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Interactive comment

Interactive comment on "In situ investigation of rapid subsurface flow: Identification of relevant spatial structures beyond heterogeneity" *by* C. Jackisch et al.

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We thank all five reviewers for their critical and constructive comments on our manuscript. We will carefully address all issues in the revision. In the general reply we provide a revised outline and an overview about the upcoming changes concerning this part of the companion MS. It is followed by detailed replies to and discussions of the comments of each review.

1 Consistency and generality of the presented experiments:

The two companion MS deal with the in situ characterization of rapid subsurface flow. In order to highlight the methodological aspects of the study, we will refer to the general interplay of form and function. In our approach, we address this interplay through the detection of responses (MS1, function) and flow-relevant structures (MS2, form).

In accordance to MS1 a possible revised formulation for the title of this MS is: “Form and function in hillslope hydrology: In situ identification of flow-relevant structures”.

We understand from the comments to both MS that the links between the different experiments, the measurements and the different aspects have not been conveyed as self-explanatory as anticipated. As suggested by the reviewers, we will revise both MS towards more clarity and self-consistency. The form – function reference shall help to clarify this.

Moreover, the lack of clear hypotheses caused substantial confusion. In accordance to the general frame, the MS at hand will primarily address form related issues along the following hypotheses:

H 2.1 Flow-relevant structures can be identified in the field under static conditions. (form described without function)

H 2.2 The characteristics of subsurface stormflow can be understood based on structural investigation. (form reveals function)

H 2.3 The localization of response patterns within the structural domain provides the missing link between form and function. (link form and function)

2 Revised outline of the MS

Obviously, the structure of the MS requires revision in order to convey the key findings about the capabilities and limitations of multiple methods for subsurface structure identification at the pedon, plot and hillslope scale. Much confusion was caused by overlaps of process and structure related aspects. The revised MS will keep the focus on form-related aspects and leave most of the process interpretation to the companion MS. This clearer focus will also make room for details about the pedon-scale exploration, which has been too brief before.

The upcoming revised MS will be outlined as follows:

1. Introduction

1.1 Form-function relationship in hydrological sciences and subsurface flow

1.2 General introduction about the identification of flow-relevant structures in the subsurface

1.3 Specific introduction including a brief summary about the headwater under study, the hypotheses, and the overall aims of the study

2. Methods

2.1 Local exploration

2.1.1 Sampling Design: Point measurements along catenas in nested sets around observation clusters during one campaign.

2.1.2 Used methods and respective scope, scale and capability

2.1.3 3D GPR survey of the hillslope

2.2 Plot scale experiments

2.2.1 Design: 3 close-by plot irrigations as repetitions with different intensity.

2.2.2 Multi-method: Coherent use of dye and salt tracers, soil moisture monitoring, snap-shots of soil water composition regarding stable isotopes, time-lapse 3D GPR

2.3 Hillslope experiment

2.3.1 Design: Minimal replicate of plot scale setup + focus on lateral reaction on the hillslope. In conjunction with natural event to have an established connectivity and to reduce the effect of initial wetting and thus irrigation intensity and amount.

2.3.2 TDR network as spatially distributed reference. GPR transects as "virtual, non-invasive trenches".

3. Results

3.1.1 Point samples remain trapped in high heterogeneity but we can derive the mean integral plot properties (without its spatial organization).

3.1.2 3D GPR survey suggests a patchy layer of structures which later on prove to be not flow related. The driven case is needed.

3.2 Under dynamic conditions we see preferential flow and a lateral reaction in the deposit layer. But we cannot determine the hillslope response - especially as neither the share reaching the deposit layer nor the characteristics of the flow network can be determined.

3.3 TDR profiles are strongly limited in their spatial reference (resolution in time and space). GPR inferred trenches give a more comprehensive picture into the hillslope flow network as discrete, connected and leaky structures.

