Pol. J. Environ. Stud. Vol. 34, No. 3 (2025), 2835-2845
DOI: *10.15244/pjoes/188045* ONLINE PUBLICATION DATE: 2024-09-18

Original Research

Temporal and Spatial Distribution of Gully Water and its Replenishment Pathways in Loess Plateau

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Received: 24 March 2024
Accepted: 27 April 2024

Abstract

The gully region of the Loess Plateau is a landform with an extremely uneven distribution of water resources. In the dry season, water shortages seriously affect the property and lives of residents. During the rainy season, excessive rainfall leads to a series of geological disasters such as landslides and collapses, mudslides, and soil erosion. The subsurface flow in the gully of the Loess Plateau provides a new way to solve this problem. The premise of redistributing water resources by using subsurface flow effectively is to find out the temporal and spatial distribution of water in gullies and its replenishment methods. However, there have been no related reports about it in recent years. In this study, a typical gully (Jiulongquan Gully, Yan'an, Shaanxi Province, China) was studied by long-term positioning monitoring and isotope tracing. The direction and proportion of hydrological cycle transformation in each water body were quantitatively analyzed using a multi-terminal mixed model. The gully water transformation relationship and the contribution rate of water resource types to gully water were identified. The result shows that the subsurface flow in slope soil was mainly concentrated in the upper soil from 0-100 cm, while the subsurface flow in the gully was mainly generated in the upper soil from 0-120 cm. For deep soil-water, there was no significant difference in the water sources at different locations of gullies. The main recharge ratios of precipitation, surface water, and groundwater to the deep soil-water were 55.39%-60.10%, 10.48%-21.85%, and 22.76%-29.42%, respectively. For shallow soil, the difference was more obvious. Compared with the upstream of the gully, the proportion of precipitation supply for the subsurface flow in the midstream of the gully increased from 38.82% to 56.42%, and the proportion in the downstream of the gully increased from 2.54% to 17.89%. Upstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to the subsurface flow were 38.82%, 58.64%, and 2.54%, respectively. For the midstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to the subsurface flow were 56.42%, 41.34%, and 2.24%, respectively. For the downstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to the subsurface flow were 8.56%, 48.51%, and 42.93%, respectively. By installing the intercepts on the slope (100 cm) and in the gully (120 cm) and the reservoirs upstream and downstream of the gully, it is expected that the subsurface flow can be used to effectively trap soil-water and regulate water distribution in the gully.

Keywords: Loess Plateau gully, spatial and temporal distribution of water, supply route

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Introduction

The Loess Plateau is about 62.38 $\times10^4$ km^2, which is a typical ecological and fragile environmental zone in China and a region with the most serious soil and water loss in the world [1-3]. In the past few decades, about 16 $\times10^4$ t of sediment has been eroded into the Yellow River, which has formed gullies of various shapes and sizes. The total number of erosion gullies in the Loess Plateau is about 6.67 $\times10^5$, and the total area is about 1.87 $\times10^7$ hm^2. These gullies are not only the main source of sediment, but also the transport and migration channels of surface runoff, sediment, and pollutants [4-5]. The existence of gullies in the Loess Plateau will lead to a series of geological disasters such as landslides and collapse, ground collapse, mud-rock flow, and soil erosion, which have caused huge losses to the lives and property of local residents and seriously affected the development of the economy and society. According to government statistics, as of 2003, geological disasters in the northern area of Shaanxi had caused more than 1,000 casualties, damaged 30,000 houses, and caused direct economic losses of more than 300 million RMB. Therefore, to ensure the stable development of society and the economy, the remediation of gullies in the Loess Plateau is a very significant and important work [6-7].

The Loess Plateau region, especially the gully region, is a region where the temporal and spatial distribution of water resources is extremely unbalanced. The annual precipitation in the gully region of the Loess Plateau is 150-800 mm, and the precipitation is concentrated in June and July, which account for 55-78% of the total precipitation [8-10]. A series of geological disasters, such as landslides and collapses, mudslides, and soil erosion, were caused by short-time rainstorms, while drought and water shortages were caused by a long period of low rainfall in this area [11-13]. How to rationally allocate the temporal and spatial distribution of water resources in the Loess Plateau, especially in the gully region, is the key to solving this problem. In recent years, the Chinese government has launched a series of land consolidation projects, especially for the gullies on the Loess Plateau, with a total investment exceeding 4.8 billion RMB. During the projects, researchers found that due to the unique geological characteristics of gullies, the soil-water content in the Loess Plateau is relatively high, and the water in the soil tends to flow sideways with the terrain, which is known as subsurface flow [14-15]. The discovery of subsurface flow in the gully region of the Loess Plateau provides a new idea for the remediation of gullies [16].

The premise of redistributing water resources by using subsurface flow effectively is to find out the temporal and spatial distribution of the water content in the gullies of the Loess Plateau, especially the subsurface flow and its replenishment methods. Subsurface flow refers to water flowing in porous media, which mainly occurs at the discontinuous interface of different layers of soil or organic matter [17-19]. The soil in the gully region of the Loess Plateau has a layered texture structure. The upper part of the soil has a high nutrient content and good moisture conditions, which belong to the strong water-permeable layer. The lower part of the soil is the brown and sticky ancient soil layer, the calcium deposit, or bedrock, which belongs to the weak water-permeable layer. This provides the soil foundation for the existence of subsurface flow. The main factors affecting subsurface flow are soil physical characteristics, stratification, and water recharge conditions. Due to the complex conditions for the occurrence of subsurface flow, the research in this field is not in-depth, especially the spatial-temporal distribution characteristics [20-21]. As these characteristics of subsurface flow are unclear, it is difficult to efficiently use subsurface flow to reallocate water resources [22]. Therefore, it is particularly important to find out the water content, especially the temporal and spatial distribution of subsurface flow and its replenishment pathways in gullies.

