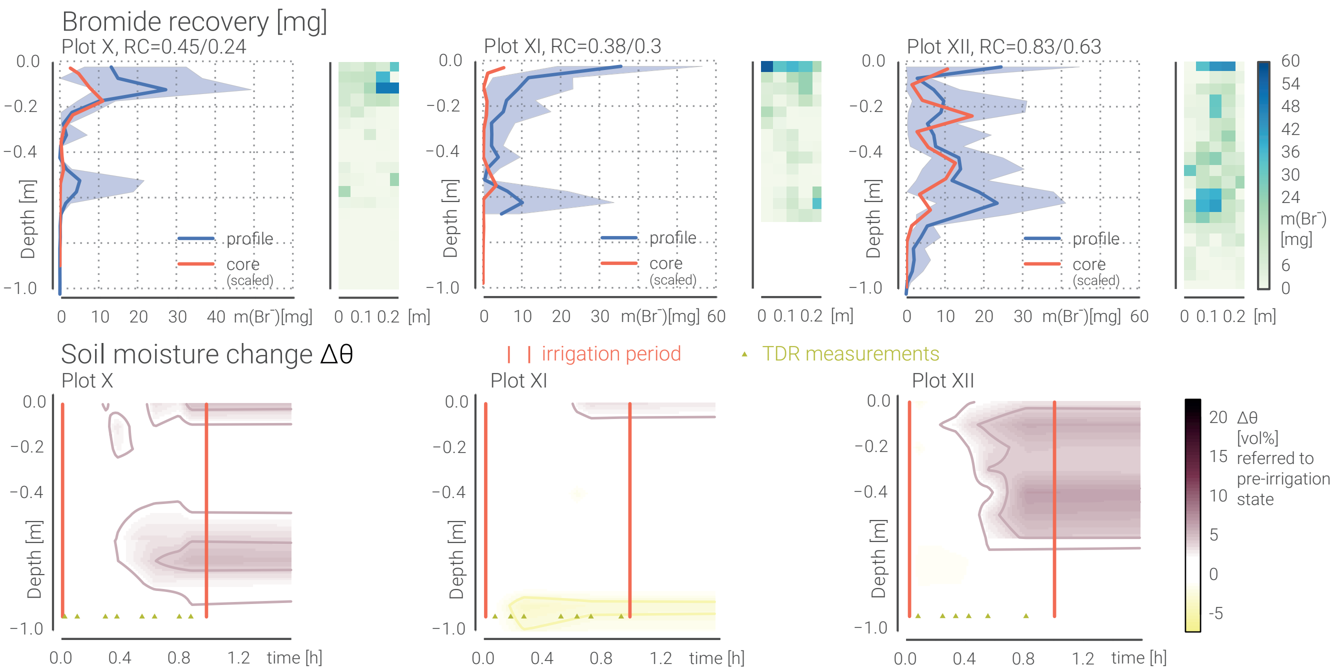

Figure 7. Results from ~~plot-scale~~ plot scale irrigation experiments with 50 mm, 30 mm and 50 mm spray irrigation for 1 h. **Top:** Recovered Bromide mass profiles and grids (5x5cm). Blue line as mean and shaded area between min/max for each depth of the sampling grid. Orange line is mass recovered in drilled profile samples (scaled to same volume reference). Recovery coefficient (RC) calculated for the profile samples (first value) and the profile and core samples (second value). **Bottom:** Observed soil moisture change referenced to the first measurement shortly before onset of the irrigation. Individual measurement times marked with triangles.

3.2.5 Derivation of vertical flow velocities

Based on all applied techniques, hydraulic conductivity and apparent vertical flow velocities were calculated (kernel density estimates plotted in figure 9). The many ~~point-scale~~ point scale measurements (left panel based on 63 ring samples, 40 infiltrometer points, 102 individual permeameter measurements) resulted in ~~rather inconsistent~~ disagreeing distributions stretching across a large spectrum of flow velocities. The reason for this spread stems from the fact that the measurements consist of matrix flow and flow in structures. The response-related methods of the irrigation experiments were in much better accordance because they all relate to the same processes. They revealed an apparent vertical velocity of $1\times10^{-3.5}\,\mathrm{m\,s^{-1}}$ (figure 9 right panel based on Bromide recovery with an estimated time of fixation (t_{fix}) after 1.5 h, first excess of TDR recorded soil moisture $\geq 2\mathrm{vol}\%$, and GPR structural similarity attributes below zero between pre-irrigation and first post-irrigation records).

All results ranged several orders of magnitude above the literature reference of $2.5\times10^{-7}\,\mathrm{m\,s^{-1}}$ ~~(mean of reported values for silt and silty~~ the Rosetta value of $6.2\times10^{-6}\,\mathrm{m\,s^{-1}}$ (Schaap et al., 2001). The role of inter-aggregate pores facilitating this quick redistribution even through comparably small voids without noticeable dye staining was corroborated.

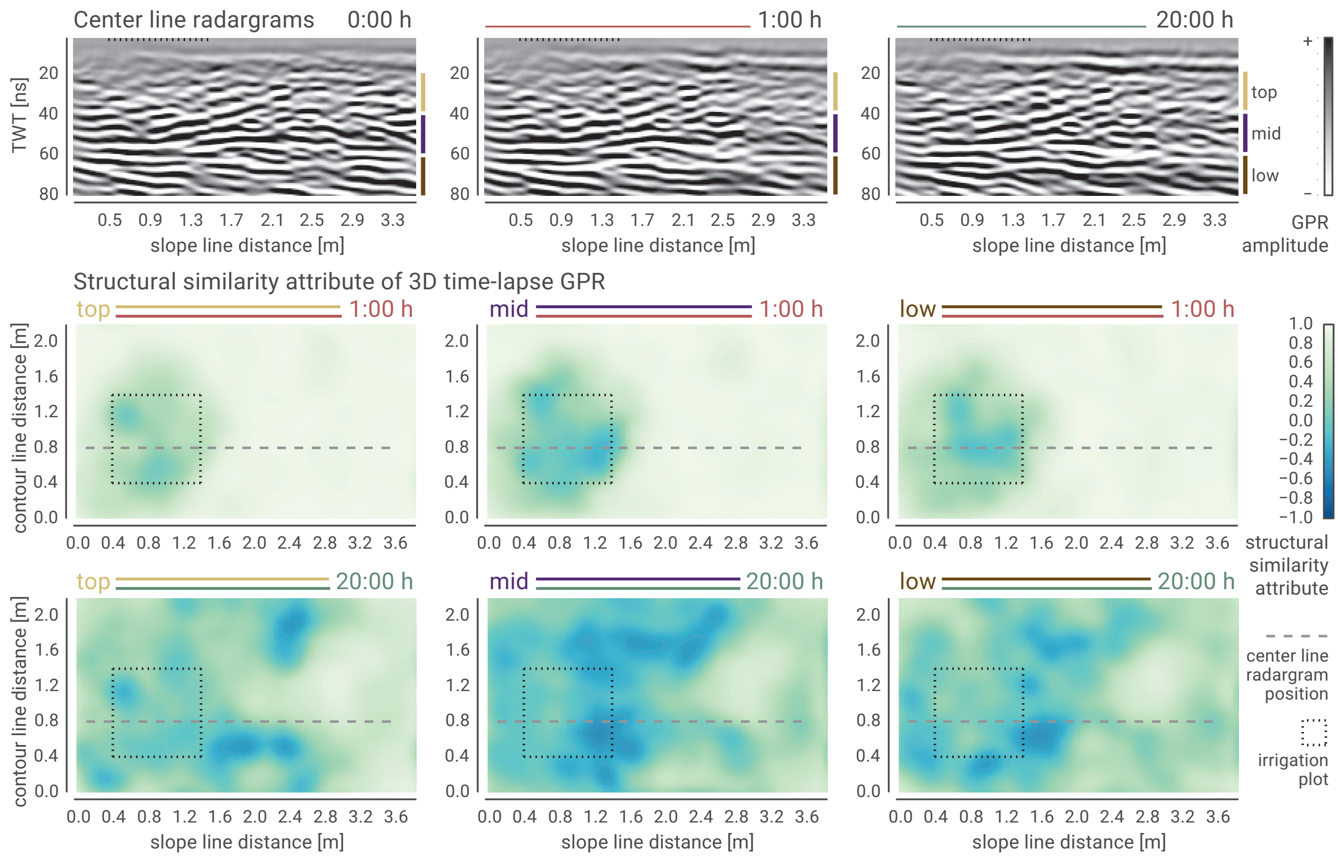

Figure 8. Time-lapse 3D GPR of irrigation experiment at plot X. Center line radargrams at the marked transect (grey dashed line in lower panels) for the three acquisition times (before 0:00 h, directly after irrigation 1:00h, 20:00 h after irrigation) are given in the top row. Two way travel time (TWT) is given as original depth reference. The structural similarity attribute of the 3D data cube is given in three different depth layers (top 20 ns to 40 ns, mid 40 ns to 60 ns, low 60 ns to 80 ns) in the lower panels. The irrigation plot is marked by a black dashed box/line. Slope line distance is increasing downslope.

