Title: Streamflow indices to identify catchment drivers of hydrograph
Author(s): Jeenu Mathai and Pradeep Mujumdar
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We sincerely thank Dr. Wouter Knoben and the anonymous reviewer for reviewing the manuscript and offering valuable critical comments to improvethe manuscript. We provide here our responses to their comments.

The line numbers mentioned in "Action" correspond to the "Clean version" of the revised manuscript.

Comments of Reviewer #1:

The manuscript "Streamflow indices to identify catchment drivers of hydrograph" by Mathai and Mujumdar estimates six streamflow indices for 621 stations in the U.S. and investigates their correlation with 15 catchment attributes, taken from the CAMELS data set in a spatial context. This study aims at identifying the drivers of streamflow indices, by distinguishing indices related to the rising and falling limbs of the hydrographs, i.e., implicitly related to different processes. The idea of the study is potentially very interesting however, in my opinion, the analyses, results and discussion presented should be further expanded and developed in order to be considered suitable for publication. The manuscript is overall well written, but I have some specific comments/suggestions regarding the organisation of some sections/figures.

Response: We sincerely thank you for the encouraging remarks and for giving us an opportunity to revise our manuscript.

Please find my specific comments below.

Major comments:

1. Methods: the method section is partly unclear (lines 85-93) and further explanations are needed. How are the diurnal increments of streamflow obtained (line 85)? How is the Weibull distribution fitted to the data (line 86)? How are the recession coefficient b1 and b2 obtained (the description of these two indices is missing)? How are the correlation coefficients, presented in the result section, calculated? Please clarify these aspects in the method section and provide references.

Response: We apologize for the lack of clarity in the text. To obtain the diurnal increments of streamflow for wet days [Fig 1 (a)], we first identify the hydrologic state of the stream (ascension and recession) (Mathai and Mujumdar, 2019). To determine the hydrologic state of a stream - increasing (wet) or decreasing (dry) - on a given day, a time series of diurnal increments is extracted by differencing the original time series with its one-day lagged time series. The positive increments are identified as diurnal increments for wet days (ascension limb).

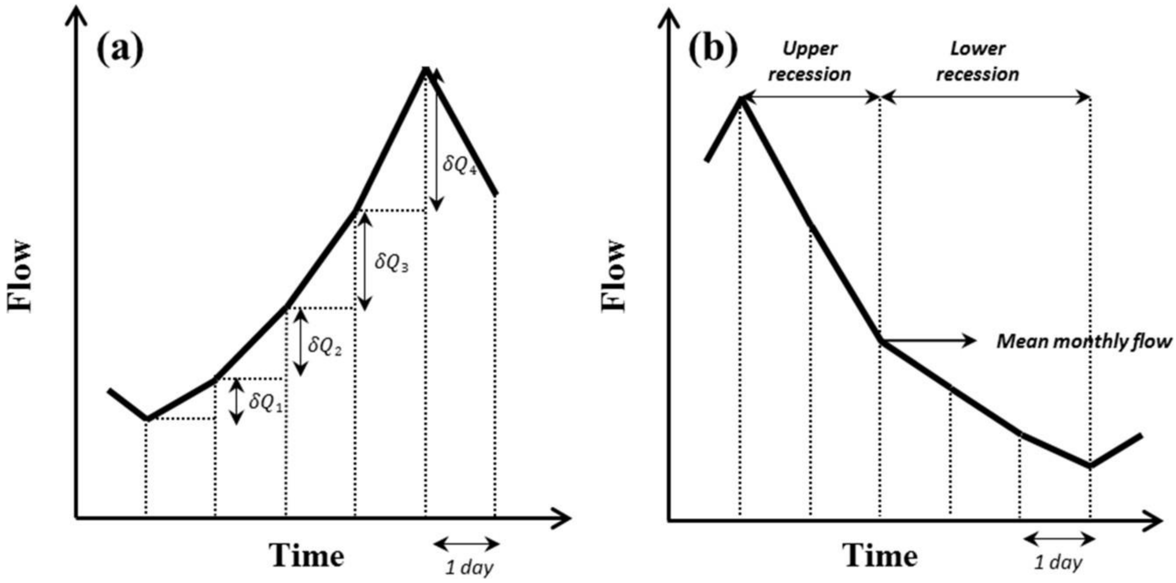

Fig 1. Schematic representation of flow series (a) ascension limb and (b) recession limb.

The diurnal increments (indicating δQ) of the ascension limb (wet days) are fitted with an appropriate probability density function. The Weibull distribution is proven to be a reasonable fit as an extreme value distribution to the diurnal increments of the streamflow (Stagge and Moglen, 2013; Szilagyi et al., 2006). The Weibull pdf is positive only for positive values of x, and is zero otherwise. For strictly positive values of the scale parameter a and shape parameter b, the density function is given by

$$f(x; a, b) = \begin{cases} \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-(x/a)^b} & x \geq 0, \\ 0 & x < 0\,, \end{cases}$$

where $a > 0,\ b > 0$. The shape and scale parameters of the Weibull distribution are estimated for each catchment from the observed diurnal increments of the streamflow.

The steps to obtain recession coefficients b_1 and b_2 are explained below (Mathai and Mujumdar, 2019):

Modeling of the recession limb (dry days) of the daily hydrograph is carried out in two stages to capture the underlying dynamics of the flow (Aksoy, 2003; Aksoy and Bayazit, 2000). Practically, the upper recession [Fig 1 (b)] corresponds to the rapid flow following a storm event and the lower recession corresponds to the baseflow recession (Stagge and Moglen, 2013). Barnes (1939) represented the emptying of water from the basin after a storm with an exponential recession given as,

$$Q_t = Q_0 e^{-bt}$$

where b is the recession coefficient, t is time, Q_t is the flow t days after the peak and Q_0 is the peak flow. Mean flow value is chosen as an appropriate measure (Sargent, 1979) to divide the recession into two stages.

The limbs with a peak flow value greater than the observed mean flow value are considered as upper recessions and those with peak flow values smaller than the observed mean as lower recessions. The upper recession is assumed to take the form of:

$$Q_t = Q_0 e^{-b_1 t}$$

where b_1 is the recession coefficient for the upper part of the recession limb, t is the number of days after the peak, Q_t is flow t days after the peak, Q_0 is the preceding peak flow. The lower recession is assumed to take the form of:

$$Q_t = Q_0^* e^{-b_2(t-t^*)}$$

where b_2 is the recession coefficient for the lower part of the recession limb, t^* is the time from the start of the lower recession, Q_0^* is the initial flow in the lower part of the recession.