4. Discussion

4.1 Methodological discussions of the capabilities and limits of the used setups and methods

4.2 Conceptual discussion of heterogeneity versus structure

5. Conclusions

H 2.1: No, the driven case is needed to identify flow-relevant structures.

H 2.2: Structural investigations (including irrigation experiments) can provide crucial information to understand the processes. However, structure alone does not reveal function.

H 2.3: Form and function are mutually paired in the hydrological system. Overly strong assumptions about structures or processes can be avoided by the presented non-invasive GPR inferred trenching method, which can visualize and localize response patterns. This allows for more specific investigations and monitoring of subsurface processes.

3 Overview about main upcoming changes

In the specific replies to the reviews much more detail is given to all raised concerns. These changes will be embedded in the following revision schedule:

1. General story line and readability

1.1 Clarity about hypotheses, science questions and story line in abstract, intro, conclusions and rest of the MS.

1.2 Shortening where possible, extension where needed.

1.3 Clarity about the linkage between the methodological and case related aspects of the MS.

1.4 Final editing by a native English speaker.

2. Introduction

2.1 strong revisions to refer to more studies around the globe

2.2 highlight the methodological aspects and refer to such works more specifically

2.3 link more clearly to the conceptual aspects of inferring hillslope-scale process understanding from local or signal measurements

2.4 clarify the used terminology and sketch of the form-function concept

3. Methods

3.1 Add the WHY to each aspect and draw their connection clearly

3.2 Add sampling design (especially of local exploration).

3.3 Add more details on the hillslope experiment (although repetitive to the companion MS).

3.4 Outline again how the methods will answer the overarching question of exploration of a structured subsurface.

4. Results

4.1 more details on local exploration

4.2 split case-related results from method-related ones

5. Discussion

5.1 Shorten discussion on case results and process interpretation to a minimum showing the limits and novelties of the results at the case of the upper Colpach basin.

5.2 Give explicit frame to methodological discussion to streamline the narrative towards the main findings.

6. Conclusions with reference to the hypotheses

Many thanks again to all reviewers and Alex Zimmermann for your time and critique to substantially improve our MS.

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4 Reply to Review 4

Review In situ investigation of rapid subsurface flow: Identification of relevant spatial structures beyond heterogeneity The presented study of Jackisch et al. (2016) investigates the identification of structures of preferential flow in the context of heterogeneity based on soil samples, TDR, GPR and tracer measurements. The content is relevant for the journal but the modalities not. The author's introduction to the topic is lopsided and incomplete.

We regret and by no means intended that the statements and selected references have caused a lopsided impression. The central focus of the MS is the identification of flow-relevant subsurface structures based on in situ exploration and experiments. This requires an integration of methodological, conceptual and experimental aspects, which we will convey much clearer in the revised version of the MS. Although a thorough review of the history and state concerning these aspects is out of scope of the MS, we will fully revise the introduction, remove too strong statements, add further references to experimental basins and reviews, and avoid overly close-related citations.

The manuscript is more a battle of material and not expedient. There is no red line. Where is the benefit of all these measurements to understand preferential flow patterns? If they would like to present syntheses of all these different measurements reorganisation and more guidance have to be conducted. The authors overextend in the method chapter with details of the measurement devices, which are unimportant for the story and could be moved to an appendix.

We clearly see the deficits in the consistency of the presentation of the study and will address this as stated in the general reply. We combine standard and novel techniques at different scales to develop a more robust methodology for hydrological exploration in structured soils. We clearly see that we need to convey the key messages more clearly. However, we disagree with the reviewer that the methodological details should be moved to the appendix. Each method is a valid and often used means to base an analysis of a plot, hillslope or catchment on. The details are required to highlight and discuss the assumptions and limitations of these methods.

Moreover, each analytical method comes with a series of necessary assumptions and limitations. As we cannot simply look into the subsurface to observe the processes through some kind of "X-ray vision", we always need to link process perception, incrementally observed responses and detected structural information. The study examines the question how to explore the structural characteristics without too strong dependence on perceptions. Moreover, we highlight that a mismatch of sampling and structures can lead to the trap of heterogeneity. In the revision we will draw the line more clearly, how a combination of such methods and a revised exploration strategy can reduce the susceptibility to misinterpretations as a result of a priori process assumptions.

