

Reviewer 1:

The page and line numbers refer to the track changes document.

General comment

This manuscript focuses on the characterization of hillslope-stream connectivity by using a novel joint event analysis of the response of stream and shallow groundwater levels. The authors examined the response timing of 18 groundwater sites located in five different footslopes in Luxembourg for 706 runoff events. The applied methodology included event detection, the quantification of response timing of groundwater compared to stream water level, the analysis of the relations between pre-event groundwater level with pre-event stream water level and runoff coefficient. The authors concluded that the joint analysis of groundwater and stream water levels provided information on the presence or absence, and on the degree of subsurface hillslope-stream connectivity. The found threshold relations between groundwater and stream water levels were interpreted as transmissivity feedback in the marls study sites, and fill-and-spill in the schist areas. The topic of this manuscript is of interest for the readers of the journal, and overall the paper is well written and structured. The presented analysis for such a large time series of groundwater levels is quite rare, and therefore is particularly important to advance our comprehension of hillslope-stream subsurface connectivity. Nonetheless, I have some specific questions/comments for the authors, and I would like to see integrated in the manuscript some more methodological details.

We thank the reviewer for taking the time to review our manuscript and are happy to see this positive assessment.

Specific comments

1. I suggest to the authors to clearly provide in the introduction the definition of subsurface hydrologic connectivity, that they considered (currently such a definition can only be guessed by the readers).

We added the following definition to the introduction (page 2 line 7-11):
"Ali and Roy (2009) collected various definitions of hydrologic connectivity used in previous studies, which differ in spatial scale (hillslope vs watershed) and observed features (e.g. water cycle or landscape). The most appropriate definition in the context of our investigation is the following: 'The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger et al. 1994; Creed and Band 1998)'"

2. The authors mentioned in the abstract that they performed their joint analysis for rainfall-runoff events, but throughout the manuscript there is no description of the rainfall characteristics (e.g., total rainfall, intensities and duration of the selected events) and where they were monitored (are the weather stations located in the study catchments?). I suggest to report such details in the text. Furthermore, I would like to see a table presenting the main summary statistics for rainfall, runoff and groundwater characteristics of the considered events.

We added the location of the two precipitation stations (Roodt and Useldange) to the map in Figure 1 (page 4). The text was modified (page 7, line 7-12). Additionally, summary statistics for precipitation, runoff and stream response can be found in Table 2 (page 16).

3. Since the analysis was carried out for the whole time series (winters and early spring included), I am wondering whether there were snowfalls, and if the authors considered snowmelt-induced runoff events and rain-on-snow events in the analysis. If such events were discarded, I suggest to integrate the description of the methodological approach for event detection. Otherwise, the authors should clearly state that they focused only on rainfall-runoff events.

On page 13, line 22-28 we added the following lines:

“As the analysis covers also winter and early spring events, the effect of snow fall and snow melt on the event detection was assessed and found to be unlikely to impact our analysis: Snow fall events are generally quite rare in Luxembourg, so the number of events affected is assumed to be low. A rain on snow event would be captured by its runoff response, but the in this case erroneous estimate of rainfall input would only impact the analysis of event runoff coefficients as our analyses mainly focus on the relationship between streamflow and groundwater responses. Pure snow melt events are not included in the analysis, as in this case there is no directly preceding precipitation event and thus this necessary event identification criterion is not met.”

4. In Table 1 (or in a new table), I suggest to provide the topographic characteristics of the groundwater sites together with their depth. These details could help to understand whether the topography is very similar (or very different) among the monitored locations, and to support the discussion at page 17, lines 15-19. Moreover, what is the extension of the riparian zone compared to the hillslopes in the study sites?

Thank you for pointing this out. We decided that the best way to visualise the topography was in a figure, rather than a table. Therefore, new added a new figure (Figure 3, page 6) illustrating the distance to stream together with ground level and piezometer depth relative to the stream bed. Table A2 on page 32 contains the corresponding values.

5. Have the authors considered their analysis of subsurface connectivity in light of recent findings by Klaus and Jackson (2018) and Gabrielli and McDonnell (2020)? Are there bedrock permeability data for the selected study sites?

We added the following (page 28, line 12):

“Studies focusing on the Downslope Travel Distances (Klaus and Jackson, 2018; Gabrielli and McDonnell, 2020) found that only lower regions of a hillslope contribute to the streamflow via interflow, while in upper regions water percolates into the deeper groundwater. In our study, however, we find that there is a threshold in the near-stream groundwater levels above which event runoff

coefficients rise strongly to values above 50%, indicating that it is not just the near stream footslope contributing to event runoff.”

6. In the section “2.4 Event detection” and Fig. 4, it is not clear which response timings were considered for complex events with multiple peaks (both in stream and ground-water level). Furthermore, which peak in stream water level is considered if there is only one peak for the groundwater level?

We edited the text as follows (page 9, line 3-5):

“If two or more events overlap they are merged into one single longer event (Figure 5) and the highest peak is determined as the event maximum. From there on it is handled as a simple event according to Figure 4.”

7. Page 11, line 5: Please provide a reference for the method used for the stormflow calculation.

A reference was added (page 13, line 5-6):

“The approach to separate baseflow from discharge was developed in the style of the constant slope method (Dingman, 2002).”

8. Page 20, line 5: “No pronounced differences...”: could the authors report the results of the applied statistical test?

As we cannot do statistical testing in this case, we changed the wording to clarify this. We now say “No clear visual differences in timing can be observed between marls and schist.” (page 24, line 25)

9. Page 21, lines 3-4: Please provide more details about the investigated relations between rainfall characteristics and event responses.

Ranked cross correlation coefficients between rainfall and response characteristics were added in table A1 (page 31).

10. Page 22, lines 8-10: Please remove these details from the available literature, and report them in a table. Please consider that other recent studies examined almost or more than 100 events (e.g., Rinderer et al., 2016; Zuecco et al., 2019).

We removed the number of events from the text and created a new table (Table 5, page 29). Unfortunately, we did not have access to Zuecco et al. (2019).

11. Page 23, line 13-16: The example of considering just two events in the data analysis is a very extreme case, and so far, I have never seen it. Therefore, please revise the sentence. The main question is how many events and piezometers do we need to capture the temporal and spatial variability of subsurface connectivity?

Thank you for stressing this point. In an effort to be more realistic we deleted “(e.g. one for winter and one for summer)” as well as “If these two events represented the two extremes (high and low pre-event water levels) one would need to assume a

functional relation for all the potential events in-between (which is likely to be flawed)” and instead added the following lines (page 29, line 6-10):

“Nonetheless, the question is not so much about how many events are necessary (in absolute numbers) as more about the necessary time period to cover the temporal variability generated by different hydrological processes. It is therefore necessary to accumulate a large number of events across all seasons. In terms of extreme events (droughts/floods) the covered time period and number of events will need to be even higher, on the one hand to capture these events, and on the other hand to put them into context.”

Technical corrections

1. Page 2, line 25: “assess”. (page 2, line 31)
2. Page 3, line 1: “hillslope” instead of “slope”. (page 3, line 8)
3. Page 4, line 2: “July”. (page 5, line 5)
4. Page 23, line 4: “these” instead of “this”. (page 28, line 5)
5. Figure 10: Based on the caption, the label of the y axis should be “Normalised pre-event groundwater level”. (page 21, Figure 11)

Technical corrections can be found at locations in parenthesis.

References

Gabrielli C.P., McDonnell J.J., 2020. Modifying the Jackson index to quantify the relationship between geology, landscape structure and water transit time in steep wet headwaters. *Hydrological Processes*, early view. DOI: 10.1002/hyp.13700

Klaus J., Jackson C.R., 2018. Interflow is not binary: a continuous shallow perched layer does not imply continuous connectivity. *Water Resources Research*, 54, 5921-5932. DOI: 10.1029/2018WR022920

Rinderer M., van Meerveld H.J., Stähli M., Seibert J., 2016. Is groundwater response timing in a pre-alpine catchment controlled more by topography or by rainfall? *Hydro-logical Processes*, 30, 1036-1051. DOI: 10.1002/hyp.10634

Zuecco G., Rinderer M., Penna D., Borga M., van Meerveld H.J., 2019. Quantification of subsurface hydrologic connectivity in four headwater catchments us-ing graph theory. *Science of the Total Environment*, 646, 1265-1280. DOI:10.1016/j.scitotenv.2018.07.269

References

Ali, G. A. & Roy, A. G., 2009. Revisiting Hydrologic Sampling Strategies for an Accurate Assessment of Hydrologic Connectivity in Humid Temperate Systems. *Geography Compass*, Blackwell Publishing Ltd, 3, 350-374. DOI: 10.1111/j.1749-8198.2008.00180.x

Hornberger, G. M.; Bencala, K. E. & McKnight, D. M., 1994. Hydrological controls on dissolved organic carbon during snowmelt in the Snake River near Montezuma, Colorado. *Biogeochemistry*, 1994, 25, 147-165. DOI: 10.1007/BF00024390

Creed, I. F. & Band, L. E., 1998. Exploring functional similarity in the export of Nitrate-N from forested catchments: A mechanistic modelling approach. *Water Resources Research*, 34, 3079-3093. DOI: 10.1029/98WR02102

Dingman, S., 2002. *Physical Hydrology*. Prentice Hall, 2002. ISBN: 0130996955, 9780130996954

Reviewer 2:

The page and line numbers refer to the track changes document.

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.

We thank the reviewer for taking the time to review our manuscript and are happy to see that Figures 8 and 9 (now Figures 9 and 10) are appreciated. We sharpened the research questions by including the following hypotheses into the introduction and discussion (page 3, line 19-24; page 29, line 13-page 30, line 18):

"Hypothesis 1: hillslopes remain disconnected from the stream for most of the time and connect only during short periods of time.

Hypothesis 2: the two geologies schist and marls differ in topography and soil characteristics. As a result, their hillslope-stream systems will show differing connectivity patterns.

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).

We added the following (page 28, line 12):

“Studies focusing on the Downslope Travel Distances (Klaus and Jackson, 2018; Gabrielli and McDonnell, 2020) found that only lower regions of a hillslope contribute to the streamflow via interflow, while in upper regions water percolates into the deeper groundwater. In our study, however, we find that there is a threshold in the near-stream groundwater levels above which event runoff coefficients rise strongly to values above 50%, indicating that it is not just the near stream footslope contributing to event runoff.”

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

The sentence was changed to (page 3, line 8-10):

“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’?

The sentence was changed to (page 3, line 14-16):

“Analysing the relationship between responses in near-stream shallow groundwater and stream thus permits us to determine the dominant processes.”

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?

Despite the aggregated information about the various sites (soil, land use, etc.) in Table 1 another Table (A3) was added containing the soil horizons. 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 sentence to this effect was added on page 5. 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.

Thank you for pointing this out. We decided that the best way to visualise the topography was in a figure, rather than a table. Therefore, new added a new figure (Figure 3, page 6) illustrating the distance to stream together with ground level and piezometer depth relative to the stream bed. Table A2 on page 32 contains the corresponding values. Unfortunately, the photographs do not help in getting a better image of the sites.

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

A footnote was added to Table 1 (page 6) stating that the slope quartiles refer to the subcatchments.

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.

We reran the analysis with Roodt station only for the schist sites and Useldange station only for the marls sites. 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 coefficient patterns remain the same. However, in the revised manuscript we are now using the two precipitation stations, one per geology to avoid the assumption of uniform distribution within the catchment.

The text was edited accordingly (Page 7, line 6-11):

“Hourly precipitation data from the Roodt and Useldange weather stations were obtained from AgriMeteo Luxembourg. Both stations are located within the Attert catchment, the Roodt station close to schist and the Useldange station being close to marls sites. Discharge data with 15 min temporal resolution were provided from the Luxembourg Institute for Science and Technology (LIST) for the Weierbach station (for schist) and the Wollefsbach station (for marls). Figure 1 shows precipitation stations (upper left plot) and discharge stations (upper right plot).”

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

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?

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?

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. This is explained on page 9, line 8.

P8L15: This would only happen in autumn?

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. We added this information on page 10, line 4.

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

The following line was edited to clarify this (algorithm 1):

“DEFINE: two fixed search intervals from peak along the rising and the falling limb (tpreSearchInterval = 24h, tpostSearchInterval = 48h)”

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

Thank you for pointing this out. The part in question was re-written (page 12, line 2-5):

“In hillslope-stream systems infiltration and runoff generation processes are highly dynamic during events on a time scale of hours and days. To gain additional insight into what happens during these periods we chose to handle the water level changes and timing as two separate aspects. This provides us with a view of the temporal behaviour on the one hand and changes in the state variables (water levels) of the hydrologic system on the other.”

P10L13: What is meant by 'hints'?

The sentence was rephrased for clarification (page 10, line 6):

“Relative timing and lags between groundwater and stream responses extracted from a large number of events hint at causal relationships.”

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

The sentence in question was rephrased (page 12, line 18-21):

We would expect that a given increase in groundwater level at a given depth would result in a more or less predetermined/deterministic increase of stream water level (assuming the groundwater fluctuations are representative of the catchment). This means that if Events A and B have similar initial conditions and cause similar groundwater level rises we would expect the stream water level rise of Event A to be the same as for Event B.

P11L26: For what purpose is this response considered negligible?

This was made clearer by shortening the mentioned sentence (page 14, line 2-3) and adding another one to the discussion (page 23, line 5-7)

“The noLocalMaximum response is very rare with only 11 occurrences.”

“The very low number of only 11 noLocalMaximum groundwater events support the suitability of the developed event detection. A high number would indicate that the chosen approach is not performing properly and would need to be questioned entirely.”

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)?

We put an effort into changing the representation of 'event type'. However, it makes the whole figure very confusing and not readable at all. We apologise for the inconvenience.

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

Similar to the situation in the previous comment, we tried to change the representation of season but could not come up with a solution that produced a clearer output.

Figure 8: Very nice graph!
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.).

We apologise for the inaccuracy in the description. We added the following explanation to the manuscript (page 7, line 17 and following):

"The way the patterns changed at the threshold was not identical for all sites. While many piezometers showed an abrupt change in slope (M_D Piezo1-3, M_J Piezo1 and S_J Piezo 2-4) others showed a converging of their envelope functions (encompassing the bundle of slope lines) (S_J Piezo1, S_V Piezo3 and Piezo4). For some piezometers the change in pattern was a sudden clustering of lines (M_K Piezo1-2, S_V Piezo2). All these observed changes in patterns signal that hydrologic processes change when the threshold values are passed."

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

We agree and added a bit more clarification (page 19, line 23-26)

"We assume that the threshold (Figure 10) marks a change in catchment state, where conditions above the threshold have the potential for high connectivity while conditions below the threshold indicate lower connectivity. To investigate if the shift in state is synchronous across the sites we plotted the event time series colour-coded by system state (above/below the threshold) (Figure 12)."

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?

Indeed it is from the qualitative discussion since there is no detailed DEM. Unfortunately, we did not measure stream incision but are now providing more topographic information in Figure 3 (page 6).

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

We corrected the figure caption of Figure 11 (page 21, former Figure 10).

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.

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. We have rephrased this section to clarify our interpretation.

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

A sentence was added (page 24, line 16-18):

"In a highly heterogeneous catchment, certain 'fast' hillslopes with very high hillslope-stream connectivity and high outflows might provoke a stream-response at the stream level gauge before the monitored hillslope responds. In this case the interpretation of low subsurface-connectivity would only hold for the monitored hillslope."

