Public justification (visible to the public if the article is accepted and published):

The reviewers, especially the more critical one, raise important concerns, which need to be considered (as the authors already did in their responses in the discussion).

Reply: We thank the editor and the reviewers for their efforts in handling our manuscript and for their constructive comments, which have helped improve its quality. These issues have been carefully considered and explicitly addressed in the revised manuscript.

In addition, I have a few thoughts:

1. Please discuss the value vs. the limitation of using only two catchments.

Reply: This point has been addressed in the revised manuscript by discussing the advantages and limitations of using only two catchments. We clarify both the benefits for process-level interpretation and the limitations regarding generalization, and we explicitly restrict the applicability of our findings to cold and semi-arid alpine basins with similar hydroclimatic and geomorphic settings. The need for future multi-basin analyses to evaluate model robustness and transferability is also clearly stated (Please refer to the last paragraph of Section 6.4).

2. The authors, as I understand it, assume complete mixing. Is this realistic? What does this mean for the simulated runoff contributions?

Reply: Yes, the model assumes complete mixing within each conceptual storage. This assumption has been criticized as unrealistic in heterogeneous soil and groundwater systems where preferential flow is important, as it may overestimate damping effects and bias runoff partitioning, for example by inflating groundwater contributions (Cain et al., 2019).

Nevertheless, simplified complete-mixing formulations remain widely used. More complex partial-mixing approaches require additional calibrated parameters and do not necessarily improve catchment-scale model performance, particularly under data-limited conditions, where increased parameterization can reduce identifiability and increase uncertainty (Hrachowitz et al., 2013; Fenicia et al., 2008). Moreover, the scale of mixing is often unknown and rarely supported by direct observations.

In this study, the snowmelt tracker is designed to estimate the long-term average of the fraction of total streamflow that originates from snowmelt. At this temporal scale, the complete mixing assumption has been shown to be robust and is widely used in catchment-scale estimates of snowmelt contributions (Li et al., 2017; Wu et al., 2021; Liu et al., 2023). In addition, the limitations associated with the complete mixing assumption are discussed in the third paragraph of Section 6.4.

Cain, M. R., A. S. Ward, and M. Hrachowitz. 2019. "Ecohydrologic Separation Alters Interpreted Hydrologic Stores and Fluxes in a Headwater Mountain Catchment." Hydrological Processes 33, no. 20: 2658–2675. https://doi.org/10.1002/hyp.13518.

Fenicia, F., J. J. McDonnell, and H. H. G. Savenije. 2008. "Learning From Model Improvement: On the Contribution of Complementary Data to Process Understanding." Water Resources Research 44, no. 6: W06419. https://doi.org/10.1029/2007WR006386.

Hrachowitz, M., H. Savenije, T. A. Bogaard, D. Tetzlaff, and C. Soulsby. 2013. "What Can Flux Tracking Teach Us About Water Age Distribution Patterns and Their Temporal Dynamics?" Hydrology and Earth System Sciences 17, no. 2: 533–564. https://doi.org/10.5194/hess-17-533-2013.

Liu, Z., Cuo, L., Sun, N., 2023. Tracking snowmelt during hydrological surface processes using a distributed hydrological model in a mesoscale basin on the Tibetan Plateau. Journal of Hydrology, 616: 128796. DOI:https://doi.org/10.1016/j.jhydrol.2022.128796

Li, D., Wrzesien, M.L., Durand, M., Adam, J., Lettenmaier, D.P., 2017. How much runoff originates as snow in the western United States, and how will that change in the future? Geophysical Research Letters, 44(12): 6163-6172.

DOI:https://doi.org/10.1002/2017GL073551
Wu, X. et al., 2021. Analysis of seasonal snowmelt contribution using a distributed energy balance model for a river basin in the Altai Mountains of northwestern China. Hydrological Processes, 35(3): e14046. DOI:https://doi.org/10.1002/hyp.14046

3. Please motivate the precipitation lapse rate of 4.2%/100m. A reference to Gao et al. (2014) is given, but I am afraid I cannot find the number in this publication.