The recession expressions for upper and lower recession are fitted by regressing ln (Q_t/Q_0) versus t and ln (Q_t/Q_0^*) versus $t - t^*$ respectively. These linear regressions are performed on each individual recession sequence. The average of the upper/lower recession parameters is taken as the upper/lower recession parameter of that catchment (on daily time series data).

In the results section, we used Spearman rank correlation for the correlation analysis (in Tables 3 and 4 of the manuscript). Green-colored coefficients represent positive correlation, and the red-colored correlation coefficients represent negative correlation. Only significant values of correlations are provided in the table, which results in some columns being blank in Table 3 and Table 4.

Action: We have improved the Methods section (from lines 80-98 in the original manuscript). Kindly examine the lines between lines 141-182 in the revised manuscript. We have also modified Table 1 (Hydrological descriptors with temporal asymmetry), distinguishing streamflow indices of rising and falling limbs separately. The second concern was regarding the Spearman rank correlation. We have now included the details of the correlation coefficient in Section 4.2 (lines 307-310) in the revised manuscript.

2. In the manuscript too much space is given, in my opinion, to the presentation of the CAMEL database and the related catchment attributes or clustering of stations. Three figures (Figure 3, Figure 4 and Figure S1) and two tables (Table 2 and Table S1) of the manuscript are directly taken from other publications (in some cases the figures are copy-pasted, and the source is cited, and in other cases the data is simply re-plotted compared to the original publication and the source is cited). I would suggest significantly reducing the room (both textand figures/tables) allocated to these "non-original" parts of the manuscript by, e.g. combining,condensing and reworking (or removing) the above cited figures and tables.

Response: Thank you for the valuable suggestions. Figure 4, which depicts topographic characteristics of CAMELS catchments across the CONUS, will be moved to the Supplement section. Table 2 in the manuscript will also be moved to the Supplement. Because the spatial maps are interpreted using Figure 3 in the results section, we wish to keep Figure 3 in the manuscript. We prefer to keep Figure S1/Table S1 in the Supplement rather than eliminating them since we use the clusters provided by Jehn et al. (2020) to interpret the results.

Action: Figure 4 depicting topographic characteristics, and Table 2 are now moved to Supplement. Please see the new Supplement (Figure S1 and Table S1 in the revised manuscript).

3. The correlation analysis between the streamflow indices and the catchment attributes (pages 16-19, Section 6.2 and 6.3), which should represent the main focus of the paper, is carried outin a bit too simplistic and superficial way. The only results presented in Section 6.2 are two correlation matrices (where the authors do not specify how the correlation coefficients are calculated) and the analysis in the 'climate index space' (Section 6.3, figure 9) merely consists in plotting the streamflow indices as a function of two (arbitrarily chosen) climate indices.

Further and more rigorous analyses should be added (e.g. are the correlations significant?) in order to properly investigate the processes represented by the time-irreversibility-based indices and to support the authors' statements. The discussion of the results is poor, and Section 6 is limited to the mere description of the figures/tables. A discussion or interpretation of the processes behind the obtained results would be advisable.

Response: We are grateful to you for your insightful recommendations and comments. We acknowledge that the discussion part is weak due to the lack of discussion of the processes that underpin the correlations. We will add an interpretation of the processes behind the correlations to the discussion section to improve it.

In the results section (Section 6.2), we used Spearman rank correlation for the correlation analysis (in Tables 3 and 4 of the manuscript). Green-colored coefficients represent positive correlation, and the red-colored correlation coefficients represent negative correlation. Table 3 and Table 4 have certain columns that are blank because only significant correlation values are provided in the table. We will clarify in the revised manuscript.

Action: We have incorporated discussion to improve the interpretations of the processes behind the correlations. Kindly examine Section 4.1 in the revised manuscript (Lines 219-289).

Specific comments:

Lines 71-74 about the novelty of the study would better fit at the end of the introduction section.
Response: We thank you for the suggestion. We will now move the main novelty part to the end of the introduction section.

Action: We have now moved the line discussing the novelty of the study to the Section-"Introduction" (lines 56-58 in revised manuscript).

Table 1: there is an apparent change in terminology (i.e. "rising limb" and "ascension limb" are used in the description of different indices). Please use consistent terminology throughout the manuscript.
Response: Thanks for pointing out this mistake. We will use consistent terminology throughout the manuscript.

Action: We have changed the 'ascension limb' to the 'rising limb', which is used everywhere in the revised manuscript. Similarly, we use 'falling limb' for 'recession limb'.

Figure 2: 3 rising limbs are taken into account in the RLD denominator, but only 2 are considered

in the RLD numerator. Why is that? How do the authors take into accountrising/falling limbs that fall only partly into the analysed period? Please specify it also in the text of the method section.

Response: Thanks for pointing out this mistake. The numerator is also 3. We will correct the numerator in the revised manuscript. In this study, we consider entire daily time series of a particular station and identify the state of the stream as ascension or recession. The limbs that correspond to the ascension state are considered rising limbs, while those belonging to the recession state are considered falling limbs.

Action: We have replaced the figure by correcting the expression (Kindly see line 137 in the revised manuscript).

Figure 2: please align the labels of the time intervals to the centre of corresponding segments.

Response: Thanks for pointing out this mistake. We will follow the suggestion and include a modified figure in the revised manuscript.

Action: We have modified the figure by correcting the alignment (Kindly see line 137 in the revised manuscript).

Section 3 (contributions of the study) and Section 4 (motivation of the study) would be better placed at the end of the introduction. The description of the Camel dataset and corresponding catchment attributes (currently in Section 4) would be better placed in the Data section 5.

Response: Thank you for the suggestions. We will move Section 3 (Contributions of the study) and Section 4 (Motivation to extend to large sample hydrology) to the end of the Introduction section.

Action: Sections 3 and 4 are now absorbed into the Introduction Section. Kindly see lines between 63-115 in the revised manuscript.

Line 105: "to identify the key drivers of streamflow hydrographs" or "to identify the key drivers of streamflow indices"?

Response: "to identify the key drivers of streamflow hydrographs" is used in the Line 105. The main goal of the study is to identify the key drivers of streamflow hydrograph (rising andfalling limbs) in terms of catchment attributes (eg. mean slope, aridity, fraction of precipitationfalling as snow).

Action: The text is now modified to clarify this point. Kindly see lines 66-69 in the revised manuscript.

Line 110: what do the author mean by "attribute class"? It's not clear to me.