3.3 Hillslope scale detection of lateral flow paths

3.3.1 3D GPR survey suggests a fragmentary layer

The 3D GPR survey at the site of the hillslope experiment identified fragmented structures in about 1.5 m depth (figure 10). This is in accordance with the soil core profile depth (figure 5~~, T1..T12~~). Especially profile ~~T7~~ 7 suggested an impermeable layer just below that depth.

~~Potential subsurface structures from 3D GPR survey and setup of hillslope experiment. Structure identification guided by the dip corrected semblance attribute. Depth estimated based on mean measured effective radar velocity in soil of 0.07 m ns^{-1}.Summary of the hillslope experiment given by locations of TDR profile tubes (purple, also location of respective soil cores in figure 5)~~

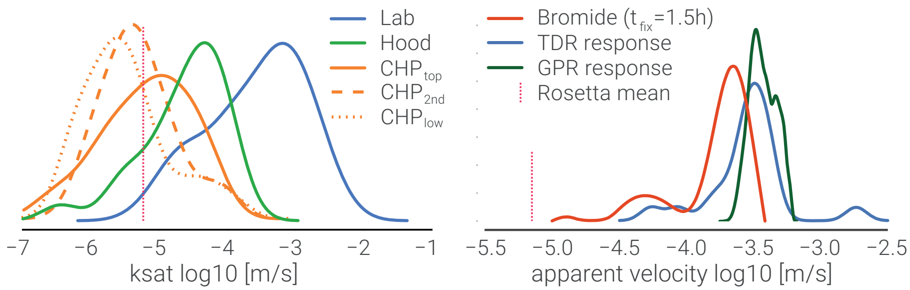

Figure 9. Saturated hydraulic conductivity and apparent vertical flow velocity kernel density estimates. Left panel: ~~Point-scale~~ Point scale measurement results (Lab: Ksat apparatus, Hood: Hood Tension-Infiltrometer, CHP: Constant Head Permeameter in different depth levels); Right panel: Results from ~~plot-scale~~ plot scale irrigation experiments. Rosetta (Schaap et al., 2001) reference based on mean values of ring samples (15.7, 47.9, 36.4 % sand, silt, clay and BD 1.1 $g\,cm^{-3}$)

~~and GPR transects (blue). Dot size of TDR scaled to maximum of observed change in soil moisture. Along GPR transects lateral marginals of the structural similarity attribute as proxy for recorded advection.~~

Although a potential structure can be identified it remains unclear to which degree this area of high spatial inhomogeneity in terms of radar reflection characteristics is flow-relevant, unless a reaction to an event is observed.

3.3.2 Hillslope responses

The results of the ~~hillslope-scale~~ hillslope scale irrigation experiment can be distinguished into the core area observations with TDR profiles only and observations at the downhill monitoring area, including TDR profiles as well as 2D GPR transects. The change of soil moisture at the core area (TDR 2 and 8 in figure 11) was very much in line with the findings from the ~~plot-scale~~ plot scale experiments. Given sufficient irrigation, both experiments showed a quick and clear response in greater depth, even before intermediate layers responded. While the patterns were similar, the signal was much stronger during the ~~hillslope-scale~~ hillslope scale experiment, which is due to the higher irrigation amount and duration. The calculated apparent vertical response velocities (lower right panel in figure 11) had a wider spread towards the faster end but ranged around the values identified in the plot irrigation experiments. The downhill profiles (e.g. TDR 9 and 11 in figure 11) showed a more diverse response. With greater distance to the core area the reaction was more and more limited to single depth levels. But since the depth levels and responses were highly divers, it remains rather ambiguous to determine their lateral connection. Overall changes in soil moisture as maximum at each TDR profile did not corroborate the potential subsurface structures identified in the 3D GPR survey (compare identified potential structures with dot sizes in figure 10). The full set of profiles ~~are~~ is reported in the companion study ~~(Angermann et al., 2017)~~(Angermann et al., 2017, this issue).

The four successive GPR transects across the downhill monitoring area provided spatially distributed images of ~~hillslope-scale~~ hillslope scale flow patterns and boundary fluxes. The structural similarity attribute of storm event water (green) and irrigation water (blue) revealed distinct, heterogeneously distributed patters (figure 12) pointing to discrete connected flow paths instead

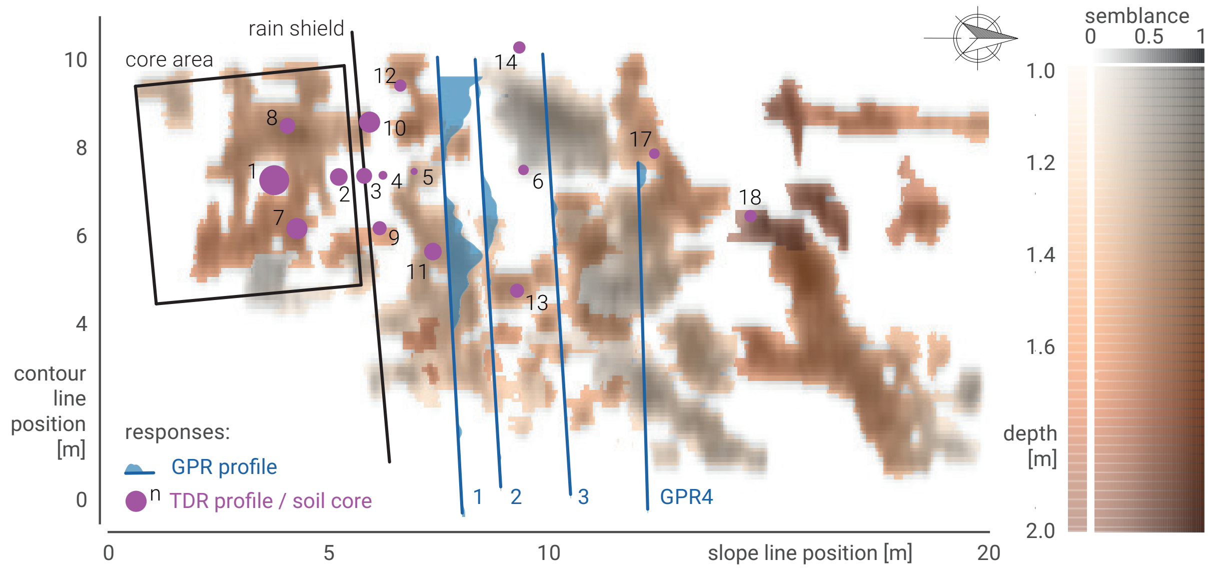

Figure 10. Potential subsurface structures from 3D GPR survey and setup of hillslope experiment. Structure identification guided by the dip corrected semblance attribute. Depth estimated based on mean measured effective radar velocity in soil of 0.07 m ns^{-1}.
Summary of the hillslope experiment given by locations of TDR profile tubes (purple, also location of respective soil cores in figure 5) and GPR transects (blue). Dot size of TDR scaled to maximum of observed change in soil moisture. Along GPR transects lateral marginals of the structural similarity attribute as proxy for recorded advection. Note that the picked potential subsurface structures are located in different depth (white to black) and that variations in spatial contrast can be seen in the semblance attribute (white to orange). Where more than one horizon has been identified the top one is plotted.

of an irregular network of inter-aggregate pores. The measurements suggested that lateral flow takes place in a very diverse network with very low similarity between the transects. Moreover, the responses to the irrigation decayed with distance to the core area.

The patches which reacted to the storm event are mostly different ones than the structures used to drain the irrigation water. Apparently the irrigation experiment initiated flow in more shallow structures (compare transect 1 irrigation reaction with transect 3 storm water in figure 12). Areas of high temporal dynamics of the similarity attribute were identified as regions of such flow-relevant structures (figure 12, bottom row). Note that the last recorded difference 18 h to 23 h after irrigation start (not shown) exhibited high similarity in all profiles. The mean of the attribute was between 0.93 and 0.96 and standard deviation between 0.076 and 0.048 for GPR transect 1 and 3 respectively. Apparently, the system had reached a steady state without much further change in soil moisture (see Appendix F for more details).