Reply: The reference was incorrectly added in the original manuscript. As explained in our response to the second reviewer, we attempted to quantify the spatial variability of precipitation within the study basins using multiple reanalysis datasets. However, the quality of these datasets in the study region is relatively poor, preventing a reliable estimation of precipitation gradients. We therefore used a nearby catchment as a reference.

The Tsagan-Turutuin-gol catchment, which also originates in the Khangai Mountains and exhibits topographic and climatic characteristics similar to those of our study basins, has a mean annual precipitation of approximately 200–300 mm and a precipitation gradient of slightly less than 10 mm per 100 m between 2000 and 3350 m a.s.l., equivalent to 4.2±0.8% per 100 m (Klimek and Starkel, 1980). In addition, the precipitation increase rate (4.2% per 100 m) has been applied in environmentally comparable alpine regions and has yielded satisfactory hydrological simulation performance, such as in the upper Heihe River basin (Gao et al., 2022).

Based on this reference, we adopted a precipitation increase rate of 4.2% per 100 m for our study basins (see Section 3.2 for details).

Klimek K., Starkel L, 1980. Vertical zonality in the Southern Khangai Mountains (Mongolia). Results of the Polish-Mongolian physico-geographical expedition. Geographical Studies Vol. I, 136: 1–107.
Gao, H., Han, C., Chen, R., Feng, Z., Wang, K., Fenicia, F., and Savenije, H.: Frozen

soil hydrological modeling for a mountainous catchment northeast of the Qinghai – Tibet Plateau, Hydrol. Earth Syst. Sci., 26, 4187 – 4208, https://doi.org/10.5194/hess-26-4187-2022, 2022.

4. Please separate results and discussion, having these in two sections makes reading just easier.

Reply: The manuscript has been revised by separating the Results and Discussion into two independent sections, as suggested, to improve readability.

Anonymous Referee #1

This study investigates the roles of topography and vegetation in hydrological processes within cold alpine basins of the Mongolian Plateau using a stepwise FLEX modeling framework. This manuscript presents a valuable contribution to cold-region hydrology in Mongolian Plateau. The research is scientifically sound, methodologically rigorous, and addresses the gap in hydrological modeling for data-scarce, cryospheric regions in Mongolia. With the suggested revisions—particularly in methodology clarity, discussion depth, and figure improvements—it will be suitable for publication. The manuscript falls between minor and moderate revisions, with the following specific recommendations.

Reply: We sincerely appreciate the constructive comments from Referee #1, which have helped us identify areas for improvement. We are also grateful for the positive evaluation and endorsement of our manuscript's contribution. Detailed responses to all comments are provided below.

Comments

1. The background is well-presented, but the uniqueness of the study area (e.g., extreme climate, sparse vegetation, and cryospheric dynamics) could be emphasized more to justify the novelty. Moreover, this work aligns well with the objectives of the new IAHS HELPING (Hydrology Engaging Local People IN one Global world) Decade (2023–2032), which emphasizes interdisciplinary approaches to address local hydrological challenges. I recommend to add this in either the Introduction or the Discussion.

Reply: We sincerely thank Referee #1 for the insightful comment and valuable suggestion. In the revised paper, we have expanded the description of the study area in the Introduction to better emphasize its unique hydroclimatic characteristics—such as extreme temperature gradients, sparse vegetation cover, and active cryospheric processes—that strongly influence regional hydrology. These features highlight the distinctiveness and scientific value of our research site. Furthermore, we have added a new paragraph at the end of the Introduction to explicitly link our study with the objectives of the IAHS HELPING Decade (2023 – 2032), underscoring the relevance of our interdisciplinary approach to addressing local hydrological challenges in cold regions.

2. The literature review should include more recent studies (post-2020) on cold-region hydrology, particularly those addressing snowmelt and vegetation interactions in similar environments (e.g., Central Asia, Tibetan Plateau).

Reply: We have updated the literature review to include more recent studies on cold-region hydrology. In particular, we have added several papers focusing on snowmelt dynamics, vegetation – hydrology interactions, and cryospheric processes in regions such as Central Asia (Feng et al., 2025) and the Tibetan Plateau (Ni et al., 2025) (Please refer to the third paragraph of the Introduction.).

