Response to Reviewer 1

The authors have made substantial revisions to the manuscript and have addressed many of my previous concerns. However, I still have several comments that I think should be further addressed before the manuscript can be considered for publication.

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. The authors have improved the Introduction a lot, and it is now much clearer why a global-scale analysis was conducted. However, the two indices, RI and RE, which go beyond the runoff coefficient and appear to be an important focus of the study, are introduced only very briefly. It would be helpful if the authors could further explain what additional insights can be gained from RI and RE.

Response: Thanks for your kind question. We have added the additional insights that can be gained from *RI* and *RE* as suggested:

"In other words, two events with identical *RC* values but contrasting *RI* values could exhibit markedly different peak discharge behaviors, a distinction that *RC* alone cannot capture." (Lines 84-85)

"The higher *RE* value may imply a larger proportion of precipitation is transformed into runoff at a faster rate within an event. It is typically associated with a larger event runoff volume and higher peak discharge, and thus a greater potential for flood generation." (Lines 88-90)

2. Although the authors have explained why they embedded a hydrological model in this framework, I still do not fully understand the necessity of using this model in the study. Quickflow can be directly derived from observations through baseflow separation, and there are also many methods for identifying runoff or rainfall–runoff events without relying on a hydrological model, such as Tarasova et al. (2018, WRR). In addition, the model fluxes and states, such as interception and soil moisture storage, are not further discussed later in the manuscript to help understand process connectivity. Therefore, it seems that the information needed to calculate RC, RI, and RE could be obtained without using a hydrological model. The only clear reason I can see for using the model is to extend the analysis back to the 1950–1980 period (Figure 1). However, the authors should clarify whether this benefit justifies building a hydrological model and introducing additional model uncertainty.

Response: Thanks for your kind question. We apologize for any misunderstanding you may have had about our research. The role of hydrological models is not only to extend the period to 1951-1980, but more importantly, to calculate net rainfall duration, which is different from rainfall duration. This cannot be achieved through data-driven methods, such as the method proposed by Tarasova et al. (2018, WRR) as mentioned.

We have updated Figure 1c as a schematic diagram to illustrate the process of hydrological models isolating net-rainfall duration Δt_R from rainfall duration through runoff generation calculation. That is to say, the net-rainfall duration Δt_R is expected to be shorter than the rainfall duration as interception, infiltration, and other hydrological losses delay or prevent rainfall from transforming directly into runoff (Lines 166-168).