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).

A clarification on how the thresholds were obtained can be found in the answer to the comment regarding Figure 9 (now Figure 10). While the threshold was only determined visually and could therefore be called subjective, it is supported by the fact that runoff coefficients for events above this threshold are more likely to be high than for events below it. This is true for nearly all piezometers.

The following lines were modified for clarification (page 26, line 22-27):

"Events with catchment states above the threshold are likely to have higher event runoff coefficients (Figure 11) and are thus assumed to generate substantial lateral subsurface stormflow caused by high hillslope-stream connectivity (more connected hillslopes or connectivity extending further upslope, or both. Catchment states below the threshold generate only minor lateral flow. In this case the spatial extent of hillslope-stream connectivity is generally low (few connected hillslopes or connectivity does not extend far up the slopes)."

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

We apologize that we did not make this sufficiently clear and have improved clarity in the revised manuscript. We added the following lines for clarification (page 25, line 19-25):

"However, our study results suggest that 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. Considering an un-investigated hillslope, one cannot know in advance which location would lead to a 'well-chosen' piezometer and which one to a 'badly-chosen'

piezometer. Nonetheless, the analysis showed that local heterogeneity did not influence the piezometers to a degree where no similarity at all could be observed. Therefore, a small number of piezometers (e.g. 3-4) should be enough to identify the characteristic patterns and which piezometers do represent the hillslope and which ones are less suited due to local anomalies. From this point on, one piezometer would be enough to describe the hillslope response and you can remove the other sensors. The well-chosen one would be 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.

References:

Gabrielli C.P., McDonnell J.J., 2020. Modifying the Jackson index to quantify the relationship between geology, landscape structure and water transit time in steep wet headwaters. *Hydrological Processes*, early view. DOI: 10.1002/hyp.13700

Klaus J., Jackson C.R., 2018. Interflow is not binary: a continuous shallow perched layer does not imply continuous connectivity. *Water Resources Research*, 54, 5921-5932. DOI: 10.1029/2018WR022920

Demand, D.; Blume, T. & Weiler, M., 2019. Relevance and controls of preferential flow at the landscape scale. *Hydrology and Earth System Sciences Discussions*, 2019, 2019, 1-37. DOI: 10.5194/hess-2019-80

Reviewer 3:

The authors studied the connectivity of hillslope to stream water using an impressive amount of data from 5 different catchments. The catchments studied were divided in two different geologies. The methodology they chose to use was focused in ground-water levels in piezometers near the streams and stream levels to try simplifying the hillslope approach that is often used when searching for connectivity with the stream. The study is interesting and I only have a few comments and questions to the authors adding to reviewers 1 and 2. I will now follow with some general comments and later into more specific comments:

- One of the goals of the study was to test if assessing the connectivity between hillslope and stream could be done with a single shallow near stream piezometer. I see your results show the answer is yes, but you miss to discuss or analyse why it worked in some piezometers and why not in others. What could you do different? In the discussions you mention that it works if you use a single well-chosen piezometer, how did you manage to have badly chosen piezometers in your network?

We thank the reviewer for taking the time to review our manuscript and are happy to see this positive résumé.

This additional explanation was added in section 4.6 in the revised manuscript (page 27, line 5-12):

Considering an un-investigated hillslope, one cannot know in advance which location would lead to a 'well-chosen' piezometer and which one to a 'badly-chosen' piezometer. Nonetheless, the analysis showed that local heterogeneity did not influence the piezometers to a degree where no similarity at all could be observed. Therefore, a small number of piezometers (e.g. 3-4) should be enough to identify the characteristic patterns and which piezometers do represent the hillslope and which ones are disturbed due to local anomalies. From this point on, one piezometer would be enough to describe the hillslope response and you can remove the other sensors. The well-chosen one would be 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.

Related to the previous comment, is there any information about the soil profiles of the piezometers? Or were they installed blindly with the cobra? What do you mean with refusal? Is that refusal as when you reach rocks/bedrock? Or would refusal count as well as when you reach a clayey layer that could divide two aquifers (valid for the sandy soils)? Is there information on the elevation of the piezometers related to the stream/streambed?

Indeed, the piezometers were drilled with the cobra and we have roughly described the profiles based on the cobra cores (see Table A3, page 33) and elevations of piezometers are now shown in Figure 3 of the revised manuscript.

The following sentence was added to clarify the term 'refusal' (page 6, line 13-14):

"Refusal was either defined as bedrock (in schist) or when a very dense layer of clay soil was reached (marls), which could not be further penetrated by the cobra."

For two of the five sites detailed information about soil profiles can be found in Sprenger et al. (2016) who investigated the areas of interest in-depth in terms of soil profiles.

Following come some specific comments:

- Page 1 Line 7: I suggest modifying the text here or earlier, "Step two" comes as a surprise since there was never a step one.

Thank you for pointing that out. We changed the text to the following (page 1, line 5-8):
"As a first step a new data analysis scheme was developed, separating the aspects of a) response timing and b) extent of water level change. This provides new perspectives on the relationship between groundwater and stream responses. In a second step we investigated if this analysis can give an indication of hillslope-stream connectivity at the catchment scale."

- P 4 L 3-12: This paragraph could be friendlier and provide more information if it was shown as well in a set of tables for the piezometers in each catchment. Stating elevation over stream bed, well depth and distance from the stream among other things. Maybe just as supplementary data, but it would help the reader visualize the piezometers better.

We decided that the best way to visualise the topography was in a figure, rather than a table. Therefore, new added a new figure (Figure 3, page 6) illustrating the distance to stream together with ground level and piezometer depth relative to the stream bed. Table A2 on page 32 contains the corresponding values.

- P 4 L 15: I mentioned it before, but does this mean that there is no information on the soil profiles?

The cobra cores were described roughly during the drilling process. This information was added to table A3 on page 33.

- P 5 Figure 2: I like this Figure and the information it provides. But I do agree with reviewer 2, either add data here or on the tables I mentioned two comments ago.

We added a new figure (Figure 3, see response above).

- P 7 Figure 3: I suggest you improve the horizontal lines that come from 'hfallThreshold' and 'hpostAmplitude' because they are hard to see in the current version.

The lines in Figure 4 (former Figure 3) were slightly modified to improve visibility.

- P 8 L 9: "...are presumed to be rather short,". Is there any data on hydraulic conductivity?

A reference for the hydraulic conductivities was added (page 6, line 8-9):
"Average hydraulic conductivities for the two soil types range from 293 to 675 cm/day (stagnosols) and from 360 to 648 cm/day (cambisols) (Sprenger et al. 2016)."

- P 8 L 34: I suggest changing All NA to allNA, as you used the term allNA in all other instances.

All NA was changed to allNA (page 11, line 7).

- P 10 L 9-10: I would suggest to rephrase this sentence and say directly what you did instead of saying first what you did not do. It would make it easier to read.

Thank you for the suggestion. The sentence was revised accordingly (page 12, line 3-4):
“To gain additional insight into what happens during these periods we chose to handle the water level changes and timing as two separate aspects.”

- P 11 L 7: why did you consider it sufficiently representative? Could you provide more information to the reader? How far is it located? Similar elevation?

We reran the analysis with Roodt station only for the schist sites and Useldange station only for the marls sites. 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. Nevertheless, we maintained the use of one closely located precipitation station per geology to avoid the assumption of uniform distribution within the catchment. The text was edited accordingly (Page 7, line 6-11):

“Hourly precipitation data from the Roodt and Useldange weather stations were obtained from AgriMeteo Luxembourg. Both stations are located within the Attert catchment, the Roodt station close to schist and the Useldange station being close to marls sites (Figure 1, upper left). Discharge data with 15 min temporal resolution were provided from the Luxembourg Institute for Science and Technology (LIST) for the Weierbach station (for schist) and the Wollefsbach station (for marls) (Figure 1, upper right).”

- P 12 L 2: Here you refer to Figure 9 before referring to Figure 8, maybe move Figure 9 to position 8 or change the text.

The early mention of Figure 10 (former Figure 9) was removed.

- P 12 L 3-4: “...low in summer and autumn.” I don’t see this generalization when I see Figure 7. There are several piezometers where autumn covers the whole spectrum. Or is there median values that we have no knowledge of?

We apologize for not being precise enough. We added the following sentence to specify the behaviour in autumn (page 15, line 1-2):

“In Autumn the wetting-up phase begins which produces events over a wider range of groundwater levels. Summer events can be found mostly at the lower end with occasional events at higher groundwater levels.”

- P 19 L 1-3: Any insights on why you had some exceptions? Because if those were your only wells this study would have completely different conclusions. If you have no insights, then that is valid as well, but it should be stated.

In case of M_D Piezo4 it is a road cut with a heavily disturbed soil (page 5, line 10). For the forested site (M_K Piezo3) there is no obvious explanation. We added this information also on page 24, line 5-6.

- P 22 Table 2: Use capital letters in each of the boxes, you used in some boxes but not all.

Corrections were made in the revised manuscript.

- P 22 L 1: “..single well chosen well..”. I agree, but how did you choose well or bad? Assuming you had installed your piezometers.

We thank you for making this point. We added an explanation to how a well-chosen piezometer would be identified (page 25, line 19-25):

“However, our study results suggest that 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. Considering an un-investigated hillslope, one cannot know in advance which location would lead to a ‘well-chosen’ piezometer and which one to a ‘badly-chosen’ piezometer. Nonetheless, the analysis showed that local heterogeneity did not influence the piezometers to a degree where no similarity at all could be observed. Therefore, a small number of piezometers (e.g. 3-4) should be enough to identify the characteristic patterns and which piezometers do represent the hillslope and which ones are less suited due to local anomalies. From this point on, one piezometer would be enough to describe the hillslope response and you can remove the other sensors. The well-chosen one would be 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.”

- P 23 L 1: The closing) is missing after Figure 10.

This was corrected

References

Sprenger, M.; Seeger, S.; Blume, T. & Weiler, M., 2016. Travel times in the vadose zone: Variability in space and time. *Water Resources Research*, Wiley-Blackwell, 52, 5727-5754. DOI: 10.1002/2015wr018077

[..*]Characterising hillslope-stream connectivity with a joint event analysis of stream and groundwater levels

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Abstract. Hillslope-stream connectivity controls runoff generation, both during events and baseflow conditions. However, assessing subsurface connectivity is a challenging task, as it occurs in the hidden subsurface domain where water flow cannot be easily observed. We therefore investigated if the results of a joint analysis of rainfall event responses of near-stream groundwater levels and stream water levels could serve as a viable proxy for hillslope-stream connectivity. The analysis focuses on the extent of response, correlations, lag times and synchronicity. [..²]As a first step a new data analysis scheme [..³]was developed, separating the aspects of a) response timing and b) extent of water level change. This provides new perspectives on the relationship between groundwater and stream responses. In a second step we investigated if this analysis can give an indication of hillslope-stream connectivity at the catchment scale.

Stream- and groundwater levels were measured at five different hillslopes over 5 to 6 years. Using a new detection algorithm we extracted 706 rainfall response events for subsequent analysis. Carrying out this analysis in two different geological regions (schist and marls) allowed us to test the usefulness of the proxy under different hydrological settings while also providing insight into the geologically-driven differences in response behaviour.

For rainfall events with low initial groundwater level, groundwater level responses often lag behind the stream with respect to the start of rise and the time of peak. This lag disappears at high antecedent groundwater levels. At low groundwater levels the relationship between groundwater and stream water level responses to rainfall are highly variable, while at high groundwater levels, above a certain threshold, this relationship tends to become more uniform. The same threshold was able to predict increased likelihood for high runoff coefficients, indicating a strong increase in connectivity once the groundwater level threshold was surpassed.

The joint analysis of shallow near-stream groundwater and stream water levels provided information on the presence or absence and to a certain extent also on the degree of subsurface hillslope-stream connectivity. The underlying threshold processes were interpreted as transmissivity feedback in the marls and fill-and-spill in the schist. The value of these measurements is high, however, time series of several years and a large number of events are necessary to produce representative results. We also find that locally measured thresholds in groundwater levels can provide insight into catchment-scale connectivity and event

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response. If the location of the well is chosen wisely, a single time series of shallow groundwater can indicate if the catchment is in a state of high or low connectivity.

1 Introduction

Hillslope-stream connectivity controls both runoff generation (Detty and McGuire, 2010; Jencso et al., 2010; Penna et al., 2015; Scaife and Band, 2017) and export of solutes, pesticides (Ocampo et al., 2006; Jackson and Pringle, 2010) and particulate matter (Thompson et al., 2013). Understanding patterns, controls and dynamics of hillslope-stream connectivity is therefore of interest not only for flood prediction but also for water quality management and policy making. Ali and Roy (2009) collected various definitions of hydrologic connectivity used in previous studies, which differ in spatial scale (hillslope vs watershed) and observed features (e.g. water cycle or landscape). The most appropriate definition in the context of our investigation is the following: "The condition by which disparate regions on a hillslope are linked via lateral subsurface water flow (Hornberger et al., 1994; Creed and Band, 1998)" Unfortunately, the investigation of this connectivity is notoriously difficult, for a number of reasons: it is variable in space and time (much more than our catchment models generally account for) and it is often controlled by thresholds, either in wetness state or in forcing (rainfall amounts and intensity) (Detty and McGuire, 2010b; McGuire and McDonnell, 2010; Scaife and Band, 2017; Oswald et al., 2011; Graham et al., 2010). Full connectivity 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). Identifying and measuring hillslope-stream connectivity becomes even more challenging as we are dealing with extensive along-stream interfaces which makes identification/pinpointing of hot spots difficult. While surface connectivity at least often leaves visible traces, subsurface connectivity is usually invisible and therefore hard to localise and measure (Blume and van Meerveld, 2015).

Standard approaches for the investigation of hillslope-stream connectivity include hillslope trench studies (often combined with piezometers) (Bachmair and Weiler, 2014; van Meerveld and McDonnell, 2006b) and tracer-based analyses (McGuire and McDonnell, 2010; McGlynn and McDonnell, 2003; Anderson et al., 1997). While the first approach gives detailed information about (usually) a single hillslope (Graham et al., 2010) it requires considerable effort in the field (both with respect to time and finances), the second approach provides an integral assessment at the catchment scale, but offers little information on spatial patterns or spatial extent of connectivity. At the stream bed interface distributed temperature sensing (DTS) can provide spatially highly resolved information of stream bed temperatures and under favourable conditions information about groundwater inflow points (Krause et al., 2012). While these datasets can be very informative, DTS systems are expensive, require continuous power supply and are time-intensive in installation. All of these methods are often employed on a short-term basis only: a few events, a season, possibly a year. As a result, one is left with the question how representative these snapshots are.

Even though state variables such as soil moisture or groundwater level do not provide actual water fluxes they are often used to assess hydrologic subsurface connectivity (Detty and McGuire, 2010; Haught and Meerveld, 2011; Freer et al., 2002; van Meerveld and McDonnell, 2006b; Ali et al., 2011; Anderson et al., 2010), and using many repeated snapshots allows to at least infer flow processes (Bracken et al., 2013). Shallow groundwater levels can provide information about catchment state

and a joint analysis of groundwater and streamflow dynamics in response to rainfall events offers basic information on runoff generation processes and hillslope-stream connectivity. The relationship of pre-event groundwater levels and streamflow response is often governed by a threshold in groundwater level above which streamflow responds much more strongly than below (Anderson et al., 2010; Detty and McGuire, 2010b; van Meerveld and McDonnell, 2006b). This threshold indicates a sudden increase in contributing area which directly translates to an increase in hillslope-stream connectivity (Anderson et al., 2010; Detty and McGuire, 2010b; van Meerveld and McDonnell, 2006b).