Feng, J., Alifujiang, Y., Kozhokulov, S., Jiang, Y., Yang, P., 2025. Quantifying hydrological sensitivity in Central Asia: A multi-factor budyko framework analysis (2000–2020). Journal of Hydrology: Regional Studies, 61, 102746, https://doi.org/10.1016/j.ejrh.2025.102746.

Ni, J., Chen, J., Tang, Y., Xu, J., Xu, J., Dong, L., Gu, Q., Yu, B., Wu, J., Huang, Y., 2025. Duration of vegetation green-up response to snowmelt on the Tibetan Plateau, Biogeosciences, 22, 2637–2651, https://doi.org/10.5194/bg-22-2637-2025.

3. The similar performance of FLEX-T and FLEX-D is attributed to low vegetation heterogeneity. However, is this finding generalizable to other basins with higher vegetation variability? A comparative discussion would be valuable.

Reply: The similar performance of $FLEX^T$ and $FLEX^D$ in our study can be attributed to the low vegetation heterogeneity of the basins considered. To assess the generalizability of this finding, we compared our results with studies in more heterogeneous cold-region basins, such as the Heihe (Gao et al., 2014) and Yigong

Zangbu river basins (Gao et al., 2020). These comparisons indicate that landscape-based discretization can improve hydrological simulations when topographic and land-cover variability are higher (Please refer to paragraphs 3 – 5 of Section 6.1).

Gao, H., Hrachowitz, M., Fenicia, F., Gharari, S., Savenije, H.H.G., 2014. Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China. Hydrol. Earth Syst. Sci., 18(5): 1895-1915. DOI:10.5194/hess-18-1895-2014

Gao, H., Dong, J., Chen, X., Cai, H., Liu, Z., Jin, Z., Mao, D., Yang, Z., and Duan, Z., 2020. Stepwise modeling and the importance of internal variables validation to test model realism in a data scarce glacier basin, J. Hydrol., 591, 125457, https://doi.org/10.1016/j.jhydrol.2020.125457.

4. Line 428-433: Please provide the exact dates (year, month, and day) of these two precipitation events to enable a more precise understanding and validation of the related hydrological processes.

Reply: In the revised manuscript, we have specified the exact dates of the two precipitation events: 14 April 2009 and 12 September 2011.

5. The discussion should explicitly address limitations, such as the lack of direct validation (e.g., snowpit measurements, isotope tracers) and the impact of data scarcity on model uncertainty.

Reply: We have addressed the main limitations of the study in the revised Discussion (see Section 6.4). Frozen soil processes were not represented due to data constraints, yet they can strongly influence hydrological partitioning in high-elevation permafrost regions. The snowmelt tracker relies on a complete mixing assumption, which cannot capture event-scale flow-path heterogeneity but is suitable for estimating long-term average contributions. Only two basins were analyzed, allowing detailed process interpretation but limiting generalizability. These points clarify how data scarcity, modeling assumptions, and the limited study area contribute to uncertainty and suggest directions for future research.

6. Line 582: Provide a clearer explanation of the relationship between the proportion of snowfall in precipitation (Ps/P) and the contribution of snowmelt to streamflow (QM/Q), while ensuring that the related terminology and trend descriptions are accurate and consistent, to enhance the coherence between figures and text, as well as overall readability.

Reply: We have clarified the relationship between the proportion of snowfall in total precipitation (Ps/P) and the ratio of snowmelt runoff to streamflow (QM/Q) (Please refer to the second paragraph of Section 5.4). All terminology has been standardized, and trend descriptions are now accurate and consistent, enhancing the coherence between figures and text.

7. Line 673-675: The description of high infiltration rates in dry grassland soils leading to reduced runoff in arid regions is rather general; it is recommended to provide relevant references to strengthen the argument.

Reply: We have revised the manuscript to clarify that soils in semi-arid and arid grassland areas are typically dry with a large initial soil-moisture deficit, and that coarse-textured soils and sparse vegetation enhance infiltration, delaying runoff generation. Relevant references, including Xue et al. (2025), have been added to support this explanation.