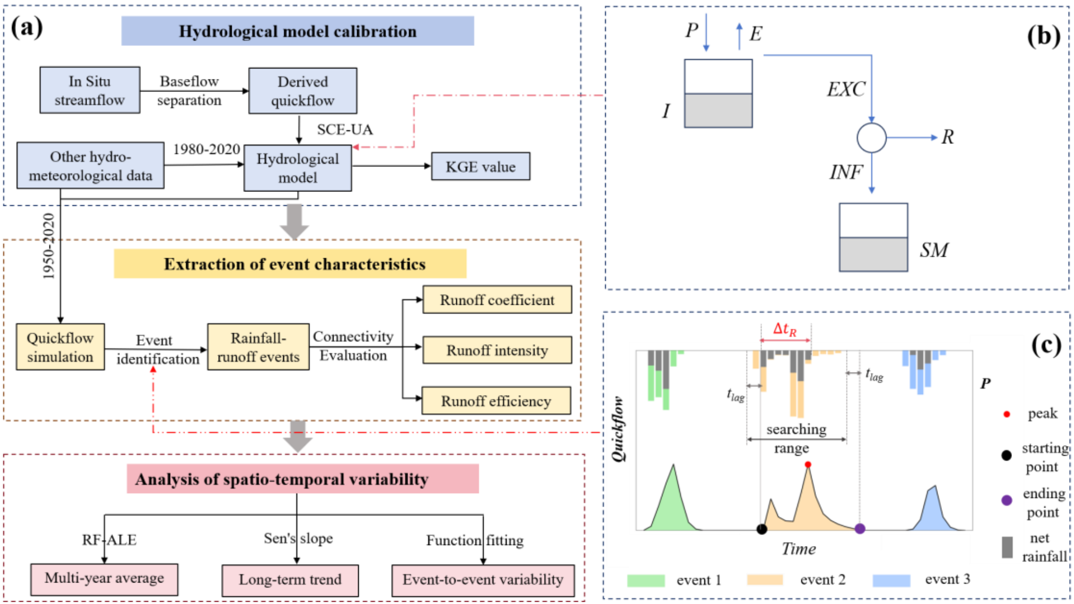

Figure 1. The workflow of this study. (**a**) General framework. (**b**) Structure of the conceptual hydrological model. (**c**) Identification of rainfall-runoff event.

3. Line 56: what the sentence of "the heterogeneity and coupled climate-landscape gradients may increase with scale" presents is not clear. Please clarify what type of heterogeneity is being referred to, and explain what is meant by "coupled climatelandscape gradients".

Response: Thanks for your kind question. We have rewritten the sentence for clarification.

"However, partly owing to the scale dependency of hydrological laws (Oda et al., 2024; Hunt et al., 2025), as the spatial heterogeneity of landscape properties increases with catchment size, it is often problematic to extrapolate the discoveries derived from small-scale investigations to larger catchments." (Lines 56-57)

4. Line 119: I think this modified equation is still not correct. When the soil is very dry, for example when soil moisture is below 1%, INF would become higher than the maximum

infiltration rate.

Response: Thanks for your kind question. We have corrected equation (4) to constrain the infiltration rate to not exceed the maximum infiltration rate:

$$INF = f_{max} * min(SM^{-b}, 1)$$

5. Line 137: show a map of KGE distribution in the supplementary information.

Response: Thanks for your kind question. We have added a global map of KGE distribution in Fig. S1.

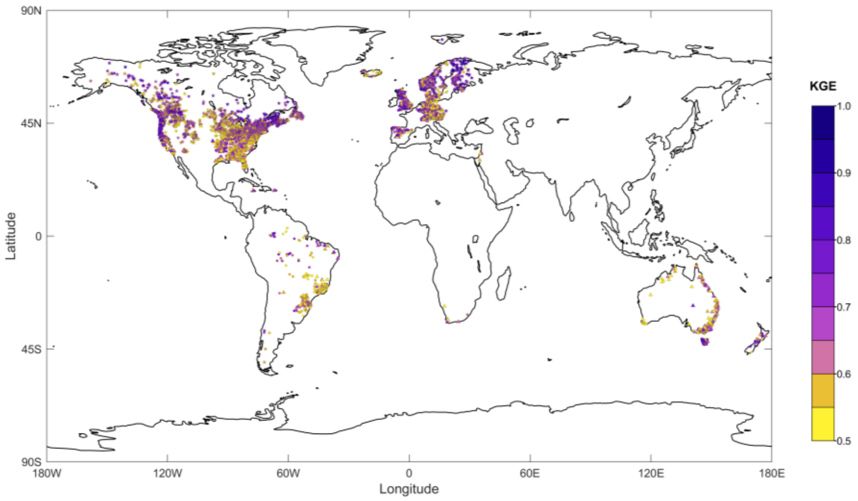

Figure S1. The spatial distribution of KGE values during the validation period for 6603 selected catchments.

6. Line 160: show these varaibles (e.g., R, P, especially ∆tR) in Figure 1c.

Response: Thanks for your kind question. We have shown the variables in the revised Figure 1c.

7. Line 161: I feel that the term "net-rainfall duration" may not accurately describe what the authors intend to express. The runoff generated during this period is not necessarily produced only by the rainfall occurring within the same period.

