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

C. Jackisch et al.

conrad.jackisch@kit.edu

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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.

Printer-friendly version

Discussion paper

4 Reply to Review 3

The manuscript presents experimental techniques and results that allow identifying relevant structures in soils at three spatial scales that could be responsible for the generation of preferential flow along hillslopes. The authors wanted to obtain a better understanding of the structure-related flow processes by utilizing all information from complementary techniques, to finally improve the conceptual modelling of hillslope hydrology. The topic, data, and analyses are of interest and fully in the scope of the journal; experimental results appear technically sound, of high quality and relevant.

General Comments: I was impressed by the large amount of high quality experimental data that are presented. Almost each one of these experiments could have been the basis for an individual study and a detailed analysis (i.e., the time-lapse GPR results); but as I understood, the idea here was to bring information obtained by the various techniques and at the three spatial scales together such that it would fit into an integrated overall conceptual picture or description of the rapid flow in hillslopes. This highly ambitious goal could probably not fully be achieved in the present manuscript such that it still has the appearance of a more-or-less loose collection of experimental results. This could probably be improved by including an introductory conceptual scheme (perhaps as a figure) in which the hypotheses are summarized such that the reader can see why and where the various measurements were required to obtain certain information.

This integration is exactly the intention of the MS and we are very thankful for highlighting options to improve it to really convey this message. The framework given in the general reply provides the structural and conceptual guidelines for the revision of the MS. We will take up the suggestion and include an introductory conceptual scheme.

Possibly, it may turn out that some information is not really necessary for the identification of the structures? The manuscript presentation should be improved. In the present form, the manuscript appeared to me more like a research report than a scientific paper and not very specific.

The proposed revised story line will clarify most of the confusion as it will relate each information to the respective hypothesis and finding. We will use the concept of form and function as framework to structure and process. It will also help to assess the importance of our data for the results of the study.

As this part of the companion paper is concerned about the identification of flow-relevant structures in the subsurface, we will shift the data of stable isotopes in the hillslope scale experiment to the companion MS, where it will be related to findings in the surface water domains.

The soil-hydrological exploration data will be described in more detail with clear reference of its capabilities and limits to reveal the underlying structures. Through this we will make it much easier to follow the specific aspects of the integral study.

Clear hypotheses and objectives are missing or hidden somewhere in the text. In contrast to the detailed experimental results, the analysis is descriptive and mostly rather general, such that the identification of the flow-structure relation seems to remain largely qualitative. For instance, flow pattern relations with structures of soil horizon and patchiness were identified, which is interesting, but how could this be quantified?

The revised version will start with a set of specific hypotheses which will be followed through the MS. We will check if form can be described without function, assess how form can reveal function, and establish the link between the two to better characterize subsurface flow in discrete structures.

We understand and share the desire for precise and more quantitative analyses of the flow-relevant structures. In the revision of the MS we will detail on this more specifically by introducing some quantitative measures to the identified structures. But we will also highlight the difficulties to quantify the dynamic flow network based on the respective measurements more clearly. This will be closely related to the generality of the presented study. This is more related to methodological limitations than to any new finding in process understanding.

Despite the large number of techniques, why was the use of tensiometers not considered, not even mentioned?

Using tensiometers would be a very insightful tool - especially in combination with the employed TDR tube probes. However, our study presents a minimal-invasive method to observe fast and highly heterogeneous subsurface flow. Moreover, there are some conceptual and technical reasons why tensiometers were not used: 1. The soils in the basin under study are subject to preferential flow as was reported in earlier studies and seen from local measurements and soil cores. Soil matric potential gradients are the driver of diffusive flow. Advective flow is mostly driven by gravity and low capillarity and friction acting against it in flow structures like voids, cracks, burrows, etc. Hence tensiometers recording matric potential would only add information at the desired scale, if we can simultaneously measure soil moisture. 2. The TDR observation tubes were installed by percussion drilling and consequent percussion push of the liners. The tube probes were lowered in these tubes to measure soil moisture in 12/18 cm increments every 10 cm. The installation of equally many tensiometers would have destroyed most of the structures in the hillslope and plots. 3. The contact of the tensiometers to the matrix is critical to gain good measurements. In barely developed soils with many voids and high stone content it is almost impossible to anticipate the positioning of such a sensor in the field (despite all difficulties coming with its installation). The sensor would only refer to a point measurement which we highlight to be largely susceptible to ambiguous reference in such a structured domain. 4. Moreover, the sensor cables would inhibit the application of GPR at the same location.

