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Nat. Hazards Earth Syst. Sci. Discuss.
"Analyzing the informative value of alternative hazard indicators for monitoring drought risk for human water supply and river ecosystems at the global scale" by Claudia Herbert and Petra Döll

Response to Anonymous Referee #2

We thank you very much for your helpful comments and constructive suggestions for improving the manuscript. Below, each comment (in italics, indicated by "**RC**") is followed by our answer (normal font, indicated by "**AC**"). Changes in the manuscript are written in bold.

RC: *This paper analyses which drought hazard indicators are suitable for assessing and monitoring streamflow drought risks for human surface water supply and for river ecosystems. The authors recommend considering the habituation of people and ecosystems to the streamflow regime when selecting indicators. Eight existing indicators and three new indicators are proposed and evaluated using the model results of WaterGap.*

The paper has potential but needs a proper revision before publication. The paper is very long and thereby is not always that clear/focussed and repetitive in some aspects. Overall sections can be shortened and may be ordered in a more logical way. For example, the introduction is very lengthy and lacks focus relevant to the objective of the work. Also, the methodology is at some aspects lengthy (too lengthy) whereas other aspects are not discussed at all. Altogether, from the current version of the manuscript, it is hard to judge the full potential of the research and research paper.

> **AC**: Thank you for the constructive feedback. We deleted and shortened repetitive or too detailed paragraphs throughout the text and used more concise language. We shortened the introduction by one page and the conclusion section by almost one page. In the introduction, we deleted paragraphs and sentences that anticipated aspects of the proposed new classification system (e.g., lines 92-118) as well as repetitive and too detailed sentences (e.g., lines 141-147).

Methods and data:

RC: *Section 2.1: First, a minor comment, the model names WaterGAP2.2d, WGHM, WaterGAP are used for the same model I assume. However, this is a bit confusing.*

> **AC:** WaterGAP consists of the hydrological model WGHM and five water use models. WGHM is only used twice in the model description. We changed the sentence in line 157 from "The model consists of the WaterGAP Hydrological Model WGHM and five water use models […]" to "**WaterGAP** consists of the WaterGAP Hydrological Model **(**WGHM**)** and five water use models […]". Throughout the text, we now use "WaterGAP" for descriptions that apply to WaterGAP in general and the term "WaterGAP 2.2d" for version-specific descriptions.

RC: *Furthermore, previous model results are used (namely from Müller Schmied et al 2021) and all details on model description and evaluation are not discussed in this paper. However, to better understand the results it would be useful to at least read a summarized description of the for this study, most important parameters, assumptions made, uncertainties, and sensitivities and how this has, or has not, an impact on the evaluation of your drought indicators.*

> **AC**: We used model output from our (at the time of writing) latest model version 2.2d. This model version is documented in Müller Schmied et al. (2021). Since modeled streamflow in WaterGAP is the result of many processes, it is difficult to select only a few parameters that have an impact on low flows. However, we moved, as suggested by another reviewer, the section describing WaterGAP model performance in model intercomparison studies (previously, Sect. 3.4) at the end of the model description. Here, we focus on studies

that analyze streamflow, low flows, and drought hazard indicators, all of which are relevant for the present study.

In the model validation (previously, Sect. 3.4), we added the new Fig. 3 below for a more detailed analysis of Q80. Furthermore, we added the paragraph below Fig. 3 describing the results of another recent WaterGAP 2.2d model validation performed by us comprising 183 gauging stations. Hence, the model validation is now focused on Q80 and a SDHI (SSI3), which are both relevant for the global-scale analysis of streamflow drought hazard indicators. We think that this is more valuable to assess the indicators than a detailed model description.

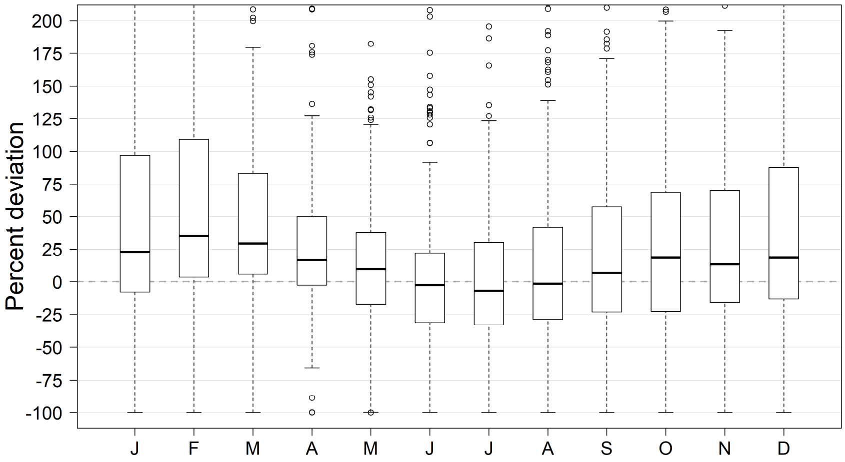

Figure 3: Percent deviations of simulated Q80 per calendar month from Q80 based on GRDC observations using the reference period 1986-2015.

