

Response to Anonymous Referee #1

We appreciate the thorough and thoughtful comments from Reviewer #1, and our responses are as follows:

General comments

The paper reports a synthesis of the results from three papers, analyzing flow duration curves (FDCs) in different ways, and some own analysis. Basis of all work is a huge amount of catchments in different parts of the US. This is a new and exciting view on FDCs. The paper addresses relevant scientific questions within the scope of HESS. The idea and theory behind this paper is very interesting and important, but the paper itself shows some weak points in analyzing the data of the connected papers. Many statements of the synthesis are based on visual inspection of ambiguous figures without considering the size of classes or groups. Therefore often the significance of a statements is unclear and conclusions are vague. Some conclusions from visual inspection are not comprehensible; the paper seems to be immature. Therefore, the work is ranked 'Major revision'.

Before we address specific comments, we do wish to note that all synthesis analysis in this paper has been carried out first in a qualitative fashion, by visual inspection of results from the preceding three papers, then followed by a detailed quantitative assessment of the same information. This methodology may not have been announced clearly enough in the paper, and the revised manuscript will ensure that readers understand that we do not wish to depend on visual inspections alone.

Bases for the synthesis are three papers which are in review process with revisions proposed. Therefore, I propose to finish the revision of this after after the end of the review process of the basis papers - when the three papers appear sharpened through the review process. Maybe then, you will gain new insights, clarifying the synthesis.

This is a review of the fourth part of the four-pronged study and refers only to this paper. Content of parts 1 to 3 of the study is taken "as is" and not commented because each paper has to be self-contained, even when they are strongly connected.

Some Specific Comments

Connections to papers part 1 to 3: There are summaries of the other three papers in the introduction and in the discussion. Why? One summary of each paper (in the introduction) with a short overview of data, methods and results would be more reasonable. Although the paper has to be self-contained, it should be easy reading up between them.

We agree that the summaries are best in the introduction to provide the context for the synthesis. We will revise this paper accordingly and shorten the section in the discussion to a brief recap of major results in relation to the synthesis findings. We do feel that a brief mention is a worthwhile addition to the discussion, but agree with the reviewer that anything more detracts from the message of the current paper.

Are there differences between the papers, concerning for instance the data base? If there are differences: why and what consequences do they have for the synthesis?

Yes, while all four papers use data from the same MOPEX dataset, which contains 428 catchments, three papers use a subset of the full dataset. The subset of 197 catchments used in this paper and the first and second papers in the series were those catchments which contained at least 50 years of continuous data for the same time period. Because the classification tree was able to obtain satisfactory results with less information, the third paper uses the full 428-catchment dataset in order to increase the number of arid catchments to be classified. As a consequence, the class designations used in the synthesis may be more appropriate than a class designation based on only 197 catchments.

Use all papers the same acronyms for the same signatures?

All four papers use the same acronyms for the signatures regime curve (RC) and flow duration curve (FDC), but the first paper uses different acronyms for the parts of the FDC (e.g. FFDC rather than Q_f FDC) . However all acronyms used are defined in each paper.

Page 7144 and Fig. 5: - “Again, we see two of these classes have a smaller range of FDC variability than the other two.” Which two do you mean? b) and d) or b) and c)?

The reviewer is correct in pointing out that is not immediately clear which two classes have a smaller range of variability. Originally we had meant b) and c), and should have specified this, since a case might also be made for d) in that the majority of the catchments there have similar FDCs, with one outlier altogether, as well as a wider spread in the largest flows. A closer inspection of this figure reveals that both b) and c) seem to taper at the top (largest flows) while a) and d) do not. Since an FDC is plotted on a log scale, any differences that appear small at this end are actually quite large, while differences between FDCs at the low end, which appear large, are actually very small. It can be further noted that both b) and c) contain subsurface-influenced Q_f , and it may be due in part to this underlying process control that b) and c) have more similar high flows. That class LJ, which represents catchments in the NE and Mid-Atlantic regions of the US, dominates both figures shows some regional pattern to this process, thus providing further visual reinforcement of the similarity in FDCs between these two model process classes. However, this figure can also illustrate the limits of a visual inspection, which is why we do not depend on patterns alone in our analysis, but also quantitatively examine these groupings in a mathematically rigorous way and show that they are meaningful and have statistically significant differences between them. As part of our quantitative analysis, using Eq. (4), we have examined the variances of the streamflow quantiles and the slopes of the FDCs, as well as the parameters of the fitted mixed gamma distribution, and grouped all by both the model process classes and by the catchment classes. Tables 1 through 4 in the paper present selected results of this quantitative analysis. In the revised paper, we will specify b) and c) as being the two classes which upon visual inspection appear to have the least amount of variability, and clarify as we do here what we mean by this.