In this study we go for a targeted as well as pragmatic approach: we target specifically the footslope and the riparian zone as the essential interface between hillslope and stream. Monitoring shallow groundwater tables in the riparian zone over longer periods of time will allow us to capture a large number of events. We hypothesise that the analysis of these events will provide not full, but representative information on hillslope-stream connectivity. Previous use of piezometers for this purpose often extended over the entire hillslope (Bachmair and Weiler, 2014; van Meerveld and McDonnell, 2006b) which increased financial and maintenance efforts. While this can be very informative, we suggest that our pragmatic approach focusing only on the footslope and a joint analysis of shallow groundwater and streamflow response to rainfall events will still allow us to develop a general picture of when and where connectivity is established and how often this occurs. Analysing the relationship between responses in near-stream shallow groundwater and stream thus permits us to determine the dominant processes. We will investigate the potential and limitations of this approach by comparing 5 footslopes covering two distinct geologies. A newly developed data analysis scheme which separates the aspects of response timing and extent of water level change opens up new perspectives on these interactions. With this study we target the following hypotheses:

- Hypothesis 1: hillslopes remain disconnected from the stream for most of the time and connect only during short periods of time.
- Hypothesis 2: the two geologies schist and marls differ in topography and soil characteristics. As a result, their hillslope-stream systems will show differing connectivity patterns.
- Hypothesis 3: monitoring at the footslope can provide information on hillslope-stream connectivity at this location but also at the catchment scale.

⁴removed: slope

⁵removed: We hypothesise that monitoring

⁶removed: and thus not only a few, but a

⁷removed: at low cost

⁸removed: a rough interpretation of

⁹removed: We thus

¹⁰removed: research questions: Can the measurements of shallow near-stream groundwater and stream water level and their targeted analysis provide information about subsurface

¹¹removed: connectivity? When does

¹²removed: connectivity occur and what are the underlying hydrological processes? How does this differ between geologic regions? Can the state of connectivity of the catchment be assessed through shallow groundwater measured at a single location?

2 Methods

2.1 Study catchment

This investigation targets the 244km² Attert catchment in western Luxembourg, with altitudes between 243 and 549m.a.s.l. (Figure 1, top left). It is driven by a runoff regime with generally low discharge in summer and high discharge in winter. Despite the seasonal differences in runoff, precipitation events are distributed over the entire year, with a mean annual precipitation of 760mm.

The catchment can be divided into three main geologies – marls, schist and sandstone – and two geologies of lower significance

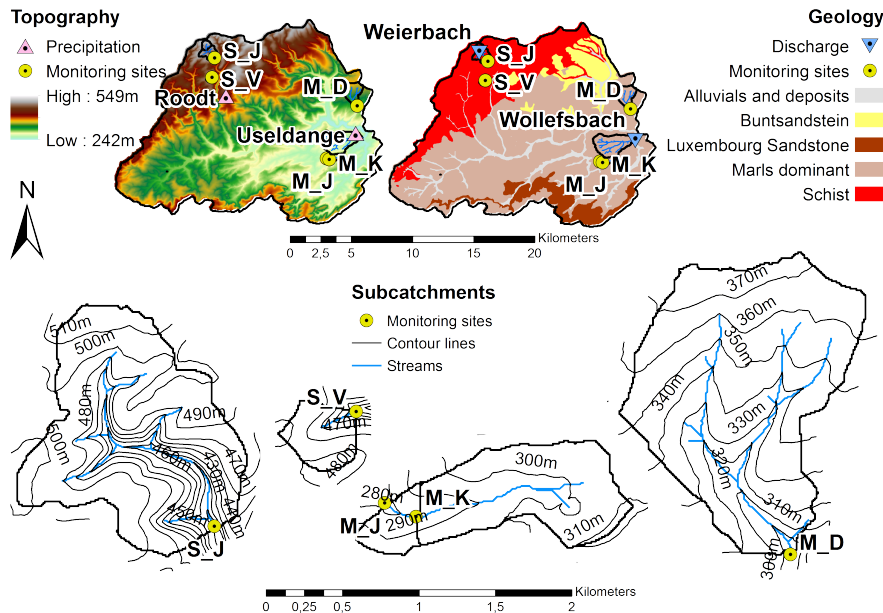


Figure 1. The Attert catchment in western Luxembourg and the five monitoring sites: M_D, M_J, M_K (marls), S_J and S_V (schist). Top left: catchment topography, top right: geology, bottom: the five subcatchments.

(alluvials and buntsandstein), shown in Figure 1 (top right). Most of the catchment is characterised by marls and Stagnasols with high clay content (20-60%), an undulating landscape and mostly agricultural land use (Sprenger et al. (2016)). The high contents of clay lead to low hydraulic conductivities and a limited drainage capacity. The north-western area (Figure 1) consists of schist bedrock and Cambisols with a texture between loam, silty loam and clayey loam which can drain freely until the soil-bedrock interface (Sprenger et al. (2016)). The landscape is here governed by elevated plateaus with mostly agricultural land use and steep forested hillslopes leading to perennial headwater streams.

A monitoring network with 45 stations was installed in the Attert catchment, recording environmental data such as climate data, soil moisture, groundwater and stream level, amongst others (Zehe et al., 2014; Demand et al., 2019). For the investigation of

hillslope-stream connectivity we selected those monitoring sites which were situated at a stream and thus allow a comparison between near-stream shallow groundwater level and the associated stream water level. Unfortunately no such site was available in the sandstone due to its very low drainage density, so the investigation focused on the two geologies marls and schist (Table 1 and Figure 1, bottom). The five selected stations were put into operation between June 2012 and July 2013 and the time span until end of [..¹³] July 2017 was [..¹⁴] used in the analysis. [..¹⁵] [..¹⁶] [..¹⁷] The spatial arrangement of the piezometers at each site can be seen in Figure 2 [..¹⁸] and the corresponding elevations and distances from the stream are provided in Figure 3. The prefixes M and S in the site names indicate the two geological regions. The following letter is part of the overall naming-scheme of the monitoring network. A full list of the sites can be found in Appendix A of Demand et al. 2019 M_D is located on a wide meadow with gentle inclination and Piezometers 1-3 have a distance to the stream between

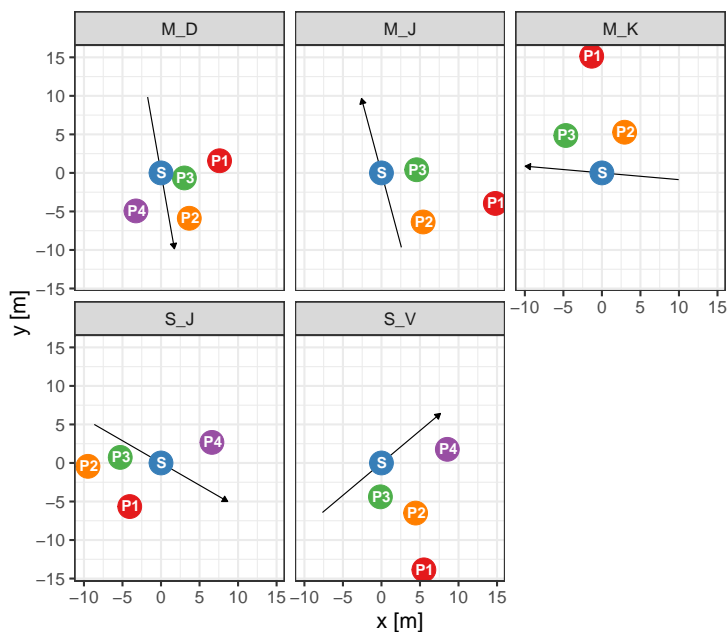


Figure 2. Schematic maps of the five sites. "P" stands for piezometer with the corresponding number while "S" stands for stream and is located at (0,0). The arrows point into the direction of stream flow. The coordinates are relative distances to the stream water level sensor (positive y-axis points north).

10 2m and 10m, while Piezometer 4 is on the steep opposite hillslope directly below a road cut (subsurface probably disturbed

¹³removed: Juli

¹⁴removed: considered for

¹⁵removed: The Atert catchment in western Luxembourg and the five monitoring sites: M_D, M_J, M_K (marls), S_J and S_V (schist). Top left: catchment topography, top right: geology, bottom: subcatchments.

¹⁶removed: Schematic maps of the five sites. "P" stands for piezometer with the corresponding number while "S" stands for stream and is located at (0,0).

The arrows point into the direction of stream flow. The coordinates are relative distances to the stream water level sensor (positive y-axis points north).

¹⁷removed: The spatial distribution of the 3-4

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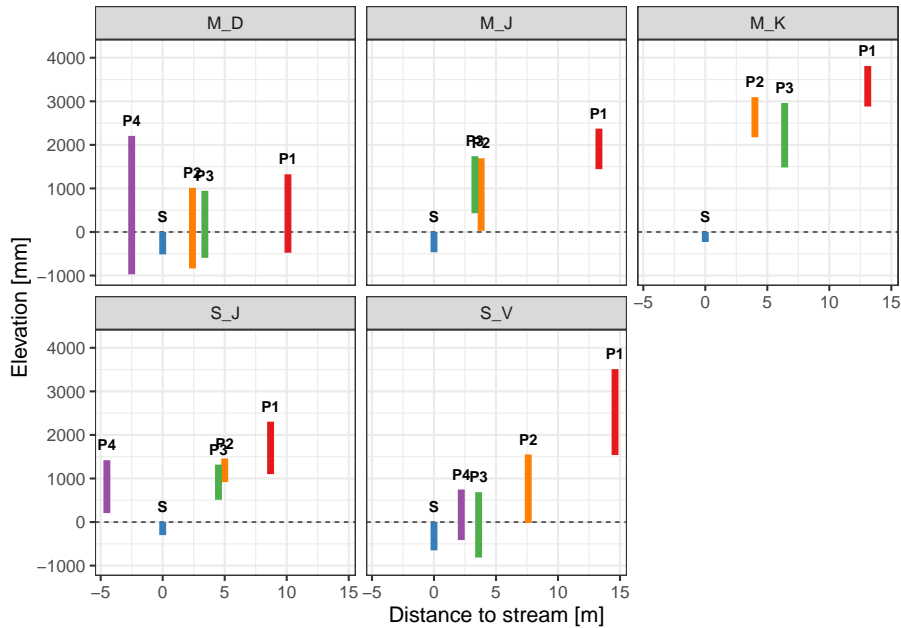


Figure 3. Elevations of ground level (upper end end of the bar) and sensor level (lower end) relative to the stream bed. Distance to the stream is shown on the x-axis. Colour coding is the same as in Figure 2.

during road construction). Piezometer depths extend to about a meter below the stream bed. The other two marls sites – M_J and M_K – are located on two nearby forested plains with the stream incised to about 2.5m and piezometer depths of around 2m. The horizontal distances between stream and piezometers are between 4m and 13m for both sites. S_J is located on a small meadow flood plain, flanked by steep forested hillslopes on both sides of the stream. Piezometer depths are here around 1.5m and reach below the stream bed. Piezometers 1-3 are situated on one side of the stream with distances of about 4 - 8m, while Piezometer 4 is located on the other side at a distance of 6m. S_V is located at a steep forested hillslope. The distance to the stream is between 2m (Piezometer 4) and 15m (Piezometer 1) and only the lower piezometers (3 and 4) extend to depths below the stream bed. Average hydraulic conductivities for the two soil types range from 293 to 675 cm/day (stagnosols) and from 360 to 648 cm/day (cambisols) (Sprenger et al. 2016)

10 2.2 Monitoring data

Each of the five sites described in section 2.1 was equipped with three to four piezometers to measure shallow groundwater level and one sensor for stream water level. Vertical boreholes were drilled until refusal using the Cobra TT jackhammer with a hollow boring head of 75mm diameter. Refusal was either defined as bedrock (in schist) or when a very dense layer of clay soil was reached (marls), which could not be further penetrated by the cobra. Perforated PVC tubings of 50mm diameter were wrapped into non-woven fabric, installed and packed with filter gravel between 4 and 8mm diameter. The uppermost

Table 1. [¹⁹] The basic attributes of the monitoring sites.

Site name	Geology	Soil	Land use	Drainage ¹	Slope quartiles ²	Upstream area	# of Piezometers
[-]	[-]	[-]	[-]	[-]	[°]	[ha]	[-]
M_D	Marls	Stagnosol	Pasture	Limited	2.3 / 3.3 / 4.5	200	4
M_J	Marls	Stagnosol	Forest	Limited	1.3 / 2.3 / 3.6	80	3
M_K	Marls	Stagnosol	Forest	Limited	1.3 / 2.2 / 3.3	68	3
S_J	Schist	Cambisol	Pasture	Free	2.3 / 4.8 / 12.2	154	4
S_V	Schist	Cambisol	Forest	Free	2.7 / 5.2 / 8.0	17	4

[1] According to Sprenger et al. (2016)

[2] Slope quartiles refer to the individual subcatchments (see Figure 1).

30cm below ground level were packed with sealing clay to prevent infiltration bypassing the soil. Depth of refusal was in most cases below 2m and the water level sensors were installed around 2cm above the bottom.

The sensors used were CTD temperature corrected pressure transducers by METER (formerly Decagon), measuring electric conductivity, temperature and water depth. Full scale is 10m, with a resolution of 2mm and an accuracy of $\pm 0.05\%$ of full scale.

- 5 Connection cables provide ventilation to the transducer and compensate for air pressure. Automated data loggers (CR1000 by Campbell Scientific) were taking measurements from all sensors with a temporal resolution of 5min. Hourly precipitation data from [²⁰] the Roodt and Useldange weather stations were obtained from AgriMeteo Luxembourg. Both stations are located within the Attert catchment, the Roodt station close to schist and the Useldange station being close to marls sites (Figure 1, upper left). Discharge data with 15 min temporal resolution were provided from the Luxembourg Institute for
- 10 Science and Technology (LIST) for the Weierbach station (for schist) and the Wollefsbach station (for marls) (Figure 1, upper right).

2.3 Event definition

- Automatic event detection is essential when working with long time series and a large number of events. To this end, it is necessary to define a generic response pattern (Figure 4). The general response pattern begins with a pre-event minimum
- 15 (h_{preMin}). When a precipitation event starts, the water level increases until it reaches its peak ($h_{maximum}$). After that peak, water level decreases and the event ends with a post-event minimum ($h_{postMin}$) that might differ from the pre-event minimum. These three points are used to describe water level changes during the event. However, the time period between the two minima (pre- and post-event) is not a robust measure for the event duration. Before or after events water levels are often not stable but subject to small but misleading trends (e.g. wetting-up phase or recession). While searching for the two minima a minimal
- 20 decline has almost no effect on the water level but inappropriately increases the extracted event duration. To compensate for that, two threshold points ($h_{riseThreshold}$ and $h_{fallThreshold}$) were introduced – one on each limb – that allow for a better

²⁰removed: Roodt station was obtained from the "Administration de la gestion de l'eau de Luxembourg".

temporal representation of each event. Both are defined as a certain percentage of $h_{preAmplitude}$ and $h_{postAmplitude}$. In the case of the rising limb the time where the water table exceeds $h_{riseThreshold}$ is called t_{rise} (see Figure 4). Analogously, the moment the water level falls below $h_{fallThreshold}$ is defined as t_{fall} . The distances to $t_{maximum}$ are described as the $t_{riseInterval}$ and $t_{fallInterval}$, respectively. So for time-related analyses these two intervals are used as they are not prone to pre- and post-event trends, but capture the actual event response dynamics. A percentage of 10% of $h_{preAmplitude}$ and $h_{postAmplitude}$ was found to be suitable for that task.