Response: Thank you so much for bringing this up. The attribute class is a broad classification of attributes based on a particular aspect/feature. *Topography, climate, and soil* are examples of attribute classes.

A data set of attributes for 671 catchments in the contiguous United States is presented using a series of maps (CAMELS dataset- Addor et al., 2017) to describe six main classes of attributesat the catchment scale: topography, climate, streamflow, land cover, soil, and geology. In this study, we present a new attribute class of ***streamflow indices related to rising and falling limbs.***

Action: The text is now modified. Kindly see lines 69-72 in the revised manuscript.

Line 180: "the landscape of each catchment is described using multiple attributes […]" I believe that the attributes of Table 2 are representative of broader catchment features than landscape (e.g. climate)

Response: We apologize for the lack of clarity in the text. Table 2 summarizes the various attributes of CAMELS dataset used in the analysis. We will remove the text (line 180) and move Table 2 to the Supplement section.

Action: Table 2 summarizing the various attributes of CAMELS is now moved to the Supplement (Table S1- in Supplement). The description provided before Table 2 in the original manuscript is now included at the end of the Section 3 – "Dataset used" appropriately.

Line 186-191: line numbers are mistakenly written into the last column of the table

Response: Thanks for pointing out this mistake. We will correct this in the revised manuscript.

Action: The line numbers are removed from the Table (Kindly see Table S1 in the Supplement).

Line 192: how are "high precipitation days" defined?

Response: High precipitation days are defined as days that have precipitation ≥ five times the mean daily precipitation (Addor et al., 2017). 'high_prec_freq' is the frequency of high precipitation days (≥ 5 times mean daily precipitation). Unit is days yr^{-1}. We will add this description in Table 2.

Action: The definition provided in the responses for high precipitation days is now included in Table S1 (Supplement).

Section 6.1: several statements in this section are not justified by the results and figures presented by the authors. This occurs e.g., in lines 219-220 "these clusters … respectively", lines 221-222 "as these clusters … rapid snowmelt", lines 226-229 "These catchments ... forest.", lines 321-232 "This is because … regions", lines 238-239 "This is due to… regions",lines 240-241 "dominant with … snowmelt" and line 246. Please support your statements withadditional figures/results.

Response: We thank you for this advice. We acknowledge that we did not provide adequate supporting references for the statements.

For Section 6.1, the features/characteristics of the 10 clusters provided by Jehn et al. (2020) are used to interpret the findings of the results. For explaining these statements, *lines 219-220 "these clusters ... respectively", lines 221-222 "as these clusters ... rapid snowmelt", lines 226-229 "These catchments ... forest.", lines 321-232 "This is because ... regions", lines 238-239 "This is due to… regions", lines 240-241 "dominant with ... snowmelt" and line 246* – westart by identifying the regions in the United States where high/low values of streamflow indices occur. The dominant catchment attributes of these identified regions are also identified using corresponding clusters. Finally, the streamflow indices and the dominant catchment attribute are related to interpret the process behind the obtained findings.

We will add these discussions in the manuscript.

in lines 219-220: We found the regions with the highest rising limb densities, as well as the dominant catchment characteristics in these clusters: high forest proportion, low aridity, and a high frequency of high precipitation events (Jehn et al., 2020). The higher the forest proportion, therefore, higher is the precipitation intercepted, resulting in shallow rising limbs. A high frequency of high precipitation episodes, on the other hand, can result in more rising limbs and higher rising limb densities.

lines 221-222: Reproduced from the manuscript [Northwestern Forested Mountains (Clusters 3, 4), located in the mountains of the western US, experience low values of rising limb density as these clusters are characterized by a dominant summer peak of discharge caused by rapid snowmelt (Fig. 6.a)].

In these clusters, we identified regions with low rising limb densities and the main catchment characteristics as dominant summer discharge peaks induced by quick snowmelt (Jehn et al., 2020). A long lag time and shallow rising limb might be caused by snow on the ground; hence low values of rising limbs might be caused by a longer lag time.

lines 226-229: Reproduced from the manuscript [Clusters (5, 7) over the NorthwesternForested Mountains of CONUS experience very high values of rising limb scale parameters. These catchments have the highest discharge, especially in the early summer, due to acombination of high precipitation and snowmelt (Jehn et al., 2020). Further, the region in the Continental US which receives the highest precipitation is included in Cluster 5 (Jehn et al., 2020). Again, Cluster 7 with high values of rising limb scale parameter is characterized by highfraction of precipitation falling as snow (Jehn et al., 2020)].

High precipitation and snowmelt might result in a large outflow. Higher discharges can create higher values of rising scale parameters because the rising limb scale parameter regulates the magnitude of the rising limb.

lines 231-232: Reproduced from the manuscript [Low values of rising limb scale parameters are shown by Clusters 2, 8, 9. This is because of low water availability, low snow fraction precipitation falling as snow, and high evaporation experienced in these regions].

Low discharge and thus lower rising limb scale parameters can be caused by excessive evaporation, low water availability, and a low snow fraction of precipitation falling as snow.

lines 238-239: Reproduced from the manuscript [All the catchments located in the Southern states of the US (Cluster 9), Great Plains and North American deserts (Cluster 8), and the Central Plains (Cluster 2) characterize low values of rising limb shape parameters (Fig. 6.c). This is due to low water availability, low snow fraction precipitation falling as snow, low leaf area index, and high evaporation experienced in these regions].

Low discharge- long lag time and thus lower rising limb shape parameters can be caused by excessive evaporation, low water availability, and a low snow fraction of precipitation falling as snow.

lines 240-241: Reproduced from the manuscript [High values of rising limb shape parameters are seen in Clusters 3, 4 (Fig. 6.c) located in the Northwestern Forested Mountains of the western US, dominant with a summer peak of discharge caused by rapid snowmelt].

The rapid snowmelt can cause flashy hydrographs with high values of rising limb shape parameters.

line 246: Reproduced from the manuscript [Clusters 6, 7 over Marine West Coast Forests and Western Cordillera smaller falling limb densities (Fig. 8.a). This is due to less presence of forest cover in these arid regions].

Our interpretation is that the falling limb density shows a positive association with the arid climate.

