Interactive comment on 'In situ investigation of rapid subsurface flow: Temporal dynamics and catchment-scale implication' by L. Angermann et al.

Response to comments by reviewer#2

We highly appreciate the thorough review and constructive comments of the anonymous reviewer. We are happy to implement and discuss the cogent remarks on data analysis and presentation of our findings and developed a concept to tackle the basic criticism regarding the story line and the conclusiveness of our results. This concept is based on the comments by all three reviewers and provides a common theme as well as overarching yet standalone story lines for the two companion papers. We will shortly present the main idea of the new concept, the revised hypotheses as well as the restructured story line of the first manuscript (MS1). As these improvements are relevant for our response to the comments by all reviewers, this part is included in all replies. Afterwards, we will address the general and specific comments made by reviewer#2, with our replies inserted in the original review.

Conceptual framework

To better elaborate the methodological aspects of the study and to provide a common theme for the two companion papers, we want to employ the concept of form vs. function. The original term 'form follows function' was first established in architecture and soon was adopted by biologists. It refers to the idea, that form and functionality are closely correlated, influence each other and co-evolve. We suggest to transfer the same idea to hydrological systems. This allows us to separate and analyze their two main characteristics: Their form, which is equivalent to the spatial structure and static properties, and their function, equivalent to internal responses and hydrological behavior. While this approach itself is not particularly new to hydrological field research, we want to employ this concept to explicitly pursue the question of what information is most advantageous to understand a hydrological system.

Accordingly, we developed different categories to organize and describe the data presented in the two manuscripts: Structural data summarizes all sorts of data which focus on direct exploration of form, e.g. soil cores. Response dynamics, on the other hand, are observations of function. They represent processes deprived of their spatial context and include soil moisture dynamics and discharge responses. In between these two categories are flow-relevant structures and response patterns, which may contain information on both, form and function of the system.

In the presented study, we apply this concept to subsurface flow within a hillslope. The first part of the study (MS1) methodologically focuses on function: We observed response patterns and dynamics from a natural rainfall event and during an irrigation experiment. The results are used to infer hydrological processes and the spatial organization of the monitored system. Based on these findings, the informative power and conclusiveness of the data will be discussed.

The second manuscript (MS2) focuses on form and starts off with a thorough structural exploration of the subsurface. It then proceeds towards observations of flow-relevant structures and response patterns and analyzes the information gain along this path.

Hypotheses and story line

The hypotheses of both manuscripts can be aligned according to the form/function framework and will clearly be stated at in the beginning. The hypotheses of MS1 will focus on the potential of response observations for hillslope hydrological field research and the application of time-lapse GPR measurements in this context:

- **H1.1** Response observations (discharge, TDR & GPR data) are sufficient to characterize subsurface flow ywithin the hillslope.
- **H1.2** Response patterns can be used to deduce flow-relevant structures in the subsurface.
- **H1.3** Time-lapse GPR measurements visualize subsurface flow dynamics and patterns and can replace hillslope trenches.

The story line will be streamlined and arranged along these hypotheses. This will help to make the manuscript easier to follow and to better elaborate the important and novel key points of our study. In the following, new or restructured sections are marked in brown.

1 Introduction

- Concept of form and function: form and function are the main defining features of a system. Applied to catchments, the concept describes any kind of spatial structure (from topography to macropores) as form, and the sum of all processes defining the hydrological behavior of the catchment as function. Both strongly influence and determine each other.
- Example subsurface flow at the hillslope: structures and heterogeneity control flow patterns and velocities and thus the occurrence of preferential flow. Which one is better suited to characterize a hillslope, form or function?
- Focus on function: What does it need to describe subsurface flow and preferential flow at the hillslope? How to observe subsurface flow processes? What do response patterns and dynamics tell us about form and function of a hillslope?
- Methodological challenge of preferential flow: former approaches at different scales: plot, hillslope- and catchment-scale.
- Hypotheses as stated above

2 Methods

- Study site description
- Hydrological response monitoring: Hydrograph and surface water isotopes
- Hillslope-scale irrigation experiment
  - Setup
  - Process monitoring
  - Piezometer isotope sampling
- Data analysis
  - TDR data analysis
  - GPR data analysis
  - Comparison natural event vs. irrigation: Distinguish the signals and calculate areal share of activated cross section
  - Response velocity calculation

3 Results

- Response to the natural rainfall
  - Hydrograph and surface water isotopes
  - Subsurface response patterns (green GPR reflection patterns)
- Irrigation experiment
  - Core area water balance
  - Soil moisture dynamics
  - 2D time-lapse GPR
  - Soil and piezometer isotopes
  - Combination of TDR and GPR
  - Response velocities
- Comparison of natural event and irrigation: Areal share and signal strength of GPR measurements before and after irrigation

4 Discussion

- Process interpretation
  - Interpretation of artificially induced response observations during and after the irrigation
  - Interpretation of the natural response observations after the rainfall event prior to the irrigation experiment
  - Identification of (flow-relevant) structures from response patterns
- Methodological discussion

- Conclusiveness of function observations without structural knowledge with regard to process identification and the characterization of a system
- Conclusiveness of function observations without structural knowledge with regard to transferability and regionalization of results
- Evaluation of GPR as trench replacement

5 Conclusions

- **H1.1** 'Response observations (discharge, TDR & GPR data) are sufficient to characterize subsurface flow within the hillslope.'