The manuscript is not stand alone. An experimental study needs a study site description irrelevant if that is presented in the companion paper or not.

Much of the confusion is caused by a too brief localization of the experiments in this part of the companion paper. Because the focus of the study is not the single experiments but the methodological and conceptual implications, we had hoped that this brevity would make understanding easier. We will change this by adding details and reducing the dependency to the companion MS.

Plot 2 has to be linked to the locations of the irrigation experiment and to the sampling.

This will be done.

The introduction chapter is not consistent written and needs modification. Where are all the old studies which investigate the presented phenomenon? The overview is incomplete, which makes the sentence on page 2 at line 15 and 28 hardly credible.

As stated above, the introduction will be revised strongly along the raised critique with more references. A central concern of the modified introduction will be to really focus on flow-relevant structures and to embed its relevance in hydrological sciences.

The block of the models (page 2 line 25- page3 line 3) is not that what I would expect in an experimental study without any simulation is presented.

The complexity of hydrological systems has caused the development of a plethora of models. They are powerful tools to advance our concepts and theories beyond the limits of singular measurements (refer to the “uniqueness of place” debate). Perceptual models are the link between experimental data and the actual numerical models (Gupta et al., 2012). For the experimentalists this can potentially lead to biased observation techniques; For the modelers it is the structural uncertainty which is difficult to assess. Exactly this motivates the study at hand to develop an exploration methodology which reduces the need for assumptions, which allows to visualize subsurface flow paths and which has the potential to validate or falsify some of the proposed model concepts. We will revise the introduction also in this regard to avoid confusion and to make the intentions clearer.

And which is typical for the complete manuscript they are always jumping from one topic to another one without identifiable reasons.

Our story line will be strongly revised (please see general reply for details). The confusion will be solved by more clarity between the methodological concerns and the case-study elements.

There are studies (Heller and Kleber, 2016) which have similar hillslope structures with comparable periglacial cover layers which lead with much less fancy measurement equipment to much more plausible results.

Thank you for highlighting this study, which investigates a similar system with a different focus. Unfortunately, the paper was not yet published at the time our MS was submitted. We will include this study to complete our references.

Regarding the value of the applied combination of methods, we would like to clarify

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that the intention here is to challenge the assumptions behind standard hydrological methods, compare the approaches and identify a set of methods which proves suitable to identify flow-relevant structures. Our study points out that point measurements and static explorations have very limited capacity for this – especially in heterogeneous conditions. And our study proposes means forward allowing to visualize subsurface flow in 2D and 3D without destroying the system and with very few assumptions. Moreover, we also discuss the current limitations of the techniques.

We are eager to resolve this misunderstanding in the revised MS.

Most of the plots are hardly comprehensible.

With the revision of the structure of the MS also the figures will be revised. The more complex figures will be improved and explained in more detail.

Specific comments: The list is not complete. There are much more points. The authors should firstly rewrite the manuscript.

P2L22: That should be questionable if double peaks are driven by preferential flow. But it is definitely too fare of the scope of the manuscript.

The MS will be restructured in order to keep the focus on the identification of flow-relevant structures.

P3L8: “highly structured periglacial soils” is in contradiction to what periglacial processes lead to “unstructured” soils.

We will add a definition of the used terminology in the revised MS. Especially what we mean with “pattern”, “structure” and “flow-relevant structure” will be clarified. In this regard only homogeneously mixed soils without any layers or preferential flow paths would be considered “unstructured”.

P3L17: 3d flow fields?

Subsurface flow takes place as diffusive flow in the matrix and as advective flow in structures. Both result in a three dimensional field of displaced water which we seek to characterize. We regret that our formulation caused confusion and will change it.

