Reviewer 1

The manuscript is presented as a review paper on multivariate extremes, specifically flood, and drought. The multivariate aspect of such extremes is intended in space, in time, and in their characteristics. The topic is relevant for preparedness and risk management in the current and future climates. However, the manuscript in its current form presents some limitations.

Reply: *Thank you very much for acknowledging the relevance of the review topic and for taking the time to provide this constructive feedback, which I address point by point below.*

The introduction on the drawbacks of the univariate approach seems in contrast with the types of multivariate extremes identified. The regional and temporal extremes fall back on a univariate approach. Indeed, they are defined based on whether, e.g., flood magnitude is above a given threshold or with a given return period at one single location. When does an extreme in one location become a multivariate extreme? How many locations should be flooded? Is the regional extent of the univariate floods an indicator of whether an extreme is multivariate or not? How so? These kinds of questions are difficult to answer from the definitions of multivariate extremes provided and it makes questioning whether it is necessary to move away from the univariate approach.

Reply: *Thank you for stressing the need to clarify the link between studying multivariate extremes and univariate frequency analyses. I agree that one good strategy of studying multivariate extremes is by defining univariate metrics that describe them, e.g. spatial flood extent for spatially compounding flood events. The point I would like to make here is that analyses of hydrological extreme events should go beyond focusing on one variable only and consider extreme events from a multivariate perspective. I rewrote the introduction by removing the part about univariate frequency analysis which gave the wrong impression that this tool is inappropriate to study multivariate extremes. Instead, the new introduction stresses that multivariate extremes consider more than one variable compared to univariate extremes focusing on one variable only:*

'In July 2021, a severe and widespread flood event affected Western Germany and parts of Belgium and the Netherlands where it led to numerous fatalities and considerable damage to infrastructure (Ibebuchi et al. 2022). After such exceptional flood events, we ask: 'how frequently do such events occur?' To answer this question, one can rely on frequency analyses which establish a link between the magnitude and frequency of events. Such analyses are often performed by focusing on one variable only, i.e. by taking a univariate perspective. In the case of the Germany flood, this would e.g. be flood peaks in one individual catchment. While such a focus on one variable enables the development of suitable preparedness and adaptation measures by providing magnitude and frequency estimates of extreme events, they have a major drawback: they neglect that extremes are often not univariate but multivariate phenomena, i.e. affect more than one variable.

To illustrate the multivariate nature of hydrologic extremes, let's again look at the 2021 flood. This flood event was not just extreme in terms of peak discharge at one location, it was also extreme in terms of the flood volume generated. Furthermore, it affected not just one catchment but multiple catchments in Germany, Belgium, and the Netherlands.

This example highlights that the multivariate nature of hydrological extremes can take multiple forms. In the case of peak discharge and volume, we are looking at an extreme event characterized by multiple variables and in the case of multiple affected locations at a *regional extreme event. These different types of multivariate extremes have in common that they involve multiple interdependent variables, which requires a multivariate perspective. In this review, I first provide an overview of different types of multivariate hydrological extremes including regional extremes, consecutive extremes, extremes with multiple characteristics, and extremes transitions. In addition, I review tools, measures, and descriptors available to describe these different types of extremes. Second, I present modeling approaches available to model extremes in a multivariate framework, such as copula models and multivariate simulation approaches. Last, I discuss challenges related to multivariate hydrological extremes, including the regionalization of multivariate extremes to ungauged basins and the assessment of future changes in multivariate extreme events.'*

In my opinion, more emphasis should be given to the descriptors of multivariate extremes, as defined by the Author, their differences, and the implication of using one descriptor rather than another. As a matter of fact, the definition of an extreme cannot be decoupled from the descriptor used. In the manuscript, they are simply listed in tables without further implications on their use.
Reply: *Thank you for highlighting the need to emphasize the descriptors of multivariate extremes. I substantially expanded the description of the different descriptors and provide an overview on what types of analyses the different descriptors can be used for.*

Section 3 on modeling multivariate extremes is about models for assessing the frequency and magnitude of multivariate hydrologic extreme events (as summarized by the Author in lines 241-243). In this section, bivariate copula models are described way more extensively compared to other methods. However, it is unclear why such a detailed description and how copula models differ from the descriptors of hydrological extremes with multiple characteristics. As a matter of fact, copulas model the dependence between two variables, where the dependence between the variables is measured by the correlation between two variables (descriptors in Table 3). It would be useful to discuss whether bivariate copulas can be applied also to regional and temporal multivariate extremes and how. Moreover, limiting the description of multivariate models to bivariate statistical methods in a review paper on multivariate extremes is not enough. I encourage the Authors to add studies and methods for higher dimensions.
Reply: *Thank you for stressing the need to expand the discussion of multivariate models and distributions beyond the bivariate case. I introduce bivariate copula models in detail because they are a useful tool to describe return periods in a bivariate setting, which is often used because return periods are difficult to generalize to higher than two-dimensional data. However, I fully agree that it is important to also introduce multivariate distributions and models going beyond 2 dimensions because some of the extremes discussed in this review (e.g. the spatial extremes) are higher dimensional phenomena. Therefore, I substantially expanded section 3 (Modeling multivariate extremes) by including descriptions of (1) suitable univariate metrics for multivariate extremes, (2) bivariate distributions and return periods, (3) multivariate distributions, and (4) multivariate simulation approaches.*

Point-by-point comments:

Line 28 and Line 280: my suggestion is to cite textbooks or the original journal papers where these concepts are first defined. For example, G. Salvadori and C. De Michele earlier works.

Reply: *Thank you for this suggestion. I included a few of the original journal papers, where the return period concept was introduced, and the paper by Salvadori and De Michele.*

Line 88: “precipitation dependence” dependence to what?
Reply: *I specified that I was referring to ‘precipitation spatial dependence’.*

Figure 4: it would help to have more information on how drought is defined
Reply: *I specified that ‘droughts were here defined using a variable threshold at the 15th flow percentile.’*

Lines 182 – 200: discussion about variables dependence is a bit vague. Which variables? Is it a bi-variate dependence? The example of dependence between peak and volume for hydraulic design should be elaborated further.
Reply: *Thank you very much for pointing out the need for clarification. I provide a few examples of variable pairs of interest, specify that we are talking about bivariate dependence, and use the example of peak-volume to illustrate the importance of considering bivariate/multivariate relationships in hydraulic design by adding the following sentences: ‘For example, flood duration and volume or flood volume and flood peak show strong correlations (Figure 6), i.e. they show bivariate dependence. […] Such bivariate interdependence is e.g. found for drought deficit and duration or drought deficit and intensity (Figure 6a,b).[…] Such dependence, e.g. between peak discharge and flood volume, is important for hydraulic design because dam failure depends not only on flood peak but also volume (De Michele et al. 2005).*

Line 321: studies in higher dimensions should be added to the manuscript
Reply: *I rewrote Section 3 (Modeling multivariate extremes) and added a subsection called ‘multivariate distributions’, which discusses different models for multivariate extremes including conditional exceedance models, max-stable models, the multivariate generalized Pareto distribution, and high-dimensional copula models such as vine copulas.*