The patchy structures at the transects highlighted the irregularly distributed nature of lateral preferential flow paths which was ~~already~~ similarly observed in the plot experiments. Although some areas exert a higher density of reacting flow paths than others, no continuous patterns could be specified throughout the hillslope. We also saw a decay of the signal strength and areal share with distance from the core area. As the patterns from transect 1 did not simply propagate further downslope, the flow

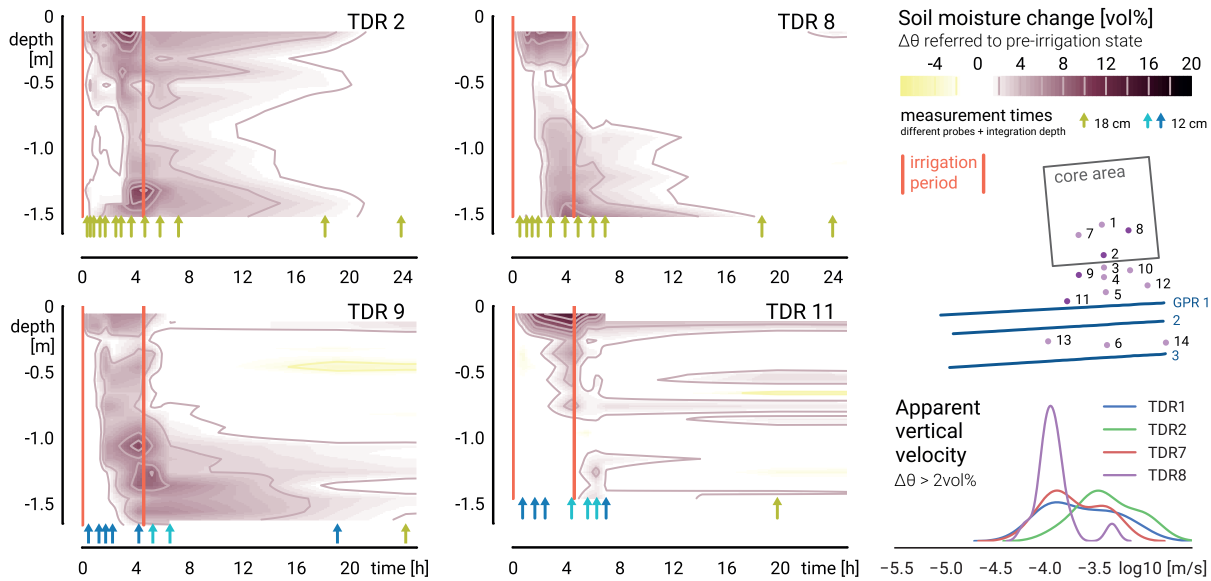

Figure 11. Development of soil moisture in TDR profiles during and after hillslope irrigation experiment. Exemplary transect with changes referenced to pre-irrigation conditions and attributed to irrigation water. Time is given in [h] after irrigation start. Individual measurements and probe reference marked with triangles. More data and explanation in Angermann et al. (2017), this issue. Right bottom: Apparent vertical flow velocity as first excess of $\Delta\theta \geq 2\text{vol}\%$ at core area profiles.

paths must be tortuous and leaky. Hence inferring the configuration of the connection between the four transects in downhill direction is not feasible. A comparison of the suggested structures of the 3D GPR survey to the overall response to irrigation recorded at the GPR transects did not correlate well (compare identified potential structures with reaction summary at GPR transects in figure 10).

4 Discussion

4.1 Identification of flow-relevant structures across scales

Our results have shown that the silty soils coincide with high porosities and high hydraulic conductivity at the ~~Darcy-scale~~point scale. Such a coincidence is not what is expected for cohesive, fine textured soils and can be explained by a setting of aggregated fine material in conjunction with a network of inter-aggregate pores. With respect to our research ~~questions,~~ question Q1, the pedo-physical ~~approaches have only limited capability to identify flow-relevant structures(Q1). Although the measurements hint to their existence, neither position nor~~ analyses initiated the recognition of these sub-scale structures. However, neither their position nor their general setup can be ~~derived from point observations . Using irrigation experiments has been far more insightful, especially in combination with time-lapse GPR.~~ identified based on point observations because of its scale below the

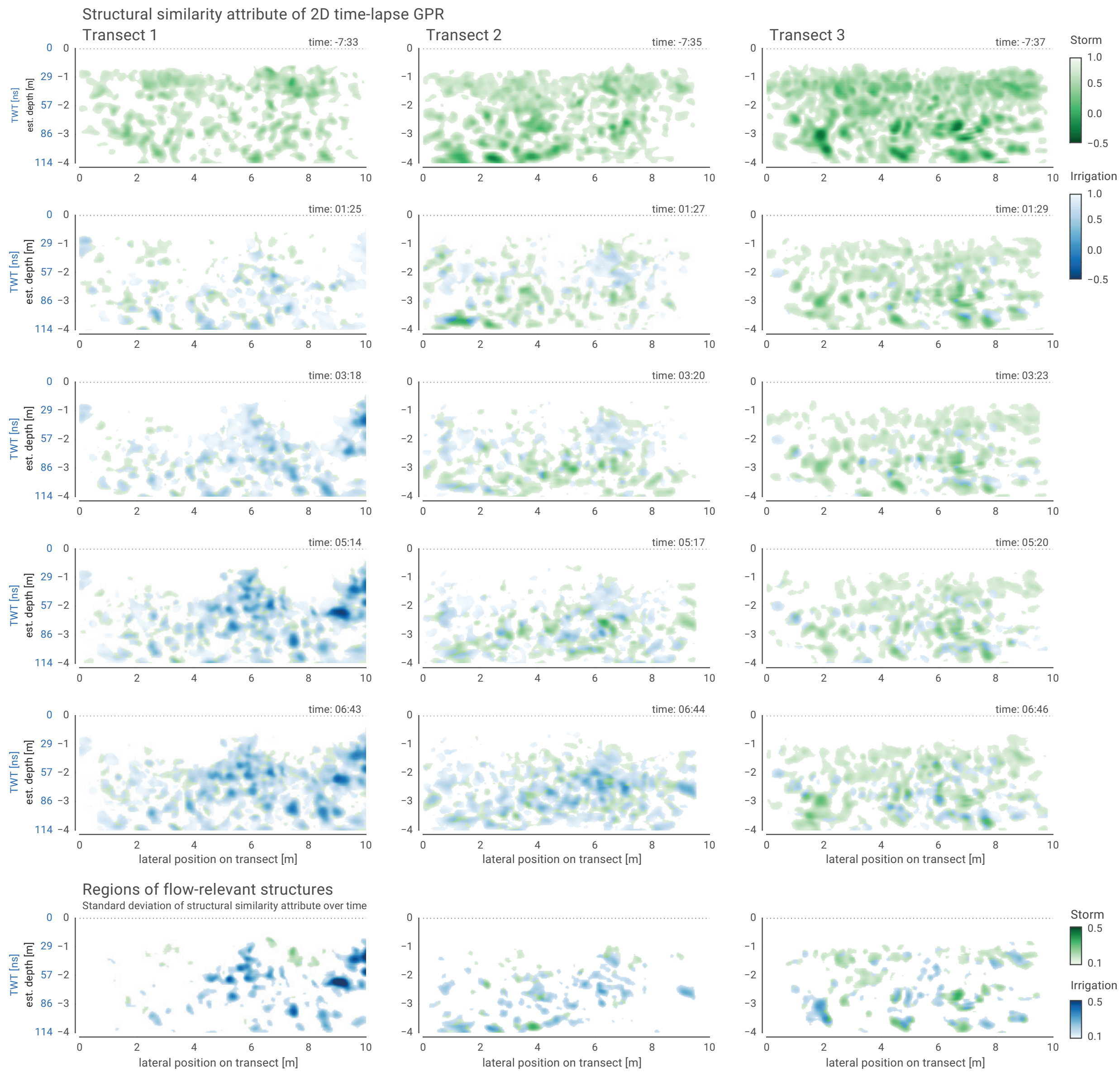

Figure 12. Structural similarity attribute in time-lapse 2D GPR transects. Blue: irrigation event water, Green: Storm event water. Columns: time series in one transect, Rows: different transects at the same time. Bottom row: Identified regions of rapid subsurface flow based on the standard deviation of all structural similarity attributes at one transect over time.

Notice: The structural similarity attribute calculates similarity between the radargram at the respective time to the last record 23 h past irrigation. A threshold or 0.15 is applied to identify significant changes. It is a qualitative measure based on the assumption that the last record is in steady state and that all differences are induced by soil water redistribution.

support of the measurements. Vice versa, methods at the next scale do not provide information about porosity and bulk density.

Irrigation experiments at the plot scale ~~suggest that~~ visualized that a network of these inter-aggregate voids ~~are~~ connects the surface to the periglacial deposit layer and is responsible for highly ~~heterogenous~~ diverse soil water redistribution. These structures are different from what we usually expect (cracks, worm burrows, roots ~~) and operate at much finer scales~~channels) at this scale. This could be depicted from dye tracer stains (figure 6), which still have the highest spatial resolution ~~.~~ on the cost of a lack of temporal insight. It requires strong assumptions about macropore-matrix interaction, time of fixation and dye supply, retention and recoverability. Despite all uncertainty about what process caused staining~~(high supply of dye water, high sorption into the matrix, long contact times, etc.) the~~ , the technique allows to identify the structures ~~affected~~ activated by irrigation and to infer much about their setting where dye has been retained. Although dye stains are closely related to actual flow and thus function, they ~~reveal~~ only reveal the potential pathways and thus form as the ~~temporal dimension remains~~ actual processes and timing remain unknown. When irrigation intensity and irrigation amount ranges near the hydraulic capacity of the macropore network while still avoiding ponding or macropore clogging~~the potential~~ , the entire network of flow-relevant structures is marked. 3D time-lapse GPR has proven to be capable to detect similar response patterns. However, the spatial and temporal resolution of the method is still ~~of concern. Some of~~ insufficient to detect the flow-relevant inter-aggregate voids marked by dye stains. Some of the structures have not even been traced with dye, nor could GPR identify ~~these specific structures~~them. Notwithstanding, the overall characteristics of the structures as patchy responses is depicted well and in a non-invasive, spatially continuous manner. Thus most of the point-sampling related issues (sections 3.1.1 and 4.4) are resolved. ~~To answer~~ Regarding research question Q2~~activating flow structures is absolutely necessary to identify them.~~ , the visualization of flow structures based on responses to irrigation succeeded at the plot scale. They are in good coherence with the quantitative findings from salt tracers, stable isotopes and soil moisture dynamics. Interestingly, the found vertical response velocity distributions correspond well to the saturated hydraulic conductivity measurements in soil samples, although their distribution is much more tight.