In a recent study, WaterGAP 2.2d model output was validated against GRDC data by comparing SSI3 based on simulated and observed monthly streamflow (SSI3(sim) and SSI3(obs)) during 1971-2000 at 183 globally distributed GRDC stations (Wan et al. 2021). Applying drought hazard classes for SSI according to Agnew (2000), the agreement between simulated and observed hazard classes in each month was analyzed. Among all stations, the agreement ranged between 29 to 88% of all 360 months (their Fig. S4 and Table S3). At 68% of all stations (covering 83% of the assessed basin area), SSI3(sim) and SSI3(obs) resulted in the same drought hazard class in 70 to 88% of the time. Moreover, the goodness-of-fit was evaluated based on the Nash-Sutcliffe efficiency (NSE) for monthly streamflow and SSI3 (their Fig. S3). With a median NSE of 0.5 and an interquartile range of 0.2-0.7 for SSI3 and 0.14-0.7 for streamflow, WaterGAP 2.2d model output showed a moderate agreement with the observations. Both NSEs exceeded 0.7 at 25 out of the 183 stations, which are located in Central and Eastern Europe (twelve stations), the United States (ten stations), and South Africa (one station).

RC: *Section 2.2: this section is very long and could be focused more on the new indicators and evaluation of the results.*

AC: Given the inconsistent indicator descriptions identified in the literature (or the absence of any description), we think that the detailed description of the conventional indicators is as important as the description of the new indicators.

RC: *In the method section, there is no description of how the results will be presented or evaluated/compared.*

AC: After dividing the "Results and Discussion" section (old Sect. 3) into two sections (see new structure below), we added an introductory paragraph at the beginning of each section (see below) explaining the objectives and the structure. Section 3 is now focused on the proposed systematic approach for selecting streamflow drought hazard indicators (SDHIs) and Sect. 4 comprises the global-scale assessment.

3 Proposed systematic approach for selecting and computing SDHIs (old Sect. 3.1)

- **3.1 Assumptions about habituation inherent in drought hazard indicators** (old Sect. 3.1.1)
- **3.2 Levels of drought characterization** (old Sect. 3.1.2)
- **3.3 Illustration of habituation-based classification approach** (old Sect. 3.2, new title)

4 Quantification of global streamflow drought hazard by a global hydrological model (old Sect. 3.3, new title)

- **4.1 Model validation** (old Sect. 3.4)
- **4.2 Discrepancies in drought hazard as quantified by different SDHIs** (old Sect. 3.3, new title)
  - **4.2.1 Drought magnitude (level 1)** (old Sect. 3.3.1)
  - **4.2.2 Drought severity (level 2)** (old Sect. 3.3.2)
  - **4.2.3 Drought severity expressed as frequency of non-exceedance (level 2)** (old Sect. 3.3.3)
  - **4.2.4 Relation between the various SDHIs** (old Sect. 3.3.4)
  - **4.2.5 Suitability of SPIn to quantifiy streamflow drought hazard** (old Sect. 3.5, new title)

AC: We added the following paragraph at the beginning of the new Sect. 3 to clarify the objectives and the structure:

Wilhite und Glantz (1985) suggested distinguishing between a conceptual and an operational drought definition, with the former referring to the general qualitative concept of drought and the latter allowing for a quantitative drought characterization including onset, severity, termination, and spatial extent. In the following Sect. 3.1, aspects that relate to the conceptual drought definition are discussed comprising the description of the targeted drought risk and the system at risk. In particular, assumptions about the habituation of the system at risk to the streamflow regime are discussed, an aspect that is currently not taken into account or not made explicit in drought hazard studies. In order to translate these conceptual definitions into operational drought hazard indicators, a new classification system for hazard indicators is proposed in Sect. 3.2. The new systematic approach is illustrated in Sect. 3.3 for selected SDHIs using streamflow observations at two gauging stations with different streamflow regimes.

