RESPONSE TO REVIEWER 2 COMMENTS

Throughout this response, the reviewer's text is presented in black, our response in blue, and the proposed revisions in green. Please also note that line numbers all refer to the current submission.

Yildiz et al. introduce a new approach to generate possible future streamflow scenarios for stress testing the impacts of possible climatic changes on river systems. The approach is elegant, requiring only three parameters to modify key characteristics of the flow duration curve (mean, standard deviation and low/high flow quantile or median, coefficient of variation and low/high flow quantile). I think this approach is a nice contribution to the literature. I have a only a few suggestions for improvement.

We sincerely appreciate your thoughtful review of our work. We are happy to hear that you consider our contribution to be a valuable addition to the existing literature. Furthermore, we are grateful for your suggestions, which we believe will strengthen this paper.

The Discussion claims that this method "compares favorably with existing statistical methods to perturb flows such as the delta change approach." However, the paper does not formally compare the proposed FDC alteration approach with the delta change approach. I think it would help sell the method to include a few FDC alterations with the same mean change but different changes in the variance and low flow quantile with using the delta change method to achieve the same mean change. Seeing differences in both the streamflow time series and resulting performance impacts from the delta change method vs. different FDC alterations that achieve the same mean change would help sell the utility of this approach for climate vulnerability assessments.

We appreciate your insightful input. Based on your suggestion, we recognize the importance of providing a direct comparison between the two methods in a visual manner.

To address this, we propose to revise Figure 3 as follows below, to clearly illustrate the differences between our proposed method and the delta approach. This addition will enhance the clarity and comprehensiveness of our study.

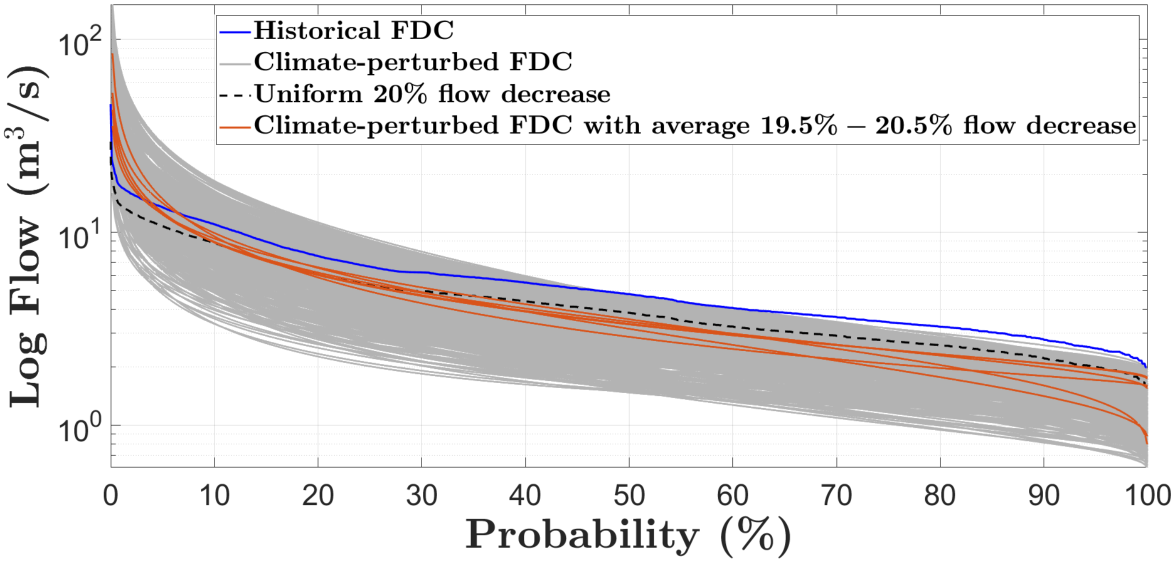

Figure 3. Plot of the flow duration curves (FDCs) of the historical records (blue line) and sampled flow duration curves (grey lines) constructed by deriving the FDC parameters for Kosugi Model shown in Table 1. The figure also compares 20% mean flow reductions, obtained either with the delta-change method (uniform multiplier, dashed black line) and future scenarios we generated with mean flow reductions between 19.5 and 20.5% (orange lines).

We will also amend the accompanying text accordingly at lines 181-182

"This versatility can be compared to the lack of flexibility provided by a uniform multiplier across the FDC of historical flows, as shown in Figure 3 with examples of a 20% reduction across the flow distribution (dotted black lines). Future scenarios from our ensemble generated with comparable mean flow reductions – ranging from 19.5% to 20.5% (orange lines) – display a wide range of low and median flow behaviours, generally lower than the dotted black line, combined with higher high flows."

Discuss the conditions of unicity (either when they are introduced or in the Discussion section). Are these conditions likely to be met, and if so why? Where might it not be true? What are the implications of not being able to explore changes that don't meet these conditions?

Thank you for highlighting the importance of existence conditions in our approach. We agree with these conditions being crucial, and we verify them across our ensemble in our application (lines 177-179). In general, we believe that this condition must be verified on a case by case basis across the generated ensembles of future flows. We also believe a general validation based on historical flows is of limited relevance, because the condition needs to be verified for all future flows in the generated ensemble, and not just for historical flows.

This being said, we are happy to give hints as to why this condition will be valid most of the time. Indeed, equations (5) and (9) are both equivalent to $CV > -(1-R)/\ln(\varepsilon)$ where $0<R<1$ is a ratio of the low flows by the mean or median.