At the hillslope scale (Q3), applications of 3D time-lapse GPR are technically impossible due to the long acquisition times. Consequently we altered the setup to four trench-like 2D time-lapse GPR ~~has facilitated~~ profiles to facilitate the required high temporal resolution~~while the structures are also less diverse~~. The responses suggest ~~similar~~ structures similar to but less diverse than the found inter-aggregate voids ~~which~~ at the plot scale. They are spatially persistent and leaky and apparently feed from diverse sources. As such the irrigation experiment caused a similar response in different structures than the previous storm event. Moreover, the relatively high input rates have proven adequately chosen to identify lateral subsurface flow paths. At this scale the capability of point-based methods for structure identification is ~~very limited . Also static methods cannot unravel structures from overall heterogeneity here.~~ even more limited as the dense network of soil moisture profile observations did not allow the derivation of a conclusive picture.

4.2 ~~Structure characterization and apparent vertical flow velocities~~

The value of pedo-physical analyses is much higher when it comes to the characteristics of flow facilitated by the revealed paths. Referring to our third research question (Q3) we have derived hydraulic conductivity and apparent vertical response velocity for comparison at all scales in figures 9 and 11. Although none of the methods is specific to the velocities achieved in the structures, the distributions clearly corroborate that the network of inter-aggregate pores elevates the velocities about three to four orders of magnitude compared to reported matrix capacity.

The results also put a critical perspective on hydrological field measurements of infiltration capacity and saturated hydraulic conductivity. Both methods rely on concepts which cannot account for anisotropy. Thus, the resulting values have to be taken with some precaution if one seeks to derive quantitative estimates. Because the inter-aggregate flow network operates at much finer scales than cracks or worm burrows, the measurements of saturated hydraulic conductivity based on 250 ml ring samples depict the overall picture. However, a very large number of samples will be necessary to converge. Yet, exactly this motivated the presented experiments.

This is much more concisely derived from the responses to irrigation basically irrespective to the applied method. The calculation based on salt tracers point to rather short times of fixation. This estimate is avoided when using time-lapse methods. However, TDR-based responses have a high uncertainty concerning the representativity of the point records. They also are highly sensitive to the selected threshold. GPR-based estimates so far lack temporal resolution and require to infer the depth of the identified signal through estimates of the radar velocity.

4.2 Heterogeneity versus structure

Based on a relatively large number of pedo-physical measurements the overall layering and mean property of a heterogeneous soil with periglacial deposit layers was described in section 3.1. Given the large effort to conduct such exploration, this result is rather dissatisfactory and could have been achieved with much simpler means (e.g. compare Heller and Kleber, 2016, in a similar setting). The attribute supported picking of potential structures in the 3D GPR data cube also had high discrepancies to the actual relevant structures (figure 10) which is in contrast to similar GPR applications by Gormally et al. (2011) and explains the large spread in the results of the hydrological measurements.

Also the low representativity of the observations of soil moisture dynamics in many TDR profiles compared to the 3D and multi-2D time-lapse GPR records in sections 3.2.4 and 3.3.2 underlines the methodological drawbacks of point observations. Moreover, low recovery of Bromide in the more than 120 samples per plot points out that the sampling of only 0.5 % of the total affected soil volume cannot fully represent the highly heterogeneous distribution of irrigation water.

It has proven particularly difficult to distinguish heterogeneityand structure. This has conceptual implications: We may regard statistical heterogeneity as random small scale changes in hydrological soil properties (de Marsily et al., 2005) and structure as spatially organized flow paths and their connectedness (Tetzlaff et al., 2010). The spatial scale of flow-relevant structures (5×10^{-3} m to 5×10^{-2} m) is several orders of magnitude below the support of standard soil samples and hydrological measurements ($1 \times 10^{-4}\,\mathrm{m}^3$ to $1 \times 10^{-3}\,\mathrm{m}^3$). At the same time we find the flow process in such structures several orders of magnitude faster than in the soil matrix (also Germann, 2014). Continuum theory assumes homogeneity within the representative elementary volume (REV). The inter-aggregate flow path network enabled the same high flow velocities as classic macropores and the

~~lateral flow paths at the hillslope scale experiment. Nevertheless, their responses can be quantified in a larger REV. Hydrological standard approaches tend to operate at a scale between the actual processes and an appropriate REV.~~

~~In more general terms, heterogeneity can be seen as deviation of the found reality from the concept of quasi-homogeneous entities. If this deviation concerns only the apparent values of the same physical process, more samples are adequate to determine their distribution. In cases (like here) where this deviation also means a shift in the physical processes, heterogeneity may introduce bias as it becomes a scale-problem: Any measurement will consist of an unknown subset of connected or not connected flow paths. This makes it impossible to unravel the properties of the different flow domains without knowing the composition of the explored ensemble of each measurement. Hence the point-based techniques cannot determine the sub-scale organization within the support of the measurement. Without detection of organization and thus flow-relevant structures they can only recover heterogeneity independent of the number of samples.~~

4.2 Event response patterns reveal flow-relevant structures

~~In order to distinguish~~ Interestingly, static methods failed to unravel structures from overall heterogeneity. This corroborates our idea that responses to an event are required for the identification of flow-relevant ~~structures from heterogeneity, approaches focussing on the dynamics of response patterns have proven to be adequate. This corroborates our hypothesis and~~ structures. Furthermore, it confirms that a combined assessment of form and function is needed to mutually reduce ambiguity. This is also shown in the companion study with a focus on function and processes at the hillslope scale (Angermann et al., 2017, this issue).

4.2.1 Soil moisture responses

In our case TDR measurements through access tubes were employed as low-impact means to monitor soil water dynamics in order to detect areas of quick and strong response. Structures in general and the inter-aggregate voids in our case cover only a very small fraction of the measured volume. We may underestimate detected flow paths when they do not alter the total volumetric soil water content much (bypassing). This can explain the observed patterns of low response in the topsoil and changes in regions where the fast flow is decelerated at some kind of bottleneck. Referring to the theoretical integration volume of 1 L it would require a macropore of about 1 cm diameter within the support of the sensor to be filled to just reach a threshold of 2 vol%. Adding this ~~20 ml~~ 20 mL of water diffusively would result in the same measurement. This shows that soil moisture measurements exhibit a conceptual bias towards the diffusive fraction of the soil water.

The quantification of advective water from the recorded changes in soil moisture has ~~proven~~ been proven as not feasible. Given the insight of the discretely structured flow domain and the high lateral response velocities identified in the companion study (Angermann et al., 2017, this issue), the soil moisture measurements leave us with many questions. Comparing the identified regions of flow structures (~~Figure~~ figure 12) with the support of a TDR sensor quickly reveals that even a large number of point observations remains highly uncertain if the overall spatial context is unknown~~(which is the case in virtually all soil moisture measurement studies). This was also shown in the experiment at plot XI~~. This is especially the case at the hillslope scale. At the plot scale, the issue is less pronounced as we have shown with the good correspondence between tracers, GPR and soil moisture reaction at plot X (figure 7 and ~~16): While tracer and GPR exhibit quick drainage of the irrigation water to the periglacial deposit layer~~8). However, at plot XI with less intense irrigation the soil moisture profile did not react despite the evidence of quick vertical redistribution in all the other methods. Apparently, the TDR records ~~are~~ were simply not close enough to the comparably few activated flow paths ~~due to their limited support. As for the local exploration, a precise location of such monitoring at specific points in the domain (e.g. directly at responsive structures and at less reactive places)may enhance the interpretability of monitoring data.~~ (figure 16).

4.2.2 Time-lapse GPR patterns

The ~~finding that~~ potential horizons identified by the static 3D GPR survey do not coincide with the observed responses (figure 10). This is another example for the requirement of a shift between active and non-active state to identify flow-relevant structures. The structural similarity attributes derived from time-lapse GPR reveal the patterns of soil water redistribution. The continuous 2D and 3D ~~fields~~ data allow to relate temporal changes in space as images of the subsurface as proposed by Gerke et al. (2010); Beven and Germann (2013) and others.

The comparison of radargrams in time needs further attention: In other time-lapse GPR applications for soil water dynamics in structured domains (Truss et al., 2007; Haarder et al., 2011; Allroggen et al., 2015b; Klenk et al., 2015) analysis is guided by reference to a reflector and its apparent displacement can be used to calculate changes in soil moisture. Alternatively, a wetting front could generate a reflector (Léger et al., 2014). In our case none of these existed~~and the detected local changes in the complex reflection patterns allowed only for qualitative interpretation~~.

On the one hand, we minimized methodological problems concerning the noise arising from the imperfect positioning of repeated GPR measurements by using a measuring platform at the plot scale, transect guides at the hillslope scale, and an automatic-tracking total station (Allroggen et al., 2015b). On the other hand we base our analysis on the structural similarity attribute ~~in stead~~ instead of pixel to pixel comparison or picked reflectors. The disadvantage is that this allows only for a qualitative measure. The advantage is that the spatial organization of areas with changing reflection and transmission properties (which are attributed to changes in soil moisture) can be revealed even in heterogeneous soils. ~~It also enables~~ The 3D applications ~~avoiding~~ at the plot scale avoid strong assumptions about the continuity of preferential flow paths when inferring 3D networks from 2D measurements (Gormally et al., 2011; Guo et al., 2014). Especially in ~~heterogeneous soils~~ the soils under study, the found response patterns (figure 8) and the excavated stained soil profiles (figure 6) ~~question a direct linear connection across several decimeters. Because of the low spatial continuity we found there, we~~ show highly tortuous flow paths. Thus we refrain from interpolations between the multi-2D transects at the hillslope ~~experiment~~scale.

