Reply to Referee A. Castellarin

General comments

Being the interpretation, analysis and modelling of flow duration curves (FDC's) one of my specific research interests I really enjoyed reading the manuscript by Cheng et al., which presents a comprehensive analysis of empirical duration curves (i.e. rainfall, total, fast and slow runoff duration curves) over a large geographical area (i.e. continental US) and a number of gauged basins (i.e. 197) aimed at deepening our knowledge on dominant geomorphological and climatic factors controlling the shape of FDC's. The research question is of broad international interest, and addresses several practical applications, such as the predictions of the curves in ungauged basins. The presentation is clear and the manuscript is well written and concise. I am reporting below a few main comments and some specific remarks, which I hope the authors will find to be useful while revising their manuscript.

We very much appreciate the thoughtful and constructive comments by Dr. Castellarin. Changes have been made in the revised manuscript according to some of the technical comments. In the following, we focus on providing some clarifications for those that remain.

- Supporting the utilization of the mixed-Gamma distribution

In my opinion, the use in this study of the mixed Gamma distribution, a 3-parameter distribution in which one parameter -alpha- is used to mimic the zero-flow (or zero rain) duration, while the other two control the 1st and 2nd order moments, should be further discussed and supported in the text. Since the analysis focuses on the shape of standardized (i.e. unit-mean) duration curves, one may wonder if the modelling of each curve (i.e. rainfall, total, fast and slow runoff) through the proposed model is really necessary. Similar findings could perhaps have been reached through the analysis of empirical values of alpha (done in the study) and variance (the study refers to the parameter k instead). A similar approach would have been more general (no limitation to a specific model). Also, one may argue that representing a complex distribution such as a flow (or rainfall) duration curve with a 2-parameter model may work in some areas but could be over simplistic elsewhere (see e.g. LeBoutillier and Waylen, WRR, 1993, Castellarin et al., WRR, 2004).

Thank you for the thoughtful comments. Fitting duration curves to a probability distribution is not the main objective of this study. It aids what we try to explore, namely the physical controls of regional patterns of flow duration curves (FDCs). There were several considerations for why the mixed gamma distribution was employed to fit different duration curves in this paper. First, the capability of the distribution to capture the shape of FDCs had been proven previously since choosing which distribution is best for fitting FDCs is not our main objective. Second, a simple distribution was preferred. A complex distribution (one with more parameters) is expected to be more robust than a simple distribution; however, complex distributions would have some correlation between different their parameters and consequently, uncertainty in the parameter estimates. This may confound efforts to distinguish the physical controls on each of the statistical parameters. Lastly, the distribution can account for the zero segments of the duration curves, since zero segments are important for precipitation and fast flow duration curves and thus closely related to climatic variability. Therefore, the mixed gamma distribution was chosen. Our results demonstrated that the mixed gamma distribution can capture the shape variations of most of our dataset's catchments.

- Deepening the discussion on how to move forward

The authors clearly show how the rainfall duration curve can be associated with the fast-runoff duration curve. They also show how the FDC for medium to large durations is strongly linked to the slow-runoff duration curve. Finally, the authors show clear geographical patterns of these curves over the study area. It is argued in the study that these outcomes may be particularly relevant for the prediction of FDCs in ungauged basins through a more process-oriented approach, and I perfectly agree with the authors on this point. Concerning this point, though, I also believe that the manuscript would be enriched by a brief discussion speculating further on how to practically exploit these results for regionalization of FDCs. Should this involve a recombination of the different duration curves? If so, the authors should anticipate how to perform such a recombination, since summation of runoff components for given duration values is not correct.

At this stage we are not interested in reconstructing an FDC for a specific catchment and/or regionalizing an FDC for an ungauged catchment. Our conclusions can benefit future work that reconstructs and/or regionalizes duration curves in ungauged basins, although some correlations cannot be directly applied.

Dr. A. Castellarin does raise an excellent point about the recombination of different duration curves to reconstruct flow duration curves. We had also considered deepening our study from this point; however, we have not yet found any interesting conclusions. Flow duration curves, by removing temporal information, cancel out the day-to-day correlation of streamflow in a time series. The fast flow and slow flow duration curves cannot be easily re-combined to obtain the total flow duration curve. For correlations between different duration curves, reconstruction of the fast flow duration curve may be advanced by similarities between the precipitation duration curve and the fast flow duration curve and the controls (i.e., precipitation characteristics) on fast flow duration. Reconstruction of slow flow duration curves may be advanced by similarities between the total flow duration curve and the slow flow duration curve and the controls on slow flow duration. However, methods for transforming precipitation duration curves into fast flow duration curves and methods for transforming total flow duration curve into slow flow duration curves are still not clear and require more investigation from both the statistical and physical perspective. It is beyond the scope of this study.