In this study, the typical gully, Jiulongquan Gully (Yan'an, Shaanxi Province, China), was monitored for a long time, and samples of soil-water, precipitation, surface water, and groundwater were collected and analyzed. The spatial and temporal distribution rules of surface water and soil-water were analyzed. The direction and proportion of hydrological cycle transformation in each water body were quantitatively analyzed by using a multi-terminal mixed model with isotope tracer technology. The relationship between gully water transformation and the contribution rate of water resource types to gully water was revealed. Through the above research, the water in the gullies of the Loess Plateau, especially the temporal and spatial distribution of subsurface flow and its replenishment methods are revealed. The methods of regulating the temporal and spatial distribution of water resources in the gullies of the Loess Plateau are discussed. This study would provide a theoretical and technical basis for solving the problem of the imbalance in the temporal and spatial distribution of water resources on the Loess Plateau.

Materials and Methods

Description of the Study Area

The study area is located in Jiulongquan Gully, Yan'an, Shaanxi, China (N36°14′40″~36°19′25″, E109°35′50″~109°39′50″) (Fig. 1). Jiulongquan gully is 9.8 km long, and the valley is generally between 250 and 500 m wide. It is upstream of the Fenchuan River basin and is a river valley and terrace landscape. The climate of this region belongs to the temperate monsoon climate, with an average annual temperature of 9°C. The average annual precipitation in this region is 573 mm, and the rainfall is concentrated in July and August [23-24]. The soils of this region are *brown, yellow woolly,* and *laterite (ancient soils)*. The main land use types are agricultural, shrubland, forest, and native grassland. Common plant types are *Robinia pseudoacacia L.*, *Caragana korshinskii Kom.*, *Hippophae rhamnoides L.,* and *Stipabungeana Trin*. Water resources

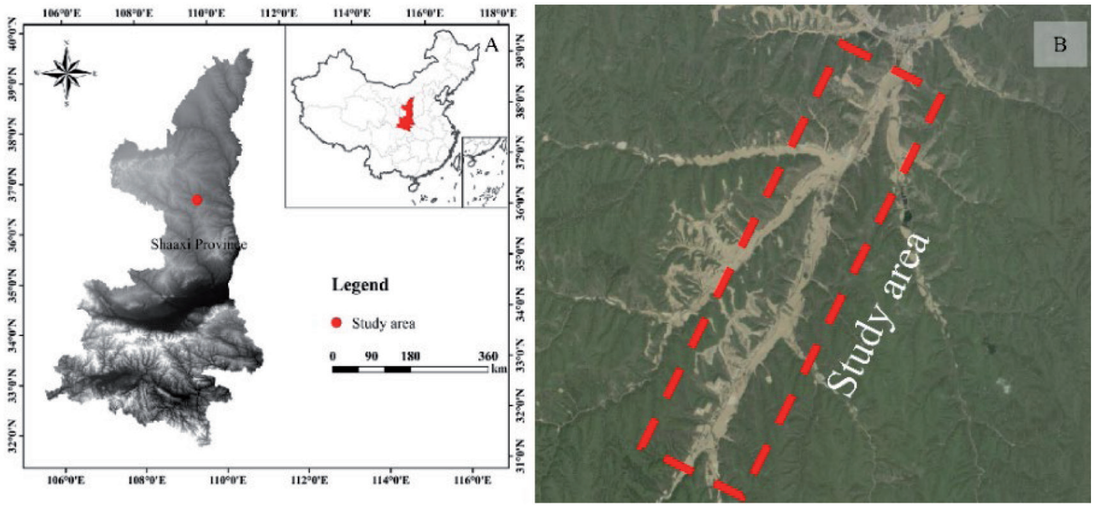

Fig. 1. Location map of the study area.

in the study area mainly consist of four types of water: atmospheric precipitation, surface water, groundwater, and soil-water. Among them, atmospheric precipitation is the main source of water resources and is also the source of recharge for surface water, soil-water, and groundwater.

Soil-water and Groundwater Level Monitoring in the Study Area

As shown in Fig. 2, typical slopes were selected for long-term soil-water observation. From the top to the bottom of the slope, 6 sampling points were arranged upstream, midstream, and downstream of the slope and the gully. Soil-water observation equipment (Trime TDR) was used for long-term positioning observation. Soil-water content was observed at 10 cm intervals from 0 to 200 cm (for soil layers less than 200 cm thick, the depth of the borehole was measured as far as it could be reached).

As shown in Table 1, groundwater level monitoring wells were selected upstream, midstream, and downstream of the gully, and Diver automatic groundwater level monitors were installed to regularly record seasonal changes in groundwater levels.

Table 1. Water level meter deployment location information.

	longitude	latitude	Elevation (m)	Well depth (m)	Well water depth (m)	Instrument depth (m)
Downstream	109.66	36.31	1113	50	9.32	3
Midstream	109.64	36.294	1141	50	11.52	3
Upstream	109.63	36.26	1154	50	6.2	2.08

Fig. 2. Soil-water monitoring point distribution.

Sample Collection for Isotope Analysis in the Study Area

To analyze the water source composition of soil-water in the gully, soil-water, precipitation, groundwater, and surface water were sampled in the 0-200 cm soil layer of the gully to determine the isotope concentrations. As shown in Fig. 3, soil-water samples were collected from upstream to downstream of the gully at three typical locations. A soil-water sample was collected at 10 cm intervals from 0 to 110 cm and at 20 cm intervals from 110 to 200 cm. The surface water was collected from the drainage gully in the gully, and the precipitation samples were obtained by taking natural rainfall.

