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Reframing gullies as recharge zones in dryland landscapes of the Loess Plateau, China

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Abstract

Large gullies in dryland landscapes are often viewed as indicators of land degradation, yet in some settings they may serve critical ecohydrological functions—supporting groundwater recharge and subsurface connectivity. In China's Loess Plateau, we assess these functions in the Nianzhuang Catchment using a multi-indicator approach that integrates stable isotopes (δ^2H, $\delta^{18}O$), chloride concentrations, and groundwater level fluctuations. Our results show that precipitation is the dominant source of recharge for shallow pore water within gully zones, while deeper fissure water is replenished more slowly through percolation from the upper layers. Restoration interventions—particularly check dams and ponds—act as focal points for groundwater infiltration, enhancing recharge in otherwise limited dryland systems. Estimated annual recharge (238–241 mm) accounts for over 43% of annual precipitation, far exceeding typical rates observed in nearby tableland and hilly areas. These findings revise prevailing assumptions by positioning gullies not simply as degraded features, but as hydrologically active zones that can buffer seasonal variability and support ecosystem resilience. The study advances a conceptual framework for using isotopic damping, chloride accumulation, and recharge partitioning as indicators of landscape function in semi-arid regions, offering valuable tools for dryland monitoring and restoration planning.

Keywords: surface water, spring water, pore water, fissure water, connectivity

1. Introduction

Groundwater recharge is a critical yet poorly understood component of hydrological cycles in dryland catchments. It is shaped by the precipitation regime, surface landcover heterogeneity, the integrity of the subsurface regolith, the characteristics of the underlying bedrock, and human interventions (Vries and Simmers, 2002; Owuor et al., 2016; Salek et al., 2018; Xu and Beekman, 2019; Zhang et al., 2020; Li et al, 2024; Medici et al., 2024). Although favorable subsurface flow pathways can locally enhance recharge, dryland regions—situated along climatic ecotones and shaped by complex land–atmosphere–biosphere feedbacks—are highly sensitive to even modest shifts in water availability. Small changes in soil moisture or runoff routing can cascade across catchments are various scales, amplifying existing vulnerabilities to ecological and social systems (Nicholson, 2011; Huang et al., 2017; Berg et al., 2016). In these "fragile" and diverse landscapes, understanding the processes that govern

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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 (Gleeson et al., 2016; Jasechko and Perrone, 2021; Scanlon et al., 2006).

Despite a growing body of research on groundwater recharge in (semi-)arid regions, significant knowledge gaps remain in landscapes with pronounced spatial heterogeneity—such as slopes, hilltops, and gullies—where infiltration pathways and recharge processes can diverge sharply over short distances (Tooth, 2012; Manna et al., 2018; Letz et al., 2021). Among these landforms, gully systems—often regarded as hallmarks of land degradation—may paradoxically serve as focal points for recharge, capturing and infiltrating surface runoff during episodic rainfall events (Tan et al., 2017; Li et al., 2024; Xue et al., 2025). Notably, gully systems may facilitate the rapid downslope transport of contaminants such as agricultural contaminants and sediments (Lian et al., 2025; Qu et al., 2025). However, the role of gullies in promoting vertical infiltration into groundwater is highly dependent on local subsurface connectivity and permeability conditions. Moreover, their broader hydrological functions remain poorly quantified—especially under the influence of widespread human interventions such as check dams and artificial ponds. While these structures are typically designed to arrest land degradation, they can substantially alter surface–subsurface connectivity and reshape recharge dynamics (Lamontagne et al., 2021; Wang et al., 2023).

This study focuses on groundwater recharge in the gully systems in loess soils. Worldwide, loess covers approximately 6% of the land surface area, forming discontinuous east–west belts in the mid-latitude forest-steppe, steppe, and desert-steppe zones of both hemispheres (Liu, 1985; Pécsi, 1990; Li et al., 2020). Among these, the Chinese Loess Plateau accounts for approximately 7.4% of the global loess area (635,280 km²; Li et al., 2020). The setting for our investigation, semi-arid landscape has been shaped by severe soil erosion, extensively modified by engineered landforms; and it is now characterized by chronic water scarcity (Fu et al., 1999; Liu et al., 2017; Liu and Li, 2017; Li et al., 2021). In such vulnerable environments, understanding the sources and sustainability of groundwater recharge is critical for long-term water resource management (Ajjur and Baalousha, 2021; Meles et al., 2024). Groundwater is a lifeline for rural communities in the hilly–gully region, yet scientific attention has largely bypassed the gullies themselves. Most research has centered on recharge processes in tablelands and loess-covered hills (Huang et al., 2011; Li et al., 2017; Lu, 2020; Wang et al., 2024), leaving the hydrological role of

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gully systems—despite their striking prominence in the landscape—largely in the shadows (Liu et al., 2011).

In this study, we integrate stable isotope analysis (δ^2H and $\delta^{18}O$), chloride concentration measurements, water table fluctuation estimations, and hydro-statistical modeling to do the following: (i) quantify pore water recharge rates; and (ii) trace flow paths among surface water, pore water, and fissure water. This integrated approach aims to advance understanding of groundwater dynamics in complex dryland terrains, generating process-based insights critical for sustainable water and land management in gully-dominated systems—not only across the Loess Plateau, but in drylands globally.

2. Hydro-geomorphological processes of the Loess Plateau

The Loess Plateau in China stands out as one of the most ecologically and hydrologically distinctive landscapes in the world (Fu et al., 2017). Spanning over 640,000 km², it harbors the planet's largest and deepest loess deposits and has long served as a cradle of Chinese civilization (Li et al., 2021). The Loess Plateau is also one of the most severely eroded regions in the world, shaped by the interplay of highly erodible soils, intense summer storms, and a long history of farming on sloping lands (Shi and Shao, 2020). For centuries, steep hillslopes were cultivated without adequate soil conservation, removing vegetation and exposing loess soils to heavy runoff during short, high-intensity monsoonal rains. These conditions led to widespread gully formation—hallmarks of degradation tightly linked to land use and rainfall extremes (Wang et al., 2006; Fu et al., 2011; Jin et al., 2020). The altered hydrological cycle on the plateau has led to sharp declines in both streamflow and groundwater levels, resulting in acute water scarcity across this arid to semi-arid region (200–750 mm annual rainfall) (Liang et al., 2015; Wang et al., 2023; Chen et al., 2023). Understanding hydrological processes in this disturbed setting is essential for guiding soil conservation, optimizing groundwater recharge, and ensuring the long-term sustainability of water resources for both people and ecosystems.

The plateau's complex stratigraphy—characterized by loess layers that can reach depths of up to 350 meters and average around 90 meters, with generally low permeability—governs groundwater storage, recharge processes, and subsurface flow behavior (Qiao et al., 2017; Zhu et al., 2018). The region is further divided into a range of distinctive landforms, or subregions, also shaped by variable erosion processes (Yang et al., 2009): Loess Yuan (flat, high-elevation tablelands); Loess Liang (elongated ridges); Loess Mao (rounded or oval-shaped hills); hills; and large-scale gullies (Fig. A1). While the

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Loess Yuan remains relatively unincised by rivers/streams and maintains a smooth surface morphology, the Liang and Mao formations exhibit profound dissection—shaped predominantly by fluvial erosion and hillslope processes, respectively.

Hills in the region exhibit undulating terrain shaped by prolonged weathering and diffuse surface runoff. In contrast, gully systems reflect both long-term geomorphic evolution and more recent intensification driven by human activity—making them products of millennial-scale natural processes and modern land-use pressures (Li et al., 2021; Jia et al., 2024). Prominent gully systems, which can stretch for several kilometers, serve as primary conduits for concentrated runoff, facilitating the downslope transfer of water, sediment, and eroded material. In doing so, they reflect and reinforce ongoing landscape evolution and contribute to downstream sedimentation challenges (Zhu et al., 2018).

To combat degradation in the hilly–gully region, extensive afforestation efforts have been implemented on hillslopes, while hydraulic structures—including check dams and ponds—have been constructed in gullies (Feng et al., 2016; Xue et al., 2025). These interventions have significantly altered runoff dynamics and water budgets (Huang et al., 2013; Yuan et al., 2022). While afforestation has reduced soil moisture in hilly areas via enhanced evapotranspiration (~8.7%), hydraulic engineering has increased soil moisture in gullies by 21% (Wang et al., 2019, 2020; Zhao et al., 2019, 2024). Notably, the additional water retained within gully systems offsets an estimated 44% of the water loss from afforested hillslopes, partially reshaping the local water cycle (He et al., 2020; Zhao et al., 2024). Under such intensive human modification, the Plateau's inherently complex landforms and stratigraphy have come to exert even greater control over groundwater recharge dynamics (Li et al., 2024).

Research on groundwater recharge in the Loess Plateau's gully regions is incomplete, with most studies concentrating on deep profiles in tableland and hilly areas (Huang et al., 2011; Li et al., 2017; Lu, 2021; Wang et al., 2024). Early scholars proposed that fissures and caves in loess enabled preferential flow, allowing precipitation to reach groundwater (Yan and Wang, 1983). However, Xu et al. (1993) argued that the vertical fractures in the loess layer do not facilitate continuous water movement; instead, the vertical joints and large pores may act as barriers, which is caused by air-blocking effects. Li (2001) argued that the formation of dried soil layers further disrupts groundwater recharge pathways, causing precipitation to cycle within the soil–plant–atmosphere system rather than contributing meaningfully to groundwater recharge. In recent years, researchers have applied isotope tracing, hydrochemical analysis, and model simulations to study recharge mechanisms in deep-loess regions (Lu, 2020; Xiang, 2020; Shi

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et al., 2021; Wang et al., 2023). 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 refers to a type of water movement through the unsaturated (vadose) zone or an aquifer where newly infiltrating water pushes the existing water downward, much like a piston in a cylinder (Gee and Hillel, 1988).

However, deep-profile recharge mechanisms observed in tableland and hilly areas may not apply to gully landscapes on the plateau. Regional-scale analyses of 40 years of soil moisture data show that precipitation infiltration in thick loess deposits is typically restricted to shallow depths, even though loess thickness in tableland and hilly areas ranges from 56.5 to 204.5 m (Wang et al., 2024; Qiao et al., 2017). In contrast, loess in gully regions is generally much thinner—often less than 50 m (Zhu et al., 2018). Infiltration on loess slopes appears similarly limited (Fig. 1).

