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Evaporation, infiltration and storage of soil water in different vegetation zones in Qilian mountains: From a perspective of stable isotopes

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Abstract: In arid areas, almost all the water resources in the basin come from mountainous areas. Nvertheless, the process of water storage and runoff generation has not been fully understood in different vegetation zones in mountainous areas, which is the main obstacle blocking human cognition of hydrological processes and water resources assessment. In current study, the spatiotemporal dynamics of stable isotopes were monitored in different water bodies and soil water storage in different vegetation zones in the upper reaches of Xiying River. The results show that: (1) The water storage capacity of surface soil was weak in vegetation zones, and soil water was mainly saved up in the middle and lower soil layers. (2) Surface and subsurface runoff could form in the Alpine Meadow and Coniferous Forest during the rainy season and the snow melting season. The lower elevation vegetation zones of Mountain Grassland and Deciduous forest evaporate strongly and infiltrate partially into the middle and bottom layers of the soil to store or recharge groundwater, rarely generating surface runoff. This work would provide a scientific foundation for reasonably explaining the mechanism of water production in mountainous areas of arid regions, and provide a reference for formulating management policies suitable for sustainable development of water resources and improving the ability to cope with climate change in arid areas.

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Key words: Xiying River; Stable isotope; Drought, Soil water storage

1. Introduction

In arid inland river basins, climate change and distribution of water resources in different vegetation zones restrict the sustainable development of the regional ecological environment (Wang et al., 2012; Tetzlaff et al., 2013). To cope with the changing natural environment, managers have formulated a series of scientific ecological governance policies based on species selection (Wookey et al., 2010), crop rotation (Zhu et al., 2019) , and ecological water conveyance (Zhang et al., 2019), which has been improving their adaptability to the evolving natural environment.

Unsaturated soil zone is the center of transforming natural precipitation into water vapor, soil water storage, and groundwater recharge. Its evaporation, infiltration, and water storage are very critical for understanding the regional hydrological process and water balance under the background of climate and vegetation changes (Brooks et al., 2010; Grant and Dietrich, 2017). Isotopes, as "fingerprints" of water, have been used to trace eco-hydrological processes such as evaporation (Barnes and Allison, 1988), groundwater recharge(Koeniger et al., 2016), infiltration path (Tang and Feng, 2004), evapotranspiration distribution(Xiao et al., 2018) and water absorption by plants (Rothfuss and Javaux, 2017).

Evaporation, infiltration, and storage are the main forms of soil water transport after precipitation input. After a rainfall, the dynamic fractionation caused by evaporation makes soil water isotopes enriched on the surface (Ferretti et al., 2003). Affected by air temperature and precipitation, soil moisture fractionation is positively correlated with evapotranspiration but negatively correlated with precipitation (Hsieh et al., 1998). Therefore, compared with autumn and winter, the isotope composition of soil profiles is quite different in spring and summer (Barberta et al., 2015), and the difference is more significant in lower altitude areas than in higher altitude areas (Cui et al., 2009). In addition, vegetation and topography will also affect the dynamic fractionation of soil water, and the increase of vegetation coverage will

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weaken the evaporation of soil water (Dubbert et al., 2013). The d-excess on hillsides were lower than in summer valleys(Simonin et al., 2014). Seasonal variation of precipitation isotopes is often used to track the seepage process in moist soil (Stumpp et al., 2012). Before soil water reaches the saturation zone, the seasonal variation of the input water isotopic signal is usually highly attenuated (Sprenger et al., 2017). High variability of isotope ~~signal~~ in the soil profile and seasonal lack of precipitation signal can identify a preferential flow in soil (Peralta-Tapia et al., 2015). The cyclic change of isotope composition reflects new water transfer to old water (Sprenger et al., 2016a). It is found that most seepage processes are the result of the interaction of plug flow and macropore preferential flow (Cheng et al., 2014), and which infiltration mode plays a leading role depends on soil structure, soil texture, precipitation intensity, and soil humidity (Wenner et al., 1991; Seiler et al., 2002). After evaporation and seepage processes, some water will be stored in the soil. Generally speaking, the water storage capacity of wet areas is higher than that of arid areas, the water storage capacity of forests is higher than that of grassland, and the water storage capacity of middle and lower soil layers with higher clay content is higher than surface soil layer (Kleine et al., 2020; Heinrich et al., 2019; Sprenger et al., 2019).