Soil samples were collected through 10-mL brown glass bottles (preventing the influence of evaporation on water isotopes) for soil-water extraction through an evaporative extraction device to determine hydrogen and oxygen isotope concentrations. Other soil samples were stored in plastic-sealed bags for the determination of wet soil weight, soil water content, and mechanical composition. The water samples were sealed and stored in 10 mL glass bottles. Finally, a three-source linear mixed model was used to analyze the sources of soil-water and its proportion in the newly cultivated land [25]. The three-compartment linear mixing model is calculated as follows:

$$\delta D=F_1\delta D_1+F_2\delta D_2+F_3\delta D_3 \quad \text{Eq. 1)}$$

$$\delta^{18}O= F_1\delta^{18}O_1+F_2\delta^{18}O_2+F_3\delta^{18}O_3 \quad \text{Eq. 2)}$$

$$F_1+F_2+F_3=1 \quad \text{Eq. 3)}$$

where δD, $\delta^{18}O$, the values of stable hydrogen-oxygen isotopes in soil-water, ‰; $\delta D_1(\delta^{18}O_1)$, $\delta D_2(\delta^{18}O_2)$, $\delta D_3(\delta^{18}O_3)$, the values of the respective stable hydrogen (oxygen) isotopes in three different water sources, ‰; F_1, F_2 and F_3, the proportions of the corresponding different water sources in the total soil-water, %.

Results and Analysis

Temporal and Spatial Distribution of Water

Distribution of Precipitation and Groundwater Level

Fig. 4 depicts precipitation and groundwater levels in gullies in a typical year (2020). As shown in Fig. 4A, precipitation from January to April was small, with a cumulative precipitation of 41.2 mm and a maximum daily precipitation of 13.3 mm. The overall precipitation during this period was small. From July to September, the cumulative precipitation reached 461.3 mm, with the maximum daily precipitation of 66.5 mm, which accounted for 65.67% of the total precipitation. The overall precipitation was relatively large during this period. Therefore, the annual precipitation in this region was mainly concentrated in July-September, and the total precipitation was 702.5 mm. From the point of view of the average annual precipitation in this region, it was a wet year. As shown in Fig. 4B, from January to June, groundwater levels in the upstream, midstream, and downstream of the gully were 6.22±0.07 m, 12.46±0.07 m, and 10.68±0.09 m, respectively. From July to August, groundwater levels in the upstream, midstream, and downstream of the gully were 8.34±0.03 m, 14.58±0.03 m, and 10.44±0.11 m, respectively. From September to December, groundwater levels in the upstream, midstream, and downstream of the gully were 5.55 ± 0.05 m, 11.79 ± 0.05m, and 10.61 ± 0.04 m, respectively. In terms of time, groundwater in the upstream of the gully (8.34 ± 0.03 m) and the midstream (14.58 ± 0.03 m) was buried deeper in July and August than in other months. From the data on groundwater depth and rainfall, there was higher rainfall and deeper groundwater depth in July and August. It indicates two problems. One is that residents

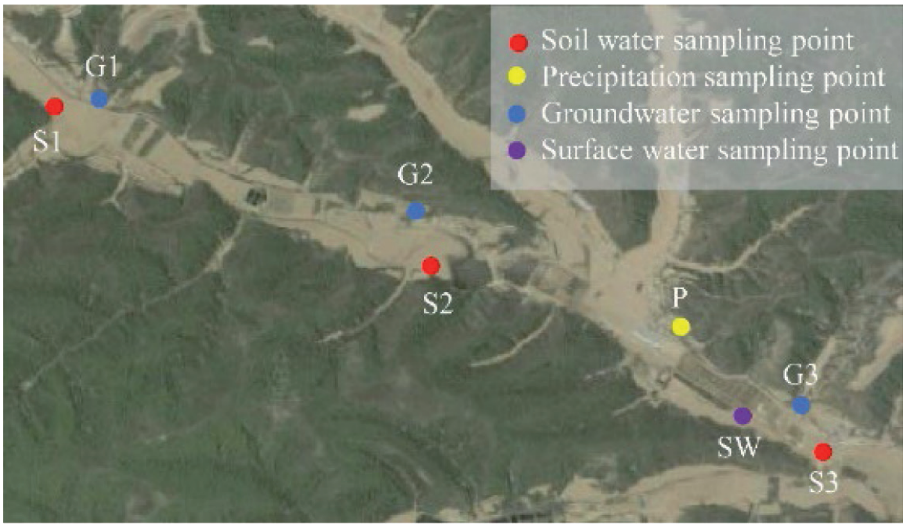

Fig. 3. Sampling points of different water bodies.