AC: We added the following paragraph at the beginning of the new Sect. 4 to clarify the objectives and the structure:

The objective of this chapter is to identify which of the SDHIs presented in Table 1 can be meaningfully quantified at the global scale using WaterGAP 2.2d and which SDHIs are appropriate for monitoring different drought risks in large-scale DEWS. After a limited validation of modeled streamflow (Sect. 4.1), SDHIs of drought magnitude and severity are compared separately (Sect. 4.2.1-4.2.3) following the classification system presented in Fig. 1. The SDHIs are shown in global maps for a selected month (March 2002), as it is important to understand the relation between indicators at a certain point in time, especially for the application in DEWS, which are focussed on the current situation or the near future. As patterns of indicators depend on characteristic of the streamflow regime and water use that are temporally constant over the reference period, the reasons for similarities and differences between indicators can be deducted in any month of the reference period. March 2002 was selected as it was among the months with the highest difference between CQDI-Q80 and CQDI-Q80-HS. In addition to the analysis for the selected time step, the latter two indicators are compared at the global scale with respect to drought occurrence during the whole reference period. Discrepancies and similarities of the indicators are discussed in more detail for two illustrative grid cells with the same CQDI-Q80 value in March 2002 (Sect. 4.2.4). Finally, the suitability of SPI with different averaging periods to estimate streamflow drought hazard is assessed using

streamflow observations from 218 GRDC gauging stations (Sect. 4.2.5). Based on this global-scale analysis and the proposed habituation-based classification approach, selected SDHIs are recommended for implementation in large-scale DEWS (Sect. 5).

Figures:

***RC:** It is not clear why the two grid cells were chosen. Also, it is not clear why March 2002 was chosen.*

AC: With respect to the two grid cells, we rephrased the first sentence in the new Sect. 4.2.4:

The relation between selected SDHIs from Figs. 4, 5 and 7 is compared for two illustrative grid cells that share the same CQDI-Q80 value of 0.04 in March 2002 (Table 2).

AC: With respect to the selected month March 2002, we added the following sentences at the beginning of the new Sect. 4:

The SDHIs are shown in global maps for a selected month (March 2002), as it is important to understand the relation between indicators at a certain point in time, especially for the application in DEWS, which are focused on the current situation or the near future. As patterns of indicators depend on characteristic of the streamflow regime and water use that are temporally constant over the reference period, the reasons for similarities and differences between indicators can be deducted in any month of the reference period. March 2002 was selected as it was among the months with the highest difference between CQDI-Q80 and CQDI-Q80-HS.

***RC:** In the current manuscript legends and labels are off for e.g. Fig 3 (what are the lower and upper labels in the left legend, and the upper label in the right); Fig 4, placement of '0' and what is meant with '0 >0'; what comes after '1'; Fig 5, placement of '0'; etc.*

AC: The legends are correct. To make the figures better comprehensible, we extended the figure captions, e.g. by explaining for one or two example the meaning of different colors. We did this for the new Figs. 4 and 5 (old Figs. 3 and 4).

Figure caption of the new figure 5 (old Fig. 4) (new text is underlined):

Figure 5: Severity of drought hazard (level 2 in Fig. 1): Cumulative deficit in March 2002 since onset of drought event as indicated by CQDI1-Q80 (a), CQDI1-WUs (b), CQDI1-Q50 (c), and CQDI1-WUs-EFR (d) for the reference period 1986-2015. <u>A deficit of zero is shown in beige. Values larger than zero and below 0.1 are shown in green.</u> A value of 0.1, for example, denotes that the current cumulative deficit is equivalent to 10% of mean annual streamflow (MAQ). WUs: mean annual surface water withdrawals.

However, in Fig. 3c (now Fig. 4c), we erroneously did not show the blue grid cells. We corrected the figure (see below together with the extended figure caption where the new text is underlined).