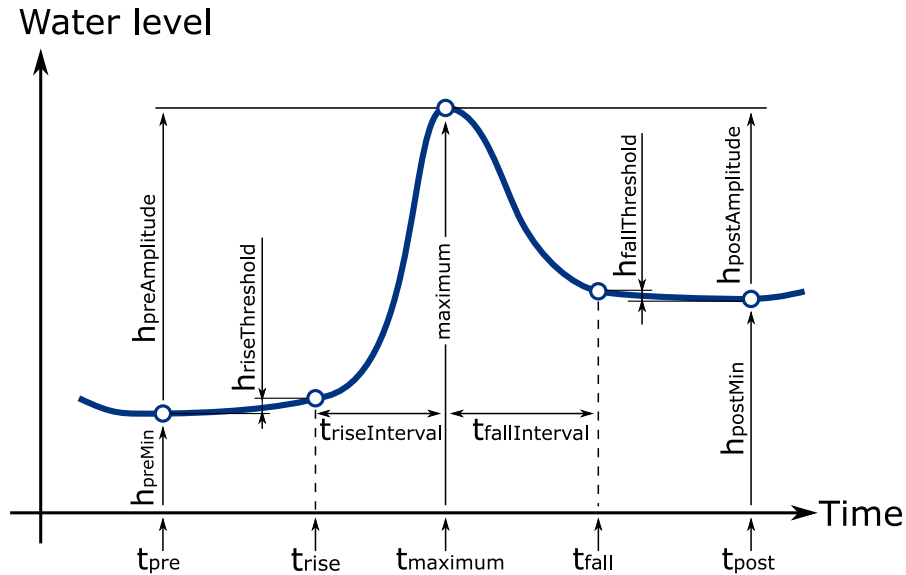


Figure 4. Event definition and characteristic variables for event response analysis.

2.4 Event detection

The purpose of the event detection is to parse the entire water level time series and extract those intervals during which the water level shows a response to rainfall. Algorithm 1 specifies the necessary steps for the event detection. At first, minimum amplitudes and search intervals need to be defined. Both parameters are subject to a compromise: The minimum amplitudes are used to prevent measurement noise from being mistakenly detected as events, with the drawback of possibly excluding actual low-amplitude events from detection. Search intervals are used to discriminate between subsequent events, which involves the risk of not completely capturing a very long event. In a second step, all local maxima of the stream water level are located. Thirdly, for each maximum the pre-defined search intervals are used in order to determine the global minima in the rising and falling limb. Defining these search intervals depends on the catchment size. Generally speaking, the search interval for the rising limb should be approximately equal to the concentration time of the subcatchment to guarantee that the complete

Algorithm 1 Event detection algorithm

DEFINE: amplitude thresholds for rising and falling limb ($h_{preAmplitudeMin} = 20\text{mm}$, $h_{postAmplitudeMin} = 10\text{mm}$)

DEFINE: $[..^{21}]$: two fixed search intervals from peak along the rising and the falling limb ($t_{preSearchInterval} = 24\text{h}$, $t_{postSearchInterval} = 48\text{h}$)

FIND: all local maxima in time series

for each maximum **do**

 FIND: absolute minima on rising and falling limb within defined search intervals

 CALCULATE: $h_{preAmplitude}$ and $h_{postAmplitude}$

if $h_{preAmplitude} < h_{preAmplitudeMin}$ **or** $h_{postAmplitude} < h_{postAmplitudeMin}$ **then**

 DISCARD: current maximum

end if

end for

MERGE: overlapping events

RETURN: t_{pre} and t_{post} of each merged event

rising limb is covered. Therefore, shorter search intervals are suited for headwaters (several hours to a day) and longer ones for lowland basins (several days). Also, the rise interval is shorter than the fall interval as such events are generally right-skewed due to retention behaviour. If two or more events overlap $[..^{22}]$ they are merged into one **single longer event** (Figure 5) and the $[..^{23}]$ **highest peak is determined as the event maximum. From there on it is handled as a simple event according to**

5 **Figure 4.**

The event detection was first applied to the stream water level time series which returns t_{pre} and t_{post} for each detected stream event. For each of these stream events a subsequent event detection is performed on the shallow groundwater level time series. Thus, we only include events in the analysis where stream water levels showed a response. Using each stream event for the detection of a possible groundwater event implies that the maximum temporal extent of the groundwater event is equal to
10 the stream event. This is a shortcoming of this method, as a time lag between shallow groundwater and stream or drawn-out groundwater recession might lead to the predefined search window clipping the drawn-out event in the shallow groundwater. However, in the case of multiple subsequent events a clear definition must exist in order to keep a one-to-one relation between stream and ground water events. If no temporal boundaries were applied for subsequent event detections, an event in the
15 shallow groundwater might overlap with two or more stream events which would drastically increase the complexity of the analysis. Because of the relatively small distances of less than 15m between stream and piezometers, and the small headwater catchments, response delays between stream and piezometer are presumed to be rather short, reducing the risk of clipping. Also, taking t_{pre} and t_{post} as the temporal extent for subsequent detections in groundwater provides a buffer for potential lag times. This one-to-one approach is considered most appropriate as it is a trade-off between good operability of the detection algorithm and a high coverage of stream and groundwater events.

²²removed: ,

²³removed: characteristic variables are recalculated for the entire event .

Amplitude thresholds were chosen via trial and error to prevent diurnal stream water fluctuations caused by root water uptake from provoking (erroneous) events. The threshold for the rising limb (20mm) is greater than for the falling limb (10mm) because during the wetting-up phase (in autumn) post-event water levels are very often higher than the pre-event water levels as the catchment becomes more saturated. [However, on shorter time scales wetting-up can also occur in other seasons.](#)

- 5 Using the same threshold for rising and falling limb would lead to the rejection of small events with such a behaviour. Search intervals were estimated by testing a range of values. A [fixed](#) time of 24h for the rising limb performed satisfactorily in our catchments even for long precipitation events and did not merge several subsequent events into one bulk event. With 48h for the falling limb the retention behaviour of the catchment was taken into account allowing for a long-tailed recession in comparison to the rise. The detection algorithm was run for each site individually, as a result the number and selection of detected events is site-specific.

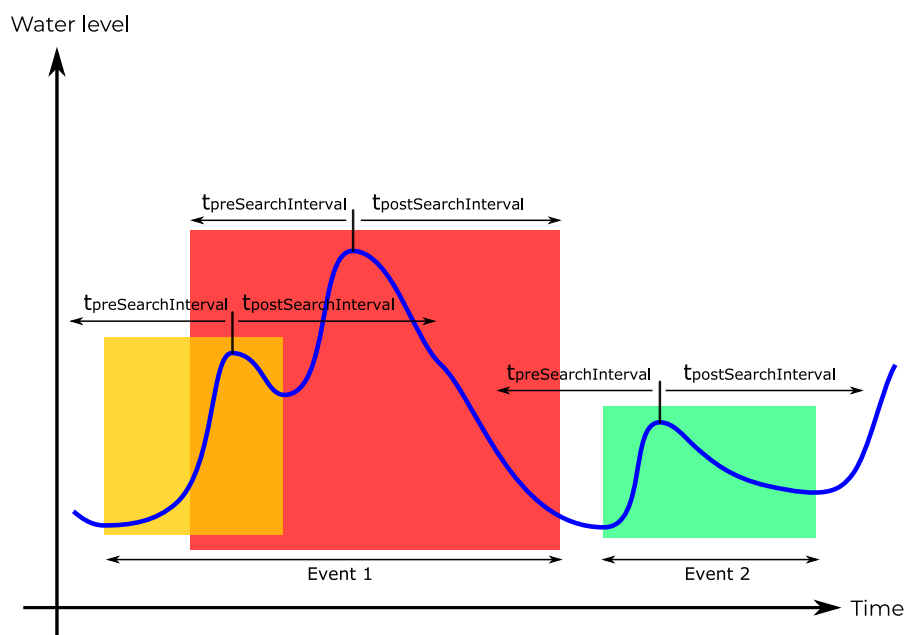


Figure 5. Merging conditions of consecutive events. Time series of water level showing three local maxima and the corresponding search windows for the minima. The coloured boxes mark the independently detected events as the interval between the two absolute minima around each peak within the respective search interval. The yellow and red events overlap and are merged into one. The green event is an independent second event.

10

2.5 Event type

Introducing event type descriptors allows to infer specific characteristics of a site and its experimental setup. The total number of events for a certain site is defined by its stream response, regardless of whether or not the shallow groundwater responds during the stream events. Event types are: *Complete* detections arise when the water level sensor was initially submerged and

the occurring event fulfils the stated detection criteria. For *Partial* detections the criteria are met but the piezometer is initially dry, so it is unknown how far below the sensor level the event started. *Dry* events are events where the piezometer is dry during the stream event and does not record any response. If no local maximum could be found in the groundwater during a stream event, the type was set to *noLocalMaximum*. *lowAmplitudes* means that the rise and/or fall amplitude thresholds are not surpassed. This might be due to a very low-amplitude response but can also cover events with a high rise amplitude but low fall amplitude, in particular when the peak is very close to the t_{post} boundary, which signals a long time lag between stream and groundwater. [..²⁴] *allNA* indicates technical sensor problems in the piezometers during the detected streamflow event. While only *complete* events contain valid state and timing variables that can be put into relation with the stream (and are subsequently used for the detailed analyses), all non-complete events also contain relevant information. Knowing about the frequency of occurrence of these other event types helps to characterise each piezometer and site.

2.6 Event analysis

The event analysis aims for a better understanding of how and under which conditions the shallow groundwater connects to the stream or disconnects from it. Observing the relation of water table dynamics between stream and shallow groundwater, can reveal connectivity patterns which in turn give insight in the underlying processes. This simultaneous view on groundwater and stream is what is defined as the groundwater-stream (response) relation. A many-event approach ensures that a high variability of catchment conditions and response behaviours is incorporated into the analysis to cover the entire bandwidth of hydrologic system behaviour. Analyses covering single or a low number of events lack the ability of estimating variability and do not allow to deduce how "typical" or "extreme" the event is and if it is representative.

Because the problem is multi-dimensional and considerably complex, a strategy was chosen that allows to examine various aspects of the hydrologic responses independently. Combining the information of these different aspects should then give a deeper insight into the occurring processes that control the various hillslope-stream-systems.

The hillslope-stream connectivity can be investigated for periods before an event starts where underlying hydrologic processes take place on more long term (seasonal) time scales and are represented by the baseflow. As a measure for this connectivity during baseflow conditions (between events) the rank correlation of all pre-event minima (h_{preMin}) between each piezometer and the corresponding stream was used. To visually compare before-event relations across piezometers and sites, each sensor's water level was normalised by its minimum and maximum h_{preMin} value.

$$h'_{preMin} = \frac{h_{preMin} - \min(h_{preMin})}{\max(h_{preMin}) - \min(h_{preMin})} \begin{cases} 0 & \text{for stream} \\ 1 & \text{for groundwater} \end{cases} \quad (1)$$

Equation 1 describes the normalisation and results in a [..²⁵] values for h'_{preMin} between 0 and [..²⁶]1. To indicate whether the normalised water level is above (stream) or below ground level (piezometers), the value 1 was subtracted [..²⁷]when

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groundwater levels were normalised. This results in values for h'_{preMin} [..²⁸] between -1 and 0 [..²⁹] for groundwater.

[..³⁰] In hillslope-stream systems infiltration and runoff [..³¹] generation processes are highly dynamic during events on a time scale of hours and days [..³²]. To gain additional insight into what happens during these periods we chose to handle the water level changes and timing as two separate aspects. This [..³³] provides us with a view of the temporal behaviour on

5 the one hand and changes in the state variables (water levels) of the hydrologic system on the other.

Relative timing and lags between groundwater and stream responses [..³⁴] extracted from a large number of events hint at causal relationships. To investigate the variability of this relative timing across all events, piezometers and sites the response behaviour was reduced to timing effects only. A very similar normalisation approach as in Equation 1 was used to compare

timings of groundwater responses with those of the stream. Equation 2 uses the time at which the stream exceeds the 10%

10 threshold $t_{rise\ stream}$ and the time where it reaches its peak $t_{max\ stream}$ to normalise groundwater and stream event timing.

$$t' = \frac{t - t_{rise\ stream}}{t_{max\ stream} - t_{rise\ stream}} \quad (2)$$

This stream-based normalisation leads to a value of 0 for the t_{rise} in the stream and 1 for the $t_{maximum}$. A corresponding groundwater event that starts at 0 and reaches its maximum at 1 has the exact same timing as the stream. Values below 0 correspond to a time before the stream responded while values above 1 correspond to a time where the stream already is in

15 recession. By applying this normalisation it is possible to compare relative time lags between stream and groundwater as well as differences in the duration.

The extent of water level increases in stream and groundwater and the relationship [..³⁵] between the two can provide useful information on the dominant runoff generation processes. We would expect that a given increase in groundwater level at a given depth would result in a more or less predetermined/deterministic increase of stream water level (assuming the groundwater

20 fluctuations are representative of the catchment). This means that if Events A and B have similar initial conditions and cause similar groundwater level rises we would expect the stream water level rise of Event A to be the same as for Event B. In this case one observation could be used to predict the other. As this also assumes that there is a connection between ground-

water and stream and that runoff generation is controlled by shallow groundwater contributions, deviations from deterministic relationships are an indication of other runoff generation processes or flow path variability. Removing the temporal component

25 and only focusing on the extent of the increase between pre-event water level and peak water level enables inspecting this relationship.

To investigate if shallow groundwater observations at a given hillslope can be used as a proxy for the state of connectivity in the entire catchment we analysed the relationship between event runoff coefficients and the depth. The runoff coefficient

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³¹removed: processes govern the hydrologic hillslope-stream system on short time scales (

³²removed:). To analyse this relation during events, timing and state changes were not examined jointly (e.g. by plotting water table time series against each other) but

³³removed: approach provides a separate

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describes the ratio of accumulated event discharge at the catchment outlet and accumulated catchment precipitation (Equation 3). Even though each experimental site monitors stream level, no reliable discharge information is available since rating curves are fragmentary and thus uncertain, or do not exist. Therefore, runoff coefficients (C) are calculated for nearby sub-catchments (Wollefsbach and Weierbach; see Figure 1). The spatial proximity ensures that detected stream water level events coincide with discharge events. [The approach to separate baseflow from discharge is based on the constant slope method \(Dingman, 2002\)](#). Baseflow ($Q_{baseflow}(t)$) was defined as the area below the straight line connecting t_{rise} and t_{fall} and was subtracted from the total discharge ($Q(t)$) to calculate the actual stormflow. Precipitation ($P(t)$) from Roodt station was considered sufficiently representative across the Attert Catchment to be used for all runoff coefficient calculations.

$$C = \frac{\int_{t_{rise}}^{t_{fall}} Q(t) - Q_{baseflow}(t) dt}{A \int_{t_{rise}}^{t_{fall}} P(t) dt} \quad (3)$$

- 10 Relating the shallow groundwater information to the event runoff coefficients can help us to assess how representative the local measurements are for the entire catchment upstream.