During field observations in the 2023 rainy season in the Nianzhuang Catchment, located in the hilly–gully region of the Loess Plateau, we found little evidence of preferential flow through cracks or macropores. Instead, infiltration appeared slow and driven predominantly percolation through the matrix (Wang et al., 2024). That year, total rainfall from May to October amounted to 420 mm, with 115 mm falling in September alone. Consistent with earlier studies (Xu et al., 1993; Li, 2001), only a few surface cracks showed signs of infiltration, and even then, the water was absorbed by surrounding soils and failed to infiltrate deeper (Fig. 1c). Moreover, soil profiles remained unsaturated from the surface to deeper layers, indicating that precipitation infiltration is generally insufficient to recharge groundwater (Qiao et al., 2017). After a 41-mm rainfall event occurring over four days, infiltration depths reached only 20–30 cm at the top of the slope, compared with 80 cm at mid-slope positions (Fig. 1b, c).

These patterns indicate that infiltration is limited at higher slope elevations, with much of the water moving laterally downslope as overland flow and accumulating in gully areas, where conditions are more conducive to groundwater recharge. Previous studies have shown that gullies and other topographic depressions function as key recharge zones, enabling concentrated surface flows to infiltrate more deeply and contribute to subsurface water stores (Gates et al., 2011; Liu et al., 2011; Zhao et al., 2021). Building on this foundation, advancing our understanding of gully-driven recharge requires targeted investigation of interactions among precipitation, surface water, and groundwater—particularly the flow paths and magnitudes of near-surface infiltration. These insights are critical for guiding water resource

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management and ecological restoration across the Loess Plateau.

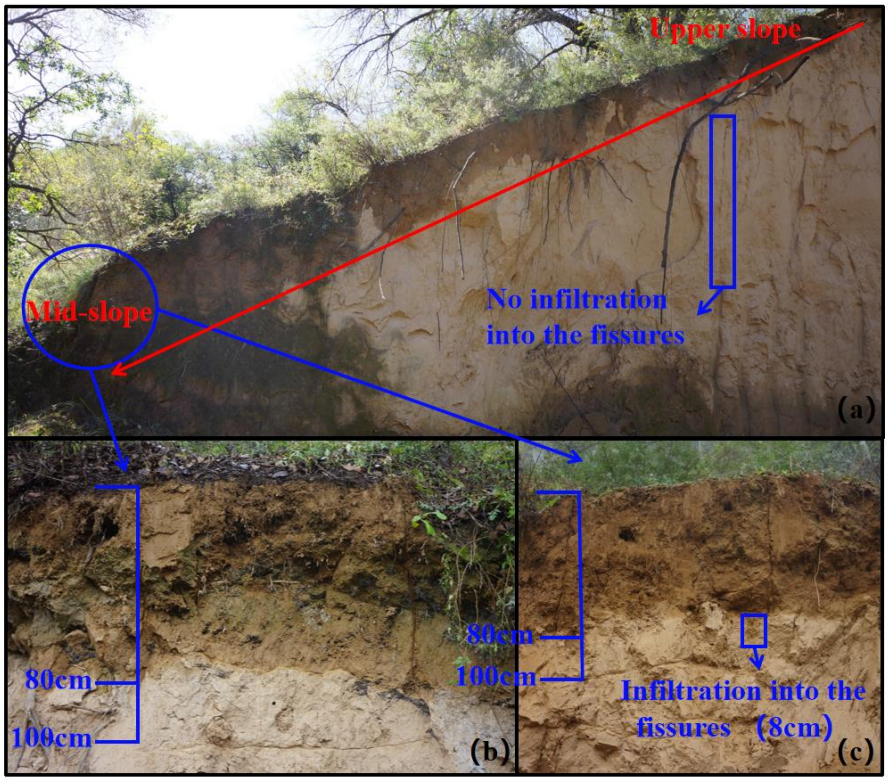

Fig. 1. The topographic profile of the Nianzhuang catchment in the hilly region of the Loess Plateau. Full profile from the top to mid-slope (a); two repeated mid-slope profiles (b, c). The photo was taken after a 41 mm rainfall event over four days. Subsequent measurements showed that infiltration depths reached only 20–30 cm at the top of the slope, compared to approximately 80 cm at the mid-slope positions.

3. Sampling site

The Nianzhuang Catchment is located northwest of Yan'an City in Shaanxi Province, China (approximately 36°42′N, 109°31′E). As a tributary of the Yanhe River—which ultimately flows into the Yellow River—the catchment spans 53.94 km² and includes the well-studied Yangjuangou sub-catchment (3.11 km²; ~36°35′N, 109°32′E), previously investigated in numerous hydrological and ecological studies (Fu et al., 1999; Liu and Li, 2017). Elevation ranges from 896 to 1,269 m, with terrain gradually sloping from northwest to southeast (Fig. 2). The region experiences a semi-arid continental monsoon climate, with a mean annual precipitation of approximately 550 ± 100 mm, concentrated

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between July and September (Liu et al., 2017).

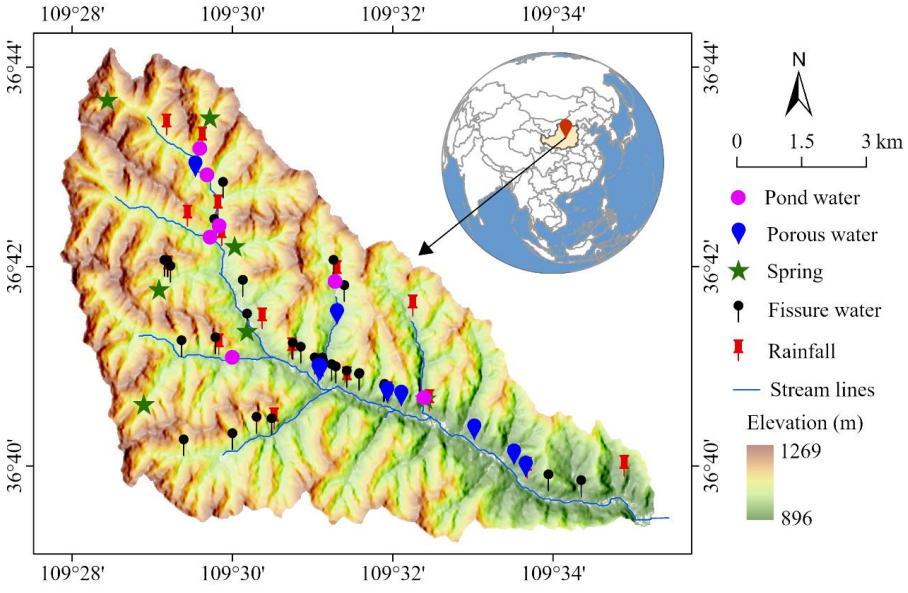

Fig. 2. The geographical location and sampling sites for rainfall, pond water, pore water, spring water, and fissure water in the Nianzhuang catchment. The Nianzhuang catchment is located in the hilly and gully region of the central Loess Plateau, with elevations ranging from 869 to 1269 m. The average depth of pore water wells is 8.0 ± 1.5 m (range: 4–10 m), while that of fissure water wells is 57.6 ± 29.2 m (range: 25–170 m). These sampling sites represent locations where both rainy and dry season samples were collected, and are all situated within the gully areas of the catchment.

The catchment features highly dissected loess terrain, with characteristic soils and landforms such as Loess Liang (ridges), Loess Mao (mounds), and steep loess slopes (Cai et al., 2019). Gullies—often "V"- or "U"-shaped—dominate the lower-lying regions and serve as important recharge zones. These landforms, together with ancient landslides, minor collapses, and sinkholes, highlight the geomorphic instability of the Loess Plateau landscape (Li et al., 2021).

The stratigraphy of the catchment reflects the typical layered structure of the Loess Plateau, which plays a key role in controlling groundwater recharge. In upland hilly areas, thick loess deposits overlie bedrock, with the Upper Pleistocene Malan Loess—light grayish-yellow, loosely textured, and silt-rich (>60%)—characterized by well-developed vertical joints and abundant hematite and goethite. Beneath it lies the Middle Pleistocene Lishi Loess, a grayish-yellow to light brown unit with prominent jointing and higher iron mineral content. Below the loess, the Neogene Red Clay appears as a distinctly reddish,

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calcareous nodule–bearing aquitard due to its low permeability. The entire sequence rests on Jurassic sandstone–conglomerate bedrock, composed mainly of quartz-rich fluvial–lacustrine deposits.

Loess thickness in the Liang and Mao regions often exceeds 150 meters, resulting in deep water tables and limited groundwater accessibility. In contrast, gully zones exhibit distinctly different hydrogeological characteristics. Here, thinner loess layers overlie Neogene and Jurassic formations, sometimes interbedded with coal seams up to 5 meters thick (Fig. 3a–c). The significant reduction in loess thickness—combined with the relatively high permeability of Neogene coarse sandstone and conglomerate (7.5–36.19 m/d)—creates favorable conditions for infiltration and focused recharge.

These dynamics are especially evident at gully heads, where surface runoff from adjacent uplands converges and infiltrates, forming efficient recharge zones. As a result, gully areas tend to have shallower water tables and more rapid water renewal, making them more suitable for domestic groundwater use. Springs frequently emerge at gully bottoms where lateral flow is facilitated at the loess–bedrock interface. Streams in this dry environment are largely intermittent.

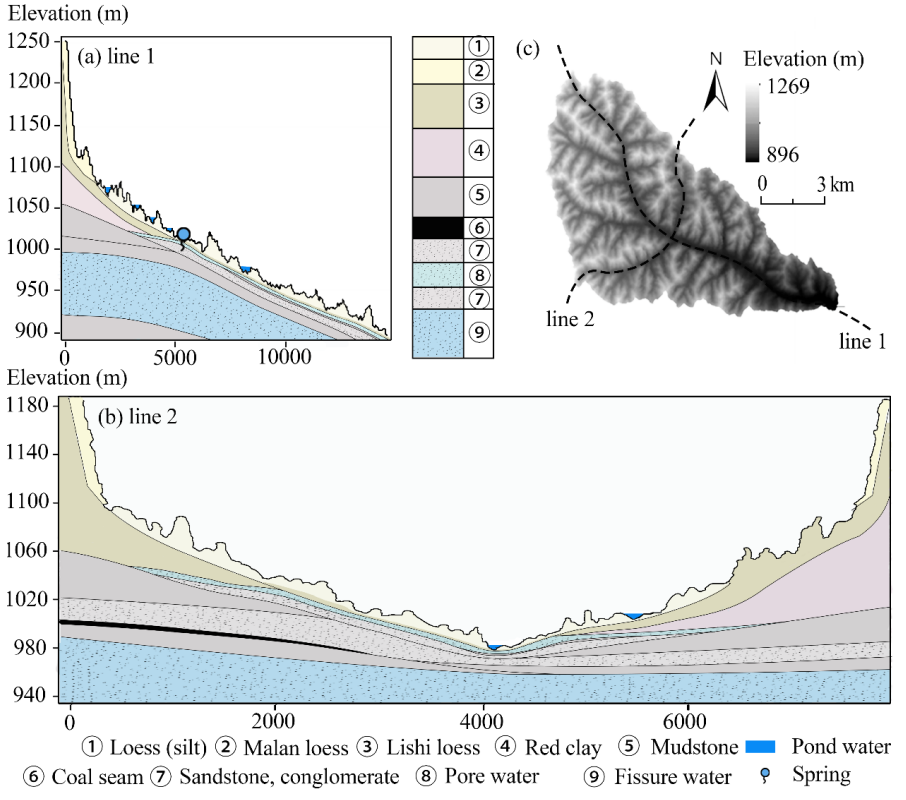

Fig. 3. Hydrogeologic cross-section of the study area. Cross-section along Line 1 (Northwest-Southeast)