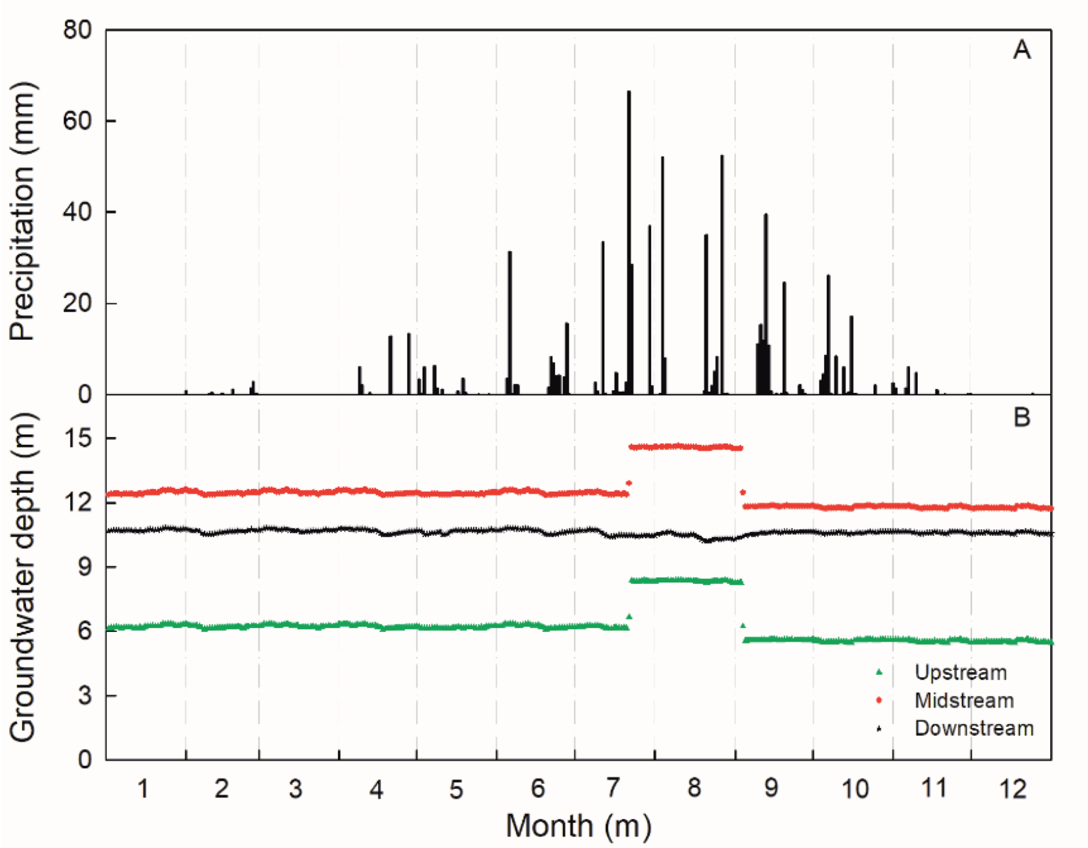

Fig. 4. The annual changes of precipitation and groundwater level gullies and valleys.

overexploited groundwater in July-August, resulting in a decrease in the groundwater level. The other is that the gully landform could not effectively store precipitation, resulting in the loss of water resources. In addition, the groundwater level upstream and downstream of the gully was slightly shallower from September to December than from January to June, indicating that the gully groundwater increases slightly after the rainy season in wet years. Geographically, compared with the upstream of the gully, the depth of the groundwater table in the midstream and downstream of the gully was relatively deep. There were some farmlands in the midstream and downstream of the gully, and excessive exploitation of groundwater for agricultural irrigation resulted in an obvious decline in groundwater.

Water Distribution in the Gully and Slope

Fig. 5 depicts the variation of water content in slope soil at different depths in different seasons. As shown in Fig. 5A, in the dry season, the water content of the deep slope soil (below 70 cm) was similar, while the water content of the shallow slope soil (0-70 cm) was very different. The water content in the middle and lower parts of the slope was relatively high compared to the upper part of the slope, and the upper aquifer in the middle of the slope (20-30 cm) was shallower than the upper aquifer in the lower part of the slope (50 cm). As shown in Fig. 5B, the location of the slope had a large influence on the soil-water content during the rainy season. From the top of the slope to the bottom of the slope, soil-water content at different depths decreased significantly. This is mainly because when the precipitation reached the slope, the rainfall would move down the slope in the form of surface runoff and flow in the soil because of gravity, which made the water content in the middle and lower parts of the slope relatively higher. Below 100 cm of soil layer, the water content of slope soil had an obvious and rapid rise, which indicated that the aquifer of slope soil was deep soil below 100 cm.

Fig. 6 describes the changes in soil-water content in the gully at different depths in different seasons. As shown in Fig. 6A, deep soil (below 110 cm) had similar water content during the dry season, while shallow soil (0-110 cm) had a large difference in water content. The water content in the midstream was higher than that in the downstream, while that in the downstream was higher than that in the upstream. The gully had a certain gradient (about 5°), and the gully presented a certain elevation difference. The existence of the elevation difference promoted soil-water migration from the upstream to the downstream in the form of subsurface flow because of gravity. It resulted in higher water content in the midstream and downstream of the gully. In addition, the