We considered the clusters provided by Jehn et al. (2020) for this study. Even though the CAMELS dataset provides an excellent overview of many kinds of catchments in contrasting climatic and topographic regions, a comprehensive dataset like CAMELS does not allow easy to find a conclusive set of clusters to explain catchment hydrologic behavior. In order to tackle this difficulty, we transformed the streamflow indices and presented them in clusters that represent distinct hydrological behavior which facilitates the interpretation of hydrological processes easier. The ten clusters represent groups of catchments with distinct hydrological behavior and have distinct spatial patterns as well. The clusters presented by Jehn et al. (2020) are formed based on agglomerative hierarchical clustering with ward linkage on the principal components of the hydrological signatures. The hydrological signatures that are identified with the highest spatial predictability are used to cluster 643 catchments from the CAMELS dataset.

Action: We have now added these discussions in the revised manuscript as interpretations to support the statements. Kindly examine Section 4.1 “Spatial Variability in Streamflow Indices” (219- 289 in revised manuscript).

Captions of Figures and tables: the captions of the manuscript often contain the description ofthe results presented in the figure/table (Figure 4, 5, 6, 7, 8, 9 and Table 3, 4). This is not needed. Please place the description of the figure/table in the main text.

Response: We thank you for your remarks. The description of the figures/tables (Figure 4, 5, 6, 7, 8, 9 and Table 3, 4) will be removed during the revision and will be placed in the text as advised.

Action: We have reduced the caption text from Figures 4, 5, 6, 7, 8, 9 and Tables 3, 4.

I would suggest combining Figure 5/6 and 7/8 into one figure with multiple panels (i.e., one figure with the current Figure 5 and 6, and another figure with the current figure 7 and 8). Thisis because the message conveyed by figures 5 and 6 and by figures 7 and 8 is similar and complementary (they present spatial patterns and spatial clusters) and it would be easier for the reader to have comparable results in a more compact form.

Response: We thank you for your suggestion. We prefer to keep these figures separate in the revised manuscript for better readability. We observed that merging them will render the material presented in the figures a little confusing.

Table 3 and Table 4: Reading the tables would be easier if rows and columns were inverted (i.e. transposed table). I would also suggest merging table 3 and 4 for a more rapid and direct comparison.

Response: We thank you for your suggestion. We will incorporate this change in the revised manuscript.

Action: The rows and columns of Tables 2 and 3 in the revised manuscript are now transposed for better readability.

Section 6.2: the streamflow indices are here referred to as “Flow descriptors”. Please use consistent terminology throughout the manuscript.

Response: Thanks for pointing out this mistake. We will correct this text in the revised manuscript.

Action: We have now used the term ‘streamflow indices’ in the revised manuscript.

Section 6.3: Why only 2 climate attributes (aridity and snow fraction) are considered?

Response: Thank you for raising this concern. We acknowledge that we chose these two climate attributes (aridity and snow fraction) rather arbitrarily in the study, out of the many possible attributes.

The climatic indices indicate a more substantial influence on hydrological signatures than the topographic, soil, land cover, and geological attributes combined (Addor et al., 2018). Additionally, the findings of Jehn et al. (2020) highlighted that the climate appears to be the most critical factor influencing hydrological behavior in the CAMELS dataset as a whole, and depending on the location, aridity, snow, or seasonality are most important.

Therefore, we attempted to determine how widely streamflow indices differ across US catchments in terms of aridity and snow fraction.

Action: We have included this discussion in the revised manuscript (Lines 349-354 in revised manuscript).

Section 6.3: The clusters G1, G2, G3 are arbitrarily chosen by re-grouping 10 pre-existing clusters. The reasons of this choice are not fully clear to me and this double clustering creates some confusion in this section. Perhaps the authors could use a clustering algorithm or better justify this choice.

Response: We are sorry for the lack of clarity in the text.

Clusters 5, 6, 7, 1, 10 are characterized by a low fraction of precipitation falling as snow and humid climate, whereas Clusters 3, 4 have humid climate experiencing a high fraction of precipitation falling as snow (Please refer Fig. 9.a in the manuscript). Clusters 2, 8, 9 are featured by a low fraction of precipitation falling as snow and arid climate (Fig. 9.a in the manuscript).

The three categories mentioned above are referred to as G1, G2, and G3, respectively. These three are the possible combinations with climate attributes- the aridity and fraction of precipitation falling as snow.

G1- a low fraction of precipitation falling as snow and humid climate
G2- humid climate experiencing a high fraction of precipitation falling as snow
G3- a low fraction of precipitation falling as snow and arid climate
The fourth combination of arid climate and a high fraction of precipitation falling as snow does not happen in actual cases.

We then tried to group the 10 clusters in the above categories to understand better how streamflow indices behave in these climate attribute combinations.

The title of Section 6.3 is unclear
Response: The title of Section 6.3 is Streamflow Indices with Attributes of Climate. As the climate is the most important factor in the US for the hydrological behavior for the CAMELS dataset (Jehn et al., 2020), the influence of climatic factors on streamflow indices is studied in this section. We will modify the title of Section 6.3 to 'Influence of Climate Attributes on Streamflow Indices'.

Action: Section 6.3 is now changed to Section 4.3 in the revised manuscript. The Section's title is changed as 'Influence of Attributes of Climate to Streamflow Indices (line 348 in revised manuscript)'.

Comments of Reviewer #2 (Dr. Wouter Knoben):

Manuscript summary

This study attempts to investigate the relationship between statistical descriptors of catchment properties (e.g mean elevation, mean aridity, forest fraction, etc) and statistical properties of the rising limbs and recessions of streamflow hydrographs. The study uses 671 catchments from the CAMELS dataset and a subset of 15 of the CAMELS' attributes. The study uses six streamflow indices/signatures; three of which describe properties of rising limbs and three of which describe properties of recessions. The signatures are the rising and falling limb density, and four parameters that are found by respectively fitting a Weibull function to the rising limbsof each catchment and two exponential regressions to the falling limbs of each catchment. Values for these six signatures are correlated with values of the 15 catchment attributes and these correlations are summarized. Part of the analysis is performed with the catchments grouped into 10 clusters defined in other work and part of the analysis is performed without this division into clusters.

Summary of comments

I have provided a summary of my thoughts about this manuscript here. I have also uploaded an annotated PDF with additional comments. Some overlap exists between the summary here and the individual comments in the annotated PDF.

Novelty

The introduction is currently missing an overview of what is already known about drivers of rising limbs and recessions. Currently no knowledge gap is defined and this makes it somewhat difficult to assess the novelty of this paper. A literature review and definition of knowledge gap should be added to the paper.

Response: Thank you your valuable review of our manuscript. Specifically, we thank you for pointing out the limitation on literature review. We will include a summary of the literature review to address the concern. We agree that a considerable work exists on identifying drivers, we provided this approach as an alternate/complementary procedure to understand the driversof rising limbs and recessions using indices related to rising and falling limbs.