In the revised version of the manuscript, a brief discussion will be added to deepen our understanding of how to move forward.

SPECIFIC REMARKS

1. Abstract - "... revealed significant space-time symmetry.", I find this passage to be unclear.

By "significant space-time symmetry" we mean that the physical controls on between-catchment variability (i.e., 197 catchments) of different duration curves were also demonstrated as controls on between-year variability (54 years of annual duration curves for 8 catchments), as shown in Figure 8 and 9. Thus, variability of the duration curves shows significant space-time symmetry. This conclusion was discussed in section 5.2.

2. p. 7003, l. 27 – please replace "Castellarin et al. (2004b) developed procedures to regionalize FDCs based on similarity of catchment climatic and morphologic characteristic in Italy" with "Castellarin et al. (2004b) reviewed the regionalization approaches proposed in the literature and compared their performance in the context of predictions in ungauged basins for a large region in central Italy".

We apologize for having not cited your paper correctly. We will revise as recommended in the final manuscript.

3. p. 7004, l. 10 - "FDC cannot, strictly speaking, be regarded as a probability distribution (Mosley and Mcerchar, 1993)" I find this statement to be misleading. It also contradicts what is stated on p. 7009, l. 10-11. The authors may consider dropping this statement.

We agree that this statement does not serve our purpose, and we will remove it in the final revision.

4. p. 7004, l. 17 - "the logistic distribution (Castellarin et al., 2004a)". This quotation is not accurate. Castellarin et al. (2004a, 2007) used the 2-parameter logistic distribution for representing the annual climatic signal and combined it with a more complex distribution (3-parameter Generalized Pareto, or 4-parameter Kappa distributions) for deriving the daily streamflow regime.

We again apologize for incorrect citation of your paper, and will revise it in the final version of the manuscript.

5. p. 7006, l. 18 – "the various FDCs,..." I would replace this with "the various duration curves", since it refers also to the rainfall duration curve.

Thank you for bringing this to our attention; we will change it in the final manuscript.

6. p. 7008, l. 16 – please briefly recall the definition of the seasonality index for the sake of completeness.

The definition of the seasonality index (SI) will be provided in the new manuscript.

7. Baseflow Index, BI – Given the relevance of this study to PUB, the authors should highlight in the text that BI is a streamflow regime index and cannot be computed for ungauged basins, if possible they should also discuss consequences in the PUB context. Also, later on in the text and in some figures BI is recalled as a geological variable. I find this to be misleading. While I acknowledge that BI may be "used as a surrogate for the collective impact of of landscape properties such as geology, ...", I would recommend not to identify it with a geological variable, making it crystal clear that BI is a property of the streamflow regime, whose empirical values are available for gauged basins only.

In the revised version, we will define the baseflow index as a property of the streamflow regime. Baseflow index reflects a collective impacts of landscape properties such as geology, soil properties, topology, vegetation on the streamflow regime. In this study, we take *advantages of the inherent feature of baseflow index to exploring the control of catchment landscape properties on the shape of duration curves.*

Use of the Baseflow index will limit the capacity of these relationships for practical applications. However, the main objective of this study is to explore the physical controls on regional patterns of flow duration curves from a statistical perspective. At this stage we are not interested in regionalization of flow duration curves. Our conclusions can be used to benefit future research seeking to reconstruct and/or regionalize duration curves in ungauged basins, although some correlations cannot be directly applied.

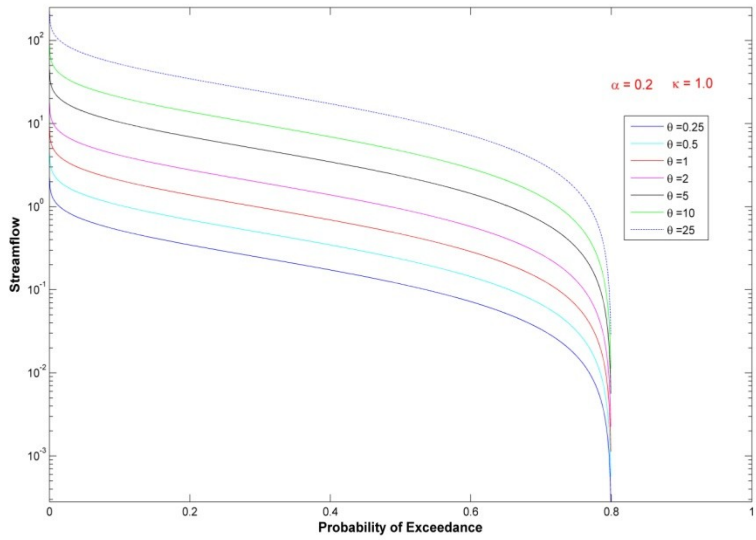
We will use a consistent representation of the baseflow index in the new manuscript. In addition, a brief discussion will be provided in terms of application for PUB context.