3 Results

3.1 Event detection

Our event detection algorithm identified between 119 and 159 stream runoff events per site and covered a period of five to six years. Not all of these were also detected in all piezometers (Figure 6 and 7). This can be due to data gaps as a result of technical failure of the sensor or data gaps as the piezometer fell dry or because the response in the groundwater was strongly dampened and thus did not fulfil the criteria of the algorithm. In general, the temporal distribution of the detected events shows similar patterns across all sites (Figure 6). It also allows to identify M_D_Piezo4 and M_K_Piezo3 as behaving very differently with many *lowAmplitudes* and *allNA* events. In the case of *lowAmplitudes* we found that many events were clipped by the pre-defined time-window due to very long delays in relation to the stream, which were longer than in the other piezometers at these sites.

[As the analysis covers also winter and early spring events, the effect of snow fall and snow melt on the event detection was assessed and found to be unlikely to impact our analysis: Snow fall events are generally quite rare in Luxembourg, so the number of events affected is assumed to be low. A rain on snow event would be captured by its runoff response, but the in this case erroneous estimate of rainfall input would only impact the analysis of event runoff coefficients as our analyses mainly focus on the relationship between streamflow and groundwater responses. Pure snow melt events are not included in the analysis, as in this case there is no directly preceding precipitation event and thus this necessary event identification criterion is not met.](#) Referring to the response type two main patterns can be distinguished (Figure 6). Sites where the sensors remain submerged throughout the observation period thus producing many *complete* events (M_D and S_J) and sites with piezometers falling dry in summer and autumn (M_K, M_J and S_V). While at the two marls sites these dry periods occur at all piezometers concurrently, at S_V the number of dry events increases in upslope direction (from

Piezometer 3 to Piezometer 1). The aggregated values in Figure 7 also reveal two response types with low occurrences – namely *noLocalMaximum* and *partial* events. A total of 68 partial events were detected. The *noLocalMaximum* response is very rare with only 11 occurrences [..³⁶]. Summary statistics for precipitation, runoff and water level responses of the detected

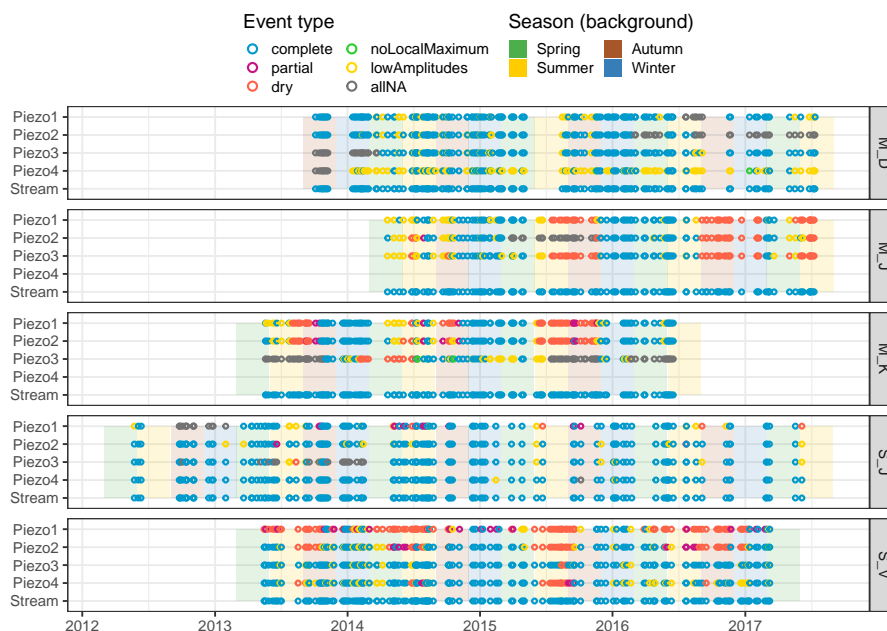


Figure 6. Spatiotemporal distribution of detected events for marls (M_) and schist (S_) between June 2012 and July 2017. Seasons are defined as the periods Dec-Feb (Winter), Mar-May (Spring), Jun-Aug (Summer) and Sep-Nov (Autumn)

stream events are shown in table 2.

5 3.2 Before-event hillslope-stream connectivity

The rank correlation coefficients were found to be lower in marls than in schist sites (background colour in Figure 8). In schist only the two upslope piezometers (Piezo1 and Piezo2) of S_V show lower correlation values (0.65 and 0.70), while the others remain above [..³⁷]0.80. For the three marls sites rank correlation coefficients are generally lower (between [..³⁸]0.42 and 0.60) with higher variation. In marls most pre-event groundwater levels cluster in the the shallow depths above -0.4 (M_K) and -0.3 (M_D and M_J)[..³⁹]. Schist groundwater levels are more evenly distributed over the entire range (Figure 8). The point colours representing the seasons illustrate that groundwater levels are generally high in winter and spring[..⁴⁰].

³⁶removed: and is thus considered negligible

³⁷removed: 0.75

³⁸removed: 0.25 and 0.75

³⁹removed: which correspond to absolute depths of -0.5 m (Figure 10)

⁴⁰removed: and low in summer and autumn.

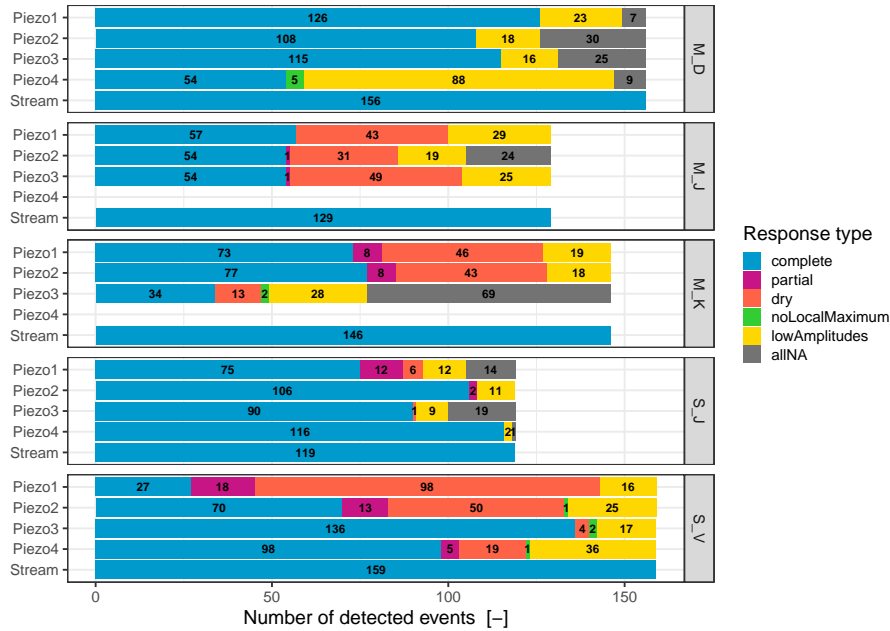


Figure 7. Number of detected events in the streams and groundwater at each stream gauge and piezometer, including types of event responses

Summer events can be found mostly at the lower end with occasional events at higher groundwater levels. In Autumn the wetting-up phase begins, which produces events over a wider range of groundwater levels.

3.3 Comparison of relative response timing between stream and groundwater

The relative timing between groundwater and stream is illustrated in Figure 9. The two black vertical lines represent the timing of the stream event with t_{rise} at $x = 0$ and $t_{maximum}$ at $x = 1$. Each horizontal bar depicts a groundwater response event with its own t_{rise} at the left end and $t_{maximum}$ at the right end. Groundwater responses that start at 0 and end at 1 have the exact same timing as the stream response. Starting values below 0 reveal a groundwater response before the stream, while an end value above 1 indicates that the stream is already in recession before the groundwater reaches its maximum. The events are sorted on the y-axis by the normalised rise time in the groundwater from delayed groundwater response at the bottom to early groundwater response at the top. Additionally, the bar colours display the normalised pre-event water levels with high pre-event groundwater level in blue and low pre-event groundwater level in red.

At M_D (Piezo1 to Piezo3), S_J (Piezo1 to Piezo3) and S_V (Piezo3 to Piezo4) a strong relation between pre-event groundwater levels and event timing can be observed. Events occurring at high pre-event groundwater levels (bluish) correspond with a mostly simultaneous rise in groundwater and stream while for events at low groundwater levels (reddish) the groundwater rise lags behind the stream. Considering the peak, high groundwater events reach their maximum before or simultaneously with the stream while during low groundwater the maximum is reached significantly after the stream. At sites M_J, M_K and S_V

Table 2. Characteristics of the stream events summarised for each site. Different values for runoff and precipitation can occur as not all sites cover the same (number of) events. Also, different runoff and precipitation stations were used for marls and schist sites (see Figure 1).

Variable	Site name	Min	Median	Mean	Max
Event Runoff [mm]	M_D	0.0	0.6	2.7	25.0
	M_J	0.0	0.4	2.4	25.9
	M_K	0.0	0.9	2.9	21.4
	S_J	0.0	0.2	1.6	24.3
	S_V	0.0	0.1	0.7	16.7
Precipitation Intensity [mmh ⁻¹]	M_D	0.3	2.2	3.6	21.6
	M_J	0.6	2.4	4.0	21.5
	M_K	0.6	2.5	3.7	21.6
	S_J	0.7	3.9	5.0	17.2
	S_V	0.4	2.9	3.9	17.2
Precipitation Sum [mm]	M_D	0.6	9.8	12.8	75.4
	M_J	1.1	10.1	13.2	62.6
	M_K	1.0	10.4	13.0	53.3
	S_J	3.1	17.3	19.4	74.5
	S_V	1.0	13.0	14.8	58.5
Rise Amplitude [mm]	M_D	20.0 ¹	64.5	88.0	378.0
	M_J	19.3 ¹	46.0	64.4	282.0
	M_K	19.0 ¹	48.0	61.6	227.0
	S_J	19.2 ¹	46.0	55.8	241.0
	S_V	19.0 ¹	43.0	51.6	137.0
Rise Interval [h]	M_D	1.4	12.2	14.7	55.2
	M_J	1.5	8.6	11.9	55.2
	M_K	1.4	8.8	10.5	55.3
	S_J	1.4	10.2	14.3	62.5
	S_V	2.8	19.0	19.1	58.9

[1] Threshold of 18mm for event detection algorithm (90% of 20mm).

(Piezo1 to Piezo2) this separation of high (bluish) pre-event groundwater on top and low (reddish) pre-event groundwater at the bottom is visible but not quite as pronounced as for the other sites.

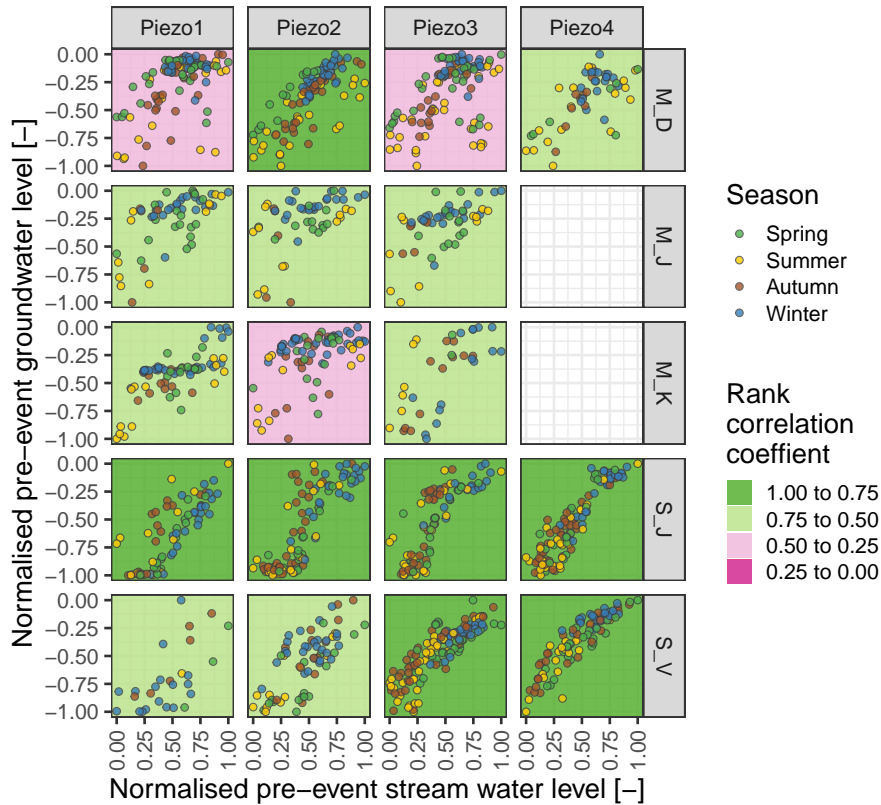


Figure 8. Normalised stream and groundwater levels before the investigated precipitation events (h_{preMin}). The background colour represents the rank correlation coefficient, the point colours illustrate the season. Both axes are normalised by minimum and maximum h_{preMin} (see equation 1). The negative range on the y-axis indicates depths below ground (groundwater), the positive range on the x-axis depths above ground (stream).

