Response to Reviewer 1

This study investigates hydrological connectivity at the global scale using an index of runoff efficiency (RE), which combines the runoff coefficient (RC) and runoff intensity (RI). The authors identify distinct spatial patterns in RC, RI, and RE, including relatively high RC values in wet regions and high RI values in dry regions, and further suggest that these spatial variations are primarily controlled by climatic factors. The manuscript also shows that hydrological connectivity, as represented by RE, responds nonlinearly to precipitation intensity. This is a very interesting idea, as it attempts to represent the complex hydrological concept of connectivity with a simple integrated index. However, I am not fully convinced by the way the manuscript links RE to the definition of connectivity, nor by the physical interpretation given to changes in RE. In particular, while RE may be a useful response-based metric, its relationship to hydrological connectivity as a broader process concept is not yet sufficiently justified. Given these concerns, I recommend that the manuscript be considered for publication only after the issues detailed in the comments below have been adequately addressed.

Response: We appreciate the reviewer's comments and recognition of the relevance of our study. We will respond and make revisions to each of the questions you have raised.

1. In the review about concepts of hydrological connectivity, Bracken et. al. (2013,10.1016/j.earscirev.2013.02.001) highlight the broad and multi-dimensional nature of hydrological connectivity. I agree that the authors aim to use the combination of RC and RI to represent the ratio and rate of the transfer process. However, RE cannot fully represent the broader concept of connectivity. For example, hydrological connectivity may also be defined in terms of spatial soil-moisture patterns or the connection state of subsurface flow systems, and these aspects cannot be captured by RE alone. I therefore recommend that the authors explore the introduction more on concepts of connectivity and better understand why RE can be one of the proxies for representing the connectivity. At present, the Introduction places too much emphasis on the limitations of RC studies.

Response: Thanks for your kind question. We added a broader concept of hydrological connectivity in the first paragraph, while also introducing the focus of our manuscript on the connectivity of the runoff generation process (*P*-*R*), distinguished from the channel routing process. In addition, we added the concept and significance of runoff intensity (*RI*) in the last paragraph, and further explained that *RE* comprehensively represents the concept of connectivity in this runoff generation process:

"Hydrological connectivity, defined as the water transfer within or between components of the hydrologic cycle, is characterised by both the ratio and rate of the transfer process (Bracken et al., 2013). This broad concept manifests across various hydrological processes such as runoff generation, channel routing, and groundwater recharge (Van Tiel et al., 2024; Wang et al., 2025; Gou et al., 2025; Phillips et al., 2011). Among these, the process connectivity of runoff generation — the transformation from precipitation to runoff—is of particular importance because it determines what fraction of precipitation actually becomes available for streamflow (rather than being lost to evaporation or infiltration) and how rapidly this transformation occurs before the subsequent routing process (Bronstert et al., 2002; Shen et al., 2020)"

"Specifically, the *RC* reflects the transformation ratio of precipitation into runoff. The runoff intensity (*RI*), defined as the ratio of runoff depth to net rainfall duration, can directly indicate the transformation rate. This indicator is closely related to the surface runoff generation rate and the magnitude of peak discharge (Bronstert et al., 2023; Léonard et al., 2006), providing critical insights into the dynamic response of catchments to precipitation events. To achieve a more holistic characterization of the runoff generation process connectivity, runoff efficiency (*RE*) is further developed to encapsulate both the volumetric ratio of precipitation transformed into runoff (captured by *RC*) and the temporal rate of this transformation process (reflected by *RI*)."

2. I do not fully understand the reason for including a hydrological model in the overall framework. The manuscript already derives quickflow through baseflow separation, which appears sufficient for the subsequent analyses. Although the authors state that the model is intended to represent interception and infiltration processes, these processes are not explicitly incorporated into the later analyses, nor are their effects quantified or discussed in a meaningful way. In addition, the event identification procedure does not seem to make use of the modeled rainfall–runoff relationship itself (e.g., the contribution of rainfall to the runoff in each step); instead, runoff events are first identified from the quickflow series and then matched to rainfall events based on timing. This makes the hydrological model useless in the framework, while introducing additional structural uncertainty.