Detailed comments:

1. The abstract is not informative and far too general. From the abstract is it unclear what was done; hypotheses, objectives, methods, results and conclusions are missing.

The abstract will be fully revised to follow the form-function frame and to specifically detail on the experiments and findings at the three scales.

2. The soil water retention data are not used in the analysis (why did you show it?), why did you present drying retention data when analysing the infiltration; rapid flow events require knowledge of wetting curves or hysteretic behaviour?

We intended to show this data to underline the heterogeneity of the headwater and to use it as reference why we cannot resolve structure from such 250 mL core samples. To improve the MS we will detail on this part much more in the revision. The drying curve is shown, because it is the standard reference we can obtain in our laboratory measurements. We agree that the wetting curve may be of more relevance in an infiltration study. However, it is out of scope of the study to analyze the spectrum of pores used by wetting against those affected during drying. We are currently addressing process concepts behind the observed hysteresis in the retention curve in another study: Zehe and Jackisch, 2016 HESSD (doi: 10.5194/hess-2016-107).

3. Page 22 Line 15: did you really observe the macropore-matrix exchange? How and where do you use it?

We observed the result of macropore-matrix exchange in terms of dye staining and soil moisture change around the macropores. Moreover, we measured the dynamics of the structural similarity attribute as proxy for soil moisture change. You are right, that these methods do not allow a direct observation of the exchange. Thus we infer the process.

The sentence will be changed to: *At the same time, multi-porosity approaches remain challenged to define the macropore-matrix exchange we infer from the observed patterns.*

4. Discussion: In the discussion, the referencing to figures or tables that show the results is mostly missing.

We will revise this and link hypotheses, results and other relevant studies more clearly.

5. Page 23 Line 10: Can't you draw a sketch of these ideas?

The MS at hand is concerned about the identification of flow-relevant structures, which cannot be identified based on static exploration or point monitoring without knowledge about the general context of the respective measurement. We will transfer purely process-related aspects to the companion MS in the revisions. There, we will consider a conceptual sketch summarizing the identified functions/processes.

6. Page 24 Line 1: How did you use the water Retention data?

We intend to show the remarkable variability. Young soils on periglacial slope deposits prevail in the headwater. They exhibit these heterogeneous soil properties. All approaches to group the samples into geomorphological classes failed to exhibit structure. This is due to a) the general mismatch of the scale of 250 mL undisturbed core samples with the relevant flow paths and b) the high content of gravel and voids, which affect the retention curve especially above field capacity and concerning its scaling with available pore space. To clarify this, the section about local exploration will be extended. We will also update the graph adding information about sampling depth and relative distance to the stream network and revise the description accordingly.

7. Page 24, chapter 4.2.2. I did not understand why tensiometers were not considered at all. The driving force is the hydraulic potential in unsaturated soils; matric potential is also more sensitive than soil moisture especially with rapid processes.

For fast subsurface flow we consider gravity-driven flow in voids and flow paths more relevant than the hydraulic potential which is rather the control of diffusive flow and macropore-matrix exchange. Please refer to the explanation given to the general comments for the details about the tensiometers.

8. Page 24, Line 16: I did not understand this statement: "...the quantification of advective water from the recorded changes in soil moisture has proven not feasible...", a new finding?

The companion MS details on findings about the observed apparent advective velocities. There it is elaborated that we can only extract spatially distributed arrival times as some sort of maximum velocity distribution. The central concern is that soil moisture sensors can only detect changes in state in their direct vicinity. To calculate flow velocities form dynamic states requires assumptions about the control volumes in order to balance incoming and outgoing changes. But this assumption of a well-mixed control volume is contradicted by the found discrete flow paths.

Hence the statement is not new. It is just another example how also in-situ observations are bound to perceptual models. In order to clarify this, we will change the paragraph accordingly.

9. Conclusions: At the end I was wondering if your goal was a novel hydrological survey tool or an improved conceptual model.

As was summarized by the reviewer earlier, it is the integration of both into a methodological revision how a hillslope or catchment can or should be surveyed to identify the elements needed for a sound conceptual model and hydrological monitoring. We intend to clarify this element of the study by introducing the three hypotheses and by keeping the focus on the identification of flow-relevant structures without too much distraction to the respective process interpretation behind. The latter is left for the companion MS, which will be streamlined in this regard.

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