Xue, D., Tian, J., Zhang, B., Kang, W., He, C., 2025. Evaluating the effect of vegetation type and topography on infiltration process in an arid mountainous area: Insights from continuous soil moisture monitoring network. Agricultural Water Management, 315, 109537, https://doi.org/10.1016/j.agwat.2025.109537.

Minor Comments

1. Some acronyms (e.g., SWE, HRUs, NDVI) should be defined at first use.

Reply: Thank you for the suggestion. All acronyms have been defined at their first mention.

2. The use of technical terms throughout the manuscript should be consistent (e.g., “modelling” and “modeling”, “elevation zones” and “elevation areas”).

Reply: In the revised manuscript, the use of technical terms has been standardized for consistency.

3. Line 193: The URL http://srtm.csi.cgiar.org is hosted by the CGIAR Consortium for Spatial Information (CGIAR-CSI), rather than the International Center for Tropical Agriculture (CIAT). Please revise the data source attribution to reflect this accurately.

Reply: This was an error, and the data source attribution has been corrected accordingly.

4. .3 illustrates the elevation band division based on DEM data, it would be more appropriate to place it in Section 3.2.

Reply: This is a good suggestion, and Fig. 3 has been moved to Section 3.2 accordingly.

5. Some figures (e.g., Fig. 5, Fig. 8) need clearer labels and legends. Fig. 13 needs better visualization.

Reply: We have improved the labels and legends in Figs. 5 and 8 and enhanced the visualization of Fig. 13.

6. Line 692: "soi/rock" should be "soil/rock".

Reply: This typo has been corrected from “soi/rock” to “soil/rock”.

7. Please correct the punctuation errors (e.g., Line 637, Line 711).

Reply: In the revised manuscript, the punctuation errors have been corrected as indicated.

8. The conclusions are well-supported but should be more concise.

Reply: The Conclusions section has been revised to be more concise while retaining all key findings and supporting evidence.

Anonymous Referee #2

This manuscript investigated the impact of topography and vegetation on catchment hydrology in two cold mountainous basins of the Mongolian Plateau using stepwise top-down modelling approaches. It is very interesting and scientifically sound. Also, it is suitable for Hydrology and Earth System Sciences. However, some improvements are still required.

Reply: We sincerely appreciate the reviewer's positive and constructive comments. In response, we have carefully revised the manuscript to address all specific points and have provided detailed explanations and modifications where appropriate. Detailed responses to all comments are provided below.

Detailed comments

1. The annual precipitation is ~200mm and ~160mm in the two basins, which belongs to sub-arid region. Therefore, most quick runoff should generate from infiltration excess runoff. On the other hand, in the FLEX, runoff generation is described as saturation excess generation. The reliability of the conclusion and the rationality of the method should be further assessed. At least, more explanations and discussions are requested.

Reply: We thank the reviewer for this valuable comment. In the revised manuscript, we explicitly represent the dominant hydrological processes associated with different landscape types.

Fig. 1 shows the daily precipitation in the two basins during the study period. Rainfall events exceeding 15 mm d^{-1} occur only 2-3 days per year, while most rainfall days receive less than 15 mm d^{-1}. Given these rainfall intensities, which generally remain below the infiltration capacity of grassland and forest soils, infiltration-excess (Hortonian) overland flow (HOF) is expected to be rare and largely restricted to bare or compacted surfaces (Blackburn, 1975; Beven and Germann, 2013).

