

Response to the interactive comment on the manuscript hess-2020-372

“Event and seasonal hydrologic connectivity patterns in an agricultural headwater catchment”

by Lovrenc Pavlin, Borbála Széles, Peter Strauss, Alfred Paul Blaschke, Günter Blöschl

We wish to thank the Editor and the two Referees for the time they spent on our manuscript and for the chance to improve it by giving us positive and constructive comments. In the following document, we reproduce all the comments of the Referees in *italic characters* followed by our answers. Numbers in brackets (highlighted in yellow) indicate the line numbers in the Marked Manuscript with tracked changes (deleted text is in red and new text in blue characters), which was uploaded as a separate PDF. The revised manuscript without the tracked changes was also uploaded as a separate PDF.

Editor

Dear authors,

Thank you very much for your manuscript. This work studies the hydrological connectivity of an agricultural catchment, exploring the temporal and spatial dynamics of groundwater, soil moisture and streamflow. Two anonymous referees provided two thoughtful reviews, highlighting the interest of the topic and the study approach. They recommended clarifying several methodological details and improving the organization of the paper to make the reading of the study smoother.

I appreciate your detailed responses to the referee comments in the interactive discussion. Based on the reviews and your answers, I think that the paper requires moderate revisions. Please, prepare a revised paper along with a response letter indicating the final changes (and text location) you have made to adapt the manuscript to the referee comments.

Many thanks again.

Kind regards,

Mariano Moreno de las Heras

We would like to thank the Editor Mariano Moreno de las Heras for the chance to improve our manuscript. We have carefully considered and addressed the Referees' comments and adapted the manuscript accordingly as detailed below.

Anonymous referee #1:

General comment

In this manuscript, the authors analysed the hydrologic connectivity of an agricultural headwater catchment in Lower Austria, by comparing the temporal dynamics of groundwater table and soil moisture measured at different sites (i.e., riparian zone, lower, mid and upper hillslope) with the streamflow response. Spearman correlation coefficient, a hysteresis index and peak-to-peak time were used for the analysis of the similarity of the response of the various groundwater and soil moisture sites with the streamflow time series. Results showed a similarity of groundwater to streamflow, with a spatial organisation suggesting a decreasing degree of connectivity to the stream from the riparian zone up to the hillslope. The soil moisture similarity pattern was spatially more homogeneous. Event characteristics were found to be a secondary control for groundwater, but a primary control for the soil moisture

similarity to streamflow. The authors also showed that the seasonal and the event similarity patterns can be quite different, indicating that hydrologic connectivity might change depending on the temporal scale used for the observations. The topic of this manuscript is potentially interesting for the readers of this journal.

We want to thank the Anonymous referee #1 for his/her positive and insightful comments on the manuscript. We have carefully considered and addressed all his/her comments in the following.

Overall, the paper is well structured, but I think that there are too many figures and some of them could be merged (e.g., Figs. 7, 8 and 9 or Figs. 10 and 11).

We are aware that the number of figures is high. We feel that figures like Fig 7.,8, 9, 12, 14, 15 and 16 are complex on their own and combining them would be confusing for the reader. To answer the issue raised, we combined Figures 10 and 11 into one (Figure 9).

Furthermore, some methodological details are not clear (e.g., a sketch/scheme for the hysteresis analysis would be helpful to understand how the index was computed) and should be better explained.

To make the method of calculating the hysteresis index clearer, we removed the equations (2) and (3) and corresponding text (lines 236-239) and added a detailed description of the calculation in Appendix B.

Specific comments

- Page 5, lines 117-124 and Table 1: The installation depths of the various piezometers vary a lot; do the piezometers reach the bedrock or an impermeable layer? Are there any conductivity data for the various soil layers and for the bedrock?

