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We thank you for your valuable comments, which have greatly strengthened the manuscript. We have incorporated your feedback, with revisions presented as follows: red for your comments, black for our responses, and blue for the revised manuscript text.

General Comments:

This manuscript presents a timely and important study that challenges the conventional view of gullies as purely erosional, degraded features by positioning them as significant zones for groundwater recharge in the semi-arid Loess Plateau. The research employs an integrated multidisciplinary approach, combining stable isotope analysis, chloride concentration measurements, water-level fluctuation analysis, and hydro-statistical modelling to trace moisture flow paths among surface water, pore water, fissure water, and spring water at a high resolution. Based on this evidence, the authors redefine the hydrological role of gullies in arid ecosystems, directly challenging the traditional view of gullies as symbols of land degradation. The findings reveal that reframing gullies are not merely degraded geomorphic units but rather critical groundwater recharge zones and subsurface connectivity hubs. Precipitation primarily replenishes shallow pore water, while deep fissure water is supplemented by slow, top-down percolation. This understanding overturns the long-standing negative perception of gullies on the Loess Plateau, highlighting their capacity to buffer seasonal hydrological variability and enhance ecosystem resilience. Overall, this study addresses a key knowledge gap regarding groundwater dynamics in gully systems and holds significant practical implications for sustainable water resource management on the Loess Plateau. The manuscript is generally well-written and structured. However, some moderate revisions are needed.

Response: Thank you for taking the time to review our manuscript and for providing valuable and constructive comments. Your feedback has greatly helped us improve the manuscript. We fully agree with your comments and have made substantial revisions to enhance its readability and academic rigor. Below are the specific changes we made, along with our point-by-point responses to your comments.

Major Concerns:

1. The manuscript sets up a contrast with "piston flow" and "preferential flow" models from tableland studies but does not clearly define what process is dominant in the gullies. The proposed "gully-dominated preferential recharge mechanism" (Line 779) is not well-defined. Is the "preferential" aspect the topographic focusing of runoff into the gully, or are there actual preferential flow paths (macropores, cracks) within the gully soils?

Response: Regarding the term "gully-dominated preferential recharge mechanism", we have clarified and revised the description as follows: In the study area, the gully system is characterized by homogeneous, fine-grained loess, where water movement primarily follows piston flow (Yu et al., 2025). In this context, "preferential" refers to the topographically driven process in which gullies act as critical convergence zones, efficiently concentrating hillslope runoff and leading to spatially focused and enhanced recharge flux, rather than indicating the presence of preferential flow paths such as macropores or fractures. The specific revision is as follows:

"Crucially, the model offers insight into the multifunctionality of ecological engineering — particularly check dams and ponds — in enhancing hydrological regulation, water security, and ecosystem restoration across the Loess Plateau. **This study identifies a distinctive cascade-type recharge process in loess gully catchments and proposes the "gully-dominated preferential recharge mechanism". This mechanism emphasizes the hydrological function of gullies as convergence pathways and efficient recharge windows at the catchment scale, rather than preferential flow paths within the soil matrix. Furthermore, water movement within the silted loess layer of the gully system remains dominated by a piston flow pattern (Yu et al., 2025).** By identifying the pivotal role of gully systems in stormwater detention, delayed infiltration, and multi-aquifer recharge, this study establishes a robust theoretical and technical foundation for improving water resource allocation, infrastructure planning, and groundwater sustainability in arid and semi-arid regions."

2. In my opinion, the manuscript could benefit from clearer articulation of the broader implications of the key findings. For example, how can this insight change land management practices or ecological restoration strategies in other dryland regions globally?