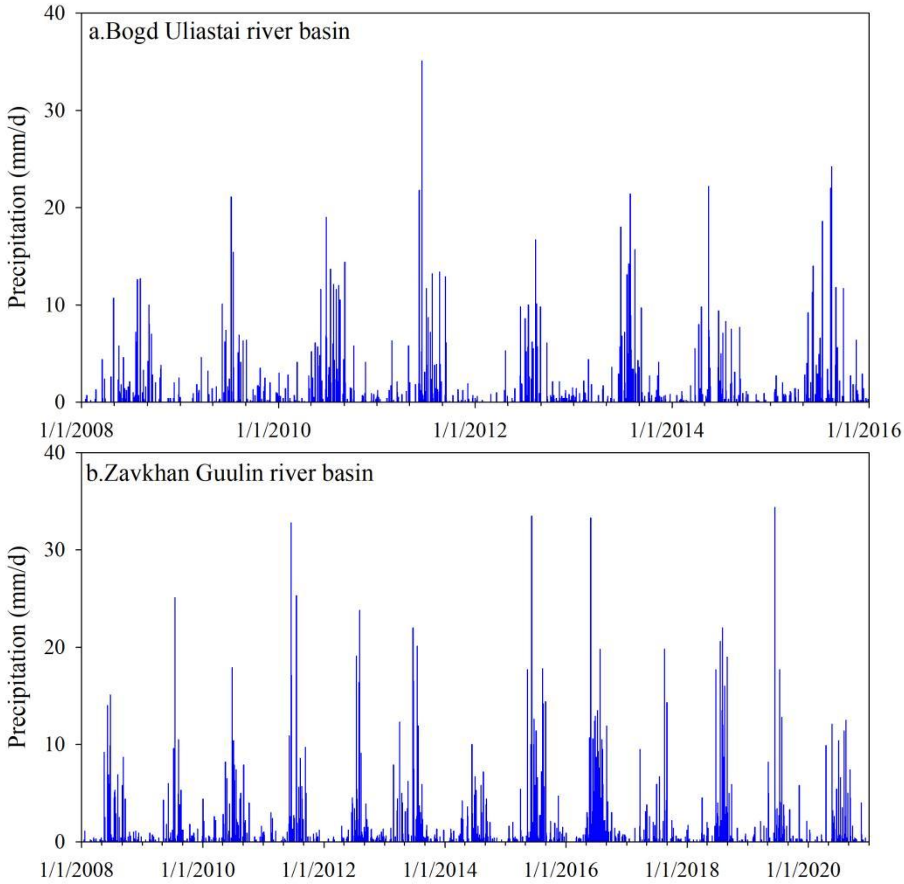

Fig.1 Daily precipitation in the two basins during the study period.

Runoff generation varies across the main landscape units, which exhibit distinct hydrological behaviors forming the basis of the FLEX^T model:

Bare soil/rock (~2% of the basin): Low infiltration capacity and sparse vegetation can produce localized HOF during high-intensity rainfall events. HOF is explicitly included in the model for these units to capture the full range of potential runoff processes.

Grazed grasslands and forests: High soil infiltration rates and well-developed macropore networks promote storage excess subsurface flow (SSF), particularly during snowmelt or prolonged rainfall (Beven and Germann, 2013; Lyford and Qashu, 1969). Hortonian runoff is negligible due to preferential flow and the high infiltration capacity promoted by the vegetation root system.

Riparian areas: Shallow groundwater tables and limited soil storage capacity favor soil overland flow (SOF) as the dominant mechanism (Dunne and Black, 1970).

Beven, K., Germann. P. 2013. Macropores and water flow in soils revisited, Water Resour. Res., 49, 3071 – 3092,doi:10.1002/wrcr.20156.

Blackburn, W., 1975. Factors influencing infiltration and sediment production of semi-arid ran- gelands in Nevada. Water Resour. Res., 11 (6): 929~937.

Dunne, T., Black, R. D. 1970. Partial area contributions to storm runoff in a small New England watershed. Water Resources Research, 6(5), 1296 – 1311.

Lyford, F., Qashu, H., 1969. Infiltration rates as affected by desert vegetation. Water Resour. Res., 5 (6): 1373~1376.

2. This study selected two alpine Basins as the study basin. In the study basins, there is only one meteorological station for each basin. To represent the spatial variation of precipitation, the authors a precipitation increase rate of 4.2% from the Heihe River basin in China. Does the precipitation increase rate of 4.2% conform to the study basins? More explanations and discussions are requested.

Reply: It should be clarified that the precipitation increase rate used in this study is not solely derived from the Heihe River basin in China. The following steps describe how the precipitation increase rate was determined in this study.