None of the piezometers reaches the bedrock as it is about 200 m deep based on unpublished seismic measurements. Stations Hxx and BPxx were drilled using a hammering rig to refusal which normally corresponds to the depth of the first consolidated lignite layer, which is less permeable than the soils above it. Unfortunately, no more details are available about the drilling and installation of these stations. Stations Gxx penetrate into but not through all the lignite layers. We added this information in two additional sentences in the Methods subsection Data (lines 131-133) as follows: "Most stations were drilled with a hammering rig to refusal which normally corresponds to the depth of the first consolidated lignite layer. Exceptions are stations G2, G3, G4 and G8 which were drilled into but not through all the lignite layers."

"Based on double-ring infiltrometer measurements on 12 plots in our study area, Picciafuocco et al. (2019) determined a mean saturated hydraulic conductivity of 46.9 mm h⁻¹ and 20.2 mm h⁻¹ for the topsoil in arable land and grassland, respectively" (added to lines 100-102). Unpublished results of pumping tests at the stations G2, G3, G4 and G6 indicate that the unconsolidated lignite layers have a hydraulic conductivity 10-100 times higher than the overlaying silt loams. We added this information to lines 104-105 as follows: "Unpublished pumping test results indicate that these non-consolidated layers have a hydraulic conductivity 10-100 times higher than the overlaying silt loams". More detailed hydraulic conductivity information is unfortunately not available.

- Pages 6 and 7: I suggest to provide more details about soil moisture sensors (e.g., brand and model), and how the authors performed an interpolation of soil moisture data at a 15 min interval when the recording interval was 1 hour (line 132). In addition, I am wondering about the sensitivity of the average soil moisture to the number of sensors used for the computation (I would be careful when calculating average values using a different number of sensors every time, particularly if there is a high variability in soil moisture along the profile). Were soil moisture data calibrated based on the soil type?

The soil moisture stations are equipped with Spade time-domain transmission sensors from Forschungszentrum Jülich, Germany. We added that to [lines 143-144](#).

Soil moisture data is linearly interpolated from 1 hour to 15 min time-step for the convenience of calculation (added to [line 161](#)).

We understand the concern about the sensitivity of average soil moisture on the number of sensors used. Therefore, we performed a sensitivity analysis on the average soil moisture by a leave-one-out method. The expected mean absolute errors of the calculated average soil moisture are $0.001 \text{ m}^3 \text{ m}^{-3}$ and $0.007 \text{ m}^3 \text{ m}^{-3}$ for one (35% of data used) or two missing (2.9% of data used) sensors, respectively.

Soil moisture sensors at each station and each depth are calibrated using gravimetric soil samples to convert the sensor outputs to the volumetric soil moisture content. This information was added to [lines 146-147](#) as follows: "Data is collected at an hourly timestep and each sensor at each site is calibrated using the gravimetric soil samples".

- Pages 7 and 8, lines 168-173: The fourth condition is not very clear, and I do not understand why the authors considered a specific recession period of 48 hours (why not 24 hours or more than 48?). Furthermore, it is not clear whether the authors also analysed the streamflow response (e.g., larger than a certain threshold) or just focused on the rainfall characteristics and the groundwater/soil moisture response. I also suggest to clarify whether all the mentioned conditions should be met for the identification of the rainfall-runoff events.

The definition of rainfall-runoff events is a stepwise process, that starts with the identification of rainfall events – i.e. steps 1-3. The rainfall-runoff event starts with the rainfall event but continues after the rainfall has stopped for a recession period of 48 hours or until a new rainfall event with the rainfall depth of at least 1 mm starts. Here we did not choose to determine the recession time on a per-event basis but rather used a recession time of 48 hours for all events. We choose this recession time as it is long enough to always cover the streamflow recession and the longer rise times of groundwater. Longer recession time would include more of the long groundwater responses but also more of the daily fluctuations in streamflow and groundwater that can mask event responses. We have rewritten the condition (4) in [lines 189-192](#) as follows: "(4) The rainfall-runoff event starts with the rainfall event but continues after the rainfall has stopped for a recession period of 48 hours or until new rainfall event with a rainfall depth of at least 1 mm starts. Selected recession time covers most of the groundwater event dynamics while minimizing the coverage of the stream baseflow fluctuations".