Response: To enhance the broader implications of the study, we have expanded the discussion to highlight the global relevance of our findings, particularly with regard to land management practices and ecological restoration strategies in other arid and semi-arid regions. The specific additions are as follows:

"However, with the reconstruction of gully systems and ecological restoration, attention must also be given to the potential risks of pollutant migration (Yu et al., 2020). The hydrological functions of gullies may enhance the movement of pollutants into groundwater, especially in areas with intensive human activities, where pollutants can enter gullies through surface runoff and subsequently infiltrate the groundwater system. During ecological restoration, excessive human intervention or soil improvement measures may lead to the accumulation and dispersion of pollutants, which may compromise groundwater security (Liu et al., 2017). Therefore, the protection and rational reconstruction of gully systems should not only focus on their hydrological functions but also consider potential environmental risks, particularly the pathways of pollutant migration. **More importantly, these findings have direct implications for land management practices and ecological restoration strategies in similar arid regions worldwide (Obuobie et al., 2012; Zhao et al., 2019; Zhao et al., 2021; Xue et al., 2025).**

The study confirms that gullies serve as critical "recharge windows" for groundwater in arid areas. This underscores the importance of systematically identifying and conserving natural gully networks in watershed management, while avoiding excessive filling or hardening to preserve their hydrological functions. In ecological restoration projects, directing surface runoff toward gullies can efficiently convert limited precipitation into groundwater storage, thereby enhancing regional water retention capacity. Beyond advancing theoretical understanding of regional hydrological processes, it also provides a sound basis for developing spatially targeted models of groundwater recharge."

Reference

Obuobie, E., Diekkrueger, B., Agyekum, W., Agodzo, S. Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana. Journal of African Earth Sciences. 71-72: 80-86, 2012. DOI: 10.1016/j.jafrearsci.2012.06.005.

Xue, S.B., Li, P., Cui, Z.W., Li, Z.B. The influence of different check dam configurations on the downstream river topography and water-sediment relationship. Journal of Hydrology. 656: 133046, 2025. DOI: 10.1016/j.jhydrol.2025.133046.

Zhao, Y., Wang, L. Determination of groundwater recharge processes and evaluation of the "two water worlds" hypothesis at a check dam on the Loess Plateau. Journal of Hydrology. 595: 125989, 2021. DOI: 10.1016/j.jhydrol.2021.125989.

Zhao, Y.L., Wang, Y.Q., Sun, H., Lin, H., Jin, Z., He, M.N., Yu, Y. L., Zhou, W. J., An, Z. S. Intensive land restoration profoundly alters the spatial and seasonal patterns of deep soil water storage at watershed scales. Agriculture, Ecosystems & Environment. 280: 129-141, 2019. DOI: 10.1016/j.agee.2019.04.028.

Specific Comments:

1. It is recommended to simplify long sentences to improve readability. For example, lines 53–56: "In these 'fragile' and diverse landscapes, understanding the processes that govern when, where, and how groundwater is replenished — including the countervailing influences of vegetation dynamics, geomorphology, and engineered features — is essential for sustaining ecosystems, securing water resources, and informing land restoration and catchment management." This sentence is structurally complex and could be simplified by breaking it into shorter clauses or highlighting the core information more clearly.

Response: We have simplified the sentence to enhance readability. The revised version is as follows:

"For these fragile and diverse landscapes, understanding how vegetation, geomorphology, and infrastructure govern groundwater recharge is crucial. This knowledge is vital for sustaining ecosystems, securing water resources, and informing restoration and management efforts."

2. The text categorises groundwater into "pore water, spring water, fissure water", and further suggested that the criteria for classification be clarified, such as medium type, storage space, and relationship with aquifer structure, to help readers understand the logical framework. The definition of "piston flow"(Line 145-146) is helpful but could be more concise. Consider: "Piston flow describes the displacement of pre-existing water by newly infiltrating water, moving frontally through the pore spaces."

Response: We have further elaborated on groundwater medium types, storage spaces, and relationship with aquifer structure to improve the clarity of the logical framework for readers.