3.4 Event-induced increases in stream and groundwater levels

The extent of water level increases in stream and groundwater and the relationship of the two is illustrated in Figure 10. Both pre-event water levels (stream and groundwater) are used as coordinates for the beginning of an event line (lower left point) and the maxima as the coordinates for the end (upper left), with stream water levels on the x-axis and groundwater levels on the y-axis. As we removed the temporal component it is important to keep in mind that peak values not necessarily occur at the same time. We observe a change in response behaviour between stream and groundwater marked by a threshold which was derived visually (dotted horizontal lines) in Figure 10. **The way the patterns changed at the threshold was not identical for all sites. While many piezometers showed an abrupt change in slope (M_D Piezo1-3, M_J Piezo1 and S_J Piezo 2-4)**

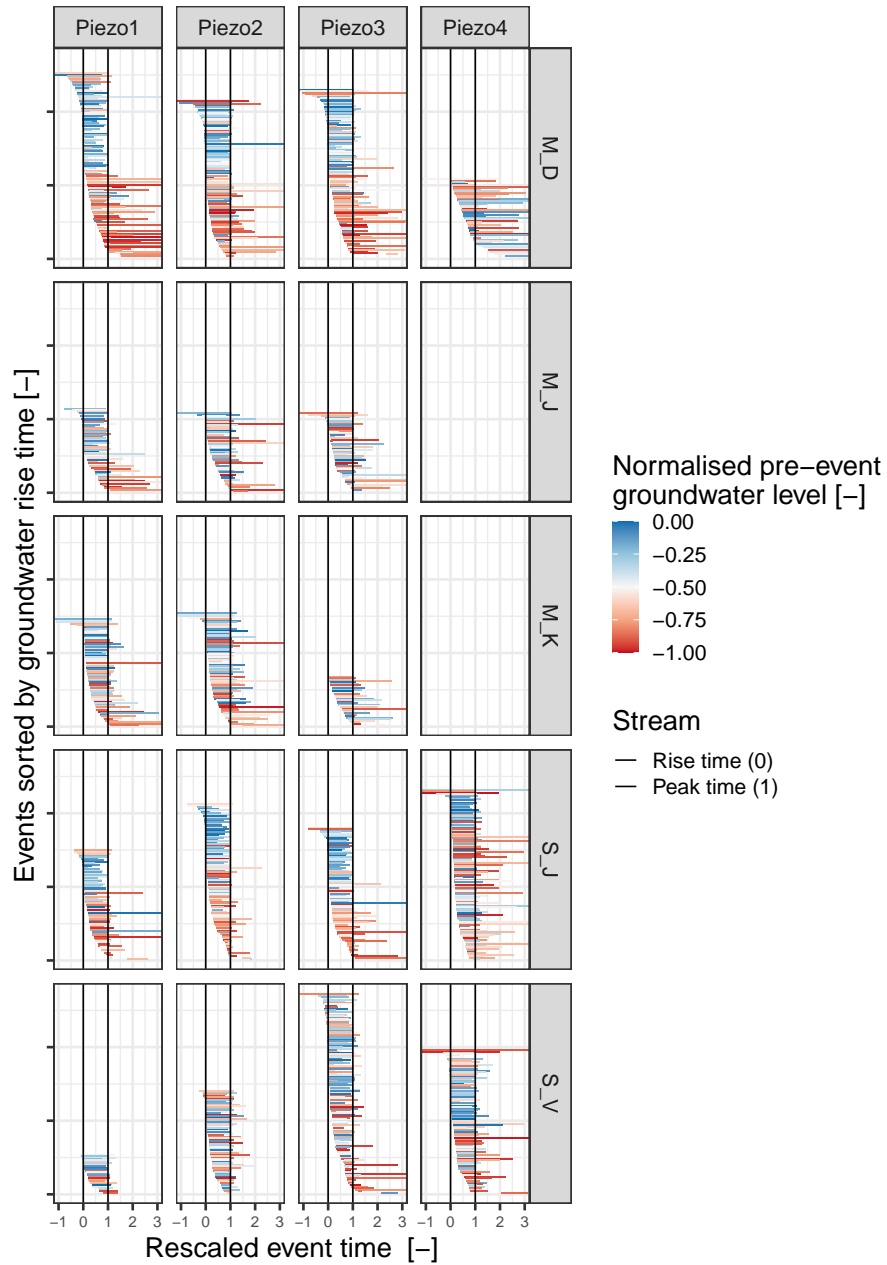


Figure 9. Timing of groundwater response relative to stream response. The two vertical lines at 0 and 1 represent the normalised rise and maximum time of each individual stream flow event. Horizontal bars each represent a groundwater event with its individual normalised rise and maximum time. Bluish colours indicate high and reddish colours indicate low pre-event groundwater levels.

while others had showed a converging of their envelope functions (encompassing the bundle of slope lines) converging again (S_J Piezo1, S_V Piezo3 and Piezo4). For some piezometers the change in pattern was a sudden clustering of lines (M_K Piezo1-2, S_V Piezo2). All these observed changes in patterns signal that hydrologic processes do change due to different pre-event groundwater levels, when the threshold values are passed. At low groundwater levels amplitudes in the rising limb are large in the groundwater and low in the stream (steep slope of lines), while above the threshold the amplitudes in groundwater are capped at a certain depth below the surface, and stream amplitudes can become large (low slope of lines in Figure 10). Also, the variability of pre-event conditions and event responses is larger below the threshold, while above, the lines are more likely to fall on top of each other and become more deterministic. This is particularly the case for M_D (except Piezo4), M_K (except Piezo3) and S_J. Winter events cluster above the threshold and the other three seasons below the threshold and in the transition zone.

3.5 Runoff coefficient

The relation between local pre-event groundwater levels and the event runoff coefficients is displayed in Figure 11. The dotted horizontal lines represent the same individual shallow groundwater thresholds for each piezometer identified in Figure 10 (but here with the normalised pre-event water level on the y-axis). Colours indicate whether the groundwater responded before the stream (red) or after the stream (blue). At M_D, S_J and S_V the pattern is very similar: below the individual pre-event groundwater thresholds runoff coefficients are very small, but increase significantly both in value as well as in variability when pre-event groundwater levels rise above the threshold. For the two forest sites in the marls region – M_J and M_K – the pattern is less clear, with some larger runoff coefficients also occurring below the threshold. A separation with regards to relative response timing (red vs blue) can be observed at M_D and S_J where groundwater responds before the stream for most events above the pre-event water level threshold. At the other three sites M_J, M_K and S_V no clear distinction can be made.

3.6 Catchment state

[..⁴¹] We assume that the threshold (Figure 10) marks a change in catchment state, where conditions above the threshold have the potential for high connectivity while conditions below the threshold indicate lower connectivity. To investigate if the shift in state is synchronous across the sites we plotted the event time series colour-coded by system state (above/below the threshold) (Figure 12)[..⁴²]. The general pattern clearly shows a common shift in hydrologic connectivity with higher probabilities of catchment states above the threshold from late autumn until early spring. However, below threshold states can occur in winter (see for example the winter of 2016) and above threshold states can also occur in summer (see for example summer of 2014). There is no clear distinction between the geological regions but there are periods where system state varies across the different sites (e.g. fall 2014). However, for most events the below/above threshold state identification is similar in timing across many piezometers.

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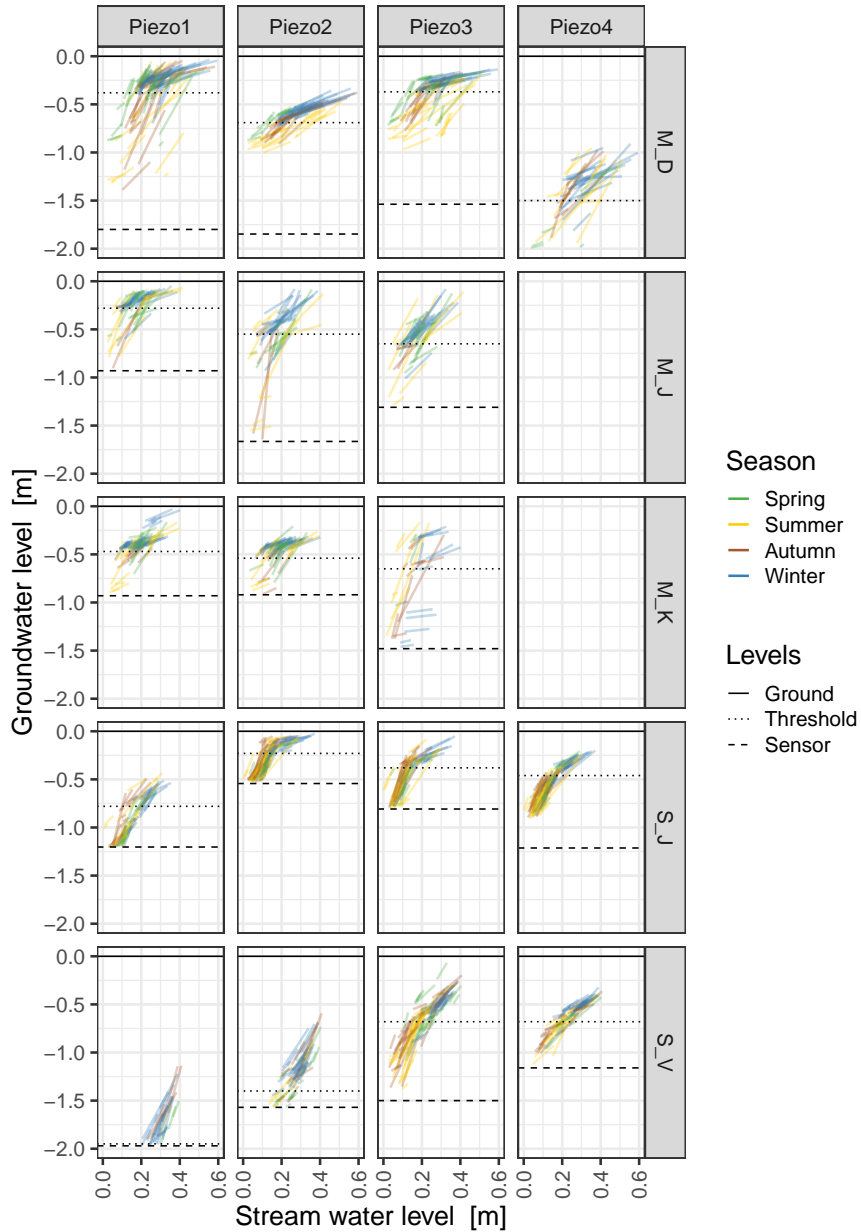


Figure 10. Responses in water tables of groundwater (y-axis) and the corresponding stream (x-axis). The lines connect the pre-event minimum with the event maximum. Note that these water levels do not necessarily occur at the same point in time as this visualisation removes the temporal dimension. The y-axis of the plot ends at a depth of 2m for purpose of comparison, thus omitting 2 events occurring below this groundwater level at M_D_Piezo4. Dotted horizontal lines illustrate the threshold between the lower (more variable but mainly steep sloping lines) and upper (less variable with shallow slopes) hydrologic response behaviour.

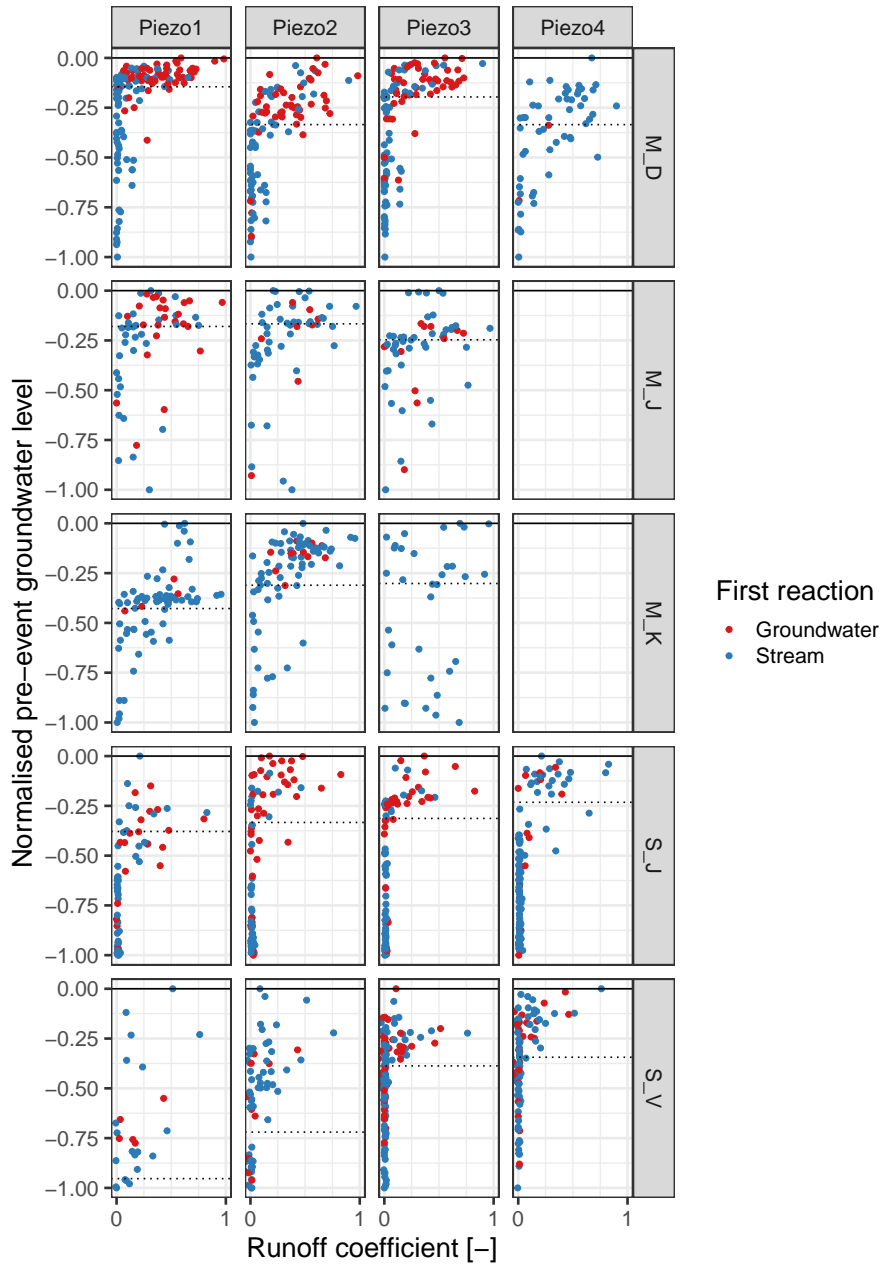


Figure 11. Event runoff coefficients versus shallow groundwater levels. Event runoff coefficients were determined for the Weierbach (schist) and Wollefsbach (marls) catchments where discharge data is available. The dotted horizontal lines illustrate the individual thresholds obtained from Figure 10. The point colours indicate whether the groundwater levels responded first (red) or the stream (blue).

To study the fraction of events that ended up above the threshold (Table 3), we focused on that piezometer per site that had the largest number of complete events (and excluding M_D_Piezo4 and S_J_Piezo4, which were situated on the opposite slope compared to the other piezometers at these sites). This selects Piezo1 at site M_D, Piezo2 at sites M_K and S_J and Piezo3 at sites M_J and S_V. The fraction of streamflow events above the threshold ranges between 23% (M_J) and 49% (M_D). There is no relationship between the fraction of events above the threshold and geology, with M_J and S_J having the lowest fractions (<30%) and M_D and S_V the highest fractions (>40%). The low fraction at sites M_J and M_K and S_V_Piezo1 is in part the result of the high number of partial and dry events (in addition to the complete events below the threshold).