Therefore, a sufficient condition for a unique solution to exist is that the coefficient of variation CV > -1/ ln(ε), which corresponds approximately to CV>0.43 if the low flow indicator is the first percentile, and CV>0.61 if it is the fifth percentile. This sufficient condition has been verified for most catchments over a wide dataset of 6807 gages in the continental US (see Ye et al., 2021). And when this sufficient condition is not met, one also needs 1-R to be close to one for the existence condition to be violated. In other words, one needs low flows to be very low in comparison to the mean (for the "mean" case) or median (for the "median" case) and this is a condition that tends to increase the value of CV. In fact in Ye et al. (2021) figure 10, all time series with zero flow days have a CV value close or equal to 1.

To clarify this in the text, we will add a separate section 2.2.3 to comment on the conditions of equation (5) and (9):

2.2.3 Domain of validity of existence conditions

In this paragraph, we explain what the conditions for the existence and uniqueness provided imply – see equations (5) and (9) for "mean" case and "median" case respectively. Both equations are equivalent to:

$$CV > \frac{-(1-R)}{\ln(\varepsilon)} \tag{11}$$

where 0<R<1 is a ratio of the low flows by the mean or median; recall that -1/ln(ε) is close to 0.43 if the low flow parameter is the first percentile, or 0.61 if it is the fifth percentile.

From equation (11), it is sufficient to have CV > -1/ ln(ε). This condition has been verified for a large majority of the catchments over a large dataset of 6807 gages in the continental US (see Ye et al., 2021). Yet for the existence condition to not be met the multiplier of (1-R) must also be close to 1. In other words, low flows must be extremely low relative to the mean (for the "mean" case) or median (for the "median" case), but this may be incompatible with a low value of CV. In fact, in Figure 10 from Ye et al. (2021), all time series with zero flow days in the sample have a CV value close or equal to 1. Together, these remarks suggest that the existence condition should be realised in most cases where flows are not strongly regulated. However, we would like to point out that the conditions of equations (5) or (9) being met for historical flows is not relevant. They need to be verified for each plausible future flow for which a FDC is generated. For this reason, we consider that checking these conditions across large databases of historical flows would be both irrelevant and out of the scope of this work.

One noted limitation in the Discussion of this FDC alteration is it does not change the length of wet and dry spells. I recommend noting this can be achieved by changing the parameters of a Markov chain-based streamflow generator (see e.g. Stagge and Moglen, 2013).

Another limitation of the FDC approach not mentioned in the Discussion is that it cannot capture changes in seasonality, which would preclude its application in snow-dominated catchments, or perhaps monsoon systems. I recommend noting this as well. See examples in the literature from Nazemi et al. (2013) and Quinn et al. (2018).

We appreciate your input on proposing alternative methods to address the limitations of our approach. We will address the two comments together. We think that suggested methods could be a possible solution to address aforementioned limitations. We will add below text in the discussion section of the manuscript, by amending its last paragraph as follows:

Our approach only considers the FDC, and says nothing of the seasonality, frequency and duration of dry and wet spells. The shifting seasonality of flows in a changing climate can easily be captured by combining our approach with methods such as the log-space rescaling of stationary flows (Quinn et al. 2018) or the reconstruction annual flow hydrographs (Nazemi et al. 2013). Beyond changes in seasonality, there is mounting evidence that climate change is bound to cause hydrological intensification, i.e., it will make dry periods longer and more severe and wet periods more intense (Ficklin et al., 2022). Information on hydrological intensification scenarios comes from outputs from large-scale climate models, and integrating that information requires turning the climate information into streamflow. One way to do it without the help of a rainfall-runoff model is to control the parameters of a daily streamflow model with a monthly climate model (Stagge and Moglen 2013). The generation of a FDC for every climate the daily streamflow model simulates could then be used to improve results, e.g., by providing a quantile-by-quantile adjustment of the synthetic streamflow generator outputs. A similar procedure could combine hydrological model simulations with statistical generation of FDCs. The latter could correct outputs from the former, if they were obtained with a calibration that reflects historical conditions.

Minor comments:

Line 70: drop “of” after “represent”

Line 140: change “Zenedo” to “Zenodo”

Line 159: change “standard deviation” to “coefficient of variation”

Line 171: drop “is” before “projected”

Line 176: change “latin” to “Latin”

Line 177: “the” is repeated

Thank you for bringing the typing errors to our attention. We will revise the manuscript to correct all the identified typing errors.

Table 1: why not explore potential increases in the median/1st percentile or decreases in the coefficient of variation?

Thanks for this comment. The reviewer is perfectly right that the method can be applied to explore opposite changes to those described in Table 1. Yet, our illustration of our methodology focuses on a region where all studies point to a drier and more variable future, as justified in lines 166-176. This explains the parameter ranges chosen in Table 1.

References:

Nazemi, A., Wheater, H. S., Chun, K. P., & Elshorbagy, A. (2013). A stochastic reconstruction framework for analysis of water resource system vulnerability to climate‐induced changes in river flow regime. Water Resources Research, 49(1), 291-305.

Quinn, J. D., Reed, P. M., Giuliani, M., Castelletti, A., Oyler, J. W., & Nicholas, R. E. (2018). Exploring how changing monsoonal dynamics and human pressures challenge multireservoir management for flood protection, hydropower production, and agricultural water supply. Water Resources Research, 54(7), 4638-4662.

Stagge, J. H., & Moglen, G. E. (2013). A nonparametric stochastic method for generating daily climate‐adjusted streamflows. Water Resources Research, 49(10), 6179-6193.

Ye, L., Gu, X., Wang, D., & Vogel, R. M. (2021). An unbiased estimator of coefficient of variation of streamflow. *Journal of Hydrology*, *594*, 125954.

Thank you again for your thoughtful comments on our manuscript.