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Discussions

Interactive comment on "Characterizing hillslope-stream connectivity with a joint event analysis of stream and groundwater levels" *by* Daniel Beiter et al.

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Reviewer 2:

The manuscript by Beiter et al details a study aimed at understanding hillslope-stream connectivity. They collected 5-6 years of paired near-stream groundwater and streamwater levels at five locations within an agricultural catchment in western Luxembourg. At each site, shallow groundwater levels were logged at 5 minute intervals at 3 to 4 piezometers located within 15 m of the stream level site. They extracted about 150 individual rainfall-runoff events from the data record using an approach that interrogates the stream water level time series. For each event identified, they also extracted

groundwater response metrics from the corresponding piezometers. They compared stream and groundwater responses to quantify temporal changes in hillslope-stream connectivity. They found a threshold-type response in stream water level linked to antecedent groundwater levels. Low antecedent groundwater levels were associated with variable stream water level responses. In contrast, high antecedent groundwater levels were associated with more consistent stream water level responses. They speculate that the hydrologic processes controlling these patterns were transmissivity feedback at the marls sites and fill and spill at the schist sites. The topic covered in this manuscript is appropriate for HESS. The study contains an impressive data set and some of the visualizations do a great job of showing these data (e.g., Figure 8 and 9). Overall, the writing is not bad, but some of the grammar is confusing which makes it difficult to understand some of the elements of the paper. Given the amount of data, I'm left feeling a little underwhelmed by the key conclusions. This might reflect the vagueness of the key research questions (page 3, lines 12-15).For example, 'provide information' is a very general statement - try to be more specific about what is learned from this sort of joint analyses. I would encourage the authors to formulate testable hypotheses to help add more structure to the manuscript. This would also help clarify the key findings of this study.

Answer: We thank the reviewer for taking the time to review our manuscript and are happy to see that Figures 8 and 9 are appreciated! We will sharpen the research question and conclusions by including the following hypotheses in the revised version of the manuscript: Hypothesis 1: hillslopes remain disconnected from the stream for most of the time and connect only during short periods of time. Hypothesis 2: marls and schist hillslope-stream systems differ in connectivity patterns as their soil properties and topography is quite different. Hypothesis 3: monitoring at the footslope can provide information on hillslope-stream connectivity at this location but also at the catchment scale.

Overall, I agree with reviewer #1's assessment, so I'll try not to repeat things here. I outline one general comment, followed by some more specific comments.

A major strength of this study is looking at the temporal dynamics of hillslope-stream connectivity. In contrast, the study is limited in capturing spatial variability in hillslope-stream connectivity. However, a key question/conclusion of the study concerns whether connectivity can be assessed using a single groundwater piezometer. The authors conclude that 'a single, well chosen, piezometer can already provide substantial information on catchment state...'. How do we know when a location is well chosen? We aren't provided any guidance on this. It is recognized that hillslope-stream connectivity can be spatially variable. How were the locations of the five sites selected? How representative are these locations of subsurface connectivity at other locations within the catchments?

Answer: Thank you for pointing this out. That 'single, well-chosen piezometer' is related to the plot scale only. It is rather hypothetical in the sense that one cannot be sure without having multiple observations per footslope (e.g. three) first. The analysis showed that despite possible local heterogeneities (e.g. soil texture, tree roots) the distributed piezometers revealed very similar patterns regarding amplitudes and temporal responses and can therefore be considered representative for the hillslope. Also 'bad-chosen' piezometers can be identified by strongly disagreeing with the other piezometers. The selection of the five sites was mainly influenced by the different geologies (marls and schist) and their subsequent influence on soil, topography, hillslope morphology and potential land use. Within these geologies headwater catchments of different sizes were considered to cover the variability of such in the Attert catchment. From this point of view the selected sites can be considered representative for headwater catchments in the Attert catchment.

Specific comments:

Abstract: This feels very long for an abstract. With some good editing this could be reduced by half.

Answer: We will make an effort to shorten the abstract.

P2L6: 'variable in space': Exactly - but this is not well addressed in this study.