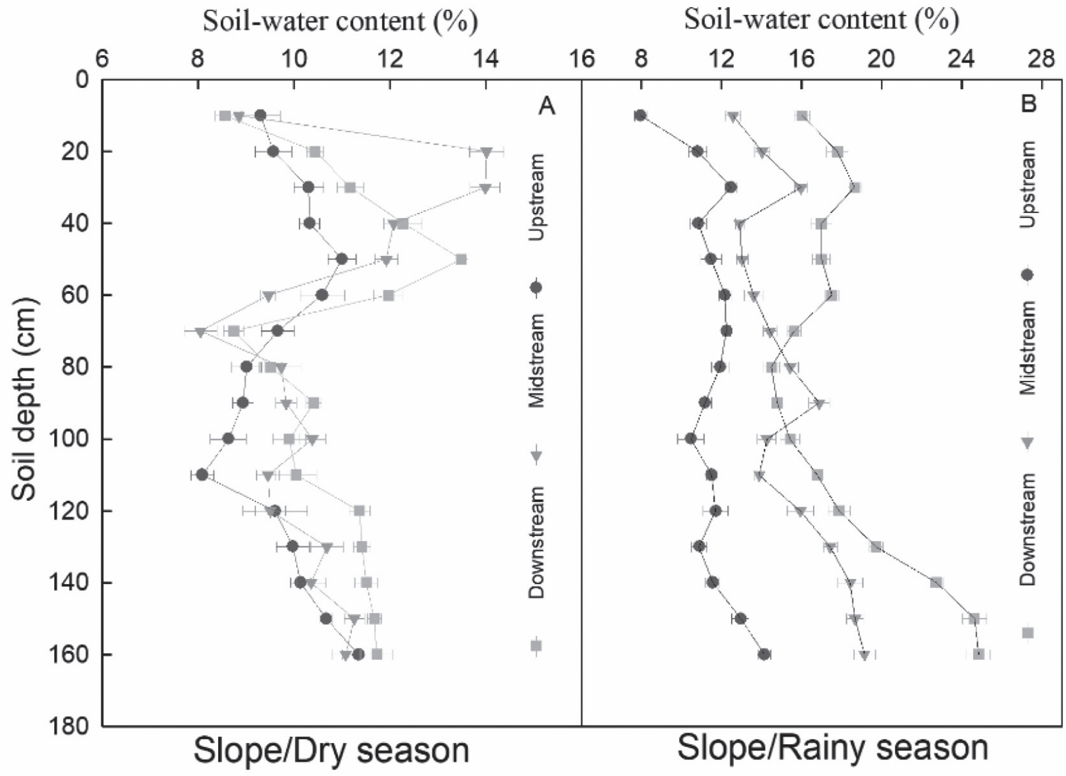

Fig. 5. Soil-water content of slope at different depths in different seasons.

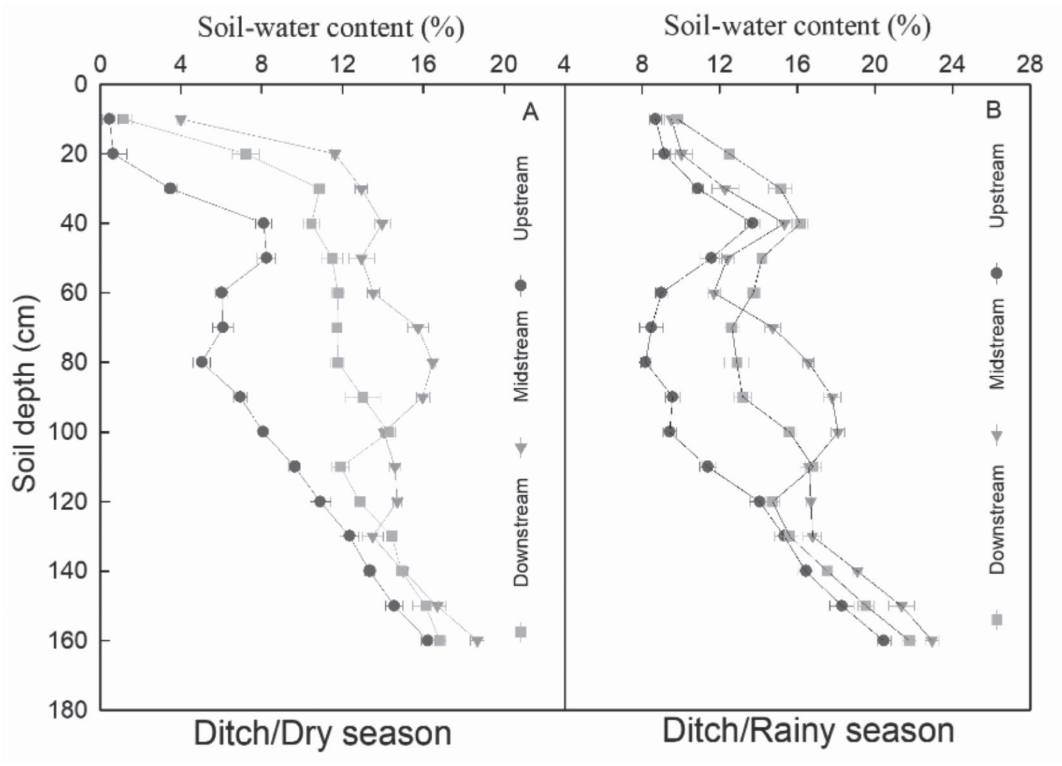

Fig. 6. Soil-water content in gullies at different depths in different seasons.

water content of shallow soil increased significantly due to irrigation of farmland in the midstream. As shown in Fig. 6B, in the rainy season, the difference in soil-water content at different locations of the gully mainly existed in the soil layer with a depth of 60-120 cm. The water content in the middle gully is higher than that in the lower gully, and that in the downstream is higher than that in the upstream. The difference in soil-water content