Response: Thanks for your kind question. We have already matched rainfall-runoff events in advance and considered the lag time of the catchment in event runoff generation. Based on the simulation of the hydrological model, the net-rainfall duration Δt_R of a rainfall-runoff event can be separated from the rainfall duration. We use the term "net-rainfall duration", which is expected to be shorter than the rainfall duration as interception, infiltration, and other hydrological losses delay or prevent rainfall from transforming directly into runoff (Lines 166-168). Thanks again for your question,

8. Line 162: Please clarify whether "the event" is defined based on rainfall or runoff, and revise the terminology accordingly.

Response: Thanks for your kind question. We have already matched rainfall-runoff events in Section 2.1.2, with each identified runoff event with one or several contributing rainfall (including snowmelt) events (Line 150). We added that this event refers to the matched rainfall-runoff event (Line 160).

9. Line 175: Please specify what kind of RCs is explored by the random forest. the temporal mean of RCs?

Response: Thanks for your kind question. We have specified the "multi-year average of *RC*s". (Line 179)

10. Line 226: Effective rainfall is generally defined as the difference between total rainfall and actual (or potential) evapotranspiration. Therefore, it is not clear why an effective rainfall of 10 mm supports the selection of a precipitation intensity of 10 mm/day.

Response: Thanks for your kind question. We apologize for the misleading use of effective rainfall.

Due to the power function form:

$$RE = RE_k * (\frac{PI}{k})^m$$

where RE_k is a parameter, and k can take various values as a unit of rainfall. We choose k equal to 10, similar to the basic assumption of the unit hydrograph in engineering hydrology, which uses one unit of net rainfall as 10 mm. We chose the reference precipitation intensity of 10mm/day, which falls within the commonly observed range of precipitation intensity across global catchments. The 10mm/day is also convenient for engineering calculations. Besides, the choice of reference intensity does not affect the fitting accuracy and shape of the fitted relationship (governed by m) but provides a stable and interpretable anchor for cross-catchment comparison.

"RE_{10} and m are the fitted model parameters. The former denotes the runoff efficiency at a reference precipitation intensity of 10mm/day, which falls within the commonly observed range of precipitation intensity across global catchments. The latter denotes the sensitivity of runoff efficiency to changes in precipitation intensity. " (Lines 229-232)

11. Line 239: Fillting out KGE < 0.5 has already been mentioned in Line 138, so I suggest removing this repeated information.

Response: Thanks for your kind question. We have removed the repeated information. (Lines 243-244)

12. Line 298: where do the authors obtain the data of actual evapotranspiration? What is the meaning of high precipitation?

Response: Thanks for your kind question. The multi-year average actual evapotranspiration in the Caravan dataset belongs to the climate attribute data of the catchment, which comes from the HydroATLAS dataset (Line 239). The frequency of high precipitation days denotes the precipitation ⩾5 times the mean daily precipitation, and the average duration of high precipitation events is the number of consecutive days where precipitation ⩾5 times the mean daily precipitation. We have added Table 2 for clarification.

Table 2. Description of 21 selected catchment attributes.

Group	Attribute	Description	Unit
climate	p_mean	mean annual precipitation	mm
	aet_mm_syr	mean annual actual evapotranspiration	mm
	aridity	aridity index; ratio of mean PET and mean precipitation	—
	frac_snow	fraction of precipitation falling as snow	—
	pre_seasonality	seasonality and timing of precipitation	—
	high_prec_freq	frequency of high precipitation days, where precipitation ⩾5 times mean daily precipitation	—
	high_prec_dur	average duration of high precipitation events (number of consecutive days where precipitation ⩾5 times mean daily precipitation)	—
	low_prec_freq	frequency of low precipitation days, where precipitation <1 mm/day	—
	low_prec_dur	average duration of low precipitation events (number of consecutive days where precipitation <1 mm/day)	—
topography	slp_dg_sav	terrain slope	°
soils	cly_pc_sav	clay fraction in soil	%
	slt_pc_sav	silt fraction in soil	%
	soc_th_sav	organic carbon content in soil	%
	kar_pc_sse	karst area extent	% cover

	ero_kh_sav	soil erosion	kg/hectare/yr
land cover	for_pc_sse	forest cover extent	% cover
	crp_pc_sse	cropland extent	% cover
	pst_pc_sse	pasture extent	% cover
	ire_pc_sse	irrigated area extent	% cover
	prm_pc_sse	permafrost extent	% cover
	pac_pc_sse	protected area extent	% cover