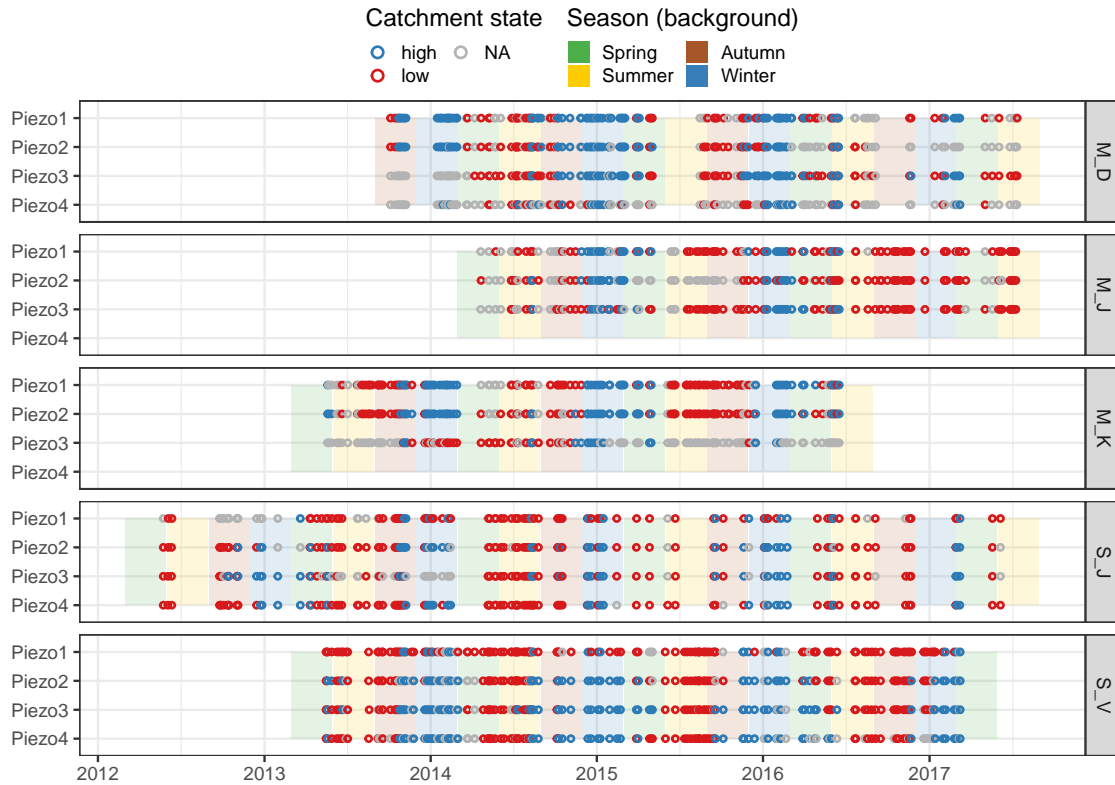


Figure 12. Catchment states at the beginning of events. In contrast to Figure 6 it shows whether or not the groundwater levels are above (high/blue) or below (low/red) the locally defined groundwater threshold levels. [..⁴³] Complete, partial and dry events are included, all other events are shown in grey (NA).

Table 3. Fractions of events below (low, including partial and dry events) and above (high) the threshold. All other event types (lowAmplitudes, noLocalMaximum, allNA) are considered NA.

Site name	Sensor name	Low	High	NA
[-]	[-]	[%]	[%]	[%]
M_D	Piezo1	32	49	19
M_D	Piezo2	30	39	31
M_D	Piezo3	36	37	26
M_D	Piezo4	17	18	65
M_J	Piezo1	54	23	22
M_J	Piezo2	49	18	33
M_J	Piezo3	60	20	19
M_K	Piezo1	52	35	13
M_K	Piezo2	49	38	12
M_K	Piezo3	21	12	68
S_J	Piezo1	65	13	22
S_J	Piezo2	61	29	9
S_J	Piezo3	49	28	24
S_J	Piezo4	74	24	2
S_V	Piezo1	77	13	10
S_V	Piezo2	52	31	16
S_V	Piezo3	44	44	12
S_V	Piezo4	43	33	23

4 Discussion

4.1 Event detection

The events summarised in Figures 6 and 7 allow us to identify erratic sensors but also reveal topographic characteristics of the various sites. Topography can explain the occurrence of *dry* events, with a deeply incised stream at M_J and M_K, where we observe the lowest fraction of complete events in the groundwater with 50% or less of the streamflow events, and the steep hillslope at S_V leading to a gradient in water level depths and thus differing responses among the piezometers as well as seasonally more strongly fluctuating groundwater levels. The low numbers of *partial* events at sites with high numbers of *complete* and *dry* events (M_J and M_K) signal that the seasonal transition between low and high groundwater levels is very abrupt, skipping intermediate levels. This might be due to pronounced capillarity fringes reaching into the very shallow subsurface. In that case, infiltrating water would reach the upper end of the fringe very quickly and only little water volume

would be necessary to lift the groundwater level significantly (e.g. Cloke et al. (2006)). The very low number of only 11 noLocalMaximum groundwater events supports the viability of the developed event detection.

4.2 Before-event hillslope-stream connectivity

Cross-correlation has been used in previous studies to assess different aspects of hydrologic connectivity, such as lag time analysis between stream and groundwater table (Allen et al., 2010; Bachmair and Weiler, 2014), relating water table connectivity to topographic indices (Jencso et al., 2009) or comparing groundwater levels with runoff coefficients (Seibert et al., 2003). Assuming well coupled hydrologic systems, high correlation coefficients would be expected, which applies to the two schist sites. Low correlation coefficients indicate a streamflow (baseflow) response that is decoupled from the groundwater. This applies to all three marls sites. However, the within-site variability is not as large as the colour-scheme suggests (for M_D between 0.42 and 0.76 and for M_K between 0.49 and 0.69). Visually comparing the point cloud patterns of the piezometers at each single site (Figure 8) reveals [..⁴⁴], despite the scatter, site-internal similarity (a site-specific fingerprint) among the piezometers (with the previously mentioned exceptions in section 3.1 of M_D_Piezo4, located in disturbed soil on a steep slope below a road, and M_K_Piezo3 [..⁴⁵](where the anomalous behaviour cannot be explained at first sight). The site-internal similarity in the point-clouds as well as the rank correlation-coefficients suggest that well-placed groundwater observation points can [..⁴⁶]provide information on hillslope-stream connectivity for the given footslope, at least for pre-event conditions. The observed differences between the geologies suggest that soil texture and bedrock structure might control regional similarities.

4.3 Comparison of relative response timing between stream and groundwater

Identical response timing of groundwater rising and peaking just before the stream suggests that hillslope groundwater is driving streamflow response and thus that hillslope-stream connectivity is high (Haught and Meerveld, 2011; Rinderer et al., 2016). That this occurs under high groundwater levels further supports this conclusion. Groundwater rising and peaking after streamflow indicates that streamflow response is probably not caused by hillslope shallow groundwater and that hillslope-stream subsurface connectivity is low. In a highly heterogeneous catchment, certain "fast" hillslopes with very high hillslope-stream connectivity and high outflows might provoke a stream-response at the stream level gauge before the monitored hillslope responds. In this case the interpretation of low subsurface-connectivity would only hold for the monitored hillslope. The depth of groundwater level (and its capillary fringe) directly influences the delay in groundwater response as this depth defines the infiltration distance. During events with low groundwater levels, precipitation falling onto or very close to the stream might generate a rise in the stream before the groundwater response (McGuire and McDonnell, 2008). Triggering an early response in stream compared to groundwater can also be the result of infiltration excess overland flow where surface runoff connects faster to the stream than it infiltrates towards the groundwater. However, this can be ruled out for schist as the high infiltration

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capacity makes overland flow unlikely, while it can not be ruled out for the clayey soils in the marls region (Wrede et al., 2015). No [..⁴⁷]clear visual differences in timing can be observed between marls and schist. The large variability in response timing confirms the need for monitoring over extended time periods as few or single event analyses run the risk of not being representative. Temporal relationship and water level responses are intertwined in a time series which makes it very intricate focusing on one while looking at both at the same time, e.g. by plotting two time series against each other and interpreting the resulting hysteresis (Kendall et al., 1999; McGuire and McDonnell, 2010; Zuecco et al., 2016). Choosing to separate the analysis of the temporal response from the water level changes allowed to better reveal the temporal relationship of the hillslope-stream system on the one hand, and water level changes on the other.

4.4 Event-induced increase in stream and groundwater levels

10 Previous studies observed transmissivity feedback as a key mechanism controlling subsurface runoff (Bishop et al., 2011; Detty and McGuire, 2010b). Transmissivity feedback has previously been observed directly via piezometers (Bishop et al., 2011) or indirectly through stable isotope composition in stream runoff (Bishop et al., 2004; Laudon et al., 2004) and tracer transport rates (Laine-Kaulio et al., 2014). In our study the capped response of groundwater events above a certain threshold is a strong indication of transmissivity feedback as one controlling mechanism (M_D and M_K). At low groundwater levels, 15 infiltrating water results in a substantial increase of the groundwater level, suggesting that lateral conductivities are low as water is added more quickly than it can flow away laterally. This changes when the water level reaches a certain level or soil horizon. Now infiltrating water is no longer increasing groundwater level substantially but instead fast lateral transport is likely to be causing the observed pronounced rise in stream water levels. This sudden fast lateral transport of the shallow groundwater is likely due to substantially higher lateral hydraulic conductivity of the upper soil horizons compared to the 20 lower soil horizons. This fits well with the findings by [..⁴⁸]Sprenger et al. (2016) who at site M_K found a strong increase in saturated hydraulic conductivity by a factor of 40 at a depth of 36 [..⁴⁹]cm, while the increase for site M_J (where we did not observe a strong capping of the response) is less than 20% (the other 3 sites were unfortunately not included in the analysis by [..⁵⁰]Sprenger et al. (2016)). A raise in the hydraulic gradient in a more uniform depth profile of hydraulic conductivities, on the other hand, would only lead to a gradual increase in lateral flow. At S_V transmissivity feedback does not seem to occur 25 as the slopes of the lines do not change as abruptly (Figure 10). This is in accordance with the findings of Angermann et al. (2017) at the same hillslope: During sprinkling experiments they observed that relatively high vertical and lateral hydraulic conductivities ($10^{-3}m/s$) lead to fast lateral responses in subsurface. The high variability of the trajectories for events with low pre-event groundwater levels can be explained by a higher variability in possible flow paths compared to conditions of high groundwater levels. Another possibility is the complete disconnection between hillslope and stream which allows varying 30 stream water levels to occur with similar groundwater levels. Whether or not a precipitation event can activate certain flow paths depends on the spatial distribution of pre-event water and the characteristics of bedrock topography (van Meerveld et al.,

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2015). Demand et al. (2019) found that preferential flow is present in particular during dry conditions. When the groundwater level is high, the majority of flow paths is already activated and the degrees of freedom to activate new flow paths are limited. Therefore, the relation between stream and groundwater converges and shifts from variable to more uniform (Figure 10). Investigating rainfall characteristics and their effect on event responses did not help explaining the underlying mechanisms.

- 5 While rank correlation coefficients between [⁵¹] *precipitationSum* and $h_{preAmplitude}$ reached [⁵²] relatively high values of 0.7 and above, [⁵³] the majority stayed below 0.2 for $t_{riseInterval}$ showing that the precipitation had no clearly identifiable effect on event timing (see table A1 in Appendix).

4.5 Runoff coefficient

Threshold behaviour is a common observation in runoff generation (Ali et al., 2013), for example Scaife and Band (2017) and
10 Detty and McGuire (2010b) observed a threshold effect of antecedent precipitation and soil moisture on stormflow, and Latron
and Gallart (2008) identified a threshold behaviour between groundwater level and runoff coefficient depending on seasonal
catchment conditions (dry, wetting-up and wet). In our study the groundwater threshold marking the change in event runoff
coefficients (Figure 11) coincides with the regime shift of water table responses (Figure 10). At M_D, S_J and S_V the pattern is
very similar: below the individual pre-event groundwater thresholds runoff coefficients are very small, but increase significantly
15 both in value as well as in variability when pre-event groundwater levels rise above the threshold. For the two forest sites in the
marls region – M_J and M_K – the pattern is less clear, with some larger runoff coefficients also occurring below the threshold.
A possible explanation could be that Wollefsbach gauge used to determine the runoff coefficients is less representative for
these forest sites, as the Wollefsbach Catchment consists almost entirely of pasture and agricultural areas. In addition, the
morphology of slopes and stream channel at the two marls forest sites is very distinct (and different to the Wollefsbach), with
20 very low gradients in the slopes but a deeply incised stream bed. As the probability of high runoff coefficients increases above
the groundwater threshold it seems that local observations of groundwater levels can give a good indication of catchment state
with respect to connectivity and storage and release behaviour. This is true even for neighbouring catchments within the same
geological region (M_D and S_V for example are not located in or downstream of the catchments used for the determination
of the runoff coefficients). We also find that especially the regime shift and the corresponding threshold can be more clearly
25 identified by groundwater level observations than by antecedent stream water level (Figure 10). This implies that near-stream
groundwater observations hold significant predictive power to estimate whether or not an upcoming precipitation event is likely
to produce major runoff at the outlet of the subcatchment.

4.6 Catchment state

The previously obtained groundwater thresholds allow us to split all events into two groups: Events with catchment states
30 above the threshold are [⁵⁴] likely to have higher event runoff coefficients (Figure 11) and are thus assumed to generate

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substantial lateral subsurface stormflow [..⁵⁵]caused by high hillslope-stream connectivity [..⁵⁶](more connected hillslopes or connectivity extending further upslope, or both. Catchment states below the threshold generate only minor lateral flow[..⁵⁷]. In this case the spatial extent of hillslope-stream connectivity is [..⁵⁸]generally low (few connected hillslopes or connectivity does not extend far up the slopes). Just taking season as a predictor for the expected event response and hillslope-stream connectivity would be too simple: while summer events are likely to be below threshold and winter events above, this is not a general rule and spring and fall events can also not be classified just by their season (Figure 12). However, our study results suggest that [..⁵⁹]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. Considering an un-investigated hillslope, one cannot know in advance which location would lead to a ‘well-chosen’ piezometer and which one to a ‘badly-chosen’ piezometer. Nonetheless, the analysis showed that local heterogeneity did not influence the piezometers to a degree where no similarity at all could be observed. Therefore, a small number of piezometers (e.g. 3-4) should be enough to identify the characteristic patterns and which piezometers do represent the hillslope and which ones are less suited due to local anomalies. From this point on, one piezometer would be enough to describe the hillslope response and you can remove the other sensors. The well-chosen one would be 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.

Even though the temporal dynamics of the switches between above and below threshold conditions are similar across most piezometers and sites, the fraction of stream events ending up above the threshold varies strongly (Table 3). While this only refers to the events and not the continuous time series it still tells us that high connectivity on event basis only occurs for roughly 20-50% of the events. While we saw higher pre-event connectivity at the schist sites (deduced from the rank correlation coefficients of pre-event stream and groundwater levels Figure 8), there was no geological pattern in the fraction of above-threshold events. These two measures describe different aspects of connectivity. While the footslope of the schist sites is well connected during pre-event conditions, this does not necessarily mean that the upslope areas at these sites are more frequently contributing to streamflow than upslope areas where the footslope is less well connected during pre-event conditions.

⁵⁵removed: and therefore have

⁵⁶removed: , while catchment

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⁵⁸removed: not well-established or

⁵⁹removed: a single well chosen piezometer can already provide substantial information on catchment state and the potential for high connectivity and thus high runoff events.

Table 4. Observations and corresponding process interpretations

Observation	Process interpretation
Low correlation of pre-event stream and groundwater levels (Figure 8)	Low or only temporary hillslope-stream connectivity (M_D, M_J, M_K)
Stream response and peak prior to groundwater response and peak, mainly under dry conditions (Figure 9)	Runoff generated by near-stream overland flow, unsaturated zone preferential flow or direct rainfall (M_D, S_J, S_V)
At high groundwater levels: little to no event-induced increase in groundwater levels but high increase in stream water levels (Figure 10)	Transmissivity feedback (M_D, M_K) and fill-and-spill (S_J)
Schist: very low runoff coefficients at low groundwater levels. Marls: higher runoff coefficients also occur at low groundwater levels (Figure 11)	Different processes are active in the two geologies at low groundwater levels, surface runoff or preferential flow paths above the shallow groundwater table can produce significant runoff in the marls
Marls: groundwater levels cluster at high values, only few data points at low levels, few points in-between (Figure 10 and Figure 11)	Groundwater ridging due to capillary fringe effects in the clayey soils

4.7 Synthesis: Process deductions

The joint analysis of shallow near-stream groundwater and stream water levels allows us to identify several runoff generation mechanisms. Observations and the corresponding interpretations are listed in Table 4. The observations described in Table 4 require a large number of events. Only if the number of events is sufficiently high we can capture the variability in responses, the frequency of different response types, the dominant responses and then interpret the underlying processes [..⁶⁰](Table 5 shows a selection of studies with the number of events analysed).