We have also responded to the comments in the annotated PDF.

Action: We have included a brief review of literature in the Section, “Introduction” (line 73-87 in the revised manuscript).

In my opinion, the paper currently does not provide what the title indicates, namely a way to identify the catchment drivers of hydrograph[s]. Instead, the paper merely shows that certain catchment attributes in the CAMELS data correlate with certain streamflow signatures. The fact that these attributes and signatures show correlations is not particularly instructive for hydrologic understanding unless it can be explained why these correlations exist. This connection is currently not discussed in the paper, apart from a single mention on line 250. Multiple papers already exist that investigate the relationship between CAMELS attributes anda variety of other things (model performance, streamflow signatures, catchment similarity, etc),and unless hypotheses about the catchment processes that explain the correlations seen in thispaper are added and tested, the main novelty of this paper seems to be that we now know that the CAMELS attributes correlate with four previously unseen streamflow signatures. In my opinion this is not enough to warrant publication.

Response: We thank you for the critical concerns raised. Reviewer #1 also has raised similar concerns.

Since this concern relates closely to that of Reviewer# 1 on Section 6.1, our response to the specific comments of reviewer #1 on Section 6.1 above may kindly be examined, in this context.

Action: We have now added appropriate discussions in the revised manuscript to support the statements. Kindly examine Section 4.1 “Spatial Variability in Streamflow Indices” (219-289 in revised manuscript).

Methods

The paper does a good job of explaining what was done but it is somewhat incomplete in explaining why various choices are made and how certain methods are implemented. For example:

Why are these six signatures chosen? Why not other ones?

Response: We have considered signatures directly associated with rising limbs and recession limbs. This distinction can help us easily distinguish the underlying processes associated with the steeper ascending and gradual descending limbs of the hydrograph. And therefore, we consider only these six signatures.

Why is only a subset of the CAMELS catchment attributes used and why specifically were those 15 attributes selected? How much independent information is contained in these 15 attributes?

Response: Thank you very much for raising this concern. Note that not all of the CAMELS attributes are used in this study. We used the same attributes in each class of vegetation, topography, soil, geology, climate which are consistent with the study of (Jehn et al., 2020), where they cluster 643 catchments from the CAMELS dataset using hydrological signatures with the highest spatial predictability (Addor et al., 2018).

The attributes used in the different classes are:

1) climate: aridity, frequency of high-precipitation events, fraction of precipitation fallingas snow, precipitation seasonality
2) vegetation: forest fraction, green vegetation fraction maximum, leaf area index (LAI) maximum
3) topography: mean slope, mean elevation, catchment area
4) soil: clay fraction, depth to bedrock, sand fraction
5) geology: subsurface porosity, subsurface permeability.

We also acknowledge that we have not performed analysis on CAMELS attributes to exclude the redundant information. These catchment attributes are chosen because they are relatively easy to obtain, which will allow a transfer of this approach to other groups of catchments worldwide (Jehn et al., 2020). Jehn et al. (2020) also describe the resulting 10 clusters concerning their *behavior, location, and attributes*, used in this study to interpret the results.

Why are the catchments divided into clusters for part of the analysis and why these clusters specifically?

Response: Even though the CAMELS dataset provides an excellent overview of many kinds of catchments in contrasting climatic and topographic regions, a large dataset such as CAMELS renders interpretations from analyses a little difficult. In order to tackle this difficulty, we transformed the streamflow indices and presented them in clusters that represent distinct hydrological behavior which facilitates the interpretation of hydrological processes easier.

We also acknowledge that the findings depend on the size of the clusters and catchment attributes considered.

We considered the clusters provided by Jehn et al. (2020). The reason for choosing these clusters is illustrated below:

The clusters presented by Jehn et al. (2020) are formed based on agglomerative hierarchical clustering with ward linkage on the principal components of the hydrological signatures. The hydrological signatures identified as those with the highest spatial predictability are used to cluster 643 catchments from the CAMELS dataset. The ten clusters that resulted represent groups of catchments with distinct hydrological behavior and capture the diversity since they closely follow ecological regions.

Action: We have added this discussion in the revised manuscript (lines 227-235).

How are the number of rising limbs and number of falling limbs determined?
Response: The definition of rising limb density and falling limb density is as follows:

RLD is defined as the ratio of the number of rising limbs and the cumulative time of rising limbs.

$$RLD = \frac{N_{RL}}{T_R}$$

FLD is defined as the ratio of the number of falling limbs and the cumulative time of falling limbs.

$$FLD = \frac{N_{FL}}{T_F}$$

The calculation of rising limbs and falling limbs is illustrated through an example as follows:

Suppose there are 10 days and corresponding streamflow states as follows:

Days	1	2	3	4	5	6	7	8	9	10
States	1	1	1	0	0	0	1	1	1	1

State 1- represents a wet day, and state 0, a dry day. In the above example, a rising limb (first three days) is followed by a recession limb (next three days), and then it is further followed bya rising limb of four days. If there is no increase or decrease in the flow with respect to the previous day, it is reckoned as part of the recession limb. We then take the ratio of all the rising limbs in a time series to the cumulative time of rising limbs. A similar procedure is used to determine the falling limb density.

How are the Weibull and exponential regressions fitted to rising and falling limbs respectively?
Response: Please see our response to major comment # 1 of the reviewer #1 (reproduced here for convenience):

We sincerely apologize for the lack of clarity in the text. To obtain the diurnal increments of streamflow for wet days [Fig 1 (a)], we first identify the hydrologic state of the stream (ascension and recession) (Mathai and Mujumdar, 2019). To determine the hydrologic state ofa stream - increasing (wet) or decreasing (dry) - on a given day, a time series of diurnal increments is extracted by differencing the original time series with its one-day lagged time series. The positive increments are identified as diurnal increments for wet days (ascension limb).