Although the 3D time-lapse attribute data of the plot irrigation experiments are of low spatial resolution (blur due to similarity attribute method and long duration of one acquisition) and limited temporal resolution (few acquisition times), they are suitable to identify regions of flow-relevant structures and their characteristics. In the multi-2D transects resolution was enhanced (short duration of one acquisition and many repeated measurements) which depicted the structures much better. Hence, time-lapse GPR can especially be improved by enhancing the acquisition time and frequency.

The observation of changes during activation of flow-relevant structures ~~enhanced the~~ generated the required contrast to overall heterogeneity. For large structures, this lead to precise identification and localization. Smaller flow paths cannot be fully resolved. Nevertheless, the continuous 2D and 3D images of the subsurface response patterns provide means to non-invasively study the form-function relationship ~~*in situ*~~ in situ and to overcome some of the restrictions of retrospective and destructive tracer methods. However, quantitative interpretation of time-lapse GPR data remains challenging.

4.3 Methodological assessment

In contrary to our first expectation, the value of pedo-physical analyses of soil core samples has been relatively high even for characteristics of flow facilitated by the revealed paths at larger scales. Structure identification is not only obscured in heterogeneity as one would expect, but properties deviating from the standard situation (fine texture, low bulk density and high porosity) gave rise to the identification of the inter-aggregate flow paths. However, the spatial organization of structures below and above the support of the samples cannot be revealed. This is also the reason for the relatively low information which could be drawn from the in situ infiltration measurements: The observed flow rates are largely affected by the capacity of the connected flow paths draining the measurement point. This adds to the critical assumption of homogeneity (Langhans et al., 2011).

Besides the high information gain through the state shift of flow-relevant structures in irrigation experiments, the employed methods at the plot scale have very specific advantages and disadvantages: Especially the laborious and costly analysis of salt tracers and stable isotopes is contrasted by relatively little additional information. Moreover, the lack of a temporal information about when the solute or water molecule was retained in a certain depth is seen problematic. Soil moisture profile dynamics and time-lapse GPR do not suffer this drawback. Both can be employed with very low or even no impact on the subsurface from the surface. While GPR requires to be operated in higher temporal resolution (see section 4.5), soil moisture profiles lack the desired spatial discretization. Dye staining delivers the highest spatial resolution to reveal subsurface structures on the cost of blindness about the temporal dynamics. Furthermore, a tomographic excavation of the stains has proven very difficult.

Under strongly structured conditions as at the hillslope under study, point observations remain a needle in a haystack. Unlike for vertical structures at the plot scale, the dense network of soil moisture profiles could not depict the lateral flow paths well. Here, the *GPR-inferred trenches* have shown to be a valuable surrogate for massive staining like in the study by Anderson et al. (2009). In addition, the temporal dynamics of the hillslope reaction could be observed.

With regard to our a priori model application, the combination of vertical and lateral flow paths (identified in the irrigation experiments) with layers of low permeability just below the structures (observed in the soil core profiles) could refine the domain towards more lateral soil water transport. The mean retention properties (derived from pedo-physical analyses) are adequate. Hence, the combination of data from all scales can contribute to a refinement of the model.

4.4 Heterogeneity versus structure

Based on numerous point scale measurements the overall layering and mean property of a heterogeneous soil with periglacial deposit layers was described in section 3.1. Given the large effort to conduct such exploration, this result appears rather dissatisfactory and could have been achieved with much simpler means (e.g. compare Heller and Kleber, 2016, in a similar setting). However, they have been key to the identification of the sub-scale inter-aggregate structures which convey to vertical drainage paths and a lateral network in the subsurface. Without high supply rates from the point scale, subsurface storm flow in the lateral structures could not be sustained.

At the hillslope scale, the attribute supported picking of potential structures in the 3D GPR data cube also had high discrepancies to the actual relevant structures (see differences between potential subsurface structures and recorded reaction in TDR and GPR profiles in figure 10) which is in contrast to similar GPR applications by Gormally et al. (2011) and explains the large spread in the results of the hydrological measurements.

It has proven particularly difficult to distinguish heterogeneity and structure. This has conceptual implications: As introduced, we regard statistical heterogeneity as random small scale changes in hydrological soil properties (de Marsily et al., 2005) and structure as spatially organized flow paths (Gerke, 2012) and their connectedness (Tetzlaff et al., 2010) or persistent spatial covariance of high conductivity values. Hence the structures require multivariate or topological characterization. To infer on the directed flow in subsurface structures, a spatially continuous observation of the reaction to an event is required. This has proven especially challenging as the spatial scale of flow-relevant structures (5×10^{-3} m to 5×10^{-2} m) is several orders of magnitude below the support of standard soil samples and hydrological measurements ($1 \times 10^{-4}\,\mathrm{m}^3$ to $1 \times 10^{-3}\,\mathrm{m}^3$).

In more general terms, heterogeneity can be seen as deviation of the found reality from the concept of quasi-homogeneous elementary volumes. If this deviation concerns only the apparent parameters of the same physical process, more samples are adequate to determine their distribution. In cases (like here) where this deviation also means a shift in the physical processes, heterogeneity may introduce bias as it becomes a scale-problem: Any measurement will consist of an unknown subset of connected or not connected flow paths. This makes it impossible to unravel the properties of the different flow domains without knowing the composition of the explored ensemble of each measurement. Hence the point-based techniques cannot determine the super-scale organization outside the support of the measurement. Without detection of organization and thus flow-relevant structures they can only recover heterogeneity independent of the number of samples.

4.5 Outlook on structure identification with time-lapse GPR

In the context of preferential flow studies in watersheds around the globe and in many different models, our results open new ways to visualize subsurface flow and to facilitate more field studies to understand stormflow generation (as recently found in a meta-analysis by Barthold and Woods, 2015). Although we cannot fully resolve macropores as needed in spatially explicit representation of macropores as vertically and laterally connected flow paths (Vogel et al., 2006; Sander and Gerke, 2009; Klaus and Zehe, 2011), our findings provide experimental basis to further develop such models. More implicit approaches like stochastic stream tubes (Jury and Roth, 1990), the scale way idea (Vogel and Roth, 2003), or dual porosity and permeability approaches (Gerke, 2006) could be extended by providing spatial and temporal context which is one of their assumptions. Also more integrating concepts like the representative watersheds (REW, Reggiani et al., 1998; Tian et al., 2006; Lee et al., 2007) could define zones for quick drainage based on repeated response observations in vertical and lateral structures.

In the form and function framework one implication of the study is that a disjunct analysis of the two is source of unnecessary ambiguity and susceptibility to bias. Although ~~this~~ the conjugated nature of form and function is very much in line with the general findings ~~of Wittgenstein (1922) and others~~and perception of early studies (Aristotele in Blits, 1999; Thompson, 1917; Wittgenstein, 1922 it contradicts a general notion in hydrological surveying and modeling to separate the two. In most models different flow paths are defined in a lumped manner using effective parameters after all. These domains and their parameters could be determined based on irrigation experiments and time-lapse GPR measurements.

While models require specific parameters about the site under study which are coherent with their conceptual assumptions or modeler's perception (Holländer et al., 2014), also the experiments are strongly shaped by our perceptual model about the processes. With this, the matter of model adequacy is not restricted to numerical aspects alone (Gupta et al., 2012). Methodologically, the ~~*in situ*~~ in situ imaging of subsurface flow processes can be used to reduce ambiguity of measurements and to constrain the process conceptualization in heterogeneous and structured soils. ~~Based on~~ In our case, the a priori model overestimated deep percolation and underestimated the velocity of lateral soil water redistribution through subsurface flow paths. Based on field information about the overall distribution of flow paths or quickly reacting areas sampling and monitoring could be guided. This would reduce the limitations of ~~point-scale~~ point scale methods with relatively little effort.

5 Conclusions

In the hillslopes under study silty, cohesive soils coincide with high porosity and high flow velocities at the ~~Darcy-scale~~Darcy scale. This motivated in depth investigation of flow-relevant structures explaining this. We have shown that subsurface heterogeneity and the mismatch of observation and process scales obscured the identification of flow-relevant structures ~~in the subsurface~~ under static conditions without a shift between active and non-active state. The pedo-physical analyses initiated the recognition of these sub-scale inter-aggregate structures. The point scale exploratory methods could ~~discover and~~ quantify the general characteristics of the subsurface only within a wide spectrum of the respective target properties. ~~Moreover~~However, they failed to identify flow-relevant structures in terms of position, distribution and capacity at larger scales. Measurements of infiltration capacity and hydraulic conductivity require special attention, because they integrate over an unknown set of advective and diffusive flow paths. The discrepancy between results from the soil core profiles and a 3D GPR survey on the one hand and the time-lapse approaches on the other hand points out that structures identified from inhomogeneities are not necessarily flow-relevant pathways.