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(a); cross-section along Line 2 (Southwest-Northeast) (b); location map of Line 1 and Line 2 within the study area (c). The Malan Loess (11.7–12.6 Ka BP) and Lishi Loess (12.6–78.1Ka BP) are two major Quaternary loess stratigraphic units in China. Based on hydrogeological research, the stratigraphy of the hilly region features a multi-layer structure from top to bottom: Upper Pleistocene Malan Loess, Middle Pleistocene Lishi Loess, Neogene Red Clay and Mudstone (*2.58–23.03* Ma BP), and Jurassic Sandstone and Conglomerate (145–201.3 Ma BP). In the gully region, the stratigraphy includes Holocene loess (silt, 11.7 ka BP–present), Middle Pleistocene Lishi Loess, Neogene sandstone and mudstone, and Jurassic sandstone and conglomerate, with some areas containing coal seams up to 5 meters thick.

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. Conceptually, “pore water” here refers to groundwater in a saturated aquifer, not to soil moisture. Fissure water occurs within fractured bedrock aquifers but is spatially discontinuous due to irregular fissure development. Hydraulic conductivity in these sandstone and conglomerate aquifers ranges from 0.0218 to 0.471 m/day (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.

Over recent decades, landscape rehabilitation through the Grain for Green Project and land reshaping under the Gully Land Consolidation Project have significantly altered the hydrological regime (Fu et al., 1999; Liu et al., 2017). Historically, surface runoff in the degraded catchment was flashy and episodic due to sparse vegetation. However, ecological restoration and small-scale engineering interventions—such as check dams, terraces, roads, and ponds—have moderated surface hydrology. Surface runoff, generated primarily during storm events, now contributes alongside delayed baseflow from groundwater recharge and interflow. The latter is often limited by the thick unsaturated zone in upland loess areas but may be enhanced in gully regions, where stratigraphy and land use favor infiltration (Wang et al., 2024; Gates et al., 2011). Gully areas also contain numerous check dams and ponds, with most water sourced from Hortonian overland flow and direct rainfall. These small water bodies, often constructed for erosion control and water retention, influence local hydrological dynamics and may play a role in enhancing infiltration and recharge.

4. Methods

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Our approach integrates stable isotope analysis (δ^2H and $\delta^{18}O$), chloride concentration analysis, and water table fluctuation monitoring to investigate groundwater recharge dynamics. The isotopic composition of water bodies reflects both their origins and the processes they undergo—such as evaporation, infiltration, and mixing (Wan and Liu, 2016; Kumar et al., 2019; Dasgupta et al., 2024). Precipitation, surface water, and groundwater typically exhibit distinct isotopic signatures due to these differing pathways (Gleeson et al., 2016; Kuang et al., 2019; Al-Oqaili et al., 2020). When isotopic patterns among water sources converge, it often indicates strong hydrological connectivity (Yang and Wang, 2023). Because stable isotopes behave conservatively, they serve as effective tracers of water sources and flow paths (Gleeson et al., 2016; Al-Oqaili et al., 2020; Dasgupta et al., 2024). In parallel, water table fluctuation (WTF) monitoring provides a means of estimating recharge by observing changes in groundwater levels in response to precipitation events (Nachabe, 2002; Heppner and Nimmo, 2005; Gumuła-Kawęcka et al., 2022). By combining these complementary methods, this study aims to elucidate groundwater recharge pathways and quantify recharge rates in gully regions—thereby identifying key recharge zones and advancing our understanding of groundwater processes in the Loess Plateau.

4.1. Field measurements of hydrological data

Precipitation was collected from October 24, 2023, to October 24, 2024, using a weather station situated in an open field within the catchment. Continuous groundwater level data were recorded from September 24, 2023, to December 20, 2024. Groundwater pressure and temperature were monitored using Onset HOBO U20-001-03 sensors (20 m range), and water table levels were calculated based on the measured pressure data. The conversion relationship between water pressure and groundwater level is given by $Y = 0.86 \times X - 22.1$ where Y represents the groundwater level and X represents the water pressure. Notably, the monitoring well is located in the pore water layer of the gully region. The well is hand-dug (1.1 m wide, 10 m deep) and is unaffected by human activities.

Soil physical properties were assessed using the cutting ring method, based on undisturbed soil cores collected at five depth intervals: 0–10, 10–20, 20–30, 30–40, and 40–50 cm. Quadruplicate samples were taken near groundwater monitoring wells in the gully using pre-weighed cutting cylinders. The samples were immediately transported to the laboratory for analysis. Bulk density, capillary porosity, non-capillary porosity, total porosity, and field water capacity were determined following the LY/T 1215-1999 standard for forest soil water-physical properties. Soil particle size distribution was analyzed using

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a laser particle size analyzer at the College of Natural Resources and Environment, Northwest A&F University. Soil texture classification followed the USDA system: sand (0.05–2 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) (Dane et al., 2002).

4.2 Water sampling

A total of 181 water samples were collected from various locations in rainy season (September 2023, 99 samples) and dry season (April 2024, 82 samples); see Fig. 2. Rainy season samples included 48 from rainfall, 7 from pond water (water retention reservoirs), 9 from spring water, 9 from pore water, and 26 from fissure water. During the dry season, samples included 31 from rainfall, 6 from pond water, 8 from pore water, 29 from fissure water, and 8 from spring water.

Pore water was collected from several shallow, hand-dug wells measuring approximately 1.1 meters in diameter and 4–10 meters in depth. Fissure water was sampled from deeper, narrow-diameter wells (0.2 meters wide, 25–170 meters deep). In areas with numerous deep wells, we employed random sampling to ensure representative coverage of fissure water sources. To minimize the risk of collecting stagnant water, all pore and fissure water wells were purged for 10–15 minutes prior to sampling. Spring water was collected directly from natural discharge points, although most springs in the region exhibit low flow rates—typically less than 0.1 L/s, occasionally reaching up to 0.2 L/s.`

A total of 18 bulk rainfall collectors were randomly and evenly distributed across the 54 km^2 study area, and samples were collected immediately following rainfall events. For nighttime precipitation, samples were collected the next morning at 6:00 AM. During the study period, we collected two types of precipitation samples: (1) spatial samples from individual events (18 in the rainy season and 15 in the dry season) across the catchment, capturing spatial variability; and (2) sequential events at a fixed station (30 in the rainy season and 16 in the dry season), characterizing seasonal inputs.

During sampling, 100 mL collection bottles were rinsed two to three times with the sample water, then slowly filled to minimize air exposure. After filling, the bottles were tightly sealed with screw caps and further secured with Parafilm to prevent evaporation and contamination. All samples were immediately stored in a portable cooler at 4°C and transported to the laboratory for isotopic and chloride concentration analysis.

4.3. Isotopic analysis

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The δ^2H and $\delta^{18}O$ values of the water samples were determined using a Los Gatos Research liquid water isotope analyzer (Model 912-0032, LGR Inc., California, USA) at the Institute of Water-Saving Agriculture in Arid Areas of China, Northwest A&F University. Each sample was injected six times in the following sequence: three standard injections, followed by six natural sample injections, and then three additional standard injections. The isotope ratios were calculated using the average composition from injections 4 through 6.

Isotope values are expressed in delta (δ) notation, which represents the relative difference in isotope ratio between a sample and the Vienna Standard Mean Ocean Water (VSMOW) reference. The measurement precision was ±0.5‰ for δ^2H and ±0.1‰ for $\delta^{18}O$. The delta values were calculated using the following equations:

$$\delta^{18}O = \left(\frac{R_{sample}}{R_{standard}}\right) - 1 \quad (1)$$

$$\delta^{2}H = \left(\frac{R_{sample}}{R_{standard}}\right) - 1 \quad (2)$$

where R_{sample} and $R_{standard}$ are the ratios of heavy to light isotopes ($^{18}O/^{16}O$ or $^{2}H/^{1}H$) in the sample and the standard, respectively. Results are expressed in per mil (‰).

4.4. Mixing process of different water bodies

Inverse transit time proxies (ITTPs) were calculated to assess differences in water transit times and mixing processes across various water bodies (Tetzlaff et al., 2009). ITTPs are defined as the ratio of the standard deviation of $\delta^{18}O$ in the water sample (e.g., pond water, spring water, pore water, or fissure water) to that in precipitation over the same time period:

$$\mathbf{ITTP} = \frac{\sigma\delta^{18}O(\text{sample})}{\sigma\delta^{18}O(\text{precipitation})} \quad (3)$$

This ratio captures the attenuation of seasonal isotopic variability in $\delta^{18}O$ as water moves through the landscape. In general, ITTP values less than 1 indicate substantial damping of the precipitation signal—consistent with longer water residence times, greater mixing, and larger storage volumes. Conversely, values approaching 1 suggest minimal damping and rapid flow paths.

However, interpretation of ITTPs must also account for fractionation processes. In particular, evapotranspiration (ET) selectively removes lighter isotopes (^{16}O), enriching the remaining water in heavier isotopes (^{18}O). This enrichment can artificially increase the variance of $\delta^{18}O$ in near-surface or shallow soil water compartments, inflating ITTP values even in systems with relatively slow transit times

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(Tetzlaff et al., 2009). This is especially relevant in arid and semi-arid regions, where ET can dominate the water balance during dry seasons.

4.5. Hydraulic connectivity estimation

Structural Equation Modeling (SEM) has been widely applied in water science to evaluate complex causal relationships among hydrological, geological, and anthropogenic variables—particularly in studies of groundwater contamination and water quality degradation (Wu, 2010; Lupi et al., 2019; Xie et al., 2025). In this study, we adapted SEM as an exploratory framework to assess hypothesized recharge linkages among water sources, using dual-isotope (δ^2H–$\delta^{18}O$) data from rainfall, pond water, spring water, pore water, and fissure water. Although SEM is not a mass-conserving approach and is less commonly used in isotope-based flowpath analysis, it enables estimation of statistically significant relationships and indirect linkages within a hypothesized recharge system.