We did not impose any thresholds for streamflow response as other thresholds (e.g. rainfall depth and the existence of groundwater or soil moisture response) already implicitly ensure a sufficient streamflow response. We have rewritten the condition

(5) to explicitly state no thresholds were imposed on streamflow in **line 192** as follows: “No threshold is imposed on streamflow, however, no streamflow data should be missing during the duration of the rainfall-runoff event”.

- Page 10, lines 209-220: *It is not clear which variable is x and which one is y; the authors should consider adding a sketch of the event hysteresis in the supplementary material along with the value of HI. Did the authors consider complex loops, such as eight-shaped hysteresis? If so, how did the authors identify the complex loops?*

We think this is an excellent suggestion. We moved variables x and y as well as the equations (2) and (3) from the main text to the **Appendix B** where we also added a sketch (**Figure B1**) and a longer explanation of the hysteresis index calculation.

We did not consider complex hysteresis loops explicitly. With our method we can calculate the hysteresis index of any shape of the hysteresis loop but based on index alone we cannot differentiate between simple and complex loops. E.g. hysteresis index of an eight-shaped loop would be close to zero and we cannot differentiate it from a very narrow loop. This is also the reason why we also consider the Spearman correlation coefficient and peak-to-peak times together beside the hysteresis index.

- Page 12, lines 260-271: *I think these lines about the response types belong to the Results; I suggest to move them to the following sections.*

We moved these lines and Figure 6 to the Results, to section 3.2 Event response types (**lines 408-428 and Figure 10**).

- *Figures 10 and 11: Details about the computation of the local regression fits (e.g., software used for the fits and statistical significance of the regressions) should be reported in the Methods.*

For entire analysis and figures, we used R programming language. For significance and fits we used members of *stats* package in R. We added information about this to the Methods (**lines 262-264**) as follows: “The entire analysis is done with R programming language (R Core Team, 2018). Statistical significance is assessed by p-values, which are calculated using the t-distribution approximation as implemented in the *stats* package in R”.

- Page 18, section 3.2.1: *An explanation of the term co-occurrence would be useful to understand the findings reported in this section. I also suggest to report all the co-occurrence values as percentages, in order to be consistent with Fig. 12.*

We added an explanation of the term co-occurrence in **line 432** and change the all ratios to percentages in the subsection 3.2.2 (**lines 430-440**).

- *Tables 3 and 4: It is not clear which Pearson correlation coefficients are statistically significant and which are not. The authors should integrate this information into the tables and the captions.*

We changed **Table 3 and 4** to show the significant correlations ($p < 0.05$) in bold font and updated the captions.

- Page 24, lines 461-464: *I suggest to the authors to consider the recent findings by Klaus and Jackson (2018) and Gabrielli and McDonnell (2020), and, if possible, check whether they*

can really consider their riparian and hillslope sites connected to the stream. Are there bedrock permeability data for this agricultural catchment?

The findings of the suggested articles are interesting. However, we are not sure if their index could be easily transferred to our catchment. We do not have a clear impermeable layer on which the water would perch but rather a series of thin, dry and possibly cracked consolidated lignite layer and very wet unconsolidated layers. Nevertheless, we have included these two references in the discussion to broaden the argument (lines 542-544)

- Figures 7, 8, 9, 12, 14, 15 and 16: These plots are very nice and colourful, but some of them (particularly the ones reporting the hysteresis index values) are quite confusing because the same relations are reported twice with a different colour. To improve the readability of these figures, I suggest to remove the lower or the upper part of the figures.

We were already considering removing part of these figures but decided against it as a sign of the hysteresis index and peak-to-peak lag time changes with the direction of reading (column- or row-wise). We find it easier to be able to read the relationship of a station to another station by following one row or column, therefore, the readers do not have to mix both.