Answer: In this sentence of the introduction we were referring to the spatial variability of hillslope-stream connectivity (surface and subsurface) at the catchment scale. Our study covered some of this spatial variability of subsurface connectivity by comparing 5 different sites, each equipped with 3-5 piezometers. Of course, it would be great to have more sites and more piezometers but even with this setup (and the advantage of the long time series measured here) it was possible to see that there are typical response patterns per site and per geology – suggesting that for some purposes we can assess certain aspects of connectivity with "representative" measurements. We will add a more detailed explanation on this in the revised manuscript.

P2L9: 'Full connectivity': What is meant here? For the entire catchment or hillslope? Some indication of the spatial scale of interest should be made in this introduction.

Answer: We agree and we will revise the sentence to: Full connectivity across entire hillslopes or catchments is usually established only during brief periods of time (Freer et al., 2002;Ocampo et al., 2006; Haught and Meerveld, 2011; van Meerveld et al., 2015). We will also add the information on the scale of interest in the introduction in Hypothesis 3: monitoring at the footslope can provide information on hillslope-stream connectivity at this location but also at the catchment scale.

Introduction: As reviewer #1 highlights, some of the more recent research on this topic should be discussed here or in the discussion (e.g., Klaus and Jackson 2019 WRR,Gabrielli and McDonnell 2020 HP).

Answer: Klaus and Jackson (2018) found that according to the Downslope Travel Distances (DTD) only lower regions of a hillslope contribute to the streamflow via interflow, while in upper regions water percolates into the deeper groundwater. We do agree that the presence of a perched groundwater table at the footslope is no proof for a connected hillslope. However, we can observe a threshold behaviour in the hillslope-stream-system that depends on initial groundwater levels. This indicates that soil characteristics (flow path system, layering) start playing a role in how water parcels travel along the hillslope. It is very likely that these heterogeneities allow a hillslope or at least the footslope to connect to the stream via interflow for a short period of time. Gabrielli and McDonnell (2020) built upon the DTD and developed a (gridded) Index which describes the general tendency of a catchment to either shed water laterally to the stream channel or infiltrate water to depth. They found high correlations between their Anisotropy Index (AI) and the assessed Mean Transit Time (MTT) for several catchments. As we are focussing on the hillslope-stream connectivity we did not make any statement towards the water age. We will add a brief discussion of these papers to the revised manuscript.

P3L1-3: An example of a run-on sentence that should be avoided.

Answer: We agree. The sentence in question was: “We hypothesise that monitoring shallow groundwater tables in the riparian zone over longer periods of time and thus not only a few, but a large number of events will provide not full, but representative information on hillslope-stream connectivity at low cost. “ We will change this to: “Monitoring shallow groundwater tables in the riparian zone over longer periods of time will allow us to capture a large number of events. We hypothesize that the analysis of these events will provide not full, but representative information on hillslope-stream connectivity."

P3L8: What is meant by a ’rough interpretation’?

Answer: Analysing the relationship between responses in near-stream shallow groundwater and stream thus permits us to determine the dominant processes. We will clarify this in the revised manuscript.

Section 2.1: Provide some information about soils and the vegetation cover. Could the sites be given more descriptive names? I realize the ’S’ and ’M’ represent the dominant geology, but what do ’J’, ’V’, ’D’, and ’K’ represent?

Answer: Aggregated information about the various sites (soil, land use, etc.) is provided in Table 1. The letters refer to a larger scale reference system of 45 sensor clusters distributed in the Attert Catchment and do not have a meaning per se. A full list of the sites can be found in Appendix A of Demand et al. 2019.

Figure 2: Could elevation be added to these plots? Or at least the elevation of the ground surface at the piezometer and the depth of the piezometer relative to the streambed? It might be really helpful to include photographs of the 5 site installations so that the readers can get a better sense of the sites.

Answer: Photographs of the 5 sites can be added. However they focus on the setup on the hillslope rather than the topography between hillslope and stream. We will take into consideration adding these photos in the supplement for a general idea of the sites. For a better topographic overview at the sites we will add elevation information to Figure 2 in the revised version.