Regarding the definition of “piston flow”, we have simplified it as follows per your comment. The specific revisions are as follows:

“Groundwater in the catchment can be broadly categorized into three types: pore water, spring water, and fissure water. Pore water is stored in permeable sandstone and conglomerate aquifers beneath loess and above mudstone or red clay. These aquifers are approximately 2–3 m thick, exhibit a sheet-like distribution, and have low water yield. Conceptually, “pore water" here refers to groundwater in a saturated aquifer, not to soil moisture. Fissure water occurs in fractured bedrock aquifers, which are spatially discontinuous due to irregular fracture development. The main water-bearing zones include cavities and jointed fissure networks, with an average aquifer thickness of about 6 m and moderate water yield. Hydraulic conductivity in these sandstone and conglomerate aquifers ranges from 0 to 0.47 m/d (Cai et al., 2019). Spring water emerges primarily at gully bases—especially in upper catchments—and originates from both pore and fissure sources, possibly supplemented by surface or pond water. Springs fed by pore water typically have low discharge rates (0–0.1 L/s) and low water yield, while those fed by fissure water exhibit moderate discharge rates (0.5–1.0 L/s) and moderate water yield.”

“These studies suggest that recharge occurs primarily through slow piston flow, with precipitation infiltrating thick soil profiles, slowly recharging groundwater in a process that can take decades to hundreds of years (Huang et al., 2013; Tan et al., 2017; Li et al., 2024). Piston flow describes the displacement of pre-existing water by newly infiltrating water, moving frontally through the pore spaces (Gee and Hillel, 1988).”

3. The manuscript lists permeability for Neogene coarse sandstone and conglomerate as 7.5–36.19 m/d (lines 213–214). These magnitudes are unusually high for such lithologies; I suspect a units or conversion mistake and recommend the authors re-examine the original data and report corrected values if necessary.

Response: In the original manuscript, the permeability unit at Line 214 was listed as 'Lu' but was incorrectly noted as 'm/d' (7.5–36.19 Lu≈0.07–0.31 m/d). In this revision, we have verified the permeability units and made the necessary conversions. The revised version is as follows:

“The significant reduction in loess thickness—combined with the relatively high permeability of Neogene coarse sandstone and conglomerate (0.07–0.31 m/d)—creates favorable conditions for infiltration and focused recharge.”

4. The text indicates that a low ITTP represents a long residence time, but the high ITTP of ponds (1.5 ± 0.7) is interpreted as "rapid turnover + evaporation dominance,"seemingly overlooking the effect of evaporation on increasing variance. Could this be due to the small sample size for ponds/springs affecting the reliability of the analysis? Additionally, what is the reason for the small sample size for ponds/springs?

Response: In our analysis, the high ITTP values observed in the pond were interpreted as resulting from the combined effects of “rapid turnover and evaporation dominance”. As an open, shallow water body, the pond experiences strong evaporation, which preferentially removes lighter isotopes, enriching the remaining water with heavier isotopes, thereby increasing the variance in isotopic composition. We acknowledge that evaporation is one of the factors contributing to the increased variance, which may introduce bias into the estimation of apparent residence times. This has been addressed in the original manuscript , as follows:

“The inverse transit time proxies (ITTPs) broadly support the dual-isotope interpretations of water source dynamics. **Pond water exhibited the highest ITTP values (1.5 ± 0.7), indicating rapid turnover and limited subsurface storage. These elevated values likely reflect inputs from direct rainfall and overland flow, as well as evaporative enrichment, which increases isotopic variability and can artificially shorten the apparent residence time.** In contrast, pore water (0.7 ± 0.3) and fissure water (0.6 ± 0.5) showed lower ITTPs, consistent with longer residence times, greater subsurface mixing, and attenuation of seasonal isotopic signals due to delayed recharge. Spring water had the lowest ITTPs (0.3 ± 0.2), reflecting slow subsurface transport and integration of older water sources. While these patterns align with conceptual expectations of residence time and flow path length, the limited number of samples—particularly for pond, spring, and pore water—warrants caution in interpreting seasonal dynamics (Fig. 7).”

Additionally, your comment regarding the potential impact of sample size on the robustness of statistical inferences is valid. It is important to note that the pond water (n=7) and spring water (n=9) samples reported in this study represent all available valid samples within the research area. This sample size significantly exceeds the minimum requirements for replicate observations in conventional hydrological isotope studies (typically ⩾ 3 replicates). The collection of 7 pond water and 9 spring water samples in a 54 km² arid-to-semi-arid study area reflects good spatial coverage and hydrological representativeness, indicating that the sampling effort is both sufficient and meaningful at the study scale. The relatively large standard deviation of the pond water samples, covering locations with varying evaporation intensities from upstream to downstream, precisely reflects the natural variability of the actual hydrological processes. Therefore, sample size alone is unlikely to be the primary factor affecting the reliability of the analysis.