Reanalysis data attempts and limitations: We have attempted to use multiple reanalysis datasets to quantify the spatial variation of precipitation within the study basins. However, the quality of these datasets in this region is relatively poor, making them unreliable for accurately estimating precipitation gradients.

Literature-based regional reference (most important): To obtain a more scientifically justified precipitation–elevation relationship, we consulted extensive literature on nearby catchments. The Tsagan-Turutuin-gol catchment, which also originates in the Khangai Mountains and exhibits topographic and climatic characteristics similar to those of our study basins, has a mean annual precipitation of approximately 200 – 300 mm and a precipitation gradient of slightly less than 10 mm per 100 m between 2000 and 3350 m a.s.l., equivalent to 4.2±0.8% per 100 m (Klimek and Starkel, 1980). In addition, the precipitation increase rate (4.2% per 100 m) has been widely applied in environmentally comparable alpine regions and has yielded satisfactory hydrological simulation performance, such as in the upper Heihe river basin (Gao et al., 2022).

Klimek K., Starkel L, 1980. Vertical zonality in the Southern Khangai Mountains (Mongolia). Results of the Polish-Mongolian physico-geographical expedition. Geographical Studies Vol. I, 136: 1–107.

Gao, H., Han, C., Chen, R., Feng, Z., Wang, K., Fenicia, F., and Savenije, H.: Frozen soil hydrological modeling for a mountainous catchment northeast of the Qinghai – Tibet Plateau, Hydrol. Earth Syst. Sci., 26, 4187 – 4208, https://doi.org/10.5194/hess-26-4187-2022, 2022.

3.In the study basins, winter temperature falls below -30 degree. It's better to discuss the impact of frozen soil.

Reply: While the proposed modeling framework captures key hydrological processes, frozen soil dynamics were not explicitly represented due to data limitations. Frozen soil is widespread across the region and can strongly influence hydrological partitioning by restricting moisture exchange between deeper soil layers and the atmosphere, reducing soil permeability, and modifying near-surface flow pathways. These effects may alter the balance between surface runoff and subsurface flow, particularly in high-elevation permafrost regions with sparse vegetation. We have now explicitly discussed this limitation in the second paragraph of Section 6.4. Future studies that incorporate explicit frozen soil parameterizations would help to better disentangle the interacting roles of topography, vegetation, and frozen ground in alpine basins.

4.Lines 259-260, there is a mistake on the description of the method for actual evaporation, i.e. “Ep” should be “Ep - Ei” (potential evaporation minus interception evaporation).

Reply: We have clarified this point in the revised manuscript. Equation 13 is correctly formulated and therefore remains unchanged; the correction applies only to the textual description.

5. The authors conducted relevant researches in other alpines basins, such as Heihe River basin. In this study, it's more useful to discuss both the similarities and the differences in order to gain a clearer understanding.

Reply: In the revised manuscript, we have expanded the discussion by comparing the study basins with other cold-region alpine basins, including the Heihe River Basin (Gao et al., 2014) and the Yigong Zangbo River Basin (Gao et al., 2020), which exhibit higher topographic and land-cover heterogeneity. These comparisons highlight that when topographic and vegetation variability is pronounced, landscape-based discretization can substantially improve hydrological simulations. In contrast, by adopting a stepwise modeling framework, the present study places greater emphasis on diagnosing runoff generation mechanisms—such as the ratio of snowmelt runoff to total streamflow and the respective roles of elevation bands and vegetation units—thereby providing complementary insights into how topography and vegetation jointly control streamflow responses in cold alpine basins.

Gao, H., Hrachowitz, M., Fenicia, F., Gharari, S., Savenije, H.H.G., 2014. Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China. Hydrol. Earth Syst. Sci., 18(5): 1895-1915. DOI:10.5194/hess-18-1895-2014

Gao, H., Dong, J., Chen, X., Cai, H., Liu, Z., Jin, Z., Mao, D., Yang, Z., and Duan, Z., 2020. Stepwise modeling and the importance of internal variables validation to test model realism in a data scarce glacier basin, J. Hydrol., 591, 125457, https://doi.org/10.1016/j.jhydrol.2020.125457.