Given the potential for isotopic signatures to be altered by evaporation, mixing, or other non-conservative processes, results must be interpreted with caution. Pathways with p-values > 0.05 were excluded during model refinement, and the final model met standard goodness-of-fit criteria (degrees of freedom < 3, RMSEA < 0.05, CFI > 0.95, NFI > 0.95). SEM analysis was conducted using SPSS Amos 26.0 (IBM SPSS, Chicago, Illinois, USA).

In addition, we applied variance partitioning to evaluate the relative contributions of different water sources to pore and fissure water. This method decomposes the total variance in isotopic composition into components attributable to individual sources (e.g., precipitation, pond water, spring water), offering a complementary estimate of source influence. While useful, this approach remains subject to the same limitations as SEM—particularly the challenges of isotopic overlap and limited resolution in environments affected by mixing and evaporation (Lai et al., 2022).

To further constrain recharge pathways, we incorporated chloride ion (Cl^-) as a conservative tracer. Unlike stable isotopes, chloride is unaffected by evaporation or biological processes, making it a robust indicator for identifying recharge sources and tracking subsurface water movement. Chloride concentrations in all water samples were analyzed using an ion chromatograph (DIONEX ICS-1100) at the College of Natural Resources and Environment, Northwest A&F University, China. Each sample was analyzed in triplicate, with charge balance errors maintained below 5% to ensure analytical accuracy. This rigorous approach enhances the reliability of chloride data, supporting its integration with isotopic

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indicators in source attribution.

4.6. Groundwater recharge

Groundwater recharge in the gully zone is quantified using the water table fluctuation (WTF) method, which infers recharge and discharge events from temporal changes in groundwater levels (Healy and Cook, 2002; Gumuła-Kawęcka et al., 2022). We recognize that recharge can originate from three hydrological sources: (1) surface water; (2) the unsaturated zone (3) and the saturated zone (Scanlon et al., 2022; Wang et al., 2024). Among these, estimates based on the saturated zone are generally most reliable, as recharge from the unsaturated zone reflects potential inputs that may never reach the water table (Beven and Germann, 2013; Huang et al., 2019). The WTF method is widely used for estimating saturated zone recharge due to its high temporal resolution and conceptual simplicity (Xu et al., 2024). Based on previous site-specific studies (Wang et al., 2024), this method is well-suited for our analysis.

The water table fluctuation method assumes that changes in the groundwater table result solely from recharge or discharge, assuming a constant specific yield (*Sy*) over time (Healy and Cook, 2002; Obuobie et al., 2012). The formula is as follows:

$$R_i = S_y \frac{\Delta H_i}{\Delta t} \quad (4)$$

where, R is the groundwater recharge (mm), *Sy* is the specific yield of the aquifer, ΔH_i (where ΔH_i>0) is the groundwater table rise caused by recharge between day $i-1$ and i, and t is time period. Specific yield, which represents the proportion of water that drains freely from the saturated zone under gravity, was determined using two methods: the soil texture empirical method and the test pit method (Liang, 2016).

Empirical values for soil texture are referenced in Table A1. The test pit method for estimating S_y is described as follows:

$$S_y = TP - FWC \quad (5)$$

where, TP (total porosity) and FWC (field water capacity) were measured using the cutting ring method.

We applied two methods to calculate the daily groundwater table increments (ΔH_i). The RISE method assumes that recharge occurs only when the groundwater table elevation increases between two consecutive days (Gumuła-Kawęcka et al., 2022). Thus, $\Delta H_i = H_i - H_{i-1}$ if $H_i > H_{i-1}$, otherwise,

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$\Delta H_i = 0$. The master recession curve (MRC) method assumes that, in the absence of recharge, the groundwater table declines daily by a specific amount (ΔH_{MRCi}). This amount represents a simplified approximation of discharge processes in the aquifer, particularly lateral outflow to nearby surface water bodies. MRC establishes a functional relationship between a daily decrement of the water table (ΔH_{MRCi}) and the water table elevation (H_{i-1}) during periods without recharge.

$$\Delta H_{MRCi} = A \cdot H_{i-1} + B \quad (6)$$

where, the coefficients A and B were fitted for each piezometer based on data from periods of continuous groundwater table decreases lasting longer than two weeks. The daily water table increment due to recharge was then calculated as: $\Delta H_i = H_i - H_{i-1} + \Delta H_{MRCi}$ if $H_i > (H_{i-1} - \Delta H_{MRCi})$, otherwise, $\Delta H = 0$.

Notably, we used water dynamics from October 24, 2023, to October 24, 2024, to calculate pore water recharge, as this period exhibited clear groundwater fluctuations, making it more representative.

5. Results

5.1. Soil properties

The upper 50 cm of the soil profile is composed primarily of silt (64.6 ± 0.6%), with smaller but nearly equal proportions of clay (18.0 ± 1.3%) and sand (17.4 ± 1.6%), classifying the loess as silt loam according to the International Union of Soil Sciences (IUSS) scheme (Fig. 4a). Total porosity and field water capacity decreased slightly with depth, averaging 24.5 ± 1.9% and 21.3 ± 1.7%, respectively (Fig. 4b). Specific yield remained relatively consistent within the 10–50 cm depth interval, averaging 3.2 ± 0.8%--falling within the expected empirical range for silt loam soils (2%–7%) (Fig. 4c).

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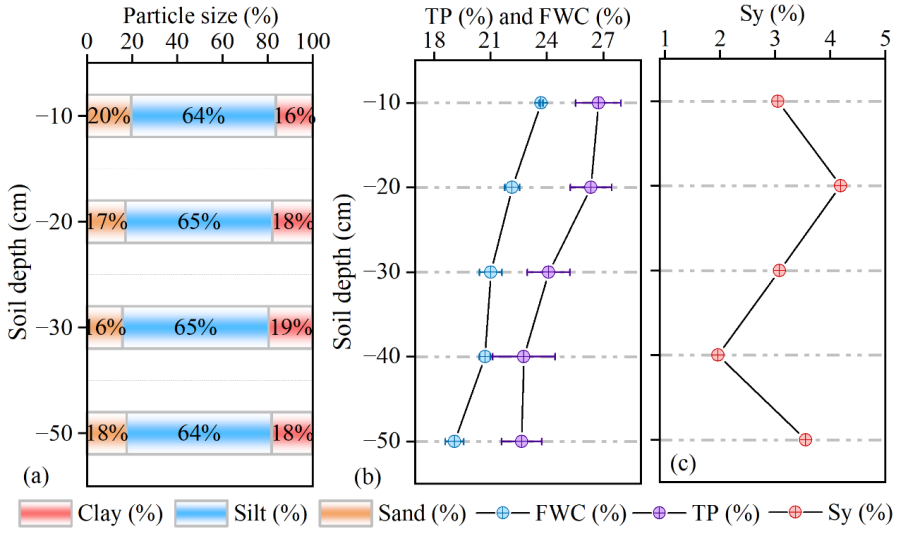

Fig. 4. Vertical variation in soil texture and water retention characteristics in the gully region of the Loess Plateau. (a) Soil particle size distribution by depth, showing relatively uniform composition across layers (10–50 cm), dominated by silt (64–65%), with moderate clay (16–20%) and low sand (16–20%) content. This fine-textured profile supports high moisture retention and slows infiltration, promoting delayed recharge. (b) Depth profiles of total porosity (TP) and field water capacity (FWC) reveal increases with depth to 40 cm, with FWC reaching ~27%, suggesting greater water-holding capacity in subsoil layers and enhanced buffering of infiltrated water. (c) Specific yield (Sy) peaks at −20 cm (4.5%) but decreases with depth, indicating shallower layers are more responsive to infiltration and release, while deeper layers tend to store water with minimal drainage. Collectively, these physical properties reflect a vertically stratified soil system where near-surface layers regulate infiltration pulses, and deeper layers act as long-term storage, shaping the timing and magnitude of subsurface recharge.

5.2. Hydrological signatures of rainfall, surface water, and groundwater sources

Pond water and rainfall exhibit similar spatial isotopic patterns, with more positive δ^2H values ($\delta^2H > -55‰$) than spring water, pore water, and fissure water (Fig. 5a, b). These values are line with the notion of direct rainfall and Hortonian runoff are the primary source of pond water. In contrast, the δ^2H values of pore, spring, and fissure water show little seasonal variation and are consistently more negative ($\delta^2H < -55‰$), than mean rainfall, indicating longer residence times and reduced evaporative influence.

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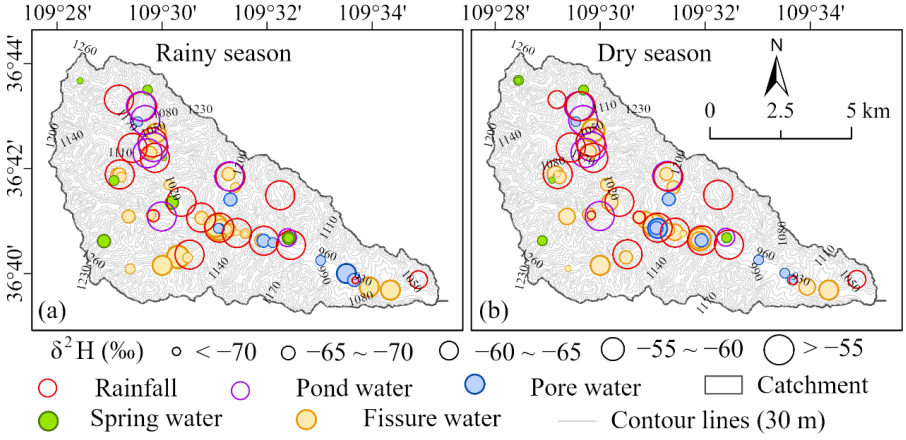

Fig. 5. The spatial distributions of δ^2H values during the (a) rainy season and (b) dry season for rainfall, pond water, spring, pore water, and fissure water in the gully region of the Loess Plateau. To highlight spatial differences among water sources, δ^2H values were classified into five intervals: < −70‰, −70 to −65‰, −65 to −60‰, −60 to −55‰, and > −55‰. Sampling points are color-coded by water type: red for rainfall, purple for pond water, blue for pore water, green for spring water, and orange for fissure water.