Response: Thanks for your kind question. We propose an integrated framework for assessing process connectivity for runoff generation that jointly considers both the transformation ratio and rate from precipitation to runoff. To obtain the connectivity indicators for runoff generation, we first derive the quickflow through baseflow separation, and then the conceptual hydrological model is constructed to simulate the quickflow generation process. Specifically, the conceptual hydrological model can calculate the event runoff depth *R* and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration), defined as the time during which *R* > 0 within an event, distinct from the event rainfall period. Only using derived quickflow through baseflow separation without hydrological simulation cannot calculate the transformation rate indicator *RI*, defined as $R/\Delta t_R$.

3. Furthermore, I think the model structure is not correct. In Formula 4, INF is proportional to SM. In other words, more wet soil leads to more infiltration. Is this correct? I therefore recommend that the authors either (1) use the quickflow estimated directly from baseflow separation and remove the model-based quickflow from the framework, or (2) improve the hydrological model and more fully justify the use of the model by explicitly identifying the events based on the model-derived rainfall–runoff process and by quantifying how interception and infiltration influence the results.

Response: Thanks for your kind question. We have corrected the INF formula as $\boldsymbol{INF = f_{max} *}$

$\boldsymbol{SM^{-b}}$. Similar to our previous reply, we first derive the quickflow through baseflow separation, and then the conceptual hydrological model is constructed to simulate the quickflow generation process. The conceptual hydrological model conceptually accounts for the effects of interception and infiltration in a simplified manner, aiming to calculate the event runoff depth R and the corresponding runoff generation duration Δt_R (i.e., the net-rainfall duration). We simulated the runoff generation process with the simulation accuracy KGE in catchments greater than 0.5 to maximize the rationality of the model simulation. We also supplemented the shortcomings related to the model in the discussion section:

"First, our analysis only relies on a single conceptual rainfall–runoff model with its own assumptions and simplifications, which may not be universally applicable across the diverse range of global catchments and introduces structural uncertainty (Parasuraman and Elshorbagy, 2008). Although parameter calibration and performance screening have already secured a reasonable level of accuracy, future work could be done for ensembling hydrological models to better capture runoff-generation processes and to enhance the robustness of the results (Solanki et al., 2025)"

4. I do not agree with the way the authors link RE, connectivity, and flood risk in the manuscript. In particular, the term flood risk is not used precisely. Flood risk is generally understood as a function of hazard, exposure, and vulnerability, whereas RE cannot quantify all components of that relationship. Instead, I would suggest linking high RE to an increased likelihood of flood generation, rather than to flood risk itself.

Response: Thanks for your kind question. We agree that the flood risk is inappropriate, and have changed the meaning of *RE* to the potential for flood generation.

5. I agree with the authors that RE reflects a trade-off between RC and RI at the long-term timescale. However, this also highlights a potential limitation of RE as a representation of connectivity. For example, do two regions with the same RE value—one characterized by very high RI and very low RC, and the other by moderate values of both RI and RC—actually exhibit the same hydrological connectivity? If not, it remains unclear how RE can serve as a robust proxy for connectivity.

Response: Thanks for your kind question. We have added the potential limitation of *RE* as a representation of connectivity in the discussion part:

"Moreover, it should be noted that the *RE* is an integrated connectivity indicator for runoff generation, and a given *RE* value can result from different combinations of *RC* and *RI*. For instance, a high *RE* may stem from a scenario of high *RC* and low *RI*, or, conversely, from a scenario of low *RC* paired with exceptionally high *RI*. This multiplicity of pathways highlights that *RE* is not determined by a single factor but emerges from the nonlinear integration of catchment-specific connectivity and infiltration processes. It is necessary to comprehensively use these indicators for characterising the connectivity of the runoff generation to improve our understanding of how the water cycle responds to the changing climate from a process perspective."

6. I wonder how the authors manage the uneven distribution of data points across regions and climate zones. What is the influence of data availability on the analysis? Can it cause bias of the conclusion?