In the future, climate warming will force water resources to become more unstable, and the dynamic interaction between water bodies stored in different media will become the main focus in the process of water circulation (Penna et al., 2018). Understanding the climatic and hydrological conditions of different vegetation zones and clarifying the regulating role of vegetation in the water cycle process can better adapt to the impact of climate change on the hydrological process in arid headwaters. In current study, the stable isotopic composition of precipitation and soil water and soil water storage's spatiotemporal dynamics were monitored in four vegetation zones with different water and heat conditions in the Xiying River Basin. In order to explore the similarities and differences of soil water evaporation, infiltration and storage, we put forward the following research objectives: (1) Evaluate the soil water storage

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capacity and its influencing factors in different vegetation zones in the basin; (2) Explore the evolution of isotopic evaporation signal and the "memory" effect of precipitation input, mixing and rewetting; (3) Analyze the mechanism of runoff generation and water storage in different vegetation zones.

2. Study area

Xiying River originates from Lenglongling and Kawazhang in the eastern Qilian Mountains (101°40′47″~102°23′5″E,37°28′22″~38°1′42″N) (Fig.1). As the largest first-class tributary of Shiyang River, it is formed by Shuiguan River, Ningchang River, Xiangshui River and, Tatu River converging from southwest to northeast, and finally flowing into Xiying Reservoir. The annual runoff of the Xiying River is 388 million cubic meters, which is mainly replenished by mountainous precipitation and melting water of ice and snow. The runoff is concentrated primarily in summer. The altitude of the basin is about 2000-5000m, which belongs to a continental temperate arid climate with strong solar radiation, long sunshine time, and large temperature difference between day and night. The annual rainfall is between 300 mm and 600 mm, and the annual evaporation is between 700 mm and 1200 mm. The zonal differentiation of vegetation in the basin is dominated by temperate Deciduous Forest, Mountain Grassland, Cold Temperate Coniferous Forest, and Alpine Meadow. The soils are mainly lime soil, chestnut soil, alpine shrub meadow soil, and desert soil.

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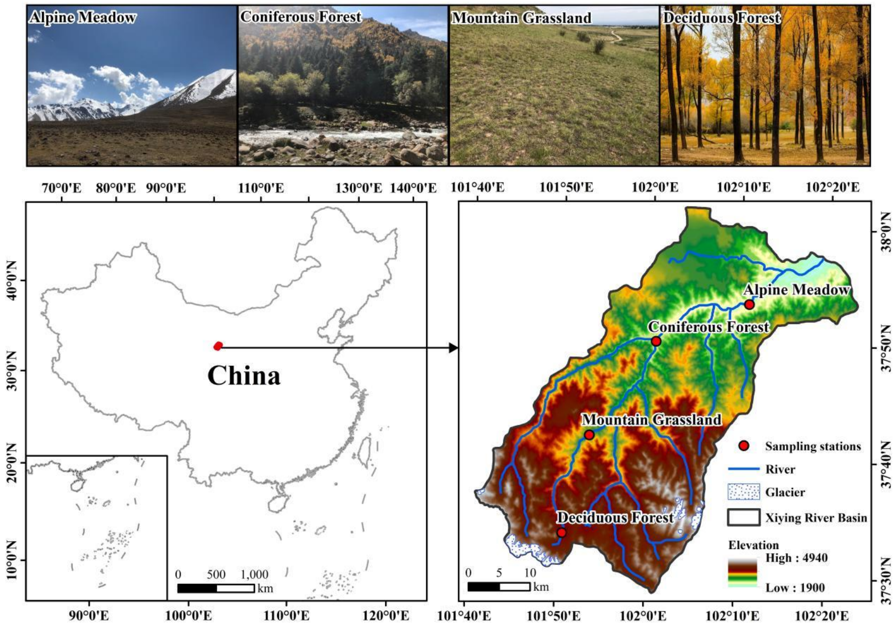

Fig. 1 Study area and location of sampling points

3. Data and methods

3.1 Sample collection and determination

In this study, soil water and precipitation samples were collected from April to October 2017 (plant growing season) in four vegetation zones in Xiying River Basin (Table 1).

Collection of soil samples: Soil samples were collected once a month at depths of 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, and 90-100 cm from soil layers in four vegetation zones. Also, four parallel samples for each soil layer were collected and performed the following operations: put three of them into a 50 mL glass bottle, sealed the bottle with Parafilm, wrote down the sampling date and depth on the bottle, then frozen and stored until experimental isotopic analysis, and another parallel sample placed in an aluminum box, weighed and documented, and stored until an experimental analysis of soil moisture content, overall soil bulk density, etc.

Collection of precipitation samples: The precipitation samples were collected by

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a plastic funnel bottle device. After each precipitation event, the collected precipitation samples were immediately transferred to an 80 mL high-density polyethylene bottle, and the bottle mouth of the samples was sealed with Parafilm film, and then frozen and stored until the experimental analysis.

Meteorological data: During the sampling period, the local meteorological data were obtained and recorded by the automatic weather stations (watchdog 2000 series weather stations) erected near the sample plot.

Table 1 Basic data of each Vegetation