The δ^2H–$\delta^{18}O$ relationships and box plots for each water source reveal key insights into the dominant hydrological processes occurring during the rainy season (Fig. 6). Firstly, rainfall follows a Local Meteoric Water Line (LMWL) of $\delta^2H = 7.7 \cdot \delta^{18}O + 8.9$ ($R^2 = 0.95$), which is closely aligned—though slightly offset—from the Global Meteoric Water Line (GMWL: $\delta^2H = 8 \cdot \delta^{18}O + 10$) (rainy season; Fig. 6a, c). This alignment confirms that precipitation in the region has a typical meteoric origin. Additionally, minimal evaporative enrichment occurred prior to collection. The relatively wide interquartile range of rainfall $\delta^{18}O$ values suggests that precipitation was derived from storm systems with considerable isotopic variability, reflecting differences in rainfall intensity, air mass origin, and temperature (Kumar et al., 2019; Oqaili et al., 2020; Dasgupta et al., 2024). However, this variability remains moderate compared with global patterns that span extreme rainfall events and broader climatic gradients.

Pond water, in contrast, exhibits a clear evaporation signature with a shallower slope of $\delta^2H = 5.6 \cdot \delta^{18}O - 17.1$ (rainy season; $R^2 = 0.95$), $\delta^2H = 4.6 \cdot \delta^{18}O - 20.7$ (dry season; $R^2 = 0.74$). This signature aligns with expectations for surface water bodies, where open exposure facilitates fractionation. The box plot confirms strong evaporative enrichment, with median values shifted significantly toward more

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positive $\delta^{18}O$ and $\delta^{2}H$ compared to rainfall (Fig. 6a, c). Pond water maintains a relatively consistent slope and range across seasons, reinforcing its stable evaporative signature and less dynamic recharge behavior.

Spring water shows a clear seasonal transition in its isotopic composition. In the rainy season, its evaporation line ($\delta^{2}H = 6.2 \cdot \delta^{18}O - 11.4$; $R^2 = 0.75$) falls closer to the LMWL, suggesting that spring discharge is augmented by recent rainfall, likely delivered through rapid infiltration and shallow subsurface flow pathways during high-intensity events (Fig. 6a, b). However, the isotopic values of spring water are substantially more depleted than those of precipitation, indicating that older water stored in the porous subsurface aquifer dominates the overall spring flow composition composed of new and relatively old water.

During the dry season, the isotopic slope flattens and deviates further from the Local Meteoric Water Line (LMWL), reflecting increased evaporative influence or prolonged residence times (Fig. 6c, d). This seasonal shift suggests that as rainfall inputs decline, spring discharge becomes increasingly composed of slow-draining, older water that has undergone greater isotopic modification—either through mixing or evaporation in near-surface storage zones. Collectively, these patterns suggest that spring water acts as a dynamic integrator of recharge processes—rapidly responding to event-driven infiltration during the rainy season, yet also reflecting the delayed mobilization of older water stored in the subsurface. This behavior may be partly explained by a piston-like displacement mechanism, where incoming rainfall pushes pre-existing groundwater toward discharge zones.

Pore and fissure water show remarkably similar isotopic signatures during the rainy season. Pore water, again sampled from a porous subsurface aquifer, follows a fitted line of $\delta^{2}H = 4.3 \cdot \delta^{18}O - 27.9$ (rainy season; $R^2 = 0.74$), while fissure water, likely drawing from the same aquifer but through weathered bedrock pathways, fits $\delta^{2}H = 3.7 \cdot \delta^{18}O - 32.0$ (rainy season; $R^2 = 0.70$). These slopes are significantly flatter than those of rainfall, pond, or spring water, a pattern interpreted as evidence of evaporation prior to recharge or mixing with evaporated surface water. However, the box plots of the isotope data present a different picture. Both pore and fissure waters are systematically more depleted in $\delta^{18}O$ and $\delta^{2}H$ than precipitation, and their narrow interquartile ranges suggest a relatively uniform isotopic composition (Fig. 6a-d). Rather than showing the enrichment expected from evaporation, these depleted and stable values point toward recharge dominated by a limited number of isotopically light rainfall events, such as early-season storms or high-altitude convective systems.

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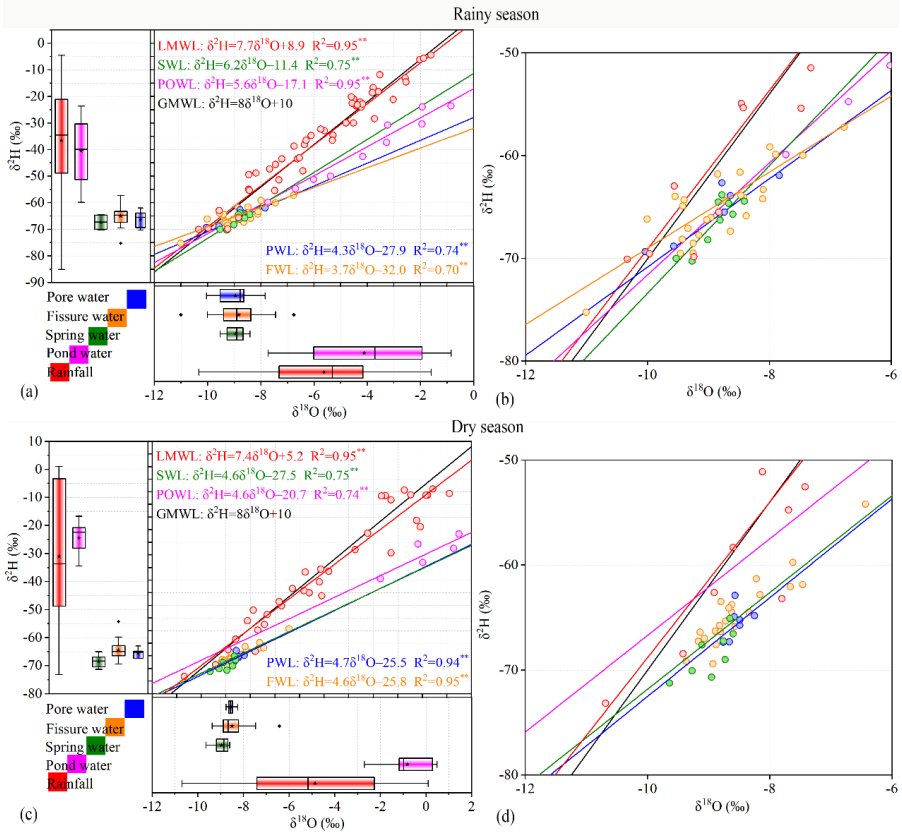

Fig. 6. Dual stable isotopic compositions of rainfall, pond water, spring water, pore water, and fissure water during the (a) rainy season and (b) dry season in the gully region of the Loess Plateau. The black line represents the global meteoric water line (GMWL, δ2H=10 + 8δ18O). GMWL is the global meteoric water line of Craig, LMWL is the local meteoric water line, SWL is the spring water line, POWL is the pond water line, FWL is the fissure water line, and PWL is the pore water line. Panels (b) and (d) are magnified views of (a) and (c), respectively, highlighting the isotopic compositions of pore water, fissure water, and spring water (x-axis: –12 to –6‰; y-axis: –80 to –50‰).

This apparent contradiction—flat regression slopes alongside depleted and uniform isotopic compositions—can be reconciled by considering longer residence times and mixing in the subsurface. The aquifer likely functions as a hydrological buffer, smoothing short-term isotopic variability and maintaining a signature reflective of older recharge. In this context, the low slopes may not indicate evaporation but instead reflect the dampening of seasonal isotope fluctuations through storage and subsurface mixing (Table A2).

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Complimenting the isotope data, Cl^- levels in pore water consistently fall between those of precipitation and pond water across both seasons (Fig. A2), supporting a mixed recharge origin. This trend aligns with the isotopic evidence from the rainy season and supports the interpretation that pond water contributes to pore water recharge via vertical percolation through the vadose zone, particularly during high-rainfall periods when infiltration capacity is exceeded. The lack of a similar isotopic pattern in the dry season likely reflects stronger evaporative enrichment of pond water, which masks its potential contribution to pore water recharge in dual-isotope space.

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).

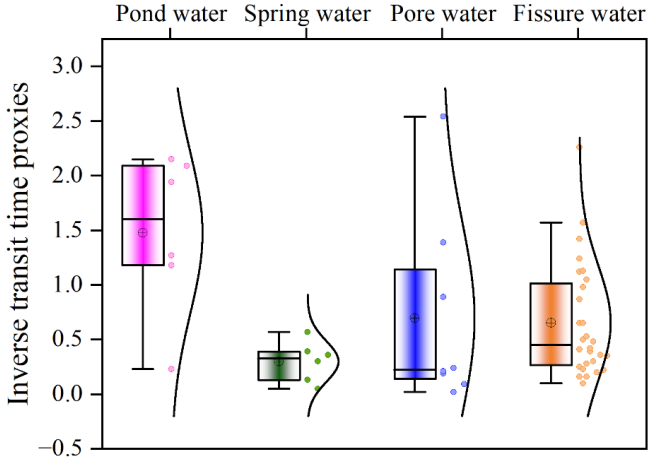

Fig. 7. Boxplots and kernel density estimates of inverse transit time proxies (ITTPs) for pond water, spring water, pore water, and fissure water. Higher ITTP values indicate shorter water transit times since precipitation, while lower values suggest longer residence and greater isotopic damping. Pond water

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exhibited the highest and most consistent ITTPs (median ≈1.5), implying rapid recharge from recent rainfall or stormflow. Spring water showed the lowest ITTPs (≈0.3), consistent with longer subsurface flow paths and storage. Pore and fissure water displayed intermediate and more variable ITTPs, reflecting mixing between recent and older water sources, as well as seasonal differences in infiltration and soil moisture replenishment.

5.3. Hydrological linkages and recharge efficiency

The SEM analysis reveals significant hydrological linkages among different water bodies in the catchment, with particularly well-defined pathways connecting rainfall, pond water, pore water, and fissure water (Fig. 8a, b). Several key pathways identified in the model are supported by multiple lines of observational evidence, including isotopic composition, chloride concentrations, and water age (ITTP). Rainfall contributes over 73% to pore water recharge, far exceeding the <17% contribution from pond water (Fig. 8c).

However, the SEM results indicate that the total effect of pond water on pore water is stronger than that of rainfall (Fig. 8b). In SEM, the total effect includes both direct pathways (e.g., pond water → pore water) and indirect pathways mediated by other variables (e.g., rainfall → pond water → pore water). This apparent contradiction likely stems from the strong statistical association between rainfall and pond water, as pond water is primarily derived from rainfall and shares similar isotopic signatures. As a result, the model may overestimate pond water's influence on pore water due to overlapping signals and correlated pathways.

These findings underscore the importance of integrating multiple lines of evidence rather than relying solely on SEM outputs. For example, chloride concentrations in pore water more closely resemble those of pond water, suggesting mixed recharge from both sources and highlighting the potential for pond water to play a prominent role under certain spatial or temporal conditions (Fig. 2a). Although dry-season isotopic data provide limited support for a strong pond water–pore water connection, the spatial distribution of chloride offers compelling evidence that pond water can contribute significantly to pore water recharge, particularly in localized areas or during specific recharge events.