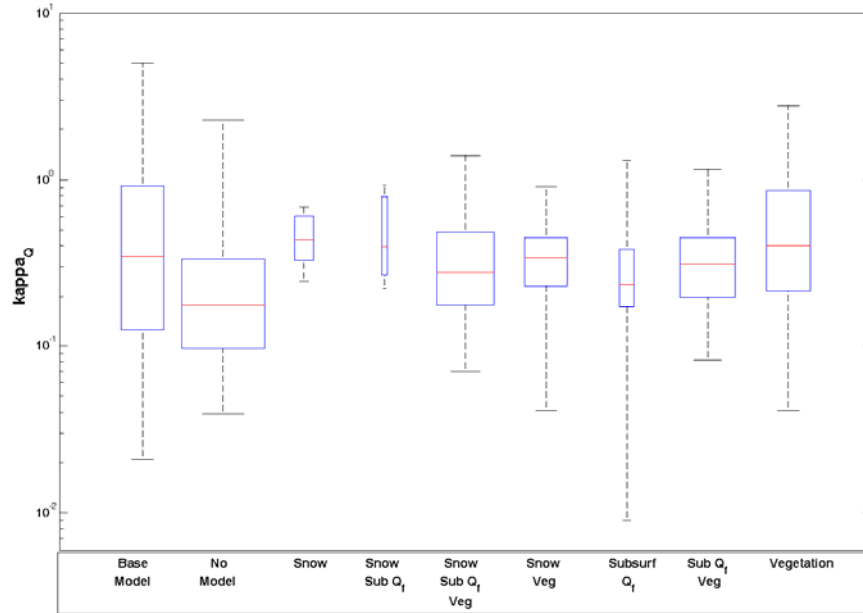
And what does this mean? - “The visual mapping presented here shows strong regional gradients ...” Please explain where I can see the regional gradients in Fig. 5.

We agree with the reviewer that “gradients” was not the best choice of words to convey our

meaning. The blue lines representing class LJ and the red lines representing class LWC are dominated by catchments in the NE and mid-Atlantic regions of the US and feature prominently in b) and c) and to a lesser extent in d). Drier catchments in the southern and western regions diverge from these (e.g. IAQ and XADB in 5a, LPC and ISQJ in 5b, and ISQJ in 5d). Perhaps “regional patterns” may better express what we wish to say. The sentence in the revised manuscript will be changed to reflect this.

Page 7147 and Fig. 7: “... catchments where vegetation featured in the dominant process generally tended to have larger values of κ and a wider range of κ values than those where other processes dominated ...”. For me, this statement is not visible in Fig 7: Process classes “Vegetation” and “SubQf, Vegetation” show a huge number of small values for κ and only a few higher values (outliers with special properties?). The values of these classes seem to be not far away from them with the additional process “Snow”. For process class “Snow, SubQf” are only 3 values visible, and their range is not so different from the other ones, expect very low values. If this class consists of only three catchments, a comparison with the other classes may be misleading!

The process class “Snow, SubQf” does indeed consist of three catchments. As stated in the paper, this synthesis of the work done in the preceding three papers would be done both by qualitative and quantitative analysis of the data and collected results from the previous papers. The qualitative analysis consisted of plotting the data using the different relationships determined from the three preceding papers and visually inspecting the results for patterns that could provide insights into underlying processes. To this end, we have included Fig. 7, as it represents a relationship between the gamma parameters determined in Cheng et al and the model process classes of Ye et al. From our quantitative analysis of the same, we see that only the grouping of the κ shape parameter into model process classes provided statistically significant reduction in variance (Table 3) and so only this grouping has been shown. We do agree with the reviewer that the figure as presented does not show a lot of difference in values of κ between groups, and thus may not be clear enough for use in a visual assessment. Therefore, we have changed the y axis in the figure to a log scale to better bring out these differences, and we have used a box plot with the width of the boxes being proportional to the size of the class. This figure is shown below, and will replace the current Fig. 7 in the revised version of the paper:



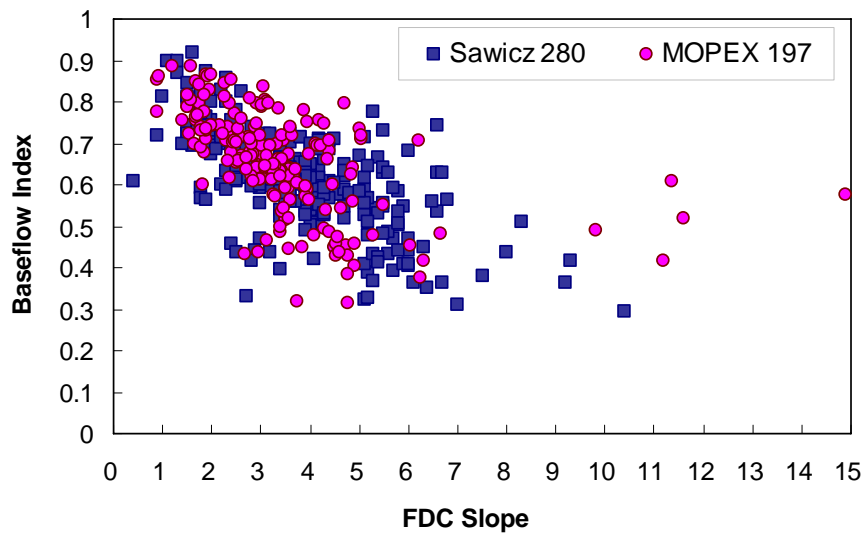
From this new figure, the wider variability in the class “Vegetation” relative to other classes (except for the Base Model class) can be seen. Not only is the range larger, but it is spread out more than other large classes such as “Snow, Vegetation”, “Snow, SubQ_f, Vegetation”, and even “SubQ_f, Vegetation”. With a log scale on the y-axis, the differences between the classes are more clear, and so the patterns that can be observed have changed somewhat. What we now see is that vegetation by itself as a dominant process seems to produce large variability in the shape parameter κ . When snow is the only dominant process, the variability seems to be smaller than with just vegetation. However, when snow and/or subsurface-influenced Q_f share dominance with vegetation, the variability seems to be lessened. From our inspection of the shapes of the FDCs in Fig. 5, this seems to be borne out, at least for “Snow, SubQ_f, Vegetation” and “SubQ_f, Vegetation”, and this may be caused by the presence of subsurface-influence Q_f. We also saw from Ye et al and Coopersmith et al that snow-dominated catchments share similar climate and physical properties; in addition, the presence of snow in heavily vegetated areas further groups the catchments by climate and geology/topography, as the majority of these catchments are found in the northeast US. This may explain in part the smaller variation in κ values for process classes containing snow and vegetation. However, process classes with snow but without vegetation contain many fewer catchments, and thus a more quantitative examination is necessary. As mentioned previously, this is why we have not relied solely on visual inspection of patterns for our synthesis analysis, but rather used it to augment a quantitative analysis of the same information. The qualitative assessment of Fig. 7 in the revised version of the manuscript will reflect the insights obtained from the new figure.

Page 7150 and Fig. 12 and 11: The problem with the statement here is that you have only five catchments in four different classes with very high slopes of the FDC – out of 197 catchments. And there is a large data gap for FDC-slope between 7 and 10. A statement based on these five catchments seems to be very vague!

We are assuming the reviewer meant to refer to Figs. 10 and 11, as Fig. 12 is something

completely different, and we will address the question as such.