Technical corrections

- Page 1, line 22: “hydrologic” instead of “hydraulic”.

We have replaced this word with the suggested one (line 22).

- Page 2, lines 45-48: I suggest to modify as follows: “Penna et al. (2015) and Detty and McGuire (2010) found that wetter antecedent conditions and higher rainfall depth increased groundwater peaks, the number of activated wells and the spatial extent of the subsurface flow network in a steep catchment in the Italian Alps and in a forested catchment in New Hampshire, respectively.”

We replaced the sentence with the suggested one (lines 47-50).

- Page 3, line 69: missing space in “moistureand”.

We added the space (line 76).

- Page 4, caption of Figure 1: Please report a brief description of the Topographic Position Index in the caption.

We added a brief description of the Topographic Position Index in the caption (Figure 1).

- Page 7, line 168: I suggest to change “by following five rules as follows” with “based on the following five conditions”.

We changed the sentence to: “We identify 53 rainfall-runoff events during 2017 and 2018 (Fig. **Error! Reference source not found.**) that meet all of the following six conditions” (lines 186-187)

- Page 10, line 218: I think that the magnitude of HI indicates more the “fatness” than the “shape” of the loop.

We changed “shape” with “size” of the loop (line 231)

- Figure 5: I suggest to increase the resolution and size of the figure.

We have replaced the figure with a bigger one with higher resolution.

- Page 15, line 313: It should be “compared” and not “compare”.

We have replaced this word with the suggested one (line 357).

- Page 16, line 322: the symbol \pm is missing between 2.7 and 14 hours.

We have added this symbol (line 366).

- Page 27, line 568: Please replace “similarly” or “similarity”.

We have replaced “similarly” with “comparably” (line 654).

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, 59215932.* DOI: 10.1029/2018WR022920372, 2020.

Picciafuoco, T., Morbidelli, R., Flammini, A., Saltalippi, C., Corradini, C., Strauss, P., & Blöschl, G. (2019). On the estimation of spatially representative plot scale saturated hydraulic conductivity in an agricultural setting. *Journal of Hydrology, 570, 106–117.* <https://doi.org/10.1016/J.JHYDROL.2018.12.044>

Anonymous referee #2:

This study analyses the connectivity between hillslopes and stream within an agricultural small catchment by looking at the spatial and temporal similarity between groundwater, soil moisture and streamflow dynamics. The study is quite complex and my overall opinion is that it is difficult to follow. I hope some of my suggestions below might help to make the reading a bit smoother. The data collected as well as the analysis carried out in the study are quite nice and show an interesting way to examine catchment hydrological connectivity. My recommendation is moderate revisions are needed before publication.

We thank the Anonymous referee #2 for the time he/she spent on this manuscript. We have considered and addressed all his/her insightful comments in the following.

Here are my comments:

1. I miss an explanation about why is interesting to study connectivity in an agricultural catchment - in other words, why are you carrying out this study in an agricultural catchment? There is a very brief reference to it in the last sentence of the Conclusions but I think it is necessary to extend this much more, by including an explanation and references in the Introduction. I think you can say something about it in L67.

The understanding of hydrologic connectivity in an agricultural setting can help us decipher how the nutrients and other chemicals move in the catchments, providing us with information for better agricultural practices and monitoring. We have expanded the

introduction with the explanation and motivation why we do this study in an agricultural catchment in **lines 71-75** as follows: “Furthermore, in agricultural catchments, the hydrologic connectivity is also important for its impact on the solutes load (e.g. nitrate and dissolved organic carbon) in streams (Aubert et al., 2013; Zhang et al., 2011). Understanding of catchment connectivity could therefore lead to better agricultural practices, but except for Saffarpour et al. (2016) and Ocampo et al. (2006), the focus of the recent connectivity studies was less on the agricultural catchments compared to forested and alpine catchments”.