Joint application of tracers and time-lapse GPR during irrigation experiments revealed details about the structures and their activation by flow. At the ~~plot-scale~~ plot scale a network of inter-aggregate pores enables fast soil water redistribution in a less directed manner and at much finer scales than usually expected in macropores like cracks, worm burrows or root channels. This facilitates high apparent vertical flow velocities ranging around $10^{-3.5}\,\mathrm{m\,s^{-1}}$, while operating in fine pores at scales very difficult to identify even with dye staining. The combination of tracer and time-lapse GPR methods enabled the more holistic view into the subsurface which was further applied to the hillslope scale. There persistent lateral pathways connecting along the hillslope have been identified through *GPR-inferred trenches*.

Our findings ~~raise strong concerns about approaches attempting to determine function from form alone~~show that form and function in hydrological systems operate in conjugated pairs and cannot be approached separately. Besides the fine scale of the ~~small~~ inter-aggregate voids~~we come back to Wittgenstein (1922): Form~~ , form requires to be addressed in its context to reveal information about structure and its characteristics. But also addressing function needs details about the spatial circumstances to be conclusive.

~~In hydrological systems form and function are mutually paired.~~ Overly strong assumptions about structures or processes can be avoided by the presented non-invasive time-lapse GPR method, which can visualize and localize response patterns at the plot and hillslope scale. They compare well with soil moisture dynamics and tracer recovery. As such the localization of responses provides the missing link to relate form with function (taken up in the companion study by Angermann et al., 2017, this issue) and to guide more specific investigation, monitoring and modeling of subsurface processes.

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Appendix A: Quick sampler for fast undisturbed core sampling on excavated profiles

In addition to the dye tracer stain records, quantitative analysis of salt tracer recovery distribution in the excavated profiles underneath the irrigation plots was done. One challenge to address was the required time to collect an adequate array of such soil samples with known volumetric reference. We developed a re-loadable core sampler with a calibrated sample volume of 66 mL.

The sampler is applied like a ring sample with attached hammering adaptor. In order to minimize time and impact on the profile we enabled a pull-withdrawal of the sample. For this, the sampler is about 15 mm longer than the desired sample. The irregular open edge is scraped off by a calibration twist drill. The prepared and accurate to volume sample is finally pushed out by a piston from the sampler into a sealable brown glass bottle for further treatment in the laboratory.

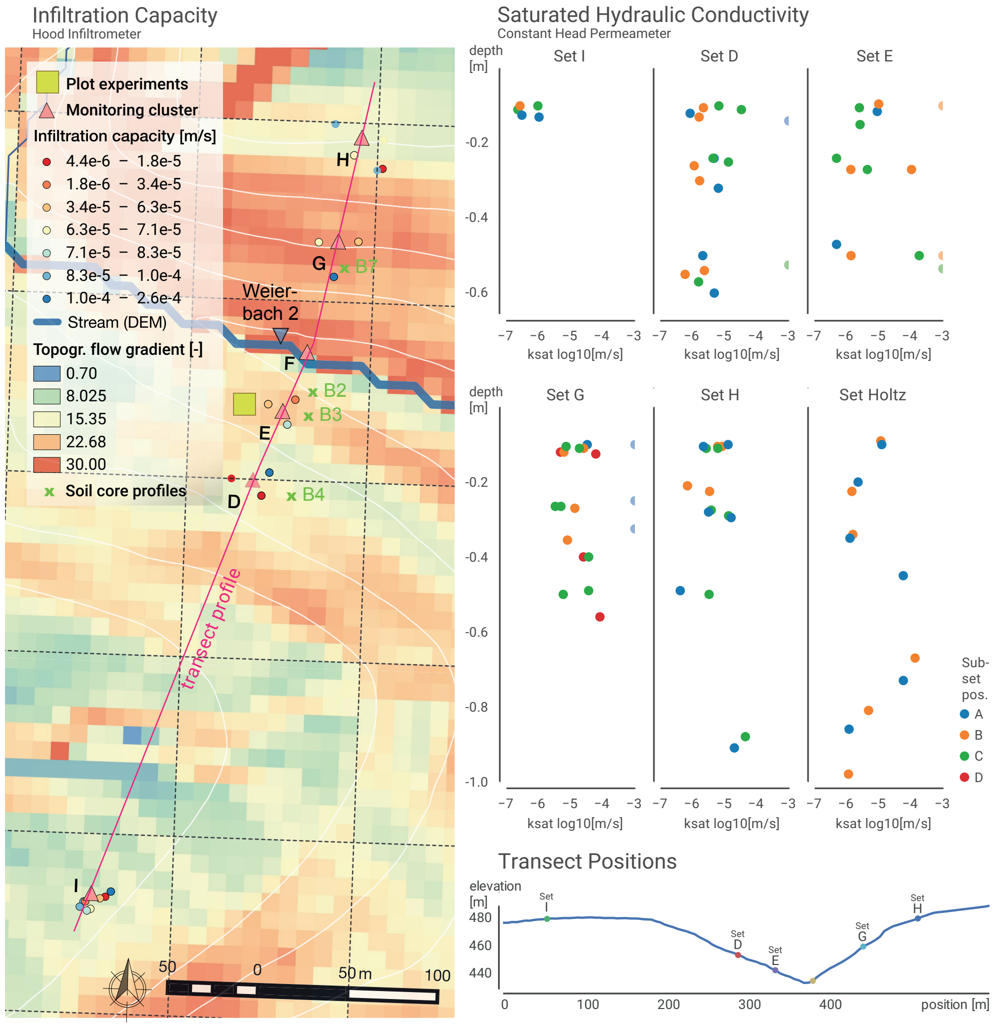


Figure 13. Hydrological exploration results. Left: Infiltration capacity (values color coded) measured with hood infiltrometer. Basemap with topographic flow gradient $G = arctan(\partial z_{rel}/\partial d_{rel})$, topography contour lines and positions of hydro-meteorological monitoring clusters. Right top: Saturated hydraulic conductivity measured with a constant head permeameter. Individual profile position in the respective nested set color coded (2 measurement holes with dist=1 m). Values exceeding the device capacity set to $10^{-3}\,\mathrm{m\,s^{-1}}$. Right bottom: Elevation profile of transect as characteristic landscape feature in the sub-basin.

Appendix B: Detailed results of hydrological measurements

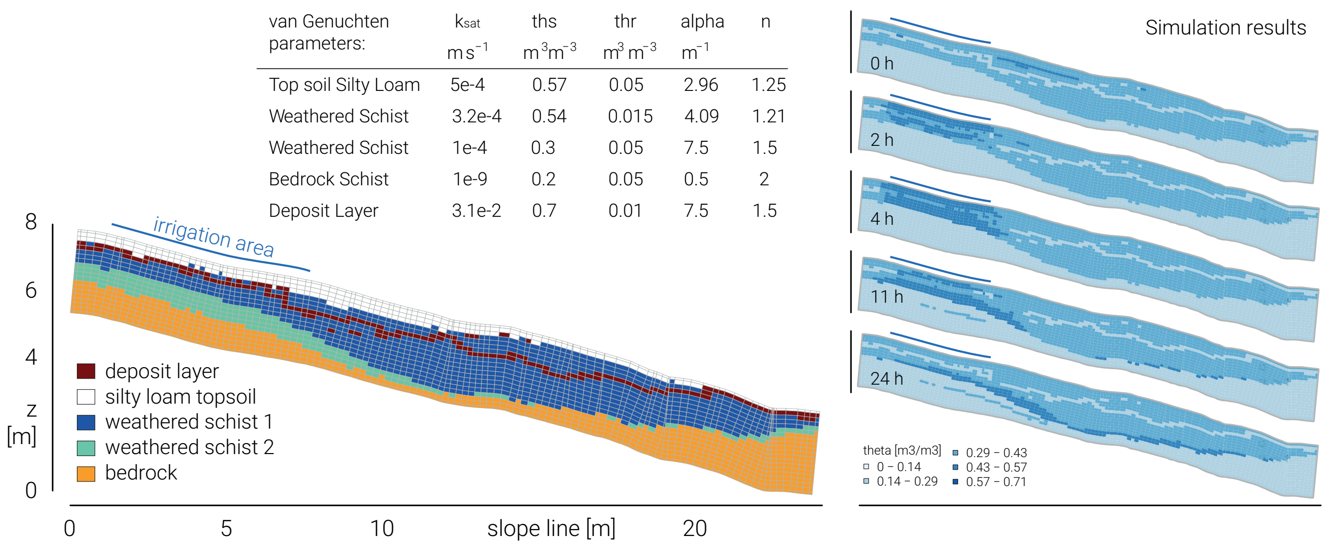
In situ measurements of infiltration capacity and saturated hydraulic conductivity had a highly heterogeneous distribution. To detail on the respective records and found profiles figure 13 shows them in spatial context.

~~Hydrological exploration results. Left: Infiltration capacity (values color coded) measured with hood infiltrometer. Basemap with topographic flow gradient $G = arctan(\partial z_{rel}/\partial d_{rel})$, topography contour lines and positions of hydro-meteorological~~

monitoring clusters. Right top: Saturated hydraulic conductivity measured with a constant head permeameter. Individual profile position in the respective nested set color coded (2 measurement holes with dist=1 m). Values exceeding the device capacity set to $10^{-3}\,\mathrm{m\,s^{-1}}$. Right bottom: Elevation profile of transect as characteristic landscape feature in the sub-basin.