Regarding the large data gap, this is due to the subset of the MOPEX dataset used. As described in the paper, the vast majority of the catchments in the MOPEX dataset (and indeed the USGS streamflow gauges in general) are located east of the Mississippi River, thus biasing the data towards humid catchments. This bias was one of the reasons the classification system was based on the full 428-catchment dataset, which increased the total number of arid catchments. Non-arid catchments in this dataset tend to have FDC slopes between 1 and 5, while the few arid catchments had very high FDC slopes, and none of the catchments in the 197, it seems, had FDC slopes between 7 and 10. One of our suggestions for future work is to apply these analyses to other datasets from around the world; if this is done, this data gap may disappear. For example, the following is a plot of BI vs FDC slope using our dataset and values obtained in Sawicz et al (2011). They also used the MOPEX dataset, but because their values were determined using only 10 consecutive years of data, their dataset consisted of 280 catchments. With nearly 100 more catchments, the data gap the reviewer has pointed out begins to be filled in. However, since the Sawicz et al catchments are also dominated by the eastern half of the US, only a few catchments fill this gap.

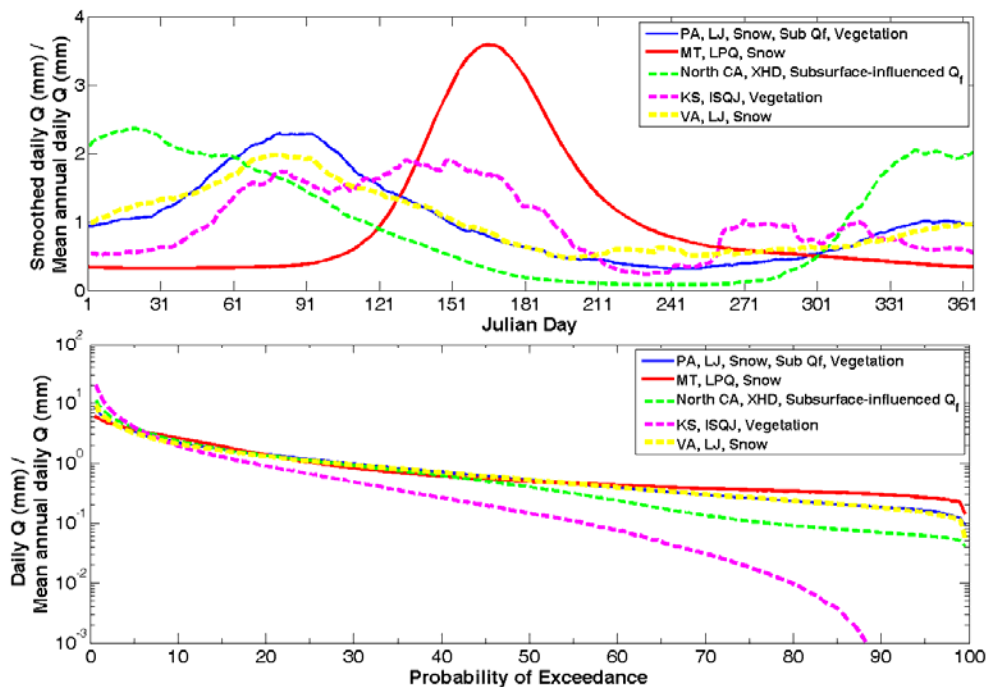


From Fig. 10 in the manuscript, the 5 “outliers” belong to classes IAQ, XADB, XACJ, and ISCJ. These are all arid or semi-arid catchments, as explained in the text and in the caption to Fig. 5, A in the class designation means arid and S means semi-arid. Fig. 5a and d show some examples of catchments in these classes, and it can be seen that they all have a much steeper FDC slope than do their more humid counterparts. By the definition of the slope of the FDC cited in the paper, only the middle portion of the FDC, specifically all streamflows exceeded between 33 and 66 percent of the time, is used to calculate the slope of the FDC. Thus arid catchments, which in this particular dataset experience zero streamflow at some point, all have very steep middle sections. In other regions of the world, this may not be the case, which adds strength to our call for similar analyses to be done on a more global scale. Fig. 11 shows the model processes associated with these particular catchments, and we found it interesting to comment on them because although all 5 catchments shared similar climate aridity and seasonality, they did not all share the same necessary model process.