2. As I said above, it is a complex study. A better correspondence between the key questions and the subsections of the Results and Discussion sections will improve the reading of the whole paper. Also, by better explaining how you are specifically going to answer these questions. Mainly: K1: “What are the spatial and temporal patterns in the relationship between the streamflow, groundwater and soil moisture responses to precipitation events in an agricultural headwater catchment?” - You have to explain somewhere how are you going to look at the temporal patterns (through wetness conditions). I think I have not seen it before the Results.

We have changed the subsection titles in the Results and Discussion sections to link them more clearly to the science questions as suggested. We have also added references to the science questions in the Methods (**lines 259-263, 266-269, 298-301**) section.

- In the discussion, “4.1. Spatial patterns of groundwater and soil moisture responses” should be “Spatial and temporal patterns of groundwater and soil moisture responses to precipitation”..?

We have changed the title of subsection 4.1 to “Spatial and temporal patterns of groundwater and soil moisture responses to precipitation” as suggested (**line 529**).

K2: “Is the relationship between the streamflow and groundwater or soil moisture dynamics more related to site- or event-characteristics?” You have to say somewhere that for this you use the type of response.

We have added this information to the subsection 2.6 in the Methods section in **lines 265-301**.

Also, what variables do you use to characterise the event. I think nothing is said before the Results.

The variables used to characterise the events are described in the Methods subsection 2.4 Rainfall-runoff event definition and characterisation (**lines 195-205**).

3. The type of responses (L260-278) should be in the Results sections.

We moved these lines and Figure 6 to the Results, to section 3.2 Event response types (**lines 407-429 and Figure 10**).

4. Landscape units of Fig1 and landscape position (Table 1) are the same? Then use the same term (in all figs -eg fig 7-, tables and text) otherwise is confusing.

Thank you for noticing that. The landscape units and landscape position are the same. We have made it consistent over the whole manuscript using only the term “landscape unit”.

5. In L215 you say “similar patterns exist among the stations in the same unit” but later on, in 3.2.1, “the other two landscape units show only low co-occurrence rates of groundwater response types between stations in the same unit” (L365). So this is a bit confusing, at least the way it is explained. Looking at how similar the hydrological response is within the landscape units is quite interesting and an important result. I think it should be further and more clearly discussed in the text.

“Similar patterns exist among the stations in the same landscape units” in line 285 means that the correlation of stations in a specific landscape unit to streamflow is similar in magnitude to the correlation of these stations among themselves. E.g. correlation of lower slope stations to streamflow is low as the correlation among these stations is also low. We have rephrased this sentence to “The similarity among the stations in the same landscape unit is comparable to the similarity to streamflow.” (line 327)

6. *The temporal pattern of similarity is only discussed with two references (Blösch et al 2016 and Penna et al. 2015). I think this should be expanded.*

We have broadened the argument with additional references in lines 565-568 and 584-585.

7. **Minor comments:**

L40-42. *Can you include studies carried out in other landscapes than grasslands and forest? For instance you can take a look at Latron & Gallart 2008 (old abandoned terraces).*

Thank you for the suggestion. We have added additional references of studies done in a catchment with old abandoned terraces and frozen terrain (lines 39-44)

L50. *Rosenbaum et al. (2012): what is the type of landscape here?*

The study site of Rosenbaum et al. (2012) is the Wüstebach test site, which is a hilly forested catchment. We have added this information to the line 56.

L59-60. *“Separation of temporal scales could also be linked to a separation of scales in space (Széles et al., 2018)”. This sentence deserves a bit more explanation,*

We have removed this sentence from the text.

Methods: you are using data of only two years, 2017 and 2018. You should indicate how representative they are (were they wet/dry/averaged years?)

We have added this information in the Methods section (line 93).

Fig 1. Please include the legend of the landscape units.

We have added the legend for the landscape units to Figure 1.

L137. *60 cm? In L130 you say 5,10,20 and 50 cm*

Thank you for pointing this out. The values in line 130 are the depths of the sensors, while the values in line 137 also include the boundary depths for the soil column (0 and 60 cm). We have rewritten Eq. (1) and the corresponding description to clarify this (lines 148-154).