P3L18 large number of measurements is not scientific

This sentence is an introductory overview about the structure of the MS. Methodological details are given 21 lines later. The description of the point measurements will be extended as stated earlier.

P3L18-20: If "the structures remained rather unknown and hardly identifiable even by precise and distributed but static methods like 3D GPR surveying" and that the structure "is rather blurred" why do they examine the phenomenon in 3D?

The subsurface is a 3D network of potential flow paths and soil matrix. In order to characterize this system, a full and scale-aware analysis is the only way to reduce the requirement of assumptions.

The 3D GPR survey was used as the geophysical method of the highest resolution to detect potential flow structures. But heterogeneity and flow-relevant structure could not be distinguished in the resulting radargram. On the one hand, this is a scale problem as preferential flow paths can be below the resolution of the technique. On the other hand, this is a conceptual problem as changes in radar velocity or strong reflectors can be caused by a plethora of conditions, which are not necessarily related to flow structures. Section 4.2.4 intended to discuss this in some detail.

The "blur" in the time-lapse 3D GPR data of the plot irrigation has primarily different reasons: Here the acquisition time of one data cube is about 30-45 minutes. With respect to advective subsurface flow and initial soil water redistribution this timing is too slow to get a sharp snap-shot.

To enhance the readability of the MS we will avoid to anticipate results in the description of the approach. We will clarify our intention in combining scales and dimensions to the methodological question of how much information can be drawn from single observations and how they complement each other.

P4L15-18: Plot and description is missing, manuscript has to be stand alone.

This will be added.

P4L19-30: Move to appendix or leave it out

We disagree that this brief description of the method should be moved to the appendix. Each measurement technique comes with a series of advantages and disadvantages. In order to discuss the limitations of singular point measurements even with the best technique and sampling design, this information is required. In order to clarify the relevance of this information, this aspect will be clearly motivated in the revised MS.

P5 L5: Locations in a plot have to be shown.

We agree and will provide an additional figure in the revised MS.

P9L5: Histogram of Ks values

We will consider a histogram as marginal plot in a revised version of figure 1.

P9L8: That data set which suggests a conductive layer is not presented? Have to be clarified.

It is present in figure 2 and 7 but was not clearly pointed out. This will be improved in the revision of the MS and the figures.

Figure 1: Clarify: local means (large connected dots) and individual measurements (small points). Plot 1B) is hard to read and should be rearranged. Transparency is not apparent. Add uncertainty bars. The colour code information is unimportant. The importance of 1C) is not clear.

The location of the points and the sampling design will be clarified in the revised MS. This will also make the legend easier to comprehend. Local means refer to the mean of all measurements in a 0.1 m increment at a specific site. Figure 1 will be strongly revised.

P9L11: Add geology information

A site description (which was only given in the companion MS) will be added and includes this information.

P10L1: Is that the base layer? Hardly identifiable in the plot. It seems to be completely heterogenic.

We agree that figure 2 deserves more clarification about potential layers. An interpretation will be added. Moreover, this ambiguity about what is structure in heterogeneity is exactly the topic of this MS. Hence it is intended to show that a derivation of a conductive layer is as problematic as to simply speak of non-resolvable heterogeneity.

Figure2: Sketch of hillslope has to added to have a better orientation what is upslope and down slope

This will be done as part of the localization of the measurements.

Chapter 4.2.4: What is the intention of that measure? Chapter is hard to follow. The usability is not clear by interpreting figure 11. The plot needs more description.

The intention of this subsection is to adequately discuss the limitations and interpretability of GPR data in hydrological applications as ours. GPR records reflections of an emitted wavelet which is affected by many factors. Soil water content is just one of them. With reference to Klenk et al. 2015 and Guo et al. 2014 our study goes a little more into detail about the requirements for GPR applications. Regarding the identification of flow-relevant structures we had to introduce a threshold for the structural similarity attribute which we corroborate here. We will revise this subsection and figure 11 to link it more clearly to our findings and discussion.

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