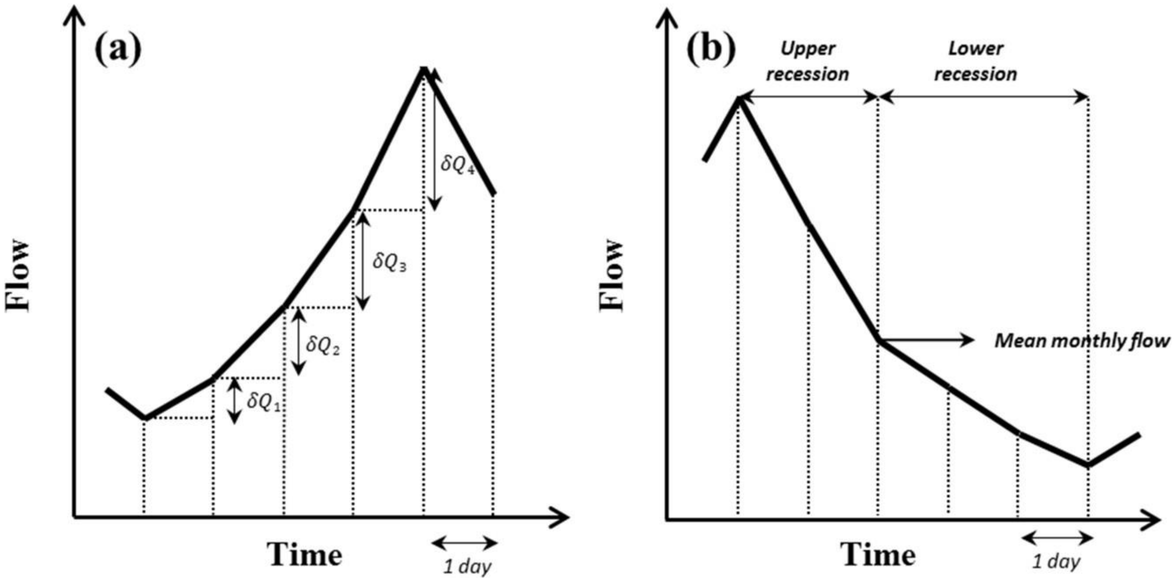

Fig 1. Schematic representation of flow series (a) ascension limb and (b) recession limb.

The diurnal increments (indicating δQ) of the ascension limb (wet days) are fitted with an appropriate probability density function. The Weibull distribution is proven to be a reasonable fit as an extreme value distribution to the diurnal increments of the streamflow (Stagge and Moglen, 2013; Szilagyi et al., 2006). The Weibull pdf is positive only for positive values of x, and is zero otherwise. For strictly positive values of the scale parameter a and shape parameter b, the density function is given by

$$f(x; a, b) = \begin{cases} \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-(x/a)^b} & x \geq 0, \\ 0 & x < 0\,, \end{cases}$$

where $a > 0,\ b > 0$. The shape and scale parameters of the Weibull distribution are estimated for each catchment from the observed diurnal increments of the streamflow.

The steps to obtain recession coefficients b_1 and b_2 are explained below (Mathai and Mujumdar, 2019):

Modeling of the recession limb (dry days) of the daily hydrograph is carried out in two stages to capture the underlying dynamics of the flow (Aksoy, 2003; Aksoy and Bayazit, 2000). Practically, the upper recession [Fig 1 (b)] corresponds to the rapid flow following a storm event and the lower recession corresponds to the baseflow recession (Stagge and Moglen, 2013). Barnes (1939) represented the emptying of water from the basin after a storm with an exponential recession given as,

$$Q_t = Q_0 e^{-bt}$$

where b is the recession coefficient, t is time, Q_t is the flow t days after the peak and Q_0 is the peak flow. Mean flow value is chosen as an appropriate measure (Sargent, 1979) to divide the recession into two stages.

The limbs with a peak flow value greater than the observed mean flow value are considered as upper recessions and those with peak flow values smaller than the observed mean as lower recessions. The upper recession is assumed to take the form of:

$$Q_t = Q_0 e^{-b_1 t}$$

where b_1 is the recession coefficient for the upper part of the recession limb, t is the number of days after the peak, Q_t is flow t days after the peak, Q_0 is the preceding peak flow. The lower recession is assumed to take the form of:

$$Q_t = Q_0^* e^{-b_2 (t-t^*)}$$

where b_2 is the recession coefficient for the lower part of the recession limb, t^* is the time from the start of the lower recession, Q_0^* is the initial flow in the lower part of the recession.

The recession expressions for upper and lower recession are fitted by regressing ln (Q_t/Q_0) versus t and ln (Q_t/Q_0^*) versus $t - t^*$ respectively. These linear regressions are performed on each individual recession sequence. The average of the upper/lower recession parameters is taken as the upper/lower recession parameter of that catchment (on daily time series data).

Action: We have improved the methods section (from 80-98 in the original manuscript). Kindly examine the lines between 141-182 in the revised manuscript.

How accurate are these fits for each catchment and what does this mean for the resulting correlations with catchment attributes?

Response: From the literature, it can be seen that the Weibull distribution is proven to be a reasonable fit as an extreme value distribution to the *diurnal increments* of the streamflow (Stagge and Moglen, 2013; Szilagyi et al., 2006). We admit that the distribution fits in this study were not checked for accuracy, and only an assumption is made on the distribution.

The rising limb scale and shape parameters are obtained after the Weibull distribution is fitted to the diurnal increments of the streamflow. The scale parameter controls the magnitude of the increasing limb, whilst the shape parameter reflects the flashiness of the increasing limb. The scale parameter is related to the magnitude of storm events which mirrors the general shape of flows in the stream. As a result, correlating these parameters with catchment attributes reveals which catchment attributes drive the magnitude and flashiness of rising limbs.

Action: We have included the description of the rising limb scale and shape parameter in the Section 2-"Methods" (lines 156-158 in the revised manuscript).

Which correlations are shown in Tables 3 and 4? Why are some correlations missing in these tables?

Response: In the results section (Section 6.2), we used Spearman rank correlation for the correlation analysis (in Tables 3 and 4 of the manuscript). Green-colored coefficients represent positive correlation, and the red-colored correlation coefficients represent negative correlation. Table 3 and Table 4 have certain columns that are blank because only significant correlation values are provided in the table.

Action: We have now included the details of the correlation coefficient in Section 4.2 (lines 307-310) in the revised manuscript.

Manuscript flow

The manuscript is well-written but may benefit from some restructuring. For example, Section3 ("Contributions of this study") could be moved to be part of the introduction.
Response: Thank you for the valuable suggestions. We will move Section 3 (Contributions of the study) to the end of the introduction section.

Action: We have now absorbed the Contribution Section in the original manuscript to the Introduction Section in the revised manuscript.

As far as I can tell, Section 6.1 relies quite heavily on descriptions of clusters in Jehn et al. (2020). To fully understand the results shown in 6.1 the reader currently needs to flip back and forth between the current manuscript and searching through Jehn et al. (2020). I suggest to make this easier for the reader by showing/reproducing the relevant data that supports these catchment/cluster descriptions in the current manuscript or in the Supporting Information if space is an issue.