5. The high recharge rate of gully groundwater, accounting for 43% of precipitation—significantly higher than that in hill areas (<20%)—is a core conclusion of this paper and key evidence supporting the claim that "gullies are critical groundwater recharge zones and subsurface connectivity hubs." While this conclusion is important, its robustness and uncertainties require further discussion, such as the assumptions underlying the recharge rate estimation method, spatial representativeness, and the impact of extreme events.

Response: The estimation method for the recharge rate has been thoroughly discussed in the manuscript, including the underlying assumptions. To further strengthen the robustness of our conclusions, we have supplemented the discussion with considerations of spatial representativeness and the impact of extreme events, as per your comment. The specific additions are as follows:

"The total recharge from 2023 to 2024 was estimated at 241.4 ± 6.0 mm and 238 ± 6.0 mm using the MRC and RISE methods, respectively. Under constant specific yield conditions, the MRC method typically estimates higher groundwater recharge and recharge days than RISE, as it accounts for groundwater table decline due to lateral outflow and other discharge processes in the absence of recharge (Heppner and Nimmo, 2005). Our findings support this pattern. **Furthermore, the key parameter for estimating groundwater recharge using the water table fluctuation method is specific yield (Sy), which depends on soil properties and water table depth (Liang et al., 2016). Shallow soil measurements (0–50 cm) using the test pit method (total porosity minus field capacity) yielded Sy ≈ 0.03, consistent with high capillary retention in near-surface loess (Wang et al., 2024). However, for water tables deeper than 2 m (as in this study, typically 4–10 m), the test pit method provides a reliable estimate of aquifer-scale drainable porosity (Nachabe, 2002; Shah and Ross, 2009; Liang et al., 2016). Accordingly, we**

adopted Sy = 0.032, aligned with values of ~0.03 reported for similar loess-derived unconfined aquifers on the Loess Plateau (Wang et al., 2023). Uncertainty analysis showed that recharge estimates vary by ± 25% for Sy, which ranges from 3.2 ± 0.8%."

"Research on groundwater recharge in the Loess Plateau has mainly focused on deep-profile unsaturated zones in the tableland and hilly areas, with tracer methods estimating recharge between 9 to 100 mm (Huang et al., 2011; Li et al., 2017; Xiang et al., 2019; Lu, 2020; Wang et al., 2024). In contrast, our study in the gully region indicates recharge of up to 240 mm, much higher than previous estimates on deep-profile unsaturated zones. This difference reflects several factors: 1) Unsaturated zone thickness—In the gully region, the unsaturated zone is generally less than 10 m thick, much shallower than in tableland and hilly areas (mean thickness of 92.2 m), making infiltration easier and promoting effective recharge. 2) Gully topography and hydrology — characterized by well-developed channels, concentrated runoff, and widespread ponds and check dams — promote focused infiltration (Liu et al., 2017; Li et al., 2021; Xue et al., 2025). 3) Research methods — Tracer methods reflect long-term recharge rates and are better suited for thicker unsaturated zones (Huang et al., 2011; Lu, 2020; Li et al., 2017). In contrast, the water table fluctuation method directly captures short-term recharge dynamics and works better in thinner unsaturated zones. Moreover, this method also better captures surface water-groundwater interactions and focused recharge effects (Gumuła-Kawęcka et al., 2022). These findings underscore the importance of studying recharge in gully regions, filling a research gap in the Loess Plateau's geomorphology and providing new ecohydrological insights. However, the robustness of our findings requires further exploration. On one hand, due to the limited spatial distribution of sampling points, the current results primarily reflect the hydrological characteristics of localized typical gullies, and their representativeness at the regional scale requires validation through future expansion of the monitoring network. On the other hand, the study period did not encompass extreme precipitation or drought events, which may significantly alter surface flow convergence conditions and vadose zone water transport mechanisms, thereby substantially impacting recharge processes. Future work should strengthen dynamic monitoring and simulation analysis under extreme hydrological scenarios."