  → Processes can be identified and characterized without any concrete information about spatial structures. However, observations are limited in spatial (and temporal) resolution and interpretations beyond observation scale remain speculative.

- **H1.2** 'Response patterns can be used to deduce flow-relevant structures in the subsurface.'

  → Response patterns allowed to develop a conceptual description of the flow paths network, which is linked to subsurface structures. However, actual structural features, such as the deposit layer or the bedrock interface, could not be located.

- **H1.3** Time-lapse GPR measurements visualize subsurface flow dynamics and patterns and can replace hillslope trenches.'

  → Time-lapse GPR measurements lack the quantitative power and the direct link to structures (obtained by excavation) of trenches. Their spatial and temporal flexibility as well as their non-invasive character, however, are very advantageous for the investigation of highly dynamics and spatially distributed flow processes. Thus, the application of time-lapse GPR measurements in combination with soil moisture measurements are a powerful tool for the observation of hydrometric responses. Depending on the research question, the method can replace labor-intense trenches and even increase the observation density due to its spatial flexibility.

The titles of the two manuscripts will be adapted accordingly. They will be rephrased to emphasize the methodological aspects of the two papers, while keeping the focus on hillslope processes. The final versions of the titles are still subject to discussion. A possible suggestion for the title of this manuscript is:

Form and function in hillslope hydrology:
In situ characterization of subsurface flow based on response observations

We hope to have given a good overview over the anticipated revisions of the manuscript. While the elaboration above was meant to provide the 'big picture', our answers to the first reviewer's general and specific comments will illustrate how this concept will help to mitigate the reviewer's concerns. In the following, our replies are inserted into the original text by reviewer#2 and marked in purple.

Answers to the general comments

This paper presents an interesting experimental approach, combining different types of measurements and techniques (soil moisture monitoring, time-lapse GPR, discharge and tracer measurements) to investigate mechanisms of rapid subsurface flow. Such combinations are often very promising as they can yield new interpretation of observations and new insight. The visual presentation of results, i.e. the figures, is very well done, the figures are informative and mostly well structured. The language is mostly suitable, with sentences sometimes being quite long. Here a language revision would certainly help to make the text more pleasant to read.

However, I do not think that the authors achieve their objective of investigating and providing new insights into rapid subsurface flow processes. As they themselves state in the Conclusions, the link between processes and structures is still missing, many statements remain speculations and thus, an exciting new insight is not really presented.

In their current version, the two companion papers were separated by their foci on temporal dynamics on the one hand (first manuscript at hand, MS1), and spatial structures on the other (second manuscript, MS2). Therefore, the discussion of the link between processes and structures was deliberately avoided in MS1 and left to the companion paper.

In the course of the revision, the foci of the two papers will be shifted towards a more methodological perspective. While we will pursue the question of how much information we can get from pure response observations in MS1, MS2 starts off with structural explorations of the subsurface. We subsume this conceptual approach under the term 'form and function', applied to hydrological systems. According to this concept, the link between processes and structures will still be part of the findings of MS2. However, the informative value of observed response dynamics and patterns and the usefulness of structural information will be discussed more thoroughly also in the revised manuscript MS1.

The experiments were no doubt labor-intensive and comprehensive, and I can understand that the authors would like to present them in their entirety. I have the impression, though, that the authors were not quite sure about the focus of the manuscript. Title and abstract speak of rapid subsurface flow and identifying preferential flow features whereas in the introduction and then later in the discussion the focus shifts to double-peak hydrographs as if the explanation of these had been the aim of the paper. The abstract does not indicate this. In-between also (multi-modal) transit-time distributions are mentioned several times but surely the experiment was not designed to investigate transit time distributions. The discussion is lengthy and focuses on methodological aspects.

We understand that the story was not well presented in the current version of the manuscript and needs to be improved. Based on the comments of the three anonymous reviewers, we decided on a common theme for the two companion papers and streamlined the story line of MS1. The revised manuscript will focus on the investigation of subsurface flow processes within the hillslope with a strong methodological perspective. The presented hydrographs will still be a minor part of the study to provide a temporal framework the subsurface flow processes observed after the rain event. The discussion of double peaks and (multi-modal) travel time distributions, however, will be minimized or avoided.