Appendix C: A priori model reference

Based on the findings of the pedo-physical exploration, we setup the 2D process model CATFLOW (Zehe et al., 2001) as representative hillslope for hypothetical *a priori* simulation of the experiment in order to determine the required irrigation intensity, the spatial extent of the observation network, the temporal resolution, and the duration of the monitoring. The model domain was set up based on the soil property estimates from the soil physical exploration assuming a fractured periglacial deposit layer as conductive layer in the hillslope (fig. 14). In a series of scenarios, the one with $30\,\mathrm{mm\,h^{-1}}$ irrigation for 4 h turned out to be well balanced with respect to anticipated hillslope reaction given a limited source area. Fast soil water redistribution was modeled to last for 12 h.



van Genuchten parameters:	ksat $\mathrm{m\,s^{-1}}$	ths $\mathrm{m^3 m^{-3}}$	thr $\mathrm{m^3 m^{-3}}$	alpha $\mathrm{m^{-1}}$	n
Top soil Silty Loam	5e-4	0.57	0.05	2.96	1.25
Weathered Schist	3.2e-4	0.54	0.015	4.09	1.21
Weathered Schist	1e-4	0.3	0.05	7.5	1.5
Bedrock Schist	1e-9	0.2	0.05	0.5	2
Deposit Layer	3.1e-2	0.7	0.01	7.5	1.5

Figure 14. CATFLOW model reference of hillslope experiment. Left panel: Table of used soil definitions and hypothetical hillslope setup. Right panel: Simulated soil moisture with $30\,\mathrm{mm\,h^{-1}}$ irrigation for 4 h.

Comparing the results from the model with the experiment shows strong deviation in terms of the activation of a conductive layer. However, this could be improved by adding a layer of low permeability below, since the modeled reaction on the bedrock interface is quite similar but slower than the observed dynamics.

Appendix D: Pore water stable isotope analysis in plot irrigation experiments

In addition to Bromide as conservative salt tracer the same percussion drilled core samples were analyzed for their stable isotopic composition (δ^{18}O and δ^{2}H) of the pore water. This was done with the direct equilibration method as proposed by Wassenaar et al. (2008) and described in detail by Sprenger et al. (2015) using a wavelength-scanned cavity ring-down spectrometer (Picarro Inc.). The precision for the method is reported to be 0.31 ‰ for δ^{18}O and 1.16 ‰ for δ^{2}H (Sprenger et al., 2016). The measured isotopic signal is given relative to the Vienna Standard Mean Ocean Water. As pre-experiment reference, a fourth reference core has been sampled prior to the experiments about 3 m upslope.

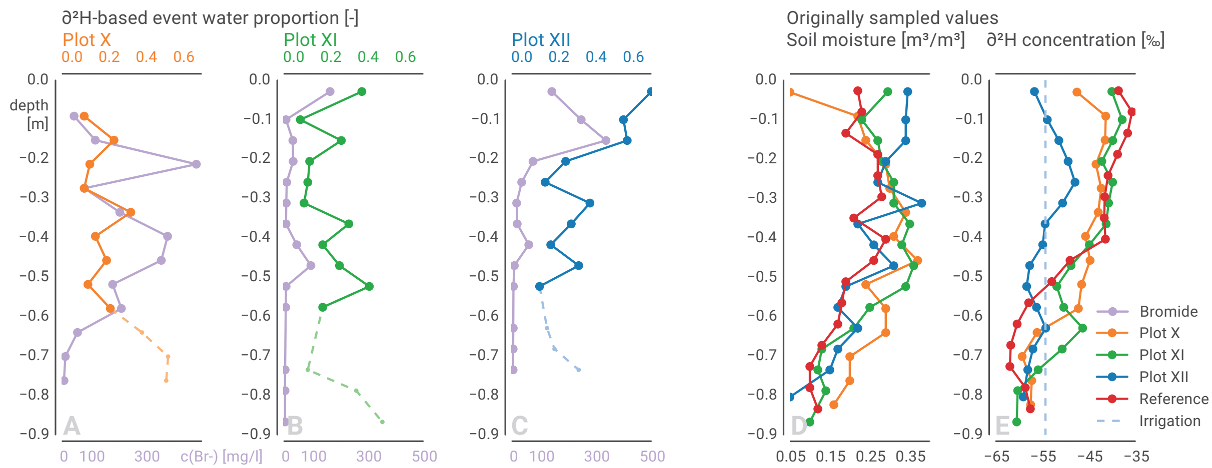


Figure 15. ~~Plot-scale~~ Plot scale irrigation experiments. Proportion of event water derived from deviations in concentration of Deuterium and Bromide in soil water of sampled cores to reference (A-C). Absolute measured soil water content (D). Deuterium concentration in samples and signature of irrigation water (E). Note that the $\delta^2 H$ concentration profiles and the signature of the irrigation water show low deviation and even coincide in 0.5 m depth. Thus the interpretation needs precaution, especially below that level (dashed lines A-C).

We calculate the volumetric event water portion [-] in the soil water as:

$$\frac{\Theta_{event}}{\Theta_{2h}} = \frac{\Theta_{2h} \cdot \delta^2\mathrm{H}_{2h} - \Theta_{pre} \cdot \delta^2\mathrm{H}_{pre}}{\Theta_{2h} \cdot \delta^2\mathrm{H}_{event}} \tag{D1}$$

with δ^2H as Deuterium composition [‰] in the pre-event reference sample (pre), in the core sample 2 h after irrigation start ($2h$), and in the irrigation water ($event$). The amount of soil water is given as Θ [mm].

Figures 15A-C show the depth profile of irrigation water as portion of total water content, calculated from the deviation in δ^2H concentration between reference and $2h$ past irrigation core samples. The results are also compared to the Bromide concentrations in the soil water phase of the same samples, showing slight correlation. However, the values are rather noisy due to low difference of the isotopic composition of the soil water and the not-enriched irrigation water. Figure 15D-E highlights the very weak soil moisture signal and low deviation between the respective soil cores close to the method's precision. Especially interpretation of the peak in about 0.5 m depth and signals below may be erroneous, because the signature of the reference core coincides with the irrigation water there.

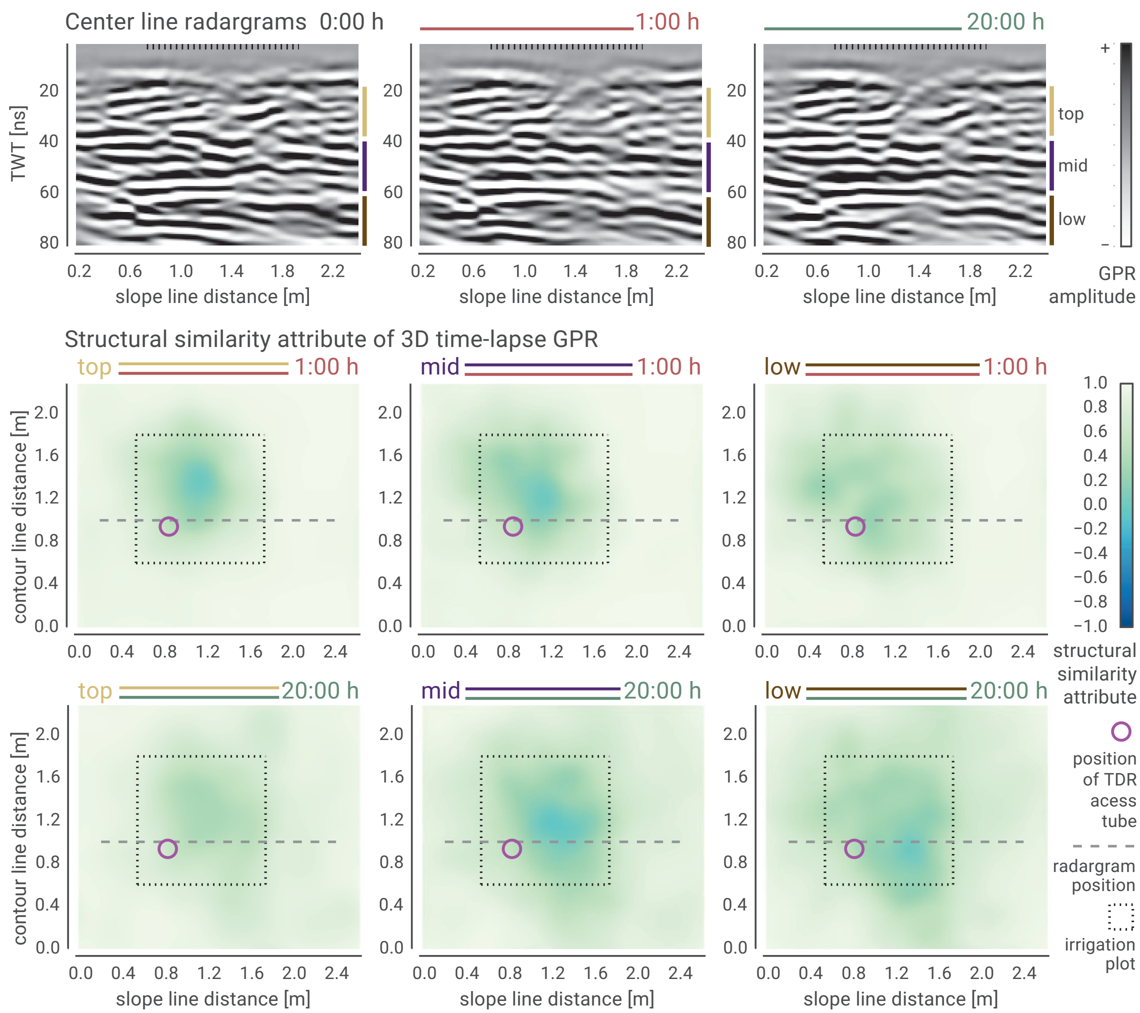


Figure 16. Time-lapse 3D GPR of irrigation experiment at plot XI. Center line radargrams at the marked transect (grey dashed line in lower panels) for the three acquisition times (before 0:00 h, directly after irrigation 1:00h, 20:00 h after irrigation) are given in the top row. The structural similarity attribute of the 3D data cube is given in three different depth layers (top 20 ns to 40 ns, mid 40 ns to 60 ns, low 60 ns to 80 ns) in the lower panels. The irrigation plot is marked by a black dashed box/line. Slope line distance is increasing downslope.