Table 1: What are the slope quartiles referring to? The hillslope or catchment?

Answer: Since a detailed DEM was not available, the slope quartiles were calculated for the subcatchment of each stream level gauge (see little topographic maps in Figure 1) to give aggregated information about the topography for each site. We will clarify this in the revised manuscript

P6L4: Where is the Roodt station? Any concerns about spatial variability in precipitation inputs? I know it is mentioned that precipitation is assumed to be uniform across the catchments for the runoff ratios; however, it seems like not all stream water level sites respond to precipitation events. This may suggest that the uniform precipitation assumption is not reasonable.

Answer: The location of Roodt station will be added to the map. Precipitation may vary to some extent over the entire catchment. However, there are indicators supporting the assumption that it is sufficiently uniform for our analyses. While we see some events which do not occur at all sites simultaneously, but these are mainly due data gaps for the respective stream gauge. Additionally, from all detected stream events those without a previous precipitation event observed at the Roodt station were removed. The number of removed stream events due to non-existing precipitation events was mostly below 10. Nevertheless, we reran the analysis for the three marls sites with data from the precipitation station at Useldange (<5km distance to marls sites) and the results are almost entirely the same. There is a very small shift of 1-2 events per site which are now (not) detected. Also the runoff coefficients patterns remain the same. We will add this explanation to the revised manuscript.

P6L21-22: Looks like this percentage was tested? How sensitive are the results to different values?

Answer: No formal test was applied. Sensitivity regarding the timing was higher when the percentages were lower due to the extended onset and offset. Higher thresholds were in general less sensitive and even more for the onset compared to the offset.

Section 2.4: Why not conduct the event detection by using the precipitation record (as is frequently done) instead of the stream level records?

Answer: The general idea was to design a stream-centred approach in order to focus on the response and its relation to the hillslope. Starting with the precipitation events would have also required us to formulate a definition for whether or not a stream event was observed. From our point of view, using event detection on the precipitation time series would not have helped investigating the interaction between hillslope and stream responses.

P8L1: Were there times when the piezometers showed a response but not the stream?

Answer: This was not investigated, due to the way the analysis was set up: we first identified the stream flow events and then used these events to check for groundwater responses.

P8L15: This would only happen in autumn?

Answer: The wetting-up phase is generally in autumn since groundwater levels are low in summer and high in winter. In particular during this period one can observe stream/piezometer events where the post-event water level lies above the pre-event water level. However, on shorter time scales wetting-up can also occur in other seasons.

P8L18-22: For the search interval, was this a moving window or fixed interval search?

Answer: The search intervals are of fixed length starting at the peak time with 24h in direction pre-peak and 48h in direction post-peak. We will clarify this in the revised manuscript.

P10L5-14: Consider re-writing this to improve clarity.

Answer: Will be revised.

P10L13: What is meant by 'hints'?

Answer: To prove causality in terms of subsurface flow one would need tracer observations. It is the many snapshots approach that – despite the lack of real proof for causality – enables the assumption of causality. This is what is meant by hint. We will clarify this in the revised manuscript.

P10L26: What is meant by 'a more or less deterministic increase'?

Answer: This refers to the assumption that two very similar groundwater responses would have two stream water responses that are also very similar to each other. This would reflect a deterministic system where the observation of one could be used to predict the other. We will clarify this in the revised manuscript.

P11L26: For what purpose is this response considered negligible?

Answer: Thank you for pointing that out. This refers to the performance of the detection method. If the number of noLocalMaximum events would be high the whole approach would need to be questioned. This will be re-phrased to make it clearer.

Figure 5 (and others): The 'Event type' colour scale is very difficult to interpret for a colour-blind person. Consider using some other way to visualize these data (shapes maybe, although that might be difficult to see as well)?

Answer: We will make an effort to improve visibility for colour-blind persons.

Figure 7: Perhaps distinguish the Seasons by shape instead of colour.

Answer: We will adjust the Figure as suggested.