Response: Thank you for this valuable suggestion. In order to better explain and interpret the spatial variability of streamflow indices shown in Section 6.1, we have used the cluster classification provided by Jehn et al. (2020). We will include the relevant details of the clusters (clusters, location, behavior, and dominating catchment attributes) in the manuscript to make it easy for the reader to follow the results.

Action: In the Supplement, we have included a figure and table (Figure S2 and Table S2) explaining details of the clusters. Kindly see Figure S2 and Table S2 in the Supplement.

Responses and Actions Taken on the Comments provided in the Annotated Manuscript

- *The line numbers mentioned in each comment are the line numbers corresponding to the annotated pdf.*
- *The line numbers mentioned in "Action" correspond to the revised manuscript.*

1. Line 1: Please check the grammar of this title.
Response: The title is now modified to " Use of streamflow indices to identify the catchment drivers of hydrograph".
Action: We have now changed the title of the manuscript to " Use of streamflow indices to identify the catchment drivers of hydrograph" (line-1).

2. Line 13: The authors may consider clarifying this term in the abstract for readers who are not familiar with it (I am not).
Response: Thank you for raising this concern. In this study, time irreversibility/temporal asymmetry refers to the steeper ascending and gradual descending parts of a streamflow hydrograph. We will clarify this term in the revised manuscript.
Action: We have now included a line describing time irreversibility/temporal asymmetry in the abstract (lines 12-13).

3. Line 24: Is "to underpin" the right choice of words here? Should this be "to understand"?
Response: Thanks for pointing this out. We will modify this line in the revision.
Action: We have changed the word "underpin" to "understand" (line 25).

4. Line 47: What are these different processes? Are there some references to support this statement?
Response: Streamflow recessions convey valuable information about the basin storage properties and aquifer characteristics (Aksoy & Bayazit, 2000). High variability encountered in the recession behaviour of individual segments is always a challenge in modeling the recession limb (Tallaksen, 1995). Various segments of recession represent different stages in the flow process and a physically based short-term or seasonal influence on the recession rate adds to the problem of deriving a characteristics recession (Tallaksen, 1995). There is thus a need to differentiate the recession to various segments and to characterize the recession rates separately. Recessions do not follow a simple form, due to their nonlinear nature (Aksoy et al., 2001). In this work, we characterize the recession into two stages: faster recession with high discharges caused by surface runoff and slower recession caused by baseflow.
Action: We have included these descriptions in the revised manuscript (lines 46-55).

5. Line 51: What I miss in this introduction is an overview of what is currently known about processes that drive rising and falling limbs and thus what knowledge gap this study addresses. McMillan (2019) may provide a starting point for this literature review.

McMillan (2019). Linking hydrologic signatures to hydrologic processes: A review. DOI: 10.1002/hyp.13632
Response: We sincerely thank the reviewer for his valuable suggestions and comments. We will incorporate the relevant literature in the next revision.
Action: We have now included a few literature studies discussing the factors affecting the shape of the hydrograph in the Section- "Introduction " (lines 73-87).

6. Line 65: It would be helpful to (1) describe what each index is meant to capture and (2) why

these indices are used (and not others).

Response: Time irreversibility refers to the temporal asymmetry of streamflow hydrograph. In this study, we consider streamflow indices associated with ascension and recession limb separately. The rising limb scale and shape parameters are obtained after the Weibull distribution is fitted to the diurnal increments of the streamflow. The scale parameter controls the magnitude of the increasing limb, whilst the shape parameter reflects the flashiness of the increasing limb. The scale parameter is related to the magnitude of storm events which mirrors the general shape of flows in the stream. The recession coefficients are obtained after the exponential recession is fitted to upper and lower recessions. The upper recession coefficient reflects the slope of the upper recession, and the lower recession coefficient reflects the slope of the lower recession of the hydrograph. As a result, correlating these parameters with catchment attributes reveals which catchment attributes drive the magnitude and flashiness of rising limbs and slope of upper and lower recession limbs. We try to link these indices with catchment attributes to explain the drivers of ascension and recession parts of streamflow hydrograph as there will be a complex interaction of meteorological and catchment processes forced by intertwined climate and catchment attributes.

7. Line 70: sub-categories of what?

Response: Here sub-categories refer to each of the attributes of the CAMELS dataset. For example, if we see climate, we have aridity, frequency of high-precipitation events, the fraction of precipitation falling as snow, precipitation seasonality as attributes.

8. Line 71: This seems oddly placed in the Methods section. Perhaps move to the end of the introduction?

Also, if I understand "time irreversibility" correctly, this sentence seems to say that this work's main novelty is top separate flow peaks in rising limbs and recessions and use signatures to relate rising & recession limbs to processes. Is that really a main novelty? Separate signatures for rising limbs and recessions have been used for a long time. See e.g. Olden & Poff (2003) who refer to this is "rise rate" and "fall rate".

Olden and Poff (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. DOI: http://dx.doi.org/10.1002/rra.700

Response: Thanks for the valuable suggestions. We will move this section (line 71) to the end of the Section- “Introduction.”

Even though a considerable way exists to identify drivers, we provided this approach as an alternate procedure to understand the drivers of streamflow hydrograph using indices related to rising and falling limbs. In this study, we consider streamflow indices associated with ascension and recession limb separately. The rising limb scale parameter controls the magnitude of the increasing limb, whilst the rising limb shape parameter reflects the flashiness of the increasing limb. The scale parameter is related to the magnitude of storm events which mirrors the general shape of flows in the stream. The upper recession coefficient reflects the slope of the upper recession, and the lower recession coefficient reflects the slope of the lower recession of the hydrograph. As a result, correlating these parameters with catchment attributes reveals which catchment attributes drive the magnitude and flashiness of rising limbs and slope of upper and lower recession limbs. We try to link these indices with catchment attributes to explain the drivers of ascension and recession parts of streamflow hydrograph as there will be a complex interaction of meteorological and catchment processes forced by intertwined climate and catchment attributes.

Action: We have moved this line to the Section-“Introduction” (lines 56-58) .

9. Line 77: How are N_RL and N_FL determined? Is every Q(t+1) > Q(t) counted as a rising limb and every occurrence of Q(t+1) < Q(t) as a falling limb, or is there some minimum number of timesteps for which either condition must be true before that set of timesteps is called a rising limb or recession?