8. p. 7009, l. 5 - "robust" has a very specific meaning in statistical language, I fear the term is miss-used here, please check.

We thank you for pointing this out. We will delete "robust" in the revised version.

9. p. 7010, l. 2 - "theta largely affects the vertical shift", would that be the mean? If so, this statement does not seem to agree with eq. (4), that shows that theta and kappa both control the mean to the same degree (at least analytically).

The vertical shift is not determined by the mean since normalized duration curves were used. The mean is $\kappa \times \theta = 1/(1-\alpha)$. The parameter theta is the scale parameter of the mixed gamma distribution, and as such it controls the spreading of the distribution. Thus, for a given kappa and alpha, the vertical shift of the shape of duration curves is determined by the spreading of the distribution, shown in the following figure. In addition to that, kappa also influences the vertical shift partly. Comparatively, the vertical shift is more sensitive to theta and the slope is more sensitive to kappa. Therefore, we concluded that the scale parameter θ largely affects the vertical shift of the FDCs and the shape parameter κ essentially controls the slope of FDCs.



10. R^2 and Ens – Why R^2 is used here? Ens is more meaningful and the redundancy of using both indexes appears also in Fig. 4.

R^2 measures the degree of linear association, i.e., it is the square of the Pearson correlation coefficient. If the estimates are wrong (e.g., biased) but linearly correlated with the observations, R^2 will be high. Ens, instead, measures the match between observations and estimates, it also accounts for the bias (Ens=1 means perfect match). Therefore, both R^2 and Ens were employed. In the revised version, a brief explanation about why both indices were used will be provided. In the revised version of the manuscript, a brief explanation will be added.

11. Eq. (7) – The meaning of "i" in the notation is unclear. i=1,...n, with n=54 times 365.25?

In Eq.(7), where i means i-th days, i = 1, ..., N. N is the total number of records of measured duration curves. In the revised manuscript, we will clarify this notation.

12. p. 7011, l. 10 - "observed duration curves", please consider replacing observed with empirical.

Thank you. We will change this in the revised manuscript.

13. p. 7011, l. 11 - "since the mean daily streamflow is strongly related to AI", from what I understood, each duration curve is standardized by dividing its values by the long-term mean of the same variable. One may wonder if the above consideration applies also to the other considered long-term mean (e.g. precipitation, etc.). Please discuss.

The catchment mean annual water balance is determined by both the water supply (precipitation) and the energy supply (potential evaportranspiration). It is known as the "Budyko framework" (Budyko, 1974) and it has been well-examined (e.g., Zhang, et.al., 2001; Zhang, et.al., 2004). From a top-down view, precipitation and potential evaportranspiration (i.e., aridity index) are the first order controls on water balance and its variability (e.g., Cheng et al., 2011; Harman et al., 2011; Sivapalan et al., 2011). Therefore, mean annual runoff is closely related to the aridity index. In this study, normalized time series were used since we want to investigate physical, rather than first order, controls on the flow duration curves.

Other variables may be closely related to mean annual runoff, such as runoff with potential evaportranspiration in energy-limited (wet) regions, runoff with precipitation in water-limited (dry) regions, etc. However, the correlation between mean annual runoff and aridity index provides a holistic representation across different climate regimes (Zhang, et.al., 2004; Yang, et.al., 2006; Cheng et.al., 2012).

14. p. 7012, l. 1-2 – Is this a repetition from the previous paragraph?

Thank you; we will condense this paragraph to avoid any repetition.

15. p. 7016, l. 1 - "to regionalize FDC", BI cannot be directly used for this task (see my comment above).Please include a discussion.

We mean that correlating the parameter kappa with catchments' physical characteristics can assist towards the reconstruction of FDCs or to regionalize FDCs to ungauged catchments. For instance, based on what this work has determined, one can observe an ungauged basin, then examine a regionalization map, and ultimately see what group best matches the ungauged basin. The Baseflow index, which was related to the shape parameters of the fitted duration curves, is not readily assessable in ungauged basins. This will limit the capacity of these relationships for practical applications.