L143. *“interpolate”. As soil moisture is collected every 15 min I guess you use 4 times the same value (for the hourly time step)..?*

The soil moisture data is linearly interpolated between hourly values. We have added this to the text (line 160).

L189. *“2.5 Event response definition and characterisation” You should indicate “Groundwater and soil moisture response definition and characterisation at the event scale”. In 2.4. you maybe need to add “Rainfall-runoff event definition and characterisation”*

We have changed the section titles as follows:

2.4 Rainfall-runoff event definition and characterisation (line 185)

2.5 Groundwater and soil moisture event response definition and characterisation (line 210)

L264. You suddenly use GW and SM - define it before and use it from the beginning.

We have defined GW and SM at the beginning of the manuscript.

Fig 6. The legends of HI may have an error. In the text (L219) it is said that "Clockwise loops, where x lags behind y, have negative HI values and counter-clockwise loops, where y lags behind x, positive HI values". Fig b), eg, is a counterclockwise and HI is negative. Is there a mistake?

Thank you for this comment, there is indeed a mistake in the text. The clockwise loops have a positive hysteresis index and counter-clockwise loops have a negative hysteresis index. We have corrected this in the text (lines 242-244).

L373. This sentence sounds a bit strange: "Only events when both events have a response are considered"

We have rephrased the sentence as: "The size of circles corresponds to the number of events when both stations had a response". (line 443)

Fig. 13. I do not understand why you depict the day of the year while at season scale you use weekly time-step (L150)

We have changed the colorbar of the figure to depict the week of the year instead of the day of the year (Figure 13).

L 412. This sentence is not clear: "Even upper slope groundwater stations, which do not correlate to other stations on the event scale, are well correlated to each other."

The sentence was rewritten as follows: "Even upper slope groundwater stations, which do not correlate well to stations in other landscape units, are well correlated to each other". (line 484)

L551. This statement needs further explanation: "4). Negative seasonal time shift of some stations suggests that soil moisture – i.e. catchment wetness - controls the stream baseflow."

Negative seasonal time shift of soil moisture to streamflow means that streamflow seasonal dynamics lags behind the soil moisture dynamics. This suggests, that on the seasonal scale the amount of soil moisture, which is a measure of catchment wetness, should increase first before the streamflow increases. Hence the catchment wetness controls the seasonal streamflow, i.e. baseflow. We have provided a further explanation in the manuscript in lines 634-637 as follows: "Negative seasonal time shift of soil moisture to streamflow means that streamflow seasonal dynamics lags behind the soil moisture dynamics. This suggests, that on the seasonal scale the amount of soil moisture, which is a measure of catchment wetness, should increase first before the streamflow increases. Hence the catchment wetness controls the seasonal streamflow, i.e. baseflow".

L565. What do you mean by "the dominant dynamics is seasonal"?

The amplitude of seasonal dynamics for this group of stations is greater than the event dynamics. We have rephrased this sentence as: "But these event responses are smaller in amplitude compare to the underlying seasonal dynamics, which is driven by the deeper flowpaths". (line 651)

L575. The explanation to the reference to the study by Exner-Kittridge et al. (2016) should be better connected to your results.

We have rephrased this paragraph to better explain the connection of their results to our findings (lines 661-663).

L586. *“but changes with catchment wetness conditions” -indicate in which sense*

We have rephrased this sentence as: “The soil moisture pattern is spatially more homogeneous and the similarity to streamflow increases with increasing wetness conditions”. (line 672-674)

L593. *This statement needs further explanation: “Differences in the similarity give us an insight into the interaction between the two subsurface systems.”*

We have rephrased this statement as: “Differences in the similarity patterns of groundwater on different time scales allowed us to divide the groundwater stations into groups which relate to their interaction with the two subsurface systems”. (line 684-686)