6. Fig. 9 shows that significant rises in groundwater levels and the main recharge period occur

during the drier autumn and winter seasons (October to April), while recharge during the summer monsoon rainfall peak is minimal. The authors explain this as effective infiltration during the "cool, low-evaporation period" (Lines 601-604). Are there other potential reasons? For example, freeze-thaw processes, soil water reservoir effects, antecedent moisture conditions, or the competition between rainfall intensity and infiltration capacity?

Response: We fully agree with your comment. In addition to effective infiltration during the "cool, low-evaporation period", factors such as freeze-thaw processes, soil water storage effects, antecedent moisture conditions, and the competition between rainfall intensity and infiltration should also be considered as influencing the dominant recharge period in autumn and winter. Accordingly, we have added the relevant content to the caption of Fig. 9, as detailed below:

"Most recharge events occur from October to April, even when rainfall is not especially high, while warm-season precipitation contributes little to recharge—likely due to increased evaporative losses and shallow soil retention. Together, these patterns suggest strong seasonal control on recharge processes, with effective infiltration primarily occurring during cooler, low-evaporation periods. Other factors, such as freeze-thaw processes, soil water storage effects, initial moisture conditions, and the competition between rainfall intensity and infiltration, may also contribute to this pattern."

We have specifically added the following content in the discussion:

"Additionally, the isotopic values of most groundwater in the gully areas are more depleted compared to those of rainfall and pond water, likely due to the recharge mechanisms and residence times of different groundwater types, and the inherent isotopic characteristics of their primary recharge sources (Ouali et al., 2024). **The depleted signatures in groundwater reflect preferential capture of isotopically light summer monsoon events, with effective percolation delayed to cooler seasons due to transient soil storage and minimized evaporation — consistent with observed water table rises predominantly from October to April.** Nevertheless, these values fall within the range of precipitation isotopic values, leaning towards the more negative end. This suggests two complementary mechanisms: (1) the thin unsaturated zone (<10 meters) provides preferential pathways for rapid infiltration of precipitation, minimizing evaporative fractionation, and (2) groundwater is likely recharged primarily by intense precipitation events (e.g., summer storms) with inherently more negative isotopic signatures.

Together, these processes explain the observed isotopic characteristics of groundwater."

7. The conceptual model (Fig. 10) emphasises the "restructuring" role of the gully system but does not discuss the potential risks of associated pollutant transport. Given that related issues are mentioned in the introduction, it is recommended to include a discussion on this aspect to present a more comprehensive perspective.

Response: Based on your comment, the potential risks of pollutant migration have been added to the discussion. It should be noted that, since this study does not involve the actual analysis of pollutant migration, the related content is discussed solely as background and future research directions. Therefore, the pollutant migration process is not explicitly represented in the conceptual model (Fig. 10) and is addressed only in the textual discussion. The specific content is as follows:

"However, with the reconstruction of gully systems and ecological restoration, attention must also be given to the potential risks of pollutant migration (Yu et al., 2020). The hydrological functions of gullies may enhance the movement of pollutants into groundwater, especially in areas with intensive human activities, where pollutants can enter gullies through surface runoff and subsequently infiltrate the groundwater system. During ecological restoration, excessive human intervention or soil improvement measures may lead to the accumulation and dispersion of pollutants, which may compromise groundwater security (Liu et al., 2017). Therefore, the protection and rational reconstruction of gully systems should not only focus on their hydrological functions but also consider potential environmental risks, particularly the pathways of pollutant migration."

References

Liu, Y.S., Chen, Z., Li, Y., Feng, W., Cao, Z. The planting technology and industrial development prospects of forage rape in the loess hilly area: A case study of newly-increased cultivated land through gully land consolidation in Yan'an, Shaanxi Province. Journal of Natural Resources. 32: 2065-2074, 2017.

Yu, Y.L., Jin, Z., Chu, G.C., Zhang, J., Wang, Y.Q., Zhao, Y.L. Effects of valley reshaping and damming on surface and groundwater nitrate on the Chinese Loess Plateau. Journal of Hydrology. 584: 124702, 2020.