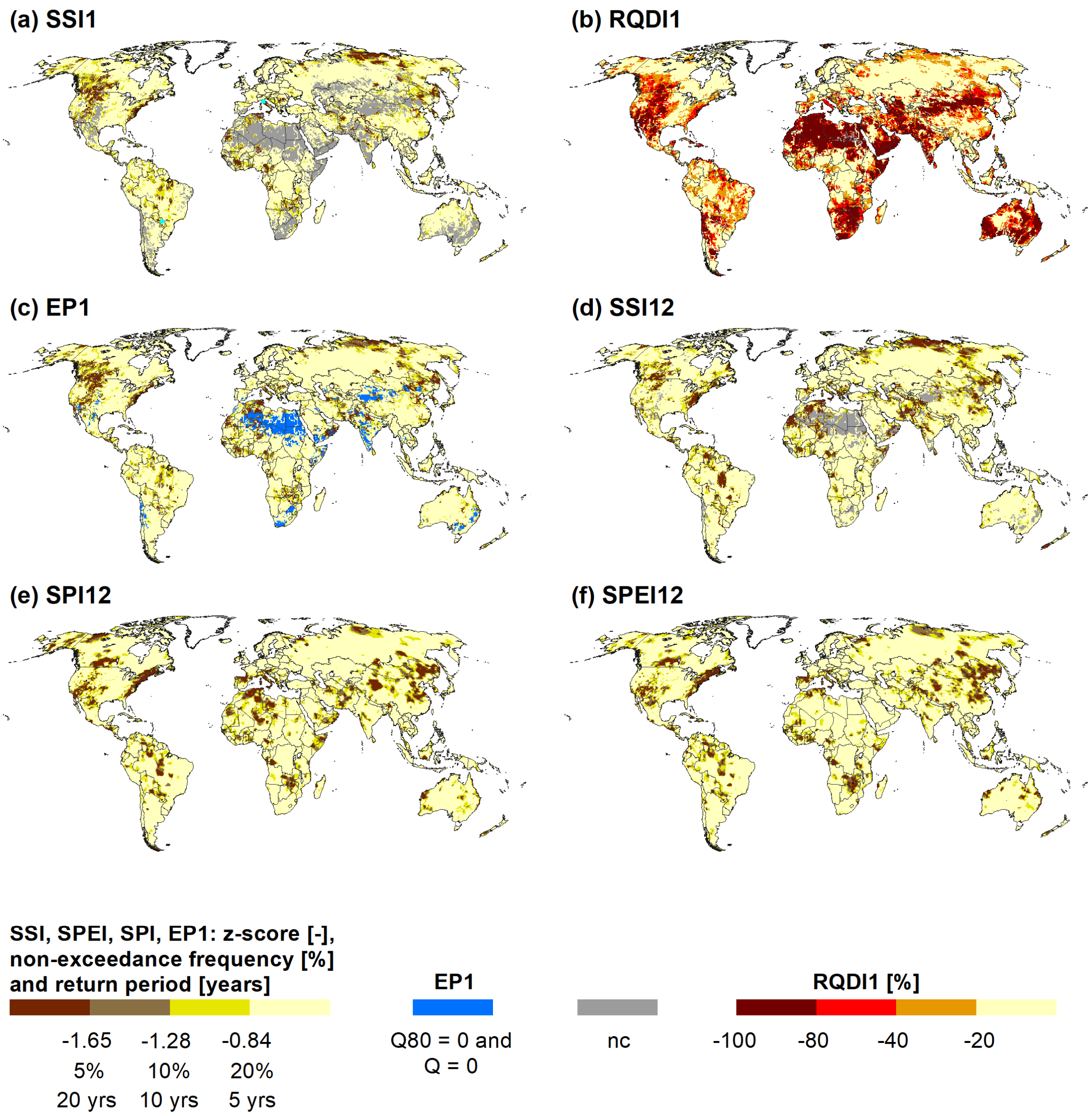

Figure 4: Magnitude of drought hazard (level 1 in Fig. 1): Non-cumulative anomaly in March 2002 as indicated by SSI1 (a), RQDI1 (b), EP1 (c), SSI12 (d), SPI12 (e) and SPEI12 (f) for the reference period 1986-2015. For the standardized indicators and EP1, the z scores and the corresponding frequencies of non-exceedance and return periods are shown. In the blue grid cells in (c), drought identification is not possible with EP1, since Q80 and Q are zero. "nc": not computable. The two grid cells from Table 2 are marked in (a) (northern Italy and central Paraguay).

References

Agnew, C. T. (2000): Using the SPI to Identify Drought.

Wan, Wenhua; Zhao, Jianshi; Popat, Eklavyya; Herbert, Claudia; Döll, Petra (2021): Analyzing the Impact of Streamflow Drought on Hydroelectricity Production: A Global-Scale Study. In: *Water Res* 57 (4). DOI: 10.1029/2020WR028087.

Wilhite, D.; Glantz, M. (1985): Understanding the drought phenomenon: the role of definitions. In: *Water International* 10 (3), S. 111–120. DOI: 10.1080/02508068508686328.