Response: To identify the hydrologic state of a stream - increasing (wet) or decreasing (dry) - on a given day, a time series of diurnal increments is extracted by differencing the original time series with its one-day lagged time series. The consecutive wet days are considered a single ascension limb, and the consecutive dry days are considered a single recession sequence. If there is no increase or decrease in the flow with respect to the previous day, it is reckoned as part of the recession limb.

10. Line 87: Can the quality of this fit be quantified? "Reasonably well" is quite vague.
Response: Thanks for pointing this out. We will modify this line.
Action: We have now changed the word “reasonably well” to “satisfactorily” (line 150).

11. Line 88: Presenting the equation here would help in interpreting these parameters.
Response: Thank you for your valuable remarks. We will include the expressions of Weibull distribution in the revised manuscript.
Action: We have now included the equation in the revised manuscript (line 154 - equation 3).

12. Line 90: Showing the equation(s) would be helpful).
Response: Thank you for the suggestion. We will include the necessary expressions in the revised manuscript.
Action: We have included the recession equations in the revised manuscript (lines 167-180 – equations 4 to 6).

13. Line 90: How are "wet" and "dry" days defined in this?
Response: To identify the hydrologic state of a stream - increasing (wet) or decreasing (dry) - on a given day, a time series of diurnal increments is extracted by differencing the original time series with its one-day lagged time series.

14. Line 99: This entire section might be better placed at the end of the introduction.
Response: Thanks for the valuable remarks. We will move this section to the end of the Section – “Introduction.”
Action: We have moved this entire section to the Section- “Introduction” (lines 63-72 and 88-92).

15. Line 103: I don't fully understand what this part of the sentSence means. For a particular basin, how are these indices consistent? I would expect them to vary based on which time period one looks at in the basin. Why should these indices be distinct from those in other basins? That will only become evident when actually calculating these indices for multiple basins.
Response: We apologize for the lack of clarity in the explanation. Spatial maps of streamflow indices are calculated and presented at an annual scale. As the temporal scale is annual, the streamflow indices calculated for a particular basin will be consistent, and these values will be distinct for multiple basins.

16. Line 179: Does these two sentences need their own subsection? It may be cleaner to remove

this header.
Response: Thanks for this suggestion. We will move Table 2 to the Supplement and remove this text in the revision.
Action: We have moved Table 2 to the Supplement and also removed the corresponding text.

17. Line 204: I suggest to rewrite this sentence. Currently it seems to imply that this study is the first to investigate the influence of climatic factors on streamflow indices and that seems to ignore a rather large body of literature. A direct google search of "hydrology climate streamflow signatures" should give a good number of examples of where this is done.
Response: Thanks for pointing this out. We will modify this line in the revised manuscript.
Action: We have now corrected this line in the revised manuscript (lines 216-218). Jehn et al. (2020) study has shown that climate is the most important attribute influencing the hydrologic behavior in the US catchments. We have included this in the revised manuscript (lines 216-218).

18. Line 210: Why are these clusters used? What does this provide over (for example) sorting the data by attribute value and plotting the 6 indices used in this study as scatter plots (e.g.: catchments sorted by aridity value on the x-axis, rising limb density on the y-axis. Repeat for other CAMELS attributes and other indices)?
Response: We acknowledge that the results depend on the clusters' amount and size, the catchment attributes considered, and the hydrological signatures used. Still, we think that the CAMELS dataset offers an excellent overview of different kinds of catchments in contrasting climatic and topographic regions. However, it seems that even a comprehensive dataset like CAMELS does not allow an easy way to find a conclusive set of clusters for catchments.

19. Line 255: Is this text necessary? The reader easily see this from looking at the figures. I don't think it needs to be repeated
Response: Thanks for your valuable remarks. We will remove this text in the revised manuscript.
Action: We have removed the text from the description of the figure.

20. Line 287: This section is purely descriptive: "X correlates with Y". Where are the process connections that might explain why these correlations are what they are?
Response: We are sincerely thankful for the critical concern raised. We acknowledge that we have not addressed why these correlations exist between these attributes and signatures. More process-based understanding is required to explain why these correlations are existing. We will try to incorporate discussion on these connections to strengthen the paper in the revised manuscript.

21. Line 288: I feel reasonably confident that I can interpret rising and falling limb density but I have no intuitive understanding of the scale and shape parameters, and of the upper and lower recession coefficient (especially because no equations are given). It would be very helpful provide the reader with an example of how to interpret these variables.
Response: Thank you for raising the concern. Kindly examine the response of this query in response sheet.

22. Line 289: Why are some correlations missing? What is the p-value of the shown correlations?
Response: In the Results Section (Section 6.2), we used Spearman rank correlation for the correlation analysis (in Tables 3 and 4 of the manuscript). Green-colored coefficients represent positive correlation, and the red-colored correlation coefficients represent negative correlation. Table 3 and Table 4 have certain columns that are blank because only significant correlation values are provided in the table.

23. Line 291: Which type of correlation is shown here? E.g. spearman, pearson
Response: For Tables 3 and 4, we used Spearman correlation for the analysis.

24. Line 296: Given that both aridity and high P frequency have strong negative correlations with the three vegetation attributes mentioned in line 291-293, this should not come as a huge surprise. I'll repeat my earlier suggestion to investigate to what extent the 15 chosen CAMELS attributes contain independent information.
Response: Thank you for raising this concern. Kindly examine the response of this query in the main response section.

25. Line 312: The orientation of these tables makes them hard to read. Suggest to rotate them by 90 degrees.
Response: Thank you for the suggestion. We will change the orientation of these tables for better readability.
Action: We have changed the orientation of the text in the tables.

26. Line 350: Again purely descriptive: "X correlates with Y". Hypotheses about process connections should be added.
Response: We are sincerely thankful for the critical concern raised. We acknowledge that we have not addressed why these correlations exist between these attributes and signatures. More process-based understanding is required to explain why these correlations are existing. We will try to incorporate discussion on these connections to strengthen the paper in the revised manuscript.

27. Line 382: This is a pretty bold statement. There are definitely studies that separate hydrographs into rising and falling limbs and that should be acknowledged.
Response: Thanks for pointing this out. We will include relevant literature in the revised manuscript.
Action: We have now acknowledged relevant studies in the manuscript.

28. Line 383: How? This study separates hydrographs into rising and falling limbs but I have not seen any mention of how this shows the importance of time irreversibility.
Response: Thank you for pointing out this. We will add a description in the revised manuscript clarifying the term 'time irreversibility' in the next revision.
Action: We have now clarified the concept of time irreversibility in the Abstract and the Section-“Introduction” (lines 12-13).

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