Events in marls cluster at high pre-event groundwater levels with 60 to 80% of events found in the upper half of the total range and only few events at low levels or in-between. At the same time the piezometers at M_J and M_K experience a considerably high number of dry events (Figure 7). Groundwater transitions fast from very low levels to levels near the surface, with only few events in-between. This fast transition hints towards extended capillary fringes where only low volumes of water are necessary to rise the groundwater table (Cloke et al., 2006). As a result of the transmissivity feedback, runoff coefficients significantly increase when groundwater levels reach the threshold as the hillslope connects to the stream (Figure 11). This behaviour can be observed in particular at the largest catchment in marls (M_D) with an undulating landscape and mostly pasture and to

⁶⁰removed: . The 150 events identified for this study are relatively high compared to many studies (e.g. Detty and McGuire (2010b) 15 events / 3 months; Ali et al. (2011) 50 events / 1 year; Penna et al. 2015 63 events / 3 years; Anderson et al. (2010) 99 events / 19 months; van Meerveld and McDonnell (2006a) 147 events / 2 years 4 months; and, exceptionally: Scaife and Band (2017) 811 events / 15 years

Table 5. Selection of studies and the number of events analysed.

Reference	Temporal extent	Number of events
Detty and McGuire (2010b)	3 months	15
Ali et al. (2011)	1 year	50
Penna et al. (2015)	3 years	63
Anderson et al. (2010)	19 months	99
van Meerveld and McDonnell (2006a)	2 years 4 months	147
Scaife and Band (2017)	15 years	811
Rinderer et al. (2016)	2 years and 3 months	133
Zuecco et al. (2019)	several years	157

a lesser degree at smaller catchments with very flat topography and forest. As several characteristics are different between [..⁶¹]these catchments, this behaviour can not be assigned to one single attribute with confidence. In schist, events are spread over the whole range of pre-event groundwater levels with no clear difference between low, in-between and high events. Since hydraulic conductivities in schist are generally very high, the sudden increase in runoff coefficient above the threshold can not be explained by transmissivity feedback being the governing process. Nevertheless, capping of groundwater response was observed at S_J. Anderson et al. (2010) found that in watersheds with lateral preferential flow the fill-and-spill mechanism was responsible for capped groundwater responses. This observation can be transferred to the schist site to explain the inhibited groundwater response making its soil-bedrock interface responsible for the threshold relationship.

10 Studies focusing on the Downslope Travel Distances (Klaus and Jackson, 2018; Gabrielli and McDonnell, 2020) found that only lower regions of a hillslope contribute to the streamflow via interflow, while in upper regions water percolates into the deeper groundwater. In our study, however, we find that there is a threshold in the near-stream groundwater levels above which event runoff coefficients rise strongly to values above 50%, indicating that it is not just the near stream footslope contributing to event runoff.

5 Conclusions

15 We found that a multi-event analysis approach including a large number of events is suitable for characterising the hydrologic response behaviour of the hillslope-stream-system and the dynamics of its connectivity. A more selective and exemplary analysis of only a few events [..⁶²]would lead to misinterpretation of the results. [..⁶³]Nonetheless, the question is not so much about how many events are necessary (in absolute numbers) as more about the necessary time period to cover the temporal variability generated by different hydrological processes. It is therefore necessary to accumulate a large number

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⁶²removed: (e.g. one for winter and one for summer)

⁶³removed: If these two events represented the two extremes (high and low pre-event water levels) one would need to assume a functional relation for all the potential events in-between (which is likely to be flawed)

of events across all seasons. In terms of extreme events (droughts/floods) the covered time period and number of events will need to be even higher, on the one hand to capture these events, and on the other hand to put them into context. Detecting threshold behaviour and identifying the correct threshold would be very unlikely [..⁶⁴] if the above conditions would not be met. Thus, the lack of information on event variability would significantly reduce the confidence of the findings.[..⁶⁵]

5 Revisiting our hypotheses, we now can say the following:

– Hypothesis 1: It was stated that hillslopes remain disconnected from the stream for most of the time. We found that the fraction of events above the threshold (with the potential of high runoff coefficients) was roughly 20-50% of the streamflow events, depending on site. Despite the high spatial variability, we were unable to detect a geological pattern. However, [..⁶⁶] as even the events above the threshold do not all produce high runoff coefficients we are
10 unable to falsify the hypothesis. Interestingly, the two schist sites showing high pre-event connectivity of stream and footslope had strongly differing fractions of events above the threshold. On the other hand, site M_D had low pre-event connectivity, but a 49% fraction of events above the threshold. Pronounced and continuous footslope-stream connectivity during baseflow conditions is therefore not an indicator of frequently occurring upslope contributions.

– Hypothesis 2: Differences between the response behaviour of the two geologies were less pronounced than expected
15 for some of the analyses, but the observed results showed that both hydrologic systems are subject to a threshold behaviour where dominating hydrologic processes change[..⁶⁷]. While both geologies show [..⁶⁸] threshold behaviour the underlying processes are likely to be different, with transmissivity feedback [..⁶⁹] occurring in the marls and a more fill-and-spill-like process in the schist. The fact that at low groundwater levels runoff coefficients in the marls tend to be higher than in the schist, in some cases even by an order of magnitude, suggests that also at low groundwater levels
20 different processes are active in the two geological regions and that in the marls surface runoff or lateral preferential flow above the shallow groundwater must provide sufficient connectivity to enable runoff generation while saturated subsurface connectivity is low.

– Hypothesis 3: Our analyses identified patterns that are representative for the site or hillslope, i.e. which were shown
25 by all or most piezometers at these sites. However, piezometers can also be located at points where very local anomalies drastically influence the response behaviour which is why at least three piezometers should be used when first investigating the hillslope-stream relation to secure redundant information and identify the most rep-

⁶⁴removed: and the

⁶⁵removed: Our analyses identified patterns that are representative for the site or hillslope, i. e. which were shown by all or most piezometers at these sites

⁶⁶removed: piezometers can also be located at points where very localised features drastically influence the response behaviour which is why at least two, or better three, piezometers should be used when investigating hillslope-stream relation to secure redundant information and identify the most representative and informative monitoring location for the hillslope or even catchment. Then a single, well chosen, piezometer can already provide substantial information on catchment state and the potential for high connectivity and thus high runoff events .

⁶⁷removed: when the system state variable (groundwater level) crosses a certain threshold. Above this threshold larger increases in stream water levels and also larger runoff coefficients are observed.

⁶⁸removed: this

⁶⁹removed: occurring

representative and informative monitoring location for the hillslope or even catchment. Then a single, well-chosen, piezometer can already provide substantial information on catchment state and the potential for high connectivity and thus high runoff events.

- 5 The proposed separation of the temporal component and the extent of water level responses for certain aspects of the data analysis proved to be useful in visualising, analysing and interpreting the event response and its variability across a large number of events. Even though the installation and monitoring of piezometers in the near-stream zone is pragmatic and much less cost- and labour-intensive than the installation of hillslope trenches, local near-stream shallow groundwater observations do hold significant predictive power for the potential catchment response. They possibly provide more information than piezometer- or
- 10 trench observations located further upslope would, as the footslope and riparian zone are both link and gate-keeper, controlling connectivity between hillslopes and streams. Due to the lower cost of piezometer installation and monitoring compared to trenches it is possible to instrument a larger number of sites which in turn makes it possible to systematically investigate subsurface hillslope-stream connectivity in different hydrologic response units instead of focusing on within-slope connectivity on single hillslopes. While we focused on 5 hillslopes in this study it would easily be possible to extend this monitoring design
- 15 to a larger number of sites thus even better capturing the spatial variability in responses and allowing a thorough investigation into which sites tend to be most representative of the catchment and if these sites can be identified a-priori based on topography or other landscape characteristics. The application of our data analysis to other sites where data is already available might open up new ways of systematic site-intercomparison as our analysis provides a novel way of [⁷⁰]visualising event responses and thus making the information contained in a large number of events more easily accessible.

⁷⁰removed: visualizing

Table A1. Spearman rank correlation coefficients between event precipitation and the response variables *riseAmplitude* and *riseInterval*.

Site Name	Sensor Name	$r_{precipSum, riseAmplitude}$	$r_{precipSum, riseInterval}$
[-]	[-]	[-]	[-]
M_D	Piezo1	0.72	0.32
M_D	Piezo2	0.79	0.24
M_D	Piezo3	0.74	0.37
M_D	Piezo4	0.72	-0.16
M_D	Stream	0.55	0.14
M_J	Piezo1	0.58	0.14
M_J	Piezo2	0.42	0.18
M_J	Piezo3	0.71	0.16
M_J	Stream	0.62	0.16
M_K	Piezo1	0.52	0.27
M_K	Piezo2	0.59	0.20
M_K	Piezo3	0.60	-0.05
M_K	Stream	0.73	0.20
S_J	Piezo1	0.72	0.19
S_J	Piezo2	0.39	0.23
S_J	Piezo3	0.48	0.21
S_J	Piezo4	0.60	0.29
S_J	Stream	0.71	0.17
S_V	Piezo1	0.61	-0.00
S_V	Piezo2	0.68	0.06
S_V	Piezo3	0.56	0.04
S_V	Piezo4	0.59	-0.01
S_V	Stream	0.73	-0.09

Table A2. Spatial information about the piezometers.

Site Name	Sensor Name	Ground Level	Sensor Level	Distance From Stream
[-]	[-]	[<i>m</i>]	[<i>m</i>]	[<i>m</i>]
M_D	Piezo1	1.324	-0.476	10.1
M_D	Piezo2	1.012	-0.836	2.4
M_D	Piezo3	0.945	-0.593	3.4
M_D	Piezo4	2.206	-0.972	-2.5
M_D	Stream	0.000	-0.514	0.0
M_J	Piezo1	2.373	1.443	13.3
M_J	Piezo2	1.692	0.027	3.8
M_J	Piezo3	1.740	0.430	3.3
M_J	Stream	0.000	-0.465	0.0
M_K	Piezo1	3.810	2.880	13.1
M_K	Piezo2	3.095	2.175	4.0
M_K	Piezo3	2.961	1.481	6.4
M_K	Stream	0.000	-0.230	0.0
S_J	Piezo1	2.304	1.101	8.7
S_J	Piezo2	1.460	0.917	5.0
S_J	Piezo3	1.319	0.511	4.5
S_J	Piezo4	1.419	0.206	-4.5
S_J	Stream	0.000	-0.300	0.0
S_V	Piezo1	3.510	1.540	14.6
S_V	Piezo2	1.551	-0.019	7.6
S_V	Piezo3	0.686	-0.814	3.6
S_V	Piezo4	0.747	-0.413	2.2
S_V	Stream	0.000	-0.650	0.0

Table A3: Soil horizons of piezometers.

Cluster	Piezometer	Horizon	Depth
[-]	[-]	[-]	[<i>cm</i>]
M_D	Piezo1	Ap	-30
M_D	Piezo1	B1	-65
M_D	Piezo1	B2	-100
M_D	Piezo1	B3	-122
M_D	Piezo1	B4	-178
M_D	Piezo1	Cv	
M_D	Piezo2	Ah	-5
M_D	Piezo2	B1	-30
M_D	Piezo2	B2	-50
M_D	Piezo2	B3	-110
M_D	Piezo2	B3	-125
M_D	Piezo2	B3	-155
M_D	Piezo2	B4	-165
M_D	Piezo3	Ah	-13
M_D	Piezo3	B1	-35
M_D	Piezo3	B2	-55
M_D	Piezo3	B3	-162
M_D	Piezo3	Cv	
M_D	Piezo4	Ah	-4
M_D	Piezo4	B1	-121
M_D	Piezo4	B2	-186
M_D	Piezo4	B3	-246
M_D	Piezo4	B4	-313
M_D	Piezo4	B5	-335
M_D	Piezo4	C	
M_J	Piezo1	Ah	-20
M_J	Piezo1	B1	-70
M_J	Piezo1	B2	-95
M_J	Piezo1	B2.2	-112
M_J	Piezo1	B3	-142
M_J	Piezo1	B3.2	-150

Cluster	Piezometer	Horizon	Depth
[-]	[-]	[-]	[<i>cm</i>]
M_J	Piezo1	B4	-170
M_J	Piezo2	Ah	-9
M_J	Piezo2	B1	-45
M_J	Piezo2	B2	-83
M_J	Piezo2	B3	
M_J	Piezo3	Ah	-10
M_J	Piezo3	B1	-41
M_J	Piezo3	B2	-60
M_J	Piezo3	B3	
M_J	Piezo4	B4	-50
M_K	Piezo1	Ah	-12
M_K	Piezo1	B1	-30
M_K	Piezo1	B2	-50
M_K	Piezo1	B3	-97
M_K	Piezo2	Ah	-15
M_K	Piezo2	B1	-35
M_K	Piezo2	B2	-93
M_K	Piezo3	Ah	-13
M_K	Piezo3	B1	-35
M_K	Piezo3	B2	-91
M_K	Piezo4	Ah	-8
M_K	Piezo4	B1	-45
M_K	Piezo4	B2	-85
S_J	Piezo1	Ah	-7
S_J	Piezo1	B	-88
S_J	Piezo1	Cv1	-110
S_J	Piezo1	Cv2	>114
S_J	Piezo2	Ah	-3
S_J	Piezo2	B	-34
S_J	Piezo2	B2	-59
S_J	Piezo2	Cv	>59
S_J	Piezo3	Ah	-9

Cluster	Piezometer	Horizon	Depth
[-]	[-]	[-]	[cm]
S_J	Piezo3	B	-35
S_J	Piezo3	B2	-58
S_J	Piezo3	Cv	>85
S_J	Piezo4	Ah	-20
S_J	Piezo4	B	-72
S_J	Piezo4	Cv	-117
S_J	Piezo4	Cv2	>117
S_V	Piezo1	Ah	-12
S_V	Piezo1	B1	-50
S_V	Piezo1	B2	-80
S_V	Piezo1	B3	-132
S_V	Piezo1	Cv1	-160
S_V	Piezo1	Cv2	
S_V	Piezo2	Ah	-11
S_V	Piezo2	B1	-58
S_V	Piezo2	Bv	-86
S_V	Piezo2	B3	
S_V	Piezo3	Ah	-13
S_V	Piezo3	B1	-62
S_V	Piezo3	B2	
S_V	Piezo4	Ah	-14
S_V	Piezo4	Rock	-24
S_V	Piezo4	B	-81
S_V	Piezo4	Cv	

Competing interests. None of the authors have financial competing interests, however, authors Weiler and Blume are members of the editorial board of the journal.

Data availability. Data will be made available in a corresponding data publication in ESSD.

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