Response: Thanks for your kind question. Because the selected 6603 catchments are unevenly distributed across regions and climate zones, we used median values for group-level comparisons to reduce the influence of unequal sample sizes and outliers. Each IPCC region must have at least 30 available sites to ensure regional representativeness. We also clarified in the manuscript that data availability may still affect the representativeness of under-sampled regions and may introduce uncertainty in regional comparisons, although we do not expect it to change the main conclusions at the climate-zone level. We have provided relevant supplements to this point in the results and discussions:

"Given the uneven spatial distribution of catchments across regions and climate zones, median values are adopted for group-level comparisons to mitigate the influence of unequal sample sizes and outliers."

"Second, the selected catchments exhibit uneven spatial distribution across regions and climate zones, a limitation that could undermine the representativeness of data-sparse areas. Although median-based summaries can reduce the effects of uneven spatial distribution, interpretation of the regional results from these underrepresented areas should be cautious. More data from the available hydrological stations would enable more refined and robust regional analyses."

Specific comments:

7. Line 32: Ombadi eta al. (2023) does not state any findings about melting rate and snowpack dynamics

Response: Thanks for your kind question. We have deleted this literature and added references related to the content.

8. Line 41: I don't think RC is a common indicator to quantify the process connectivity. For example, Phillips, et al. (2011, 10.1002/hyp.8123) shows distinct definitions of connectivity and runoff coefficient, although they are correlated.

Response: Thanks for your kind question. Hydrological connectivity, defined as the water transfer within or between components of the hydrologic cycle, is characterised by both the ratio and rate of the transfer process. This study only focuses on the runoff generation process (*P*-*R*), distinguished from the channel routing process. Thus, *RC* can serve as an indicator of the connectivity of the runoff generation process with respect to the transfer ratio, i.e., what fraction of precipitation becomes runoff (rather than being lost to evaporation or infiltration).

9. Line 76: add hypotheses or research questions in the last paragraph.

Response: Thanks for your kind question. We have added the research questions in the last paragraph.

"Applying this framework in 6,603 catchments worldwide over 1950–2020, we answer the following critical questions: (a) What are the global spatial patterns of the process connectivity indicators, and to what extent do climate and landscape attributes drive their spatial heterogeneity? (b) What are the temporal dynamics of process connectivity indicators across multiple temporal scales, including long-term trends and event-to-event variability? "

10. Line 200: the explanation of event-to-event variability analysis is not clear; Why the authors used 10 mm/day as a criterion, rather than other rainfall intensity values.

Response: Thanks for your kind question. We have elaborated on the explanation of event-to-event variability analysis and provided the reason for 10mm/day:

"To analyze the event-to-event variability of process connectivity indicators, we first examine the variations of the indicators across events that are grouped by distinct discharge quantile intervals (0-20th, 20-40th, 40-60th, 60-80th, and 80-100th percentiles) for each catchment."

"In alignment with standard engineering hydrology practice, where unit hydrographs are universally defined using 10 mm of effective rainfall, a unit precipitation of 10 mm is adopted (Lu et al., 2015; Singh et al., 2014)."

11. Line 296: typo. Transformation ratio (i.e., runoff coefficient)

Response: Thanks for your kind question. We have corrected.

"This indicates that long-term trends of the transformation ratio (i.e., runoff coefficient) and the transformation rate (i.e., runoff intensity) from precipitation to runoff show great synergy, meaning that regions with a higher transformation ratio may simultaneously experience a faster transformation rate under climate change."

12. Figure 4: I recommend including "slope" in the analysis. "Slope" has been widely recognized as an important factor in the concept of hydrological connectivity. In addition, I wonder why "area" was included in the random forest analysis, given that both RI and RC are already normalized by area.

Response: Thanks for your kind question. We apologize for the previous incorrect description of our variables. We include the slope variable as the "slp_dg_sav" for analysis in the revised version. In addition, we have removed the area variable in the revised version. Figure 4 and related descriptions have been revised.