Figure 8: Very nice graph! Answer: Thank you!

Figure 9: Could the approach used to set those thresholds be discussed a bit more? I realize they were done visually, but there are some sites/piezometers that I would argue don't have a clear threshold (most of S_V, S_J piezo1, most of M_K, etc.).

Answer: It is true that thresholds were defined visually and for some piezometers this abrupt change in slope does not appear. In such cases a threshold was set to the level where the envelope functions (encompassing the bundle of slope lines) start converging again (S_J P1, S_V P3 and P4). For some piezometers the change in pattern was a sudden clustering of lines (M_K P1 and P2, S_V P2) above a certain value. All these observed changes in patterns signal that hydrologic processes do change due to different pre-event groundwater levels. We will add this explanation to the revised manuscript to clarify the choice of thresholds.

Section 3.6: Please define 'catchment state' - this seems to appear out of nowhere (unless I missed it earlier).

Answer: We will revise the manuscript to properly introduce the definition of catchment state.

P17L15: It's not clear to me where the topographic characteristics come from? Is this

simply the qualitative discussion in Section 2.1. Are there stream incision data for all the sites?

Answer: Indeed it is from the qualitative discussion since there is no detailed DEM. Unfortunately we did not measure stream incision but we will provide the average slopes over the measurement plots in the revised manuscript published by Demand et al. (2019).

Figure 10: Appears that the figure caption for the y axis is incorrect.

Answer: Thank you for pointing this out. The axis shows the "Normalised pre-event (groundwater) levels". We will correct this in the revised manuscript.

P19L1-3: I'm struggling with this logical leap between the results shown in Figure 7 and how they 'indicate that well-placed groundwater observation points can be representative of the given footslope, at least for pre-event conditions'. Given the close proximity of the within-site piezometers, there seems to be a surprising amount of scatter in these plots.

Answer: Despite the scatter, the similarity of the pattern (Figure 7) between piezometers at one site is relatively high compared to the similarity between sites, which leads to the assumption of a fingerprint that represents the functional link between a certain hillslope and the stream. Differences in patterns of piezometers at one site are due to local heterogeneities (e.g. hydraulic conductivities). In reverse this gives insight in how strong heterogeneities effect hillslope-stream responses.

P19L8-10: Or could it be that another portion of the catchment is connected, but not the hillslope with the piezometers?

Answer: This might be the case, yes. The catchment could contain "fast" hillslopes that manage to provoke a stream response at the stream level gauge before the adjacent (monitored) hillslope responds. We will mention this in the revised manuscript.

P21L28-31: How is it known that connectivity 'does not extend far up the slopes' when those observations were not made? The substantial conclusions in this section are based on somewhat subjective placement of a threshold. It could even be argued that no clear threshold exists for some of the sites (see comment regarding Figure 9 above).

Answer: It is correct that we did not monitor upslope groundwater levels and this statement is an interpretation of the data. We reason that the observable increase in runoff coefficient (Figure 10) signals either more hillslopes being connected or that the connectivity of hillslopes leads further upslope, or both. In return, when groundwater tables are below this threshold, the spatial extent of subsurface connectivity is generally low. This could apply to the zones further upslope as well as other hillslopes within the catchment. We will clarify this in the revised manuscript.

P22L1-2: Again, I'm not clear on where the evidence is for this statement.

Answer: We apologize that we did not make this sufficiently clear and we will improve clarity in the revised manuscript. What we mean here is that looking at Figure 10, it would be sufficient to have the information of one of the piezometers per site to know if pre-event groundwater levels are above or below the threshold. If a rainfall event were to occur when groundwater levels are above the threshold the likelihood of high runoff coefficients is increased. To identify this state (above/below threshold) we do not need all of the piezometers currently installed at a certain hillslope – one would be enough and we could now potentially dismantle the other piezometers. For the one that we would keep monitoring we would pick one that on the one hand is consistent in its response pattern with the majority of the piezometers at this site and on the other hand has the clearest threshold signal among these. Please also see additional explanations to this end in previous answers.

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