At the moment I doubt that the manuscript presents sufficient new data and findings beyond speculations to justify a publication. Maybe it would be an option to combine this manuscript and the mentioned companion paper by Jackisch et al as they present the missing link between processes and structures as stated in the Conclusions, last paragraph.
The companion paper by Jackisch et al. presents many experiments and results which were not introduced in the manuscript at hand and does not include all of the data presented here. The presentation of the entire set of methods, results and conclusions clearly exceeds the frame of one paper. We therefore suggest to revise the two manuscripts. We will clearly elaborate their specific and distinct perspectives, while also allowing slightly more overlap than in the original version so that the links between processes and structures can be pointed out.

Answers to line-by-line comments

- P. 2, L 3: preferential flow and rapid subsurface flow are not per se synonyms
'rapid subsurface flow' will be removed and the use of these terms checked throughout the manuscript.

- P. 3, L 12: if the explanation of double-peak hydrographs is indeed the motivation, this should be mentioned in the abstract
As stated above, the story line of the manuscript will be revised in a way, that the focus is on the hillslope response. The abstract will be revised accordingly.

- Section 2.1/2.2 and 3.1: I was a little confused that first it seemed to be a study focusing on the irrigation experiment whereas later on also longer-term behavior is described as result. I would only focus on description of the event and potentially, move descriptions of the general hydrological behavior of the catchments to the site description.
As suggested, the first three sentences of Section 3.1 will be removed and the necessary information will be given as part of the site description.

- Section 2.3.2: I had difficulties to exactly understand the TDR measurements with access tubes and would recommend to describe the soil moisture monitoring more clearly. Could you insert the prongs of the moisture probe via the access tubes in different depths?
The used Trime Pico IPH probes (IMKO GmbH) do not have prongs, but aluminum plates as TDR wave guides. These plates are mounted on opposite sides of the probe, pressing against the access tube and measuring through the PVC access tube. We will clarify our description of the procedure, possibly also including a sketch.

- P. 8, L 1: predominantly
Will be corrected in the entire manuscript.

- P. 8, L 6: which three TDR probes? Unclear
This will be clarified three lines above:
- before: 'Two versions of the TDR sensor were employed, with either

0.12 m or 0.18 m integration depth.'
- now: 'Soil moisture was measured manually. To enable parallel measurements and increase temporal resolution of the measurements, three probes were used in parallel. These probes differed slightly in their sensor design: Two TDR probes had an integration depth (i.e. sensor length) of 0.12 m and one probe had an integration depth of 0.18 m. '

- Fig. 2: I would not show the location of the piezometers here as you do not discuss any results. That may only be confusing. You can still mention in the text that you installed them but they measured any transient water tables. Also, it would help if you could indicate the three diverging transects in the figure.
  In the revised manuscript we will include the isotope data from water seeping into these piezometers as well as soil core samples taken during installation, which are currently presented in MS2. Due to these changes, the piezometers' positions will be of relevance in the revised manuscript. We therefore suggest to include them in the map of the revised manuscript. We will add lines to indicate the three diverging transects.

- P. 9, L1: ...transect of 6 piezometers 'intended to observe transient water levels'...
  We will change the sentence as suggested.

- P. 9, L 28-29: add numbers of soil moisture profiles here to make sure it is clear to the reader which profiles you are referring to
  Will be added.

- P. 13, L 1: intensity of irrigation stated here is different to intensity stated in the methods section
  This discrepancy is based on the three different monitoring methods we applied: a flow meter, a tipping bucket, and 42 rain collectors. While the flow meter and tipping bucket are considered more reliable with regard to absolute amount, the rain collectors were mainly used to evaluate the homogeneity of the irrigation intensity. We will relate the measurements to each other and correct this discrepancy.

- P. 13, L 1: when did surface runoff cease?
  Surface runoff ceased approximately 20 min after the end of irrigation. We will include this information in the revised manuscript.

- P. 13, L 4-5: I am not sure what is meant with 'overshoot'. Is this shown in Fig 4? Please explain more clearly.
  We will rephrase the sentence and explain the observation: 'All profiles showed a mass recovery of more than 100 % (i.e. higher storage increase than water input at measuring time, see Fig. 4) in the first 60 min of the irrigation period.'

- P. 15, L 12: I would recommend to make the way times are stated consistent between text and figure (3.3 hours vs 03:18)
  Will be done.

- Fig. 5: where is the map for TDR 5?
  TDR 5 showed only very low soil moisture dynamics. It was left out to

leave more space in the whole-page figure for the 'more interesting' profiles. We will try to find a way to put all profiles in that figure.

- Fig. 5: And the decreases in soil moisture shown e.g. in the lowest row of profiles is not really discussed in the text.
The decrease in soil moisture can be attributed to the fading signal of the natural rain event. However, it is minimal compared to the soil moisture increase observed elsewhere and close to noise level. We will add this information to the manuscript and discuss it accordingly.