8. The conclusion section (Section 7) provides a good summary of the study's core findings. However, some statements appear slightly absolute, such as the claim to be "the first to quantitatively identify the unique cascading recharge processes in a thin loess gully catchment" (Lines 781-782). While the research is innovative, caution is advised with phrases like "the first." It would be preferable to provide supporting literature references or adopt a more measured description.

Response: We have revised the relevant phrasing to address your concern. The specific revision is as follows:

"More importantly, these findings have direct implications for land management practices and ecological restoration strategies in similar arid regions worldwide. The study confirms that gullies serve as critical "recharge windows" for groundwater in arid areas. This underscores the importance of systematically identifying and conserving natural gully networks in watershed management, while avoiding excessive filling or hardening to preserve their hydrological functions. In ecological restoration projects, directing surface runoff toward gullies can efficiently convert limited precipitation into groundwater storage, thereby enhancing regional water retention capacity."

9. The manuscript is largely well-written, but some sections contain complex or awkward sentence structures that could be improved for readability. For instance, the introductory and results sections sometimes use dense scientific language, which might be simplified without losing technical precision. Additionally, the formatting of the references section could be revisited for consistency.

Response: Thank you for your positive assessment of the manuscript and for the constructive comments for improvement. We fully agree that enhancing clarity of expression and ensuring formatting consistency are essential for both readability and scientific rigor. In response to your comments, we have implemented the following comprehensive revisions:

First, we thoroughly reviewed the entire manuscript, with particular emphasis on the Introduction and Results sections, and systematically revised sentences with complex structures or awkward phrasing. While preserving scientific accuracy and completeness, we improved clarity and fluency by breaking up long sentences, refining sentence structure, and optimizing the density of technical terminology.

Second, in accordance with the journal's guidelines, we carefully checked and standardized all in-text citations and the reference list to ensure full compliance. In addition, following your Specific Comment 10, we have incorporated the recommended key references into the manuscript.

We believe these targeted revisions have substantially improved the clarity, readability, and formatting consistency of the manuscript.

10. Some important references are missing from the introduction and discussion sections:

De Vries, J. J., & Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal, 10(1), 5-17.

Huang L.M., Shao M.A., Advances and perspectives on soil water research in China's Loess Plateau. Earth-Science Reviews, 2019: 102962.

Huang, L.M., Wang, Z.W., Pei, Y.W., Zhu, X.C., Jia, X.X., Shao, M.A., Adaptive water use strategies of artificially revegetated plants in a water-limited desert: A case study from the Mu Us Sandy Land. Journal of Hydrology, 2024, 644: 132103.

Xiang, W., Si, B. C., Biswas, A., & Li, Z. (2019). Quantifying dual recharge mechanisms in deep unsaturated zone of Chinese Loess Plateau using stable isotopes. Geoderma, 337, 773-781.

Response: We have carefully verified that the recommended references have been added or appropriately cited in the manuscript. We fully agree that including these important references significantly enhances the breadth and rigor of the study, and we have standardized the citation format in accordance with the journal's guidelines.

References

Huang L.M., Shao M.A. Advances and perspectives on soil water research in China's Loess Plateau. Earth-Science Reviews. 199(2): 102962, 2019. DOI: 10.1016/j.earscirev.2019.102962.

Huang, L.M., Wang, Z.W., Pei, Y.W., Zhu, X.C., Jia, X.X., Shao, M.A. Adaptive water use strategies of artificially revegetated plants in a water-limited desert: A case study from the Mu Us Sandy Land. Journal of Hydrology. 644: 132103, 2024. DOI: 10.1016/j.jhydrol.2024.132103.

Vries, J.J.D., Simmers, I. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal. 10(1): 5-17, 2002. DOI: 10.1007/s10040-001-0171-7.

Xiang, W., Si, B.C., Biswas, A., Li, Z. Quantifying dual recharge mechanisms in deep unsaturated zone of Chinese Loess Plateau using stable isotopes. Geoderma. 337: 773-781, 2019. DOI: 10.1016/j.geoderma.2018.10.006.