At deeper levels, the linkage between pore water and fissure water is supported by their nearly identical isotope values and similar ITTPs, suggesting a shared subsurface origin and a strong hydrological connection (Fig. 8a, b). In contrast, although there is some hydrological connectivity

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between pore water and spring water, differences in isotopic slopes and residence times may lead to an overestimation of their interaction. However, their nearly identical chloride concentrations provide more direct and reliable evidence of connectivity.

Although the model results initially suggest that rainfall—mediated through pond water—is the primary source of pore water recharge, discrepancies among the different indicators call for a more critical interpretation of the evidence. The contradictions observed across isotopic, chloride, and ITTP data underscore the need for further quantitative validation.

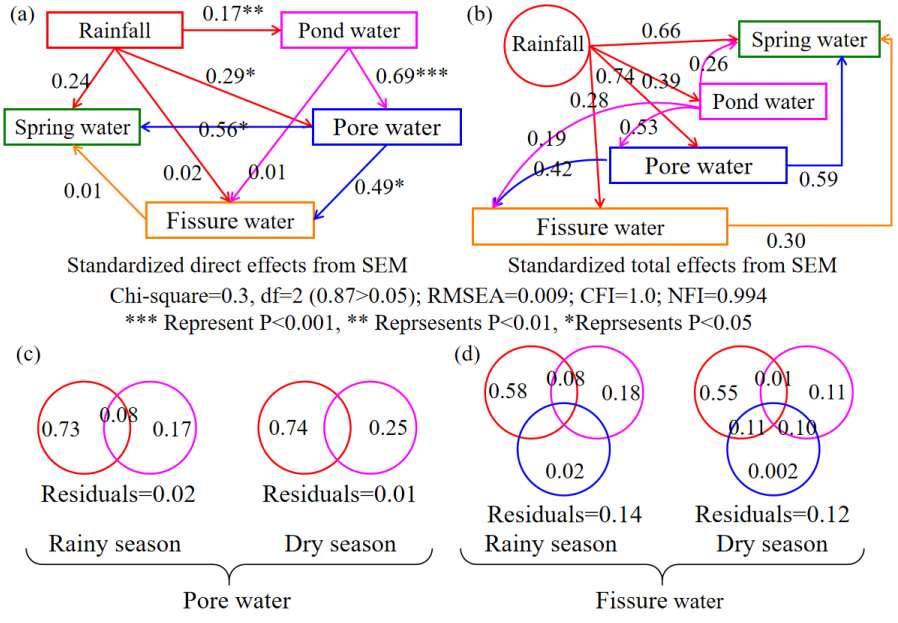

Fig. 8. Structural equation modeling (SEM) and variance partitioning results illustrating hydraulic connectivity among water sources in the gully region of the Loess Plateau. Panels (a) and (b) show the standardized direct (a) and total effects (b) among rainfall, pond water, pore water, spring water, and fissure water, based on $\delta^{18}O$ and $\delta^{2}H$ data. Arrows indicate hypothesized water flow pathways, with line thickness proportional to effect size. Asterisks denote statistical significance (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$). The model fit is excellent ($\chi^2 = 0.3$, $df = 2$, RMSEA = 0.009, CFI = 1.0, NFI = 0.994), supporting the robustness of these inferred connections. Panels (c) and (d) present variance partitioning results showing the relative contributions of source waters to pore water and fissure water during the rainy and dry seasons, respectively. In panel (c), rainfall (red) and pond water (pink) explain a large portion of pore water variability, with some shared explanatory power and modest residuals. In panel (d),

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fissure water reflects a more complex origin, with contributions from rainfall (red), pond water (pink), and pore water (blue), and greater overlap and residuals, especially during the dry season.

To address the contradictions observed in the SEM and variance partitioning results, we apply the water table fluctuation method to independently estimate the recharge rate from rainfall to pore water. Groundwater level fluctuations in the gully system revealed clear seasonal recharge dynamics, with an initial rise in the pore water table beginning on October 24, 2023, followed by a decline through early spring (March 1, 2024) and a gradual recovery starting June 20, 2024 (Fig. 9a). Between October 24, 2023, and October 24, 2024, cumulative recharge was estimated at 238.0 ± 6.0 mm (RISE) and 241.4 ± 6.0 mm (MRC), with 159 and 167 recharge days, respectively (Fig. 9b). Given that annual precipitation totaled approximately 550 mm, recharge efficiency was approximately 43–44%, underscoring the significance of focused infiltration in sustaining shallow aquifer recharge within the gully environment.

This recharge efficiency is lower than the precipitation-to-pore water contribution estimated by the variance decomposition method and may more accurately reflect “actual” recharge, as statistical estimates can be biased by similarities in isotopic signatures. When integrated with dual-isotope and SEM analyses, the WTF-based results support a conceptual model in which storm-driven runoff is efficiently captured and redistributed through loess soil matrices and retention structures (e.g., ponds, check dams), activating a hierarchy of shallow and deeper subsurface flowpaths. These flowpaths link pore water, fissure water, and spring discharge across the complex gully landscape, reflecting both vertical and lateral connectivity within the groundwater system.

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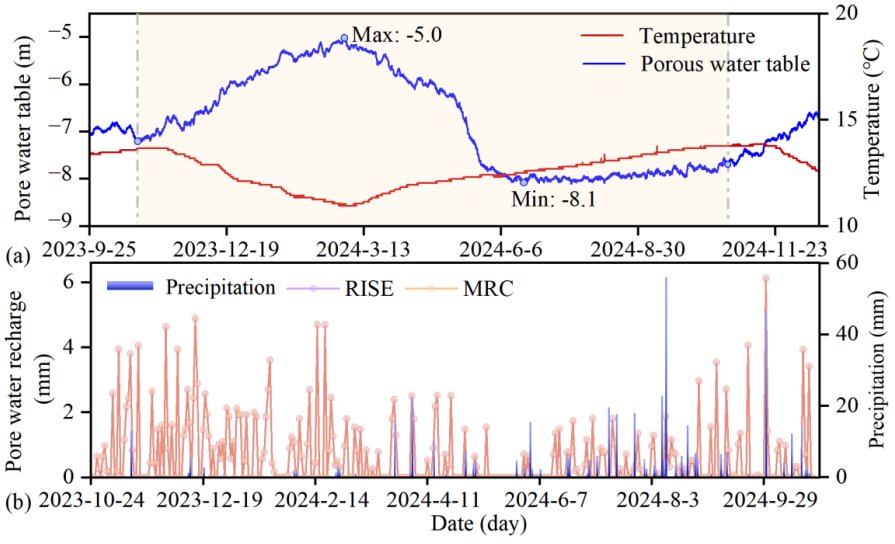

Fig. 9. Temporal dynamics of pore water table depth, temperature, precipitation, and recharge in the gully region of the Loess Plateau. (a) Daily time series of pore water table depth (blue line) and surface temperature (red line) from September 2023 to November 2024. The water table fluctuates seasonally, rising from ~−8.1 m in late summer to a maximum of ~−5.0 m in early spring (March 2024), indicating delayed infiltration and cool-season recharge. (b) Daily precipitation (blue bars) and modeled pore water recharge estimates using the RISE and MRC methods. 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.

6. Discussion

6.1. Isotopic compositions of various water bodies in the gully region

In hydrological studies, the isotopic composition of water bodies reflects both sources and changes in hydrological processes (Wan and Liu, 2016; Kumar et al., 2019; Dasgupta et al., 2024). Precipitation, surface water, and groundwater usually exhibit differences in isotopic characteristics due to variations in evaporation, infiltration, and mixing (Gleeson et al., 2016; Kuang et al., 2019; Al-Oqaili et al., 2020). However, similar isotopic distributions among different water bodies often indicate a strong hydrological

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connection in their water sources (Yang and Wang, 2023).

Our study found that rainfall and pond water have similar spatial isotopic distribution patterns, indicating that pond water primarily originates from rainfall. This reflects the region's geographical and hydrological characteristics. In this severely eroded gully region, the local government has constructed an extensive network of ponds and check dams to capture hillside runoff (Liu et al., 2017; Xue et al., 2025). As a result, most precipitation from the hills converges into these gully ponds and check dams. A lower pond water line slope indicates evaporation fractionation during retention. Evaporation preferentially removes lighter isotopes (^{1}H and ^{16}O), enriching heavier isotopes (^{2}H and ^{18}O) and shifting the pond water's isotopic composition from its precipitation source (Aragu et al., 1998; Zhang and Wu, 2009; Gleeson et al., 2016). This similarity is primarily due to the fact that pond water originates from rainfall and its runoff in the hilly-gully region (Liu et al., 2011; Ji et al., 2024). 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 the different groundwater types (Ouali et al., 2024). Nevertheless, these values fall within the range of precipitation isotopic values, leaning towards the more negative end, suggesting that groundwater is likely directly recharged by significant precipitation events. This is due to the thin unsaturated zone (<10 m) in the gully areas, which facilitates rapid infiltration and direct recharge from heavy rainfall.

To further investigate the complexity of different types of groundwater in the gully area, we conducted hydrological and geological surveys, collecting water samples from spring water, pore water, and fissure water. The results show that the isotopic values of spring water, pore water, and fissure water are closely clustered, indicating a strong interconnection among the different types of groundwater within the hydrological cycle. This is likely due to their shared geological and hydrological environments (Bouwer, 2002; Li et al., 2021; Zhang et al., 2022). Our study found that the water line slope of pore water and fissure water was higher in the dry season than in the rainy season, with values falling between the slopes of pond water from the rainy and dry seasons. To investigate the cause of these results, we analyzed groundwater level dynamics, which showed that water tables were lower at the end of the rainy season but rebounded afterward, making dry-season tables higher. This suggests that rainy-season groundwater mixes with evaporatively enriched water, lowering its slope, while dry-season groundwater is recharged by delayed rainfall and pond water, increasing its slope. These findings reveal that isotopic composition is influenced by both current and prior hydrological conditions. They also highlight the

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complexity of evaporation fractionation regulated by water mixing and demonstrate the significant impact of pond construction on groundwater recharge and regional hydrology in the gully regions.

6.2. Groundwater recharge processes in the gully region

In recent years, discussions of groundwater recharge sources have primarily focused on tableland and hilly areas with thick loess deposits, although only a few researchers have examined gully regions (Li et al., 2017; Xiang, 2020; Lu, 2020). For example, Liu et al. (2011) found that groundwater near valleys in the hilly loess area is replenished by precipitation, runoff, and surface water. Our findings support this study, identifying rainfall and surface water as major sources of gully groundwater recharge. We classify groundwater into three types (spring water, pore water, and fissure water) and propose a gradual recharge process, including (1) direct and indirect recharge from precipitation to pond water and pore water, respectively; (2) concentrated recharge from pond water to pore water; and (3) percolation recharge from pore water to fissure water. This reflects the complexity of the groundwater system and the significant impact of human activities (e.g., ponds and check dams) on hydrological processes.