Page 7157 and Fig. 12: First statement: FDC of MT and KS in Fig. 12 are described to have a “as much steeper slope overall” Second statement: FCD in Fig. 12 of PA and VA, overlying the FDC of KS: “not substantially different from the MT catchment described earlier” – if FDC of PA, VA and KS is the same, and not substantially different from the MT catchment, then MT and KS must be similar too! If there are differences between the FDCs of PA, KS and VA, they are not apparent in Fig 12. Maybe another scale of the ordinate (between 10 and about 10^{-1}) shows differences.

Regarding the first statement, we cannot find where the paper states that the FDCs of both MT and KS in Fig. 12 are described as having a much steeper slope overall. On Line 6 the FDC of MT is introduced, and on Line 8 it is described as having a fairly flat slope. On Lines 11 the FDC of KS is introduced, and on Line 12 it is described as having a much steeper slope overall. If it would add clarity we can add “of MT” and “of KS” to the appropriate FDC slope description in the revised version of the paper.

Regarding the second statement, the reviewer is absolutely correct about the figure as it was presented. Unfortunately this is due to a gross oversight on our part – the data used to make the FDC of the KS catchment was actually not from KS. The figure has been redone (see below), using the proper catchment data, and now the KS FDC does show the characteristic steep slope of an arid catchment, clearly contrasting with the very flat slope of the MT FDC, as well as those of PA and VA. The corrected figure will appear in the revision of the paper, and we thank the reviewer for bringing this to our attention.



Technical corrections:

Page 7135, next to last line: ... flow days., was introduced ...

This will be corrected in the final version of the paper; we thank the reviewer for bringing it to

our attention.

Pages 7139, 7142 and 7143: formulas are not complete (Result/Signature is missing)

We will add $SI =$ to Eq. (1) on page 7139, $\sigma^2 =$ to Eq. (3) on page 7142, and $E =$ to Eq. (5) on page 7143, as recommended by the reviewer.

Page 7159: first sentence in “Conclusions”: o “... analysis brought to light regional patterns ...” ...brought light into regional ...?

To clarify our meaning, we will change “brought to light” to “revealed”, as in: “... analysis revealed regional patterns that led to insights...”

o over or nearly 200 catchments?

This should be “nearly 200 catchments”; we thank the reviewer for catching this oversight.

Fig. 6: θ or κ ?

We thank the reviewer for bringing this typographical error to our attention; the caption for Fig. 6 should refer to the parameter θ . This will be changed in the final revision.

Fig. 12: “log” is missing in the name of the ordinate

We assume the reviewer is referring to the FDC part of the figure, and the fact that the y axis is on a log scale. From the literature, including the classic Vogel and Fennessey (1994, 1995) papers on the FDC, the y axis for FDC plots is in logarithmic scale, i.e., the intervals represent orders of magnitude of the variables (not of the log of the variables). We have assumed this to be a matter of convention, and therefore no mention of “log” is made in the plot itself. If it would add clarity we can address this briefly in the initial description of the FDC.

Language:

The authors often use very long sentences, mostly hard to read,

We will edit the sentences the reviewer has brought to our attention, as well as any others the non-native English speaking co-authors highlight.

sometimes also due to syntax errors. Examples:

Page 7133: This transfer function between the variability...

We have edited the sentence and the passage containing it to make our meaning more clear; the revised version appears below in quotes, and the paper will be changed accordingly in the final version.

“Encoded within these signatures are the combined impacts of climate, geology, topography, ecology, and even human activities. We hypothesize that some function relates each hydrologic signature, the FDC included, to both the climate and the landscape, thus connecting the

variability of climate inputs to the variability of runoff. This function can then be determined empirically, through the application of complex process-based models, or some combination thereof, both in detail for a small region via a process-based (Newtonian) approach, or through a comparative, data-based (Darwinian) approach. On the basis of these analyses, unique functions can then be defined for regions of similar catchment and landscape properties.”

Page 7149: “... examine more closely the climate and catchment properties transformed by the FDC.” FDC transforms the climate and catchment properties?

We agree with the reviewer that the FDC most certainly does not do any transforming, but rather manifests the interactions between climate and catchment properties. We have therefore edited the sentence as follows, and the corrected version will appear in the final revision of the paper.

“What remains is to examine more closely the relationship between the FDC and the climate and catchment properties that define its shape.”

Page 7158/59: Last sentence: very long and unclear

We have revised the last sentence as follows, and the final version of the paper will reflect these changes.