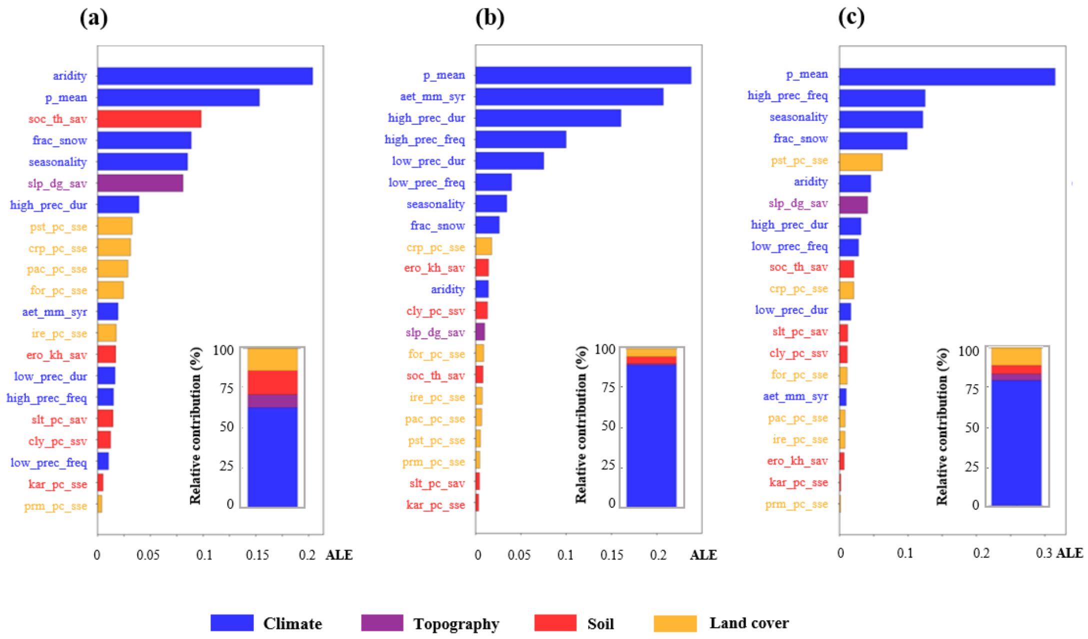

Figure 4. The Influence of catchment attributes on process connectivity indicators based on the interpretable machine learning approach (RF-ALE). (**a**) runoff coefficient. (**b**) runoff intensity. (**c**) runoff efficiency. Blue, purple, red, and yellow correspond to the categories of catchment attributes related to climate, topography, soil properties, and land cover, respectively. The proportional contribution of each category is illustrated by the bar height in the lower-right corner.

13. Figure 5: modify the y axis. Now this scale makes it hard to find the difference between the values.

Response: Thanks for your kind question. We have modified the scale size of Figure 5.