- I do not fully understand how the authors distinguish in the GPR maps between natural event water and irrigation water. Can that be done with the GPR signal? Please explain in a little more detail.
The discrimination was made based on the dynamics of the GPR signal. We assume that the irrigation is causing any (significant) increase in soil water content after irrigation start. This assumption is not per se valid, but in our case supported by the increasing signal strength and the dynamics after irrigation start. On the other hand, measurements taken before irrigation start show all areas activated by the natural rainfall event. Thus, areas where soil water content is decreasing during the irrigation are interpreted as flow paths that were only activated during the natural rainfall event, but not during irrigation. The procedure is described in the Methods section (P. 10, L. 24-28 of the original manuscript) as well as in the figure caption of Fig. 6. We will improve the description and mention the necessary assumptions.

- P. 17, L 2-3: is this a speculation or really supported by the results?
We clearly see the fading signal after the natural rain event as well as the increase and decrease initiated by the irrigation. Also, the patterns are distributed across the GPR transects. While we cannot specify the size and characteristics of these distributed structures, a groundwater table or flow layer would have caused a clear and more organized signal in a specific depth. In the revised manuscript we will provide more detail on these findings and also discuss the informative power of the observed response patterns. We will also rephrase the annotated sentence to avoid over-interpretation.

- P. 17, L 5-6: maybe better say 'water that was supplied from upslope areas was more important...'
Will be changed.

- Fig. 6: there seems to be one map missing of transect 4 in the lower right corner where the legend is located?
The measurement was omitted to fit in the legend while showing the other measurements in bigger size. As described in the text, transect 4 seemed not to be affected by the irrigation experiment much and shows generally low dynamics. The figure is at maximum possible size already and we feel that it is not appropriate to further shrink the size of the subplots. However, we will try to find a different solution or explain the reason for omitting the last sub-plot in the figure caption.

- P. 22, L 13: agreed instead of fitted
Will be changed.

- P. 22, L 24-25: again, is this a speculation?
  This is the interpretation of the response patterns in both, GPR and TDR results. The 2D GPR reflection patterns clearly show that there is a heterogeneous soil moisture response, but no groundwater table or defined flow layer. The heterogeneity between the TDR profiles as well as the delayed signal in the intermediate depths of the core area profiles also imply preferential flow. We agree, that any interpretations beyond these findings are speculative, and will leave them to the second manuscript where they are backed by structural information. The focus of the revised manuscript will be shifted towards the methodological aspects of interpreting response patterns and dynamics. Thus, we will highlight the informative value of the presented data rather than their interpretation.

- P. 22, L 30: here now it sounds as if the investigation of double-peak hydrographs is the main objective of the paper. This comes as a surprise as it was not mentioned neither in the abstract nor in the title.
  The catchment response was meant as a reference to evaluate the hillslope-scale observations, but was discussed too thoroughly. We will revise the story line, focus it on the investigation of hillslope responses and reduce the discussion of the catchment-scale observations to the necessary and helpful amount.

- I am not sure that from these measurements of soil moisture at discrete points in time lateral flow can really be inferred.
  We agree that discrete measurements in time alone are per se not useful to infer lateral flow. However, our experimental setup allows for a clear separation between observations at the irrigated area and the downhill monitoring are. Due to the lack of water input at the downhill monitoring area, all increases in soil moisture downslope of the rain shield are the result of lateral flow or a combination of lateral and vertical flow. Thus, the spatial arrangement of measurements provides the necessary context to interpret the observed dynamics.

- P. 24, L 28-33: I do not think the reasoning here for the high input rates in convincing. I wonder how useful the observed patterns are for more realistic rainfall conditions.
  In the frame of the anticipated revision, we will restructure the discussion. The general discussion on the experimental design, including the annotated paragraph, and different aspects of soil moisture monitoring in general will be drastically shortened and the sentence deleted.

- P 26, L 11: soil moisture should be used with caution as indication for flow, and this has been discussed in the literature before
  We agree and will rephrase the sentence accordingly

- P26, L 19-24: this is not new
  As mentioned earlier, the general methodological discussion will be drastically shortened. We will avoid such general statements or provide the necessary references, if required. The revised discussion will focus on the (methodological) link between form and function of hydrological systems and the explanatory power of response patterns and dynamics in that context.

- Conclusions: I would not mention transit-time distributions here. That surely goes beyond the focus of the paper and may be a stretch to infer.
  The discussion of catchment-scale observations will be reduced to the aspects which are important to evaluate the hillslope-scale interpretations. These aspects do not include transit-time distributions, nor will they be part of the conclusions of the revised manuscript. Thanks for pointing this out.
- P29, L 14: stable
  Will be corrected.