In the deep-profile unsaturated zones of the hilly region on the Loess Plateau, previous studies have used chloride mass balance and tritium peak methods to estimate groundwater recharge from precipitation, typically accounting for 2%–22% of annual rainfall, with water residence times in the unsaturated zone lasting several years or even hundreds of years (Huang et al., 2011; Tan et al., 2016; Li et al., 2017; Wang et al., 2024). However, these studies did not address the catchment role of gully regions. Field observations and past studies show that precipitation rarely directly infiltrates thick loess in hilly areas (Xu et al., 1993; Li, 2001). Instead, it forms surface runoff that converges into gullies and accumulates in ponds or other water bodies (perched water), serving as a concentrated recharge source for groundwater (Yu et al., 2025), reflecting the sustained and delayed impact of gully runoff on groundwater recharge, which is consistent with the results of this study.

Notably, our study does not consider confined water. Tan et al. (2016) indicated that the groundwater in the high mountain-hilly loess aquifer does not originate from the upwelling of ancient regional groundwater, and there is no evidence of deep confined water beneath the loess strata in the high mountain-hills. Additionally, our findings represent only the groundwater recharge results in the gully regions for two reasons: 1) The hydrological system is complex, with significant variations across different landscapes of the Loess Plateau (Li et al., 2019; Li et al., 2021). For example, Li et al. (2019)

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found that groundwater dominates the hydrological system in the tableland on the Loess Plateau, where surface water (streams) is recharged by groundwater because river channels are deeper than the bedrock. 2) Our data collection focused on gully because the "Loess Liang" and "Loess Mao" hillside areas are covered by thick loess with minimal water sources.

6.3. Groundwater recharge rates in the gully region

In many parts of the world, identifying the sources of groundwater recharge and its renewability is essential for effective water resource management (Ajjur and Baalousha, 2021; Meles et al., 2024). In the hilly-gully region of the Loess Plateau, where groundwater is considered a crucial source of safe water, understanding the origins and recharge of aquifers provides valuable information for water resource planners (Liu et al., 2011; Wang et al., 2024). This knowledge is essential and should be shared with regions facing similar challenges.

Groundwater recharge can be quantified from three hydrological sources: surface water, the unsaturated zone, and the saturated zone (Scanlon et al., 2022). Recharge estimates based on the saturated zone are generally more reliable than those from the unsaturated zone, as the latter represents potential recharge that may not ultimately reach the groundwater table (Beven and Germann, 2013; Huang et al., 2019). The groundwater table fluctuation method is widely used for estimating saturated zone recharge due to its high temporal resolution and intuitive nature (Gumuła-Kawęcka et al., 2022; Xu et al., 2024). In our study area, ITTPs estimated similar transit times for both pore water and fissure water. Therefore, we used the groundwater table fluctuation method to assess the recharge of pore water in the gully region. 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 groundwater table fluctuation method is specific yield, which depends on factors such as soil properties and water table depth. This value can be derived from empirical soil texture, pumping tests, or the test pit method (Nachabe, 2002; Liang et al., 2016). Shah and Ross (2009) found the test pit method reliable for water tables deeper than 2 m. In this study, with a water table exceeding 2 m, the specific yield was 0.32, consistent with values of 0.3 in similar soil conditions (Wang

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et al., 2023).

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; 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. Furthermore, our study demonstrates the potential of artificial ponds to regulate water resources and enhance recharge, with valuable implications for water management and ecological engineering.

6.4. Revised conceptual model

To convey our evolving understanding of the spatial structure and dynamics in the Gully Region, we developed a conceptual model that reframes gullies not simply as erosion features but as active hydrological conduits for groundwater recharge (Fig. 10). This model integrates stable isotope signatures, variations in chloride concentrations, ITTPs, groundwater level dynamics, and soil physical properties such as porosity and field water capacity. Through this integrative framework, we elucidate the transformation of precipitation into various forms of subsurface water by explicitly tracing its movement through a cascade of compartments—from surface ponding in dammed gullies, to infiltration through the unsaturated zone, and eventual recharge into both the porous aquifer and underlying bedrock fissure systems.

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This conceptual reframing is grounded in the stark hydrological contrasts between hilly uplands and gully systems and directly addresses a critical knowledge gap in understanding the hydrological functioning of gully environments. In the hilly uplands, thick loess deposits—often exceeding 90 m (including low-permeability aquifers)—combined with steep slopes (>15°) severely restrict vertical infiltration. Compounded by short-duration, high-intensity rainfall events that provide insufficient moisture for deep profile wetting, this results in the rapid conversion of rainfall into surface runoff (Li et al., 2021; Zhu et al., 2018). This runoff is systematically funneled downslope into gully systems, a process further intensified by engineered interventions such as check dams and retention ponds that intercept and concentrate overland flow. Because precipitation seldom infiltrates directly into the thick loess of upland regions (Xu et al., 1993; Li, 2001), most infiltration occurs after surface water accumulates in gullies—particularly within perched water bodies like ponds—which subsequently serve as focal points for groundwater recharge (Yu et al., 2025).

Crucially, gully systems possess distinct hydrogeological characteristics: the loess mantle is much thinner (typically < 25 m), and the soils are dominated by silt loam textures with moderate specific yield (0.02–0.05) and high field capacity (21–28%). These properties promote transient water storage and enable temporally delayed, depth-partitioned infiltration. Based on our integrated analyses of stable isotopes, chloride concentrations, and inverse transit time proxies, we find that gullies function not as passive erosional features but as active recharge conduits. This conceptualization captures a critical spatial transition—from runoff generation in the hilly uplands to focused recharge in gully zones—emphasizing the pivotal role of gully systems in regulating groundwater recharge across the Loess Plateau landscape.

Combined hydrological monitoring and multi-indicator analysis further reveal that following the rainy season, infiltration depths on hilly slopes are typically shallow—less than 1 m—while groundwater levels in gully areas exhibit pronounced rises exceeding 2 m. Recharge estimates based on the water table fluctuations reach up to 240 mm, far surpassing values observed in deep unsaturated zones of tablelands and hills (Huang et al., 2011; Li et al., 2017; Lu, 2020; Wang et al., 2024). These results reinforce the role of gullies as focal points for groundwater recharge and are consistent with prior studies. For instance, in hilly areas, precipitation rarely recharges groundwater due to the thick loess layers, with an average infiltration depth of only 1 meter (Wang et al., 2024).

Liu et al. (2011) found that groundwater near valleys in the hilly loess area is replenished by

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precipitation, runoff, and surface water. Moreover, fissure water exhibits more depleted isotopic signatures and higher chloride concentrations, indicating deeper percolation of pore water or mixing with older recharge sources. These patterns, supported by ITTPs and partial SEM linkages, reveal a hierarchical recharge sequence: event-driven infiltration enters the shallow pore aquifer, some of which slowly percolates into deeper fissure zones. This hierarchical mechanism is facilitated by the combination of thin loess mantles, engineered interventions (e.g., check dams and ponds), and delayed hydrological responses.

By integrating multiple lines of evidence, this conceptual model redefines gullies as selective recharge corridors shaped by both geomorphic structure and human intervention. It challenges the traditional view of gullies as purely erosional landforms and emphasizes their dual hydrological function: acting both as runoff conveyance channels and as transient reservoirs that store and redistribute water across space and time. This recharge capacity is jointly governed by topographic convergence, reduced loess thickness, and the presence of engineered structures such as check dams and retention ponds.

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. Compared to the traditional piston-flow and preferential flow models commonly applied in the region, the proposed "gully-dominated preferential recharge mechanism" marks a notable theoretical advancement. Whereas previous models primarily emphasize vertical infiltration through homogeneous loess layers, this study is the first to quantitatively identify a cascade recharge process unique to thin-loess gully catchments. 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. Beyond advancing theoretical understanding of regional hydrological processes, it also provides a sound basis for developing spatially targeted models of groundwater recharge.

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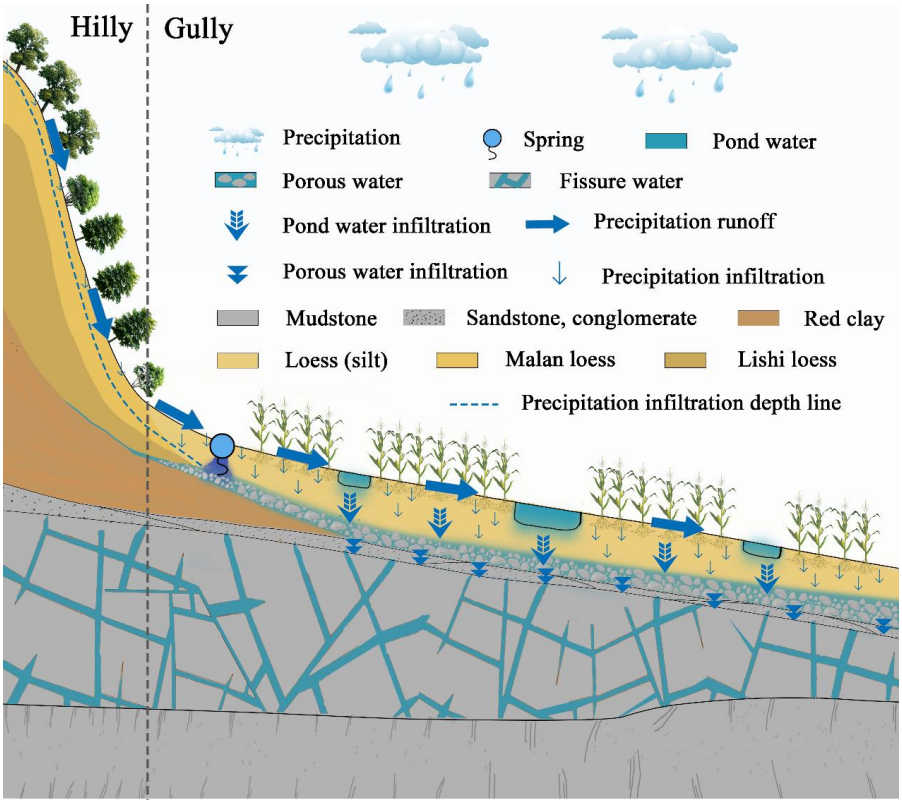

Fig. 10. Hydraulic connections between different water bodies in the hilly-gully region of the Loess Plateau. The study area consists of hilly and gully regions. In the hilly area, the stratigraphic sequence from top to bottom is Malan loess, Lishi loess, red clay, sandstone, and mudstone. Rainfall infiltration within the Malan loess is less than 1 m, and the area is mainly covered by vegetation. In the gully area, the stratigraphy from top to bottom includes loess (silt), sandstone and conglomerate, and mudstone. Pore water is found within the sandstone and conglomerate, while fissure water occurs in bedrock fractures (mudstone). Numerous check dams or ponds are distributed throughout the gully area. The vertical separation between the pore water and pond water ranges from 3 to 5 m. Corn is the main crop cultivated in this region. Most springs in the study area are located at the junction of the hilly and gully regions and are discharged from pore water.