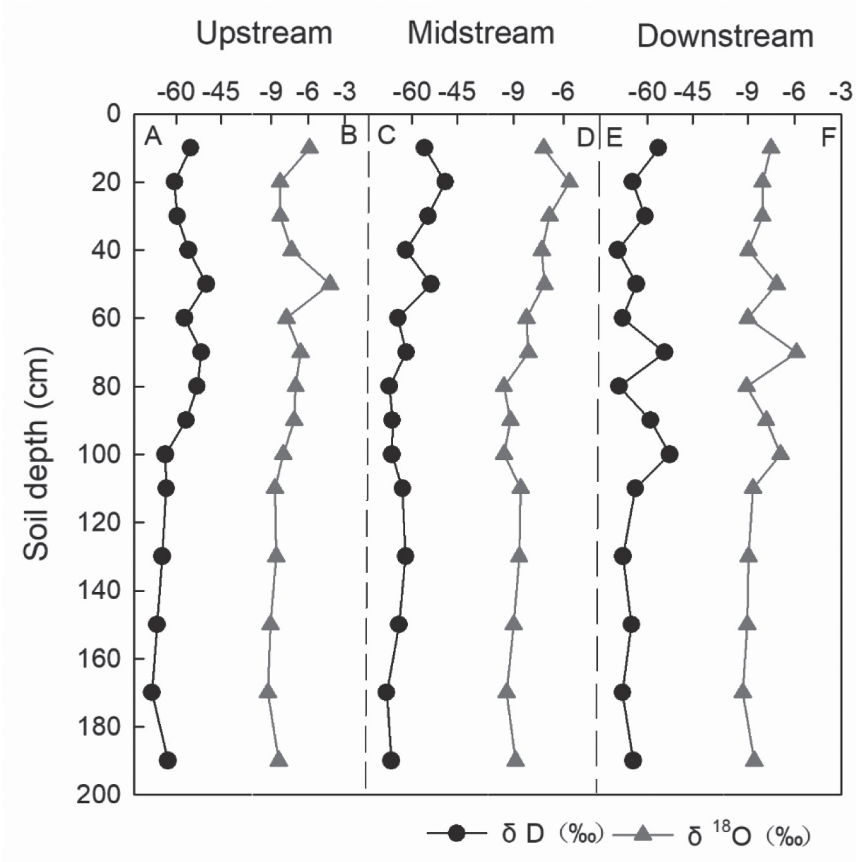

Fig. 7. Distribution characteristics of hydrogen and oxygen isotopes of soil-water in gullies at different locations and depths.

indicated that, without the interference of human factors, the subsurface flow caused by the elevation difference mainly existed in the 60-120 cm soil layer.

The Isotope Tracing in Different Bodies of Water in Gullies

Spatial distribution characteristics of hydrogen and oxygen isotopes

Fig. 7 describes the distribution characteristics of hydrogen and oxygen isotopes in gully soil at different positions and depths. As shown in Fig. 7, with the increase in soil depth, δD and $\delta^{18}O$ of soil-water showed an overall trend of depletion. The hydrogen isotope values and oxygen isotope values in the 120~200 cm soil layer were significantly lower than those in the 0~120 cm soil layer. When the depth of the soil was about 100~120 cm, the hydrogen and oxygen isotopes increased to a certain extent. This phenomenon is because the isotopes in precipitation will greatly affect the isotope content of shallow soil water after precipitation infiltration. However, with the increase in soil depth due to plant transpiration and evaporative fractionation, the isotopes showed a trend of dilution. Combined with the grain size distribution of soil at different depths (Table 2), the clay content at 100-120 cm was the highest compared with other depths, indicating that there was a relatively dense soil layer. Therefore, it caused the two layers of soil-water sources to have a large difference, thereby resulting in the difference between the upper and lower distribution of soil-water isotopes.

Table 2. Average particle size distribution of soil at different soil depths.

Solid depth (cm)	Clay particle (%)	Powder particle (%)	Sand (%)
0~20	6.12	79.53	14.35
20~40	6.69	77.59	15.72
40~60	6.80	76.01	17.19
60~80	6.32	74.75	18.93
80~100	6.93	78.80	14.27
100~120	9.25	76.63	14.12
120~140	7.96	76.47	15.57
140~160	8.28	77.77	13.95
160~180	7.73	75.84	16.43
180~200	8.12	76.23	15.23

Analysis of Replenishment Methods for Soil-Water

Fig. 8 depicts the source pathway of soil-water. According to δ D and $\delta^{18}O$, the three-end-member mixing model was used to analyze the replenishment pathway of soil-water in the upstream, midstream, and downstream

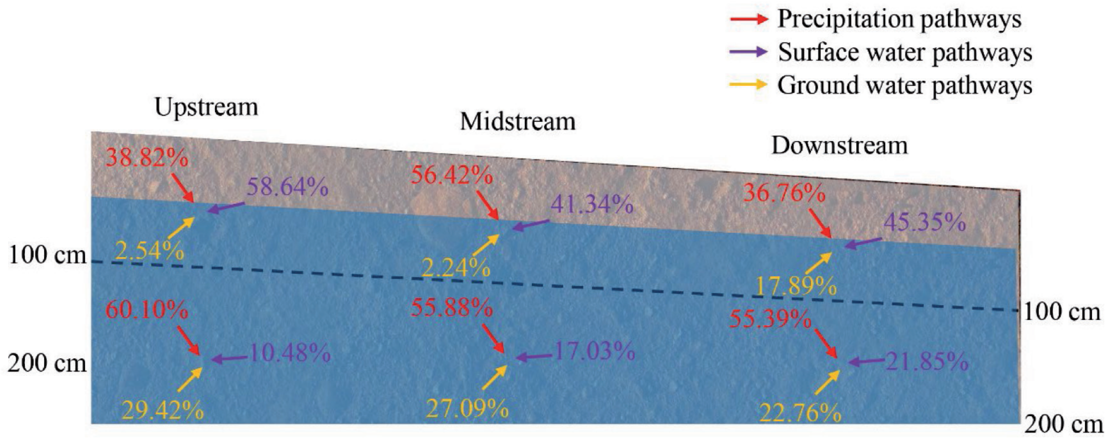

Fig. 8. Analysis of the source of soil-water in gully.