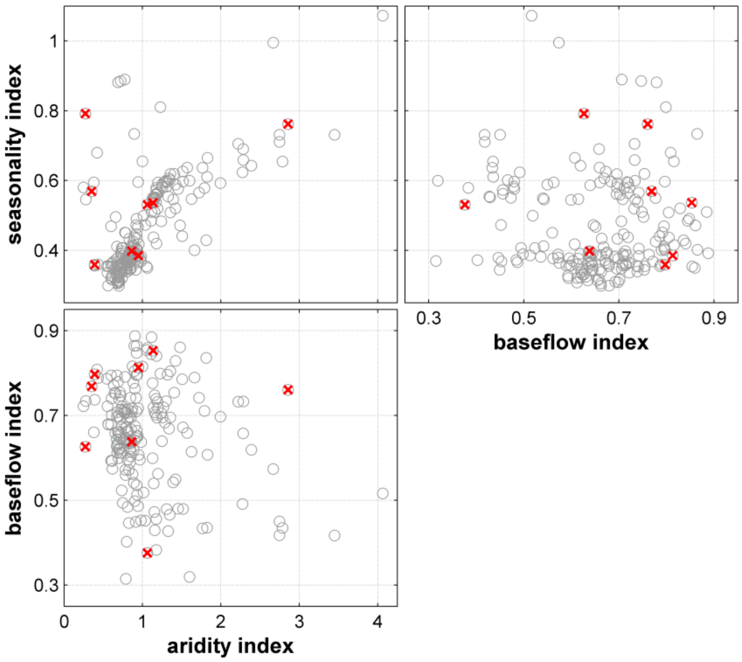
In the revised manuscript, a brief discussion will be provided in terms of this work's application for PUB.

16. p. 7017, l. 26 - "54 catchments", please check.

Thank you. It should be "54 years"; we will revise this in the new version.

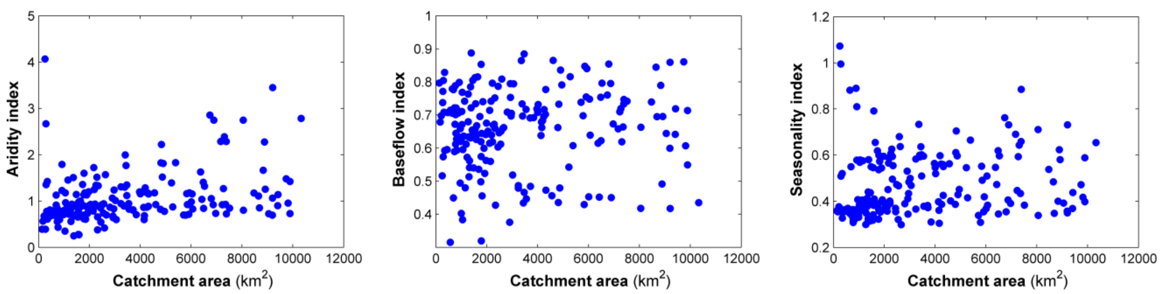
17. "8 selected catchments" - It would be good to compare their relevant indices (i.e. SI, AI, BI, etc.) with the indices of the whole set of 197 catchments (boxplots?).

We thank you for the thoughtful comments. SI, AI and BI were used to select 8 representative catchments for analysis of annual duration curves. These 8 catchments are picked out considering not only representativeness according to climatic and geologic conditions (i.e., aridity index, baseflow index and seasonality index) but also its spatial distribution. The 8 catchments for annual duration analysis (red crosses) and the all the studied 197 catchments (open circles) referring to aridity index, baseflow index and seasonality index are compared in the following figure, which will be included in the revised manuscript as auxiliary materials. The spatial distribution of these 8 catchments was shown in Fig. 3.



18. Fig. 1 – This representation highlight dependence of the measure of interest from the geographical location only. Is there any dependence of these measures on catchment area (which spans more than an order of magnitude in the study area)?

The dependence of different indices on catchment area is shown as follows:



No strong dependence of AI, BI and SI on catchment area can be found.

The catchment area may play a very significant role in determining the shape of the lower half of the curves (Singh, 1971). However, runoff was in depth (mm) and normalized in this study. The dependence of the shape of duration curves on catchment area should have been significantly reduced.

19. Fig. 8 and Fig. 9 - "geological variables", please revise.

Thank you; we will revise it.

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