6.5. Limitations and future research directions

This study underscores the limitations of relying on a single indicator to infer groundwater recharge pathways, as doing so may lead to oversimplified or potentially misleading interpretations of complex

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hydrological processes. While stable isotope signatures confirm that precipitation contributes to pore aquifer recharge, they do not provide clear evidence of direct recharge from pond water to either pore or fissure groundwater during the dry season. In contrast, the spatial distribution of chloride concentrations offers compelling support for focused pond water leakage into the shallow groundwater system.

Although variance decomposition analysis and structural equation modeling suggest statistical linkages among different water bodies and provide useful clues about potential recharge pathways, these associations may be confounded by overlapping isotopic signatures or by non-conservative processes such as evaporation and mixing, potentially leading to an overestimation of hydrological connectivity. In the absence of mass balance constraints, the pathways inferred through SEM may not accurately reflect the actual flow processes within the groundwater system. By contrast, the water table fluctuation method captures both vertical and lateral recharge processes, yielding estimates that are more likely to reflect actual recharge rates. Drawing on this empirical evidence, the present study further substantiates the critical role of gully zones in regional groundwater recharge.

Despite effort to address uncertainties, limitations remain in terms of spatial and temporal sampling density. For example, the lack of long-term tracers such as groundwater age, combined with limited observations of groundwater level fluctuations, constrains our ability to assess recharge dynamics over multi-year timescales. Additionally, the current sampling design includes only two campaigns during the rainy and dry seasons, which may be insufficient to fully capture the seasonal variability of ITTP values. This, in turn, may affect the accuracy of groundwater renewal frequency estimates and the strength of inferred hydrological connections. In arid and semi-arid regions, groundwater recharge is typically triggered by infrequent, high-intensity rainfall events. However, existing sampling strategies based on seasonal intervals often lack the temporal resolution necessary to capture these short-lived, event-driven recharge processes effectively.

Future research should address these issues through several improvements: (1) conducting higher-frequency, event-scale sampling to systematically monitor rainfall, spring discharge, and pond water level dynamics, thus capturing the influence of key hydrological events on recharge processes; (2) expanding the spatial coverage of pore and fissure well monitoring to improve the accuracy of regional recharge pattern identification; and (3) incorporating additional environmental tracers (e.g., ^{3}H, ^{22}Na) to trace flow paths and estimate recharge lag times. In addition, systematic observation of event-scale hydrological processes should be strengthened by establishing a high-frequency, event-driven monitoring

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network to better capture the nonlinear coupling among rainfall, surface runoff, and groundwater dynamics. This approach would significantly improve our understanding of rapid infiltration events and associated recharge mechanisms.

From a methodological perspective, integrating statistical techniques—such as SEM and variance decomposition analysis—with process-based physical models like MODFLOW and HYDRUS can provide mechanistically constrained insights into recharge pathways. Compared to correlation-based statistical methods, physical models offer greater precision in characterizing groundwater flow and recharge processes across both temporal and spatial dimensions, helping to reduce uncertainties associated with non-conservative tracer behavior and the absence of mass balance constraints. Regarding measurements, hydrometric instrumentation within check dams and beneath pond beds could further quantify the recharge effects of various engineering interventions under specific hydrological conditions. Additionally, integrating isotopic data with mean transit time modeling, combined with targeted field monitoring and improved spatial analysis, could help elucidate recharge pathways, quantify temporal dynamics, and enhance process-level understanding of groundwater recharge in complex dryland landscapes. Collectively, these efforts will contribute to a stronger theoretical foundation and offer practical guidance for the precise management of water resources, the design of ecologically appropriate engineering interventions, and the implementation of effective landscape rehabilitation strategies.

7. Conclusion

Through integrated analysis of stable isotopes, chloride concentrations, water table fluctuations, and inverse transit time proxies, we developed multiple lines of evidence to reframe gullies in the Loess Plateau as hydrologically significant recharge zones, rather than solely as indicators of erosion and degradation. Precipitation events drive substantial recharge to shallow pore aquifers, with annual rates exceeding 238 mm—accounting for a large fraction of annual rainfall. While isotopic evidence for recharge from pond water is obscured by evaporative fractionation, chloride concentrations provide a clear signal of subsurface connectivity. Recharge in this system is both spatially concentrated and temporally selective, shaped by terrain configuration, loess stratigraphy, and ecological engineering structures such as check dams and ponds.

These findings offer a process-based foundation for developing hydrological indicators of landscape function and restoration performance in dryland environments. Specifically, recharge magnitude, isotopic

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damping, and solute accumulation patterns may serve as diagnostic tools for identifying effective recharge zones and tracking system responses to intervention. To refine these indicators, future studies should incorporate high-frequency monitoring, event-based sampling, and multi-tracer approaches. Collectively, this work challenges conventional views of gullies as hydrological liabilities and demonstrates their underappreciated role as targeted recharge assets—advancing dryland groundwater sustainability and providing actionable insights for landscape-scale ecological restoration and management.

Author contributions:

ZXJ: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data curation, Validation, Writing-original draft. ADZ: Conceptualization, Formal analysis, Validation, Visualization, Writing-review & editing. LW: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing-review & editing.

Data availability:

Data are available from the corresponding author upon reasonable request.

Conflicts of Interest:

The contact author has declared that none of the authors has any competing interests.

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Appendix A

1. The typical loess landforms on the Loess Plateau is shown.

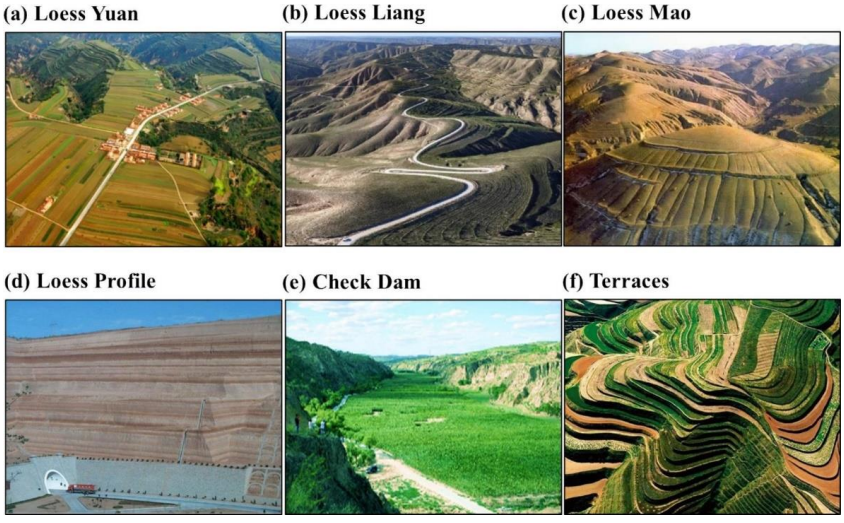

Fig. A1. Typical loess landforms are (a) Loess Yuan, (b) Loess Liang, and (c) Loess Mao. (d) A loess profile, (e) check dams and (f) terraces on the Chinese Loess Plateau. (adapted from Jia et al., 2024)

2. The specific yield of different soil textures is shown.

Table A1. The specific yield of different texture of soil (adapted from Liang, 2016)

Texture	Average Specific Yield	Minimum Specific Yield	Maximum Specific Yield	Coefficient of Variation (%)
Clay	0.02	0.00	0.05	59
Silt	0.08	0.03	0.19	60
Sandy Clay	0.07	0.03	0.12	44
Fine Sand	0.21	0.10	0.28	32
Medium Sand	0.26	0.15	0.32	18
Coarse Sand	0.27	0.20	0.35	18
Gravelly Sand	0.25	0.20	0.35	21
Fine Gravel	0.25	0.21	0.35	18
Medium Gravel	0.23	0.13	0.26	14
Coarse Gravel	0.22	0.12	0.26	20

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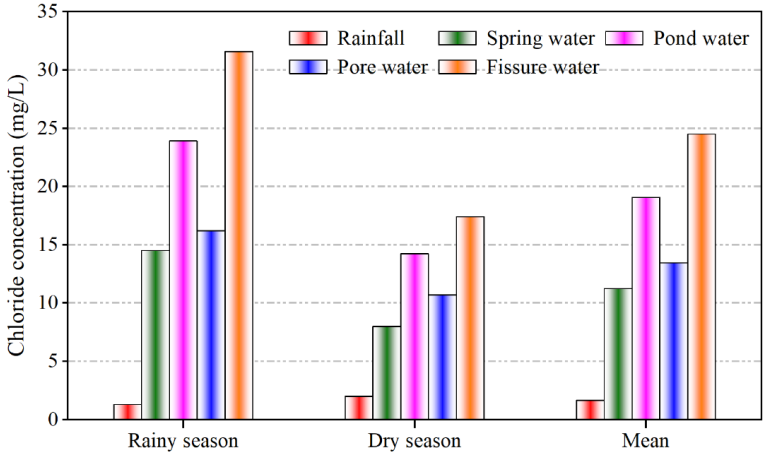
1168 3. The isotopic composition (δ^2H and $\delta^{18}O$) of various water sources in the rainy and dry seasons is shown.

1169 Table A2. Isotopic composition (δ^2H and $\delta^{18}O$) of various water sources in the rainy and dry seasons

	Rainy season		Dry season	
	δ^2H	$\delta^{18}O$	δ^2H	$\delta^{18}O$
Rainfall	−36.6±20.4‰	−5.6±2.3‰	−31.0±23.2‰	−4.9±3.0‰
Pond water	−40.5±13.1‰	−4.1±2.3‰	−24.5±6.9‰	−0.8±1.3‰
Spring water	−67.3±2.6‰	−9.0±0.4‰	−68.4±2.2‰	−9.0±0.4‰
Pore water	−66.3±3.1‰	−9.0±0.6‰	−65.4±3.8‰	−8.5±0.6‰
Fissure water	−65.0±3.8‰	−8.8±0.9‰	−64.5±5.5‰	−8.5±0.9‰

1170 4. The chloride concentrations of various water sources in the rainy and dry seasons is shown.



1171

1172 Fig. A2. Chloride concentrations of various water sources in the rainy and dry seasons.