13. Line 394: According to Figure 5, the dominant influential factors for RI are P_mean and aet_mm_syr, rather than average duration and frequency of high-precipitation events.

Response: Thanks for your kind question. We have revised the relevant statements: "For the runoff intensity (*RI*), however, average duration and frequency of high-precipitation events show strong impacts". (Lines 397-398).

14. Line 412: use "process connectivity" instead of "runoff generation connectivity".

Response: Thanks for your kind question. We have corrected. (Lines 411, 415).

15. Line 452-454: it has been already discussed in the previous paragraph.

Response: Thanks for your kind question. We have removed redundant sentences.

16. Table S1: It would be better to move this table into the main manuscript, as it would help readers better understand Figure 5.

Response: Thanks for your kind question. We have moved Table S1 to Table 2 in the main text.

Response to Reviewer 2

The authors have already satisfactorily addressed most of the points raised in the first round of revision. Nevertheless, I would still like to make a few comments that require further clarification.

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. I am still not fully convinced by author's reasoning on why using a hydrological model is necessary to derive the RI and more specifically the net-rainfall duration Δt_R. To further clarify this point, the authors may want to consider adding further explanation on how the net-rainfall duration is extracted based on the modeling results, e.g., with a simple conceptual figure visualizing an example of a rainfall-runoff event, including the baseflow, stormflow, and rainfall time series, indicating Δt_R.

Response: Thanks for your kind question. We have updated Figure 1c and provided a conceptual graph of the net-rainfall duration Δt_R for a rainfall-runoff event, and improved the relevant statements：

"*R* denotes the event runoff depth (i.e., the net rainfall depth), and *P* refers to the event rainfall (including the snowmelt) depth. Δt_R is the runoff generation duration of the event and is named as the net rainfall duration, specifically referring to the time during which $R > 0$ within the event, distinct from the event rainfall period of the event (Fig.1c). Thus, Δt_R is expected to be shorter than the rainfall duration as interception, infiltration, and other hydrological losses delay or prevent rainfall from transforming directly into runoff." (Lines 166-168)