of the gully. As shown in Fig. 8, there were differences in the ratio of soil-water recharge at different positions of the gully, and the ratio of soil-water recharge at different soil depths was also different. In the upstream of the gully, the recharge ratios of precipitation, surface water, and groundwater to the 0-100 cm soil depth were 38.82%, 58.64%, and 2.54%, and the recharge ratios to the 100-200 cm soil depth were 60.10%, 10.48%, and 29.42%. Upstream of the gully, soil-water in the shallow soil layer mainly came from the recharge of surface water, and soil-water in the deep soil layer mainly came from the recharge of precipitation. This was because there was no effective cut-off gully in the upstream of the gully, which caused a high flow of surface runoff in the upstream, thereby resulting in the main source of soil-water in the shallow layer being surface water. Since precipitation was the only water source in this region, surface runoff formed in the middle and late rainfall. In the early stages of rainfall, water seeped directly into the ground, which made the soil-water in the deep layer mainly come from precipitation. In the midstream of the gully, the recharge ratios of precipitation, surface water, and groundwater to 0-100 cm soil depth were 56.42%, 41.34%, and 2.24%, and the recharge ratios to 100-200 cm soil depth were 55.88%, 17.3%, and 27.09%. For the midstream of the gully, both the shallow soil layer and the deep soil-water mainly came from precipitation. The water composition in the midstream was relatively complex. Soil-water came not only from precipitation and surface water, but also from the recharge of subsurface flow in its upstream. The source of soil-water in the deep soil layer in the midstream of the gully was like that in the upstream, while the source of soil-water in the shallow soil layer was different. In the midstream of the gully, there were some intercepts that came into contact with part of the surface water. As a result, the recharge proportion of surface water in the shallow soil layer in the midstream of the gully decreased, while the recharge proportion of precipitation increased. In the downstream part of the gully, the recharge ratios of precipitation, surface water, and groundwater to 0-100 cm soil layer depth were 8.56%, 48.51%, and 42.93%, and the recharge ratios to 100-200 cm soil layer depth were 55.39%, 21.85%, and 22.76%. For the downstream of the gully, soil-water in the shallow soil layer mainly came from the recharge of surface water and groundwater, while that in the deep soil layer mainly came from the recharge of precipitation. The source of soil-water in the deep soil layer in the midstream of the gully was like that in the upstream, but the source of soil-water in the shallow soil layer was different. Due to the limited drainage capacity of the gully, there was a certain amount of water downstream of the gully, and the recharge of the soil flow in the midstream and upstream made the soil-water source more complicated. Due to more surface water and shallow groundwater, the recharge ratio of surface water and groundwater in the shallow soil layer was greatly increased.

Discussion

The Relationship Between the Temporal and Spatial Distribution of Soil-Water and the Formation of Subsurface Flow

The concentrated rainfall, special soil characteristics, and special geomorphological features together contributed to the generation of subsurface flow (as shown in Fig. 9). Due to the lack of water resources in the Loess Plateau, rainfall was an important source of water resources in this region. As shown in Fig. 4, the annual precipitation was concentrated in July-August, and the cumulative precipitation in these two months reached 461.3 mm, accounting for 65.67% of the total precipitation. The concentrated rainfall provided a sufficient water source for subsurface flow. The soil profile in the study area had obvious stratification. The upper soil was a strong permeable layer such as loessial soil, while the lower soil was a weak permeable layer such as a viscous paleosoil layer (cinnamon soil, red soil, etc.), calcareous layer, or bedrock [26-27]. The special soil layer provided the soil foundation for the generation of subsurface flow. The gully and the slope with a certain slope (more than 5 °) provided the driving force for the subsurface flow. The three together promoted a certain degree of subsurface flow in the study area (as shown in Fig. 9) [28-29].

The distribution characteristics of soil-water effectively indicated the location of soil-water storage layer and subsurface flow. As shown in Fig. 5, the water storage layer of slope soil was below 100 cm. In the dry season, there were significant differences in shallow soil-water content. The high aquifer in the middle of the slope was shallower than the high aquifer in the upper and lower parts of the slope [30]. It indicated that there was also a certain amount of subsurface flow in the dry season, which occurred in the 0-70 cm shallow soil [31]. During the rainy season, the water content at different slope positions varied significantly (lower slope > middle slope > upper slope) [32]. Sufficient rainfall caused obvious subsurface flow in the soil, and the subsurface flow was generated in the soil layer of 0-100 cm [33]. As shown in Fig. 6, the water storage layer of the soil in the dry season was below 110 cm, and the water storage layer in the rainy season was below 120 cm. In the dry season, soil-water content varied significantly at different locations in the gully [34], and subsurface flow occurred in the 0-110 cm soil layer [35]. In the rainy season, the difference in soil-water content at different positions of the valley mainly existed in the soil layer with a depth of 60-120 cm, which means that the subsurface flow caused by the height difference mainly existed in the soil layer of 60-120 cm [36].

Soil hydrogen and oxygen isotope analyses revealed the source of subsurface flow [37]. As shown in Fig. 8, the sources of soil-water were clearly demarcated at a depth of 100 cm. For deep soil-water, the difference in water sources at different locations of the gully was not obvious. Precipitation, surface water, and groundwater recharged 55.39%-60.10%, 10.48%-21.85%, and 22.76%-29.42% of deep soil-water, respectively. For shallow soil, the difference was more obvious. Compared with the upstream of the gully, the proportion of precipitation supply in the midstream of the gully had increased, and the proportion of groundwater supply downstream of the gully had increased [38]. The difference in water sources in the 0-100 cm shallow soil of different positions of the gully also fully showed that the subsurface flow was concentrated in the 0-100 cm soil layer, which was the same as the analysis results of soil-water content [39].

