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Hydrology and
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Discussions

Interactive comment on "Applied tracers for the observation of subsurface stormflow at the hillslope scale" *by* J. Wienhöfer et al.

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We gratefully acknowledge the thoughtful review of anonymous referee #2. In the following we would like to respond to the specific comments.

Comment 1. The role of steep slope

One of the main uniqueness of this manuscript is the steepness of the studied hillslope, as the authors mentioned in Abstract, Introduction and so on. However, they did not discuss the role of slope gradient in subsurface storm flow. It would be necessary to include a comment on roles of steepness of hillslopes.

Response to comment 1

Subsurface storm flow was introduced as a generic term for rapid lateral flow processes. The lateral component of these flow processes increases with steeper slope angles, and water flows become more and more parallel to the ground surface. We will slightly revise the introduction with a comment on the steepness of slopes.

Steepness of the slope directly translates into a higher hydraulic gradient. By assuming water flowing parallel to the ground surface and average slope to be parallel to the slope of the bedrock, we can approximate the hydraulic gradient in steady-state conditions by the topographic gradient. Following this reasoning, we can estimate a bulk saturated hydraulic conductivity of the entire transport domain from the tracer BTC. Average tracer velocity is equal to the Darcy velocity divided by porosity, while Darcy velocity is hydraulic conductivity multiplied with hydraulic gradient. The average slope gradient at our study site is about 0.5 (30 m/60 m; Fig. 1b). Considering 0.5 as a value for porosity, we obtain that bulk hydraulic conductivities are identical to the observed mean tracer velocities (Table 3). These are as high as the conductivities measured in situ for the top soil (Sect. 2.1), although they are integrated over a considerably larger domain. We therefore can conclude that the tracers were transported in flow paths with similar hydraulic conductivities as in the top soil under saturated conditions, which means that the transport domain is characterized by a continuing network of preferential flow paths. We will add this result to the revised manuscript.

Comment 2. Heterogeneity of flow velocity (Table 3)

Based on Table 2, it would be useful to include a brief comment on the heterogeneity of flow velocity in section 4.1. These discussions could be useful to understand processes of preferential flowpath in the hillslope. I am very interested in relatively small (less than one order magnitude) spatial variability of flow velocity, although the flow path i.e., results of dyes staining test, highly varied in space.

Response to comment 2

The flow velocities, i.e. the differences in times to tracer breakthrough, tracer peak and centre of mass, are not only to be seen in relation to the different transport distances, but also with regard to the specific application plots. This means that velocities not only vary as a function of distance, but also as a function of location. Or, in other words, the transport from a specific application plot to the measurement locations is determined by pathways that are highly specific and discrete in space, as also shown with the dye staining tests. Therefore, it seems rather impossible to quantitatively assess the spatial variability of flow paths or flow velocities at this hillslope at this scale. In fact, we found it rather astonishing that the variability in the observed velocities was "only" about one order of magnitude. This implies that comparable transport regimes were active for the different parts of the hillslope tracer tests. With reference to the specific comment #1 (see above), the variability of tracer velocities reflect the variability of bulk hydraulic conductivity. However, a clear relation to distance has not been observed (e.g. higher velocities along longer distances). We will include a brief statement about the variability of flow velocities and the specificity of flow paths connecting different locations along the hillslope in the revised manuscript.

Comment 3. Flowpath of the spring (Page 2980 Lines 13 and 14)

Unfortunately, I cannot fully understand the discussion about spring discharge. As I understand, the authors consider that the preferential flowpaths in soil layer are connected with bedrock aquifer. It would help to know how these were identified.

Response to comment 3

The spring shows both perennial discharge and fast reactions to rainfall events. The base discharge of the spring is thought to be due to a bedrock aquifer constantly supplying the spring. Unfortunately, this hypothesis was not made clear in section 2.1, and has been added in the revised version. The fast reactions in spring discharge have been shown to be due to preferential flow paths in the soil layer by the tracer experiments. If the spring's discharge is also partly from a bedrock aquifer, it is straightforward to assume that the two flow domains are connected.

Comment 4. Page 2981 Lines 5 through 18

The authors propose that the multiple peaks of BTCs could be explained by discrete structure of the preferential network. I am interested in this suggestion, but I cannot fully understand the process of it. Do the authors consider that as similar to the previous hillslopes studied by Tsuboyama et al., (1994), Sidle et al. (2000), Uchida et al. (2004) etc., the contributed preferential network changed/extended as change of soil water content/groundwater level due to change of rainfall intensity? Could you provide more details how the flowparhs were discrete?

Response to comment 4

The preferential flow paths at this site are constituted by soil pipes and shrinking cracks in lower (> 15 cm depth) soil layers. These structures are described as "discrete" in the sense that each of the structures has an individual position and extent in space, and this determines how all together do or do not form a discrete preferential network (and also if tracer is transported to a specific measurement location at all).

The hydrological functioning of this network is proposed to be controlled by different rainfall patterns and resulting changes in groundwater level/ soil water content, similar to the previous hillslope studies that have been cited. The preferential flow paths are thought to be activated depending on their position and the spatial and temporal distribution of rainfall (throughfall) and infiltration into the uppermost soil layer. The topology of the entire ensemble of activated features, i.e. the connectivity of the network, determines regions and times of subsurface flow and storage within the network. The multiple tracer peaks are considered to be a snapshot of this phenomon, bound to the discrete preferential network active during the observation.

Comment 5. Figure 7 and Page 2985 Lines 15 through 24

Did you consider that there is a linier relationship between travel distance and travel time? Also, did you consider that there are two different linier relationships (for salt and for uranine) between travel distance and travel time? The authors have to clarify this point.

Response to comment 5

No, we do not propose a linear relationship between travel distance and travel time, and we do not think this is evident from our data, especially considering the relatively small number of data points. In fact, a linear relationship of travel time and travel distance would suggest a constant transport velocity (cf. our response to comment #2 on the variability of transport velocities above). As mentioned in the discussion section (p. 2985, lines 19-21), the differences between salt and uranine are considered either to be due to different transport behaviour of the tracers, or because different transport regimes are related to the differing flow paths in the hillslope experiment.

We discussed the relationships of travel time variance and travel distance as a possibility to distinguish between a convective-dispersive and a stochastic-convective transport regime. This is a well-known approach in soil physics to test whether a transport regime is well mixed, or not mixed at all. The latter case corresponds to the "near field" for instance observed in Taylor dispersion, where the trajectory of each fluid particle is determined by its initial location. Information on the transport regime tells us about the effective length scale of dominating heterogeneities.

The data again do not reveal an obvious relationship, i.e. both models are comparably significant, and we argue that a linear relation as the simplest case would support the use of a CDE transfer function. However, we are aware that the CDE approach is valid for transport distances that ensure complete mixing of solutes. This is inconsistent with the rather small Peclét numbers in our experiments, which suggest that transport is not well mixed. We therefore tend to conclude that the characteristic length scale of the heterogeneous transport domain is comparable to the extent of our study site.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 6, 2961, 2009.