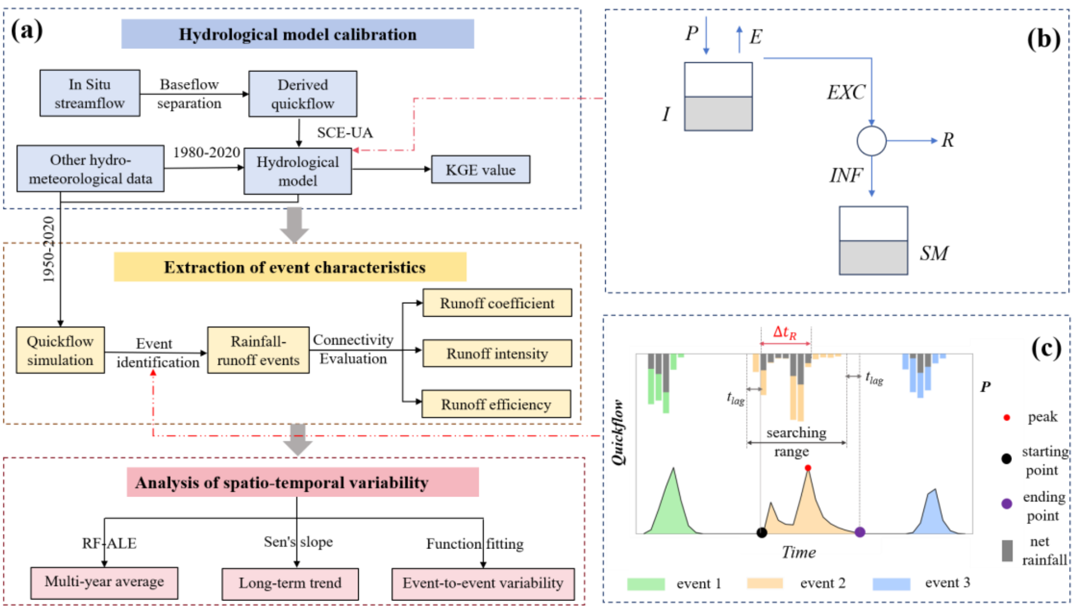

Figure 1. The workflow of this study. (**a**) General framework. (**b**) Structure of the conceptual hydrological model. (**c**) Identification of rainfall-runoff event.

2. L 49: Consider adding here the study of Hövel et al. (2025), dealing with thresholds in runoff generation processes in experimental catchments.

Response: Thanks for your kind question. We have added the reference of Hövel et al. (2025). (Line 49)

3. L 149: The threshold of 0.1 mm d-1 across all catchments needs additional justification. For example, how sensitive is the number of events identified to this threshold, or does it influence the ratio between multi- and single-peak events?

Response: Thanks for your kind question. According to the process of identifying rainfall-runoff events, we first identify runoff events and then match them with rainfall events. That is to say, the final number of rainfall-runoff events is equal to the number of runoff events. A runoff event may correspond to one or several rainfall events (Line 150). The setting of 0.1mm/day for rainfall events is not expected to have a substantial impact on the relevant characteristics of runoff events, such as the number of runoff events and the ratio between multi- and single-peak runoff events. In addition, we added a discussion about the potential uncertainties associated with setting the rainfall event at 0.1mm/day:

"In addition, the 0.1 mm d^{-1} threshold employed to delineate rainfall events is an empirical truncation criterion that may alter event boundaries, especially under hydroclimatic extremes." (Lines 478-479)

4. L 404: Consider adding here the study of Kuentz et al. (2017), evaluating drivers of flow signatures in Europe through catchment classification.

Response: Thanks for your kind question. We have added the reference of Kuentz et al. (2017). (Line 407)

5. L 498: What exactly do the authors mean by "compensatory balance" when referring to the transformation ratio and rate across climate? I would recommend additional clarification here.

Response: Thanks for your kind question. We have rewritten this sentence to make the meaning clearer (Lines 500-501):

"According to the long-term average values of the metrics, we find a relatively high *RC* and low *RI* in wet areas, while a relatively low *RC* and high *RI* in dry areas, highlighting a trade-off between the transformation ratio and rate across climates."

6. L 501-506: Sentence is too long, consider splitting.

Response: Thanks for your kind question. We have rewritten this sentence (Lines 504-508):

"The analysis of long-term trends reveals a synergy of transformation ratio and rate, with hotspots of increasing process connectivity identified in the Amazon, southeastern South America, central North America, northern Australia, and northeastern South America, suggesting a larger event runoff volume and higher peak discharge, and thus a higher potential for flood generation. In contrast, hotspots of decreasing process connectivity are found in western North America and the Mediterranean, associated with a relatively lower potential for flood generation."

7. Technical points: I appreciate that the authors added a paragraph on the study's limitations to the discussion. To improve clarity, I suggest dividing the section into two parts, for example: 5.1 Factors driving RC, RI, and RE, and 5.2 Limitations (or similar).

Response: Thanks for your kind question. We have divided the section into two parts as suggested (Lines 385, 465).

8. In my view, the comment related to the font sizes in most of the figures is not yet resolved. I would encourage the authors to particularly make figures 3, 5, 6, and 7 more readable.

Response: Thanks for your kind question. We have enlarged the font sizes in Figures 3, 5, 6, and 7 as suggested.