How To Use Subsurface Flow To Regulate Water Resource Allocation in the Loess Plateau Gully

How to use subsurface flow to effectively regulate water resources is the key to solving the problem of water shortages [40]. As shown in Fig. 4, there was higher rainfall and deeper groundwater depth from July to August, which meant that the existing gully landforms could not effectively retain precipitation and caused the loss of water resources [41]. It can be seen from Section 4.1 that the subsurface flow on the slope was mainly concentrated in the upper soil layer at 0-100 cm, while the subsurface flow in the gully was mainly concentrated in the upper soil layer at 0-120 cm. By setting up multiple water interception gullies at a certain depth on the slope (100 cm) and the gully (120 cm), the subsurface flow could be used to effectively retain soil-water and reduce geological disasters such as landslides, debris flows, and soil erosion caused by short-term high-flow rainfall [42]. As shown in Fig. 8, the layout of the intercepting gully should not only be arranged in the midstream and downstream of the gully, but also in the upstream of the gully. The improved interception gully is expected to effectively intercept soil-water, especially surface water and precipitation. The intercepted soil-water can be collected for irrigation by building a reservoir [43]. As shown in Figs. 4 and 6, both the upstream and downstream of the gully had high groundwater levels, and the water sources were relatively sufficient. Both need to build a reservoir upstream and downstream of the gully. The reservoir upstream of the gully is used to collect rainwater, which can be irrigated in the dry season, while the reservoir downstream of the gully mainly collects the soil-water intercepted by the interception gully. Mcdaniel et al. [44] found that the subsurface flow can even reach more than 80% of the total rainfall during the rainy season, which means that most of the rainy season precipitation will be collected

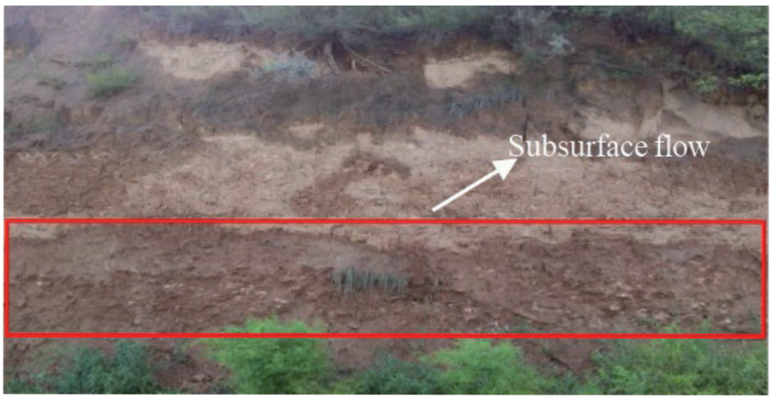

Fig. 9. Obvious subsurface flow in gully and slope.

through the layout of intercepting gullies and reservoirs [45]. The distribution of water resources in the gully region of the Loess Plateau can be effectively regulated by the arrangement of intercepting gullies and reservoirs.

Jiulongquan Gully, located in Nanniwan Town, Yan'an City, Shaanxi Province, is a typical representative area of the Loess Plateau's hilly and gully region, with remarkable topography, geomorphology, soils, climate, and vegetation, which makes the region an ideal place to study water resource management and soil erosion problems on the Loess Plateau. The region is characterized by long gullies and rolling hills and has a typical loess landform. The region has a temperate semi-arid climate with relatively low and unevenly distributed annual precipitation, similar to the climatic characteristics of much of the Loess Plateau. The area is dominated by drought-tolerant shrubs and herbaceous plants, and the vegetation cover and types also reflect the general conditions of the Loess Plateau. In conclusion, the study area has typical characteristics of the Loess Plateau in terms of topography, geomorphology, soil, climate, and vegetation, so the research results in this paper are representative and generalizable. However, at the same time, it is also necessary to consider inter-regional differences and carry out relevant research and application of the results according to local conditions, so as to achieve sustainable management of water resources and effective prevention and control of soil erosion on the Loess Plateau.

Conclusions

1. The subsurface flow was caused by the concentrated rainfall, the special landform, and the special soil quality.
2. The subsurface flow on the slope is mainly concentrated in the upper soil of 0-100 cm, while the subsurface flow in the gully is mainly concentrated in the upper soil of 0-120 cm.
3. For deep soil-water, there is no significant difference in the water sources at different locations of gullies. Precipitation, surface water, and groundwater recharged 55.39%-60.10%, 10.48%-21.85%, and 22.76%-29.42% of deep soil-water, respectively. For shallow soil, the difference was more obvious. Compared with the upstream of the gully, the proportion of precipitation supply for the subsurface flow in the midstream of the gully increased from 38.82% to 56.42%, and the proportion in the downstream of the gully increased from 2.54% to 17.89%.
4. For the upstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to subsurface flow were 38.82%, 58.64%, and 2.54%, respectively. For the midstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to subsurface flow were 56.42%, 41.34%, and 2.24%, respectively. For the downstream of the gully, the main recharge ratios of precipitation, surface water, and groundwater to subsurface flow were 8.56%, 48.51%, and 42.93%, respectively.

Acknowledgements

The study was supported by the projects of "Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd and Xi'an Jiaotong University (Program No.2021WHZ0090)", "The Natural Science Basic Research Plan in Shaanxi Province of China (2024JC-YBQN-0323)", "Shaanxi Provincial Land Engineering Construction Group (DJTD-2023-2, DJNY2024-35, DJNY2024-36)".

Conflict of Interest

The authors declare no conflict of interest.

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