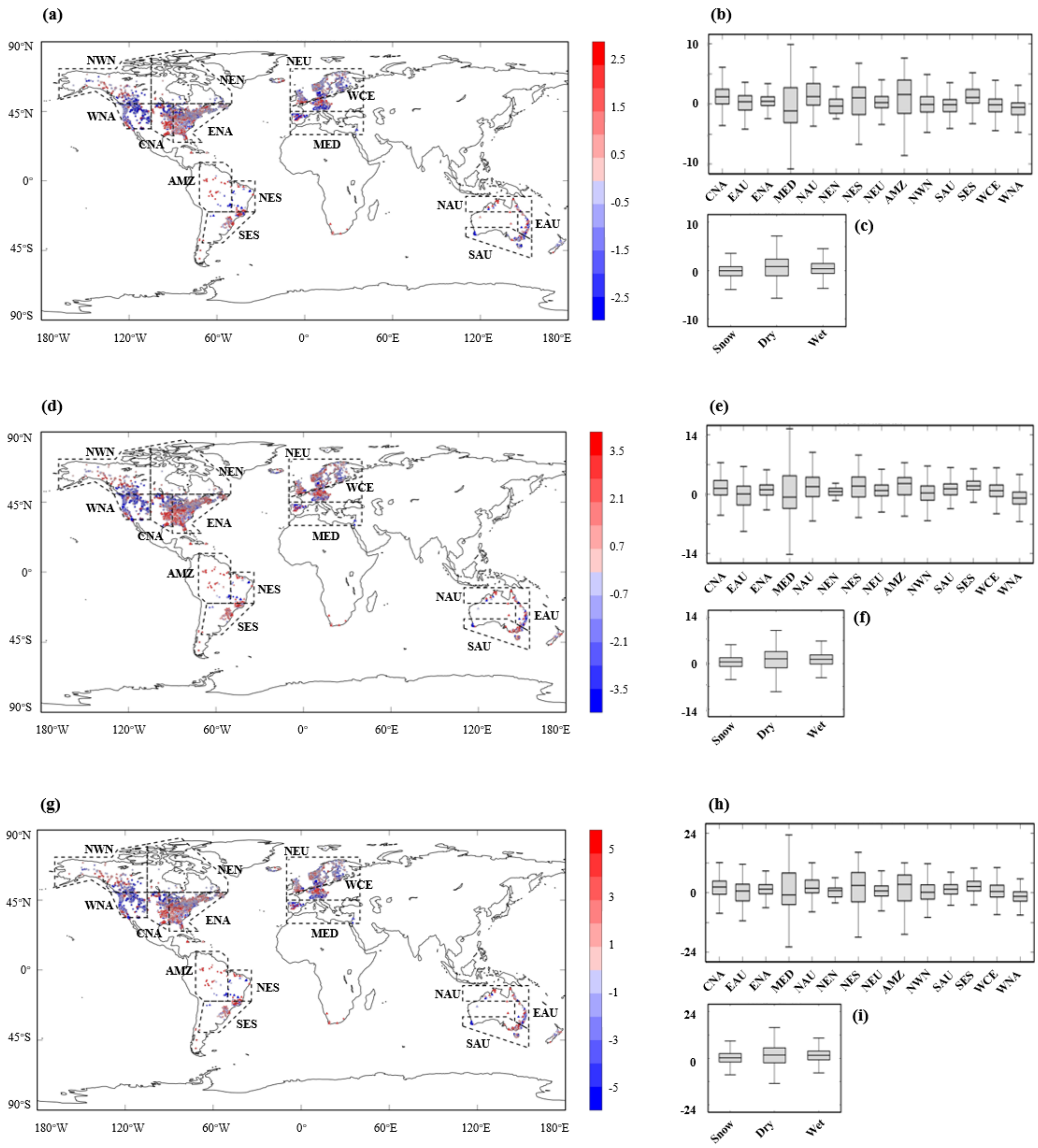

Figure 5. The long-term trends of the process connectivity indicators over 1950-2020. (**a-c**) for the runoff coefficient. (**d-f**) for the runoff intensity. (**g-i**) for the runoff efficiency

14. Line 417: There is no clear connection between the sentences before and after "However." The high sensitivity of RE to rainfall intensity is expected because both RC and RI are sensitive to rainfall intensity, and RE is the product of these two variables. However, this does not resolve the issue with RE arising from the trade-off between RC and RI.

Response: Thanks for your kind question. What we want to explain is that, in terms of long-term average spatial variability, *RE* shows *RC* dominance in wet areas and *RI* dominance in arid areas. For a specific catchment, the time variability of *RE* at the event scale exhibits a nonlinear response with precipitation intensity, which may lead to both high *RC* and high *RI*, resulting in a synergistic effect. We have revised the relevant statement:

"Besides, at the event scale, *RE* exhibits a strongly nonlinear response to meteorological forcing within a given catchment, particularly marked by a pronounced amplification with increasing precipitation intensity. Specifically, our analysis reveals that *RE* increases nonlinearly with the intensity of individual precipitation events, where high-intensity storms produce substantially greater *RE* values compared with low-intensity events (Fig. 7). Such behaviour is difficult to detect in long-term averages, where the effects of individual events with varying intensities are smoothed out over time**.** This nonlinear amplification indicates that, during heavy storms, **both the ratio and the rate of precipitation to runoff transformation increase simultaneously and substantially**. "

15. In addition to the influence of rainfall intensity on RE, total rainfall depth may also affect connectivity or RE. It is recommended to discuss whether saturation-excess runoff in wet catchments could influence connectivity, as well.

Response: Thanks for your kind question. We have added discussions on the effect of total rainfall depth on connectivity:

"Finally, the empirical power-law relationship developed here does not exactly account for event total precipitation depth and antecedent soil moisture, which can influence runoff-generation connectivity by governing storage filling and the expansion of saturated contributing areas, particularly in wet catchments where saturation-excess runoff is more prevalent. "