“However, this clear Spring peak/Summer low flow regime behavior is generally not seen in the RCs of catchments in the Midwest, which are dominated by grassland and more seasonal precipitation. Because the averaging processes inherent in producing a regime curve further smooth out the differences between the extreme flows, RC FDC slopes from catchments in this region deviate even further from their corresponding FDC’s slope.”

Page 7159: Syntax of first sentence in point 5

We have changed point 5 to read as follows, and the appropriate changes will be made to the final version of the paper.

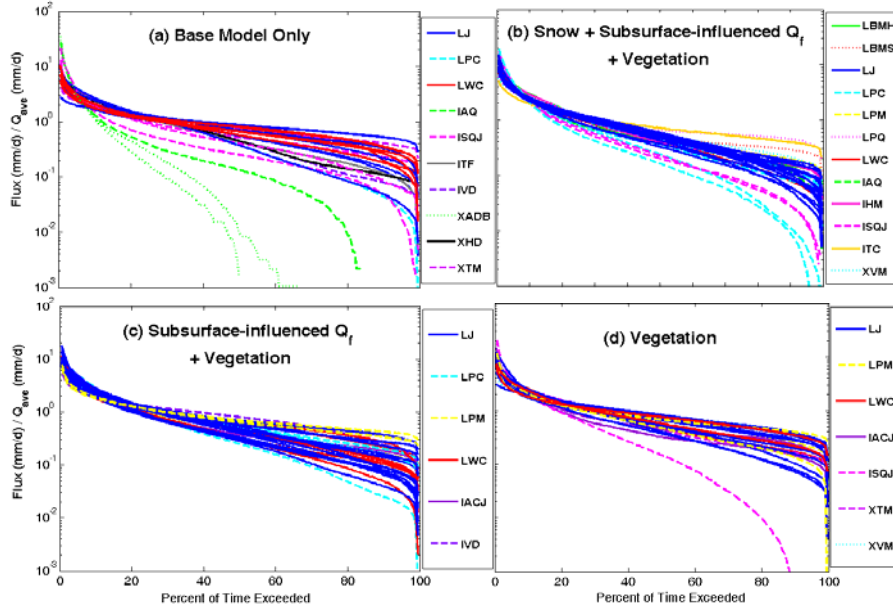
“Quantitative analysis performed in this synthesis paper showed that both the process and empirical classes, which are based on the regime curve, were connected to the broad properties of the flow duration curve (the slope of the middle limb and the parameters of the mixed gamma function). However the regime behavior captures different aspects of variability compared to what is reflected in the FDC.”

A more precise language with shorter sentences would improve readability of the paper.

If the reviewer finds any further sentences unclear, we will attempt to improve upon them, as we have for the ones already mentioned. We thank this reviewer for the opportunity to improve the clarity of our writing.

Presentation Quality / Figures:

Some figures are not clear. Some statements depend on the order of plotting and signs/FDCs are covered by other signs/FDCs. Example1: Fig. 5 c): the plot is blue on red, if you plot in another



If this is satisfactory, it will appear as such in the final revision.

Example2:

Fig. 6: Numbers of catchments per class are not visible: are there two or twenty similar values for XVM? Are there 6 or more values for XADB? Values have to be ordered by size before plotting and sings must allow seeing number of catchments.

There are 3 catchments in class XVM, but there are exactly 2 values for XADB (the pink circles in Fig. 6). We wish to avoid ordering by class size, because the exact number of catchments in each class would still not be known, only the relative “more or less than other classes”. We do wish to plot the graph to make clear our interpretation, and thus we have changed the ordering from alphabetical to order of seasonality, with all low seasonality classes (those beginning in L) on the left, the intermediate seasonality classes (those beginning in I) in the middle, and the highly seasonal classes (those beginning in X) on the right. We have also attempted to address the reviewer’s concern about sizes by adding the number of catchments per class to the legend, and changing the y-axis to a log scale to better bring out the differences between the classes. The updated figure appears below, as it will appear in the final revision.

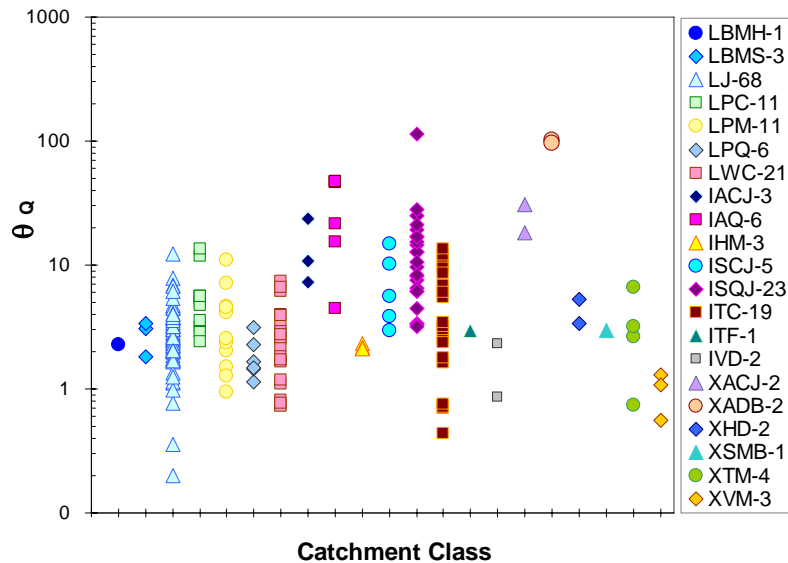


Figure.6: Abbreviations in the legends are not explained.

The caption for Fig. 6 states that the gamma parameter θ is grouped by catchment class, and therefore the abbreviations in the legend are catchment classes. This is analogous to the caption for Fig. 7, except that the model process classes are written out. In the caption for Fig. 5 we do give a brief description of what L, I, and X mean, as well as what V, H, T, S, and A denote, and this is discussed in the text as well. Details of what every letter in the class abbreviation means can be found in Coopersmith et al. However, since we have ordered the classes by seasonality we can briefly define L, I, and X in the caption for Fig. 6 as well.

The range of values may be a function of size of classes and/or outliers. - Size of classes is not clearly visible. Comparison of classes with only one or two values with large classes without wellfounded explanations will lead to not significant results.

We agree with the point the reviewer is making. As we have mentioned previously, there is a definite limitation to what can be gained from a qualitative analysis of the data. Thus we have not depended upon visual inspection alone, but have proceeded to do a quantitative analysis as well. However, this is not to say that there is not value in visual inspection of the data; indeed there are insights that can be gained from it. Sometimes patterns present themselves very clearly, and sometimes the patterns are not immediately self-evident. However, for Fig. 6, now that we have ordered the various classes by seasonality, we can see that as a group, low-seasonality catchments, which also tend to be more humid have lower values of θ ($\theta < 20$, while catchments with higher seasonality explore a wider range of q . Within the group of intermediate to high seasonality catchments, those that are more arid (A or S in the abbreviation) tend to have a higher θ than those that are more humid. We may speculate on why this may be, given where catchments with such designations tend to be located, and then we proceed with the quantitative analysis for verification.

IHM, and three catchments of ISQJ in Fig. 13: are this all catchments of these classes or are other catchments not visible in this figure? Maybe another order of plotting them can underline the statement in the text. - There is a lot of free space in Fig. 13 and simultaneously many signs one upon the other: Another scale of the ordinate with a diagonal reference line can bring more insights in this figure. Another way for more information would be the reduction of numbers of (important) catchment classes.

There is only 1 catchment in class LBMH, three of class IHM, and after a second look at the figure as presented, we can see 5 of class ISQJ, which is a problem, as there are 23. The free space in the original figure arises from the axes being equal (so that the diagonal reference line is implied) and the slopes of the RC FDCs (on the y axis) being much smaller than the slopes of the corresponding FDCs. We have changed the order of the catchments, reduced the y-axis, and added a 1:1 reference line, as shown below. In addition, we have greyed out most of the catchments, leaving the original colors and shapes only for those classes mentioned in the text, and brought these to the front of the plot. We have done this in order to simplify the figure while at the same time still showing how the RC FDC and FDC slopes of all 197 catchments relate to each other. If these changes are satisfactory, the final version of the paper will reflect this. We thank the reviewer for bringing this to our attention, thus enabling us to improve the clarity of our figures.