In line with the findings of Klaus et al. (2013) the isotopic signal of non-enriched water required strong assumptions for its interpretation. In our case this specifically applies to the plot scale core samples where we calculated the difference to the pre-experiment core regardless the fact, that soil water and irrigation water deviated only slightly (≥ 15 ‰) and even had the same values ~~in~~ at 0.5 m depth. Moreover, the reference core was required to be at a different location. Hence, flow paths and

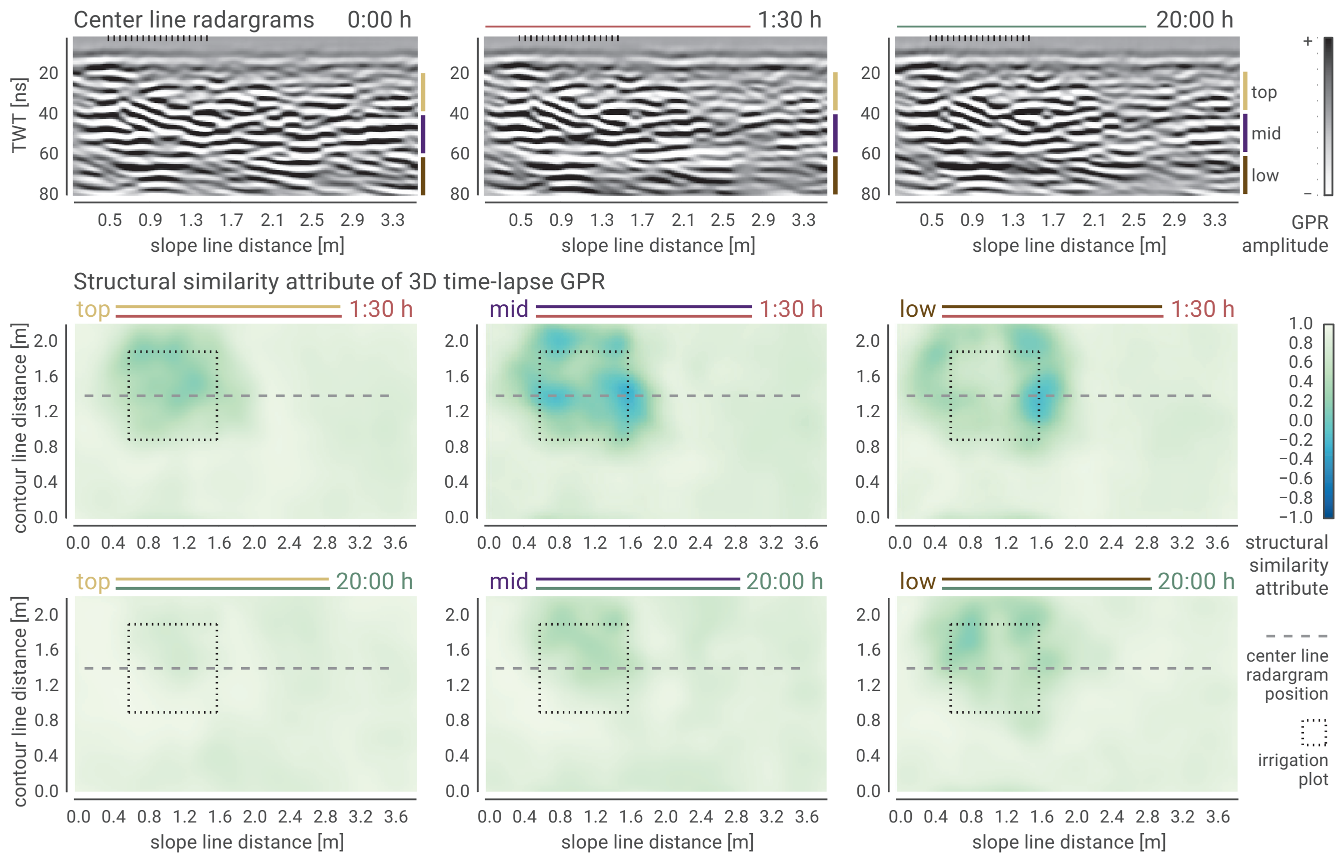


Figure 17. Time-lapse 3D GPR of irrigation experiment at plot XII. Center line radargrams at the marked transect (grey dashed line in lower panels) for the three acquisition times (before 0:00 h, directly after irrigation 1:30h, 20:00 h after irrigation) are given in the top row. The structural similarity attribute of the 3D data cube is given in three different depth layers (top 20 ns to 40 ns, mid 40 ns to 60 ns, low 60 ns to 80 ns) in the lower panels. The irrigation plot is marked by a black dashed box/line. Slope line distance is increasing downslope.

thus the initial isotope profile are not necessarily the same as at the respective plots. However, as assumably ideal tracer the stable isotope data allowed for an additional and coherent measurement. With respect to the overall findings of rapid flow in discrete structures the assumption is justified.

Appendix E: Results 3D time-lapse GPR at Plot XI and XII

In addition to the results in section 3.2 here the radargrams and structural similarity attributes for the other two ~~plot-scale~~ plot scale experiments are given in figure ~~17 and 16~~ 16 and 17. In plot XI with less intense irrigation the lateral spread of water is less pronounced. As found by the tracer methods, interaction with the soil matrix was elevated in plot XII. Moreover, the acquisition of the GPR data took longer at this plot.

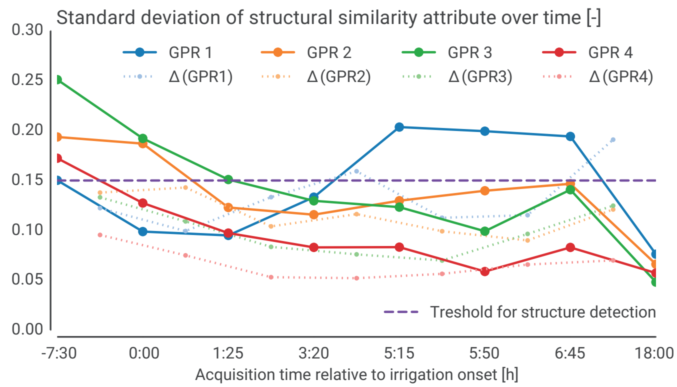


Figure 18. Standard deviation of structural similarity attribute at the different GPR transects in the hillslope experiment over time (solid lines) and standard deviation of the differences of two successive attribute distributions (dotted lines). The used threshold for the detection of flow-relevant structures is marked as dashed purple line.

Appendix F: Technical concerns of time-lapse GPR and the structural similarity attribute

The demand on the precision of the repeated acquisition with spatial determination and antenna contact to the ground are very high and are assumed to be nearly perfect within our experiments. Under field conditions precision is limited due to numerous effects like micro-topography, top-soil conditions, signal attenuation and even weather. The missing of distinguished reflectors also inhibited any estimation of quantitative values. Further, the referenced depths in figure 12 are only estimates based on a constant mean GPR velocity which can also vary in time and space depending on the initial conditions.

The highlighted assumptions clearly frame the limits of the technique. The overall sensitivity of the approach can be judged from the structural similarity attribute of the last pairs of records in the hillslope experiment when we assume the soil water to be in equilibrium again. Figure 18 presents the development of the standard deviations of the structural similarity attribute of the respective transects over time. In dotted lines we plotted the standard deviations of the stepwise attribute differences. The standard deviations of the attribute for the last pairs of records is 0.06. Using this value as methodological noise reference, it implies that weak responses and local effects must not be over interpreted. Hence, the introduced threshold of 0.15 for irrigation signal detection appears to be a reasonable choice for qualitative interpretation in our case.

Another limit is the interpretability of changes in the radargrams, as water can have different effects under different situations. A wetted well-defined surface may quickly become a reflector which is easy to detect. However, tortuous flow paths may not be as ideal. Small structures might be well below the limits of detectability in the complex reflection pattern. As such the structural similarity attribute can only detect zones of significant changes which can be induced by many lumped small structures, one big flow path, or even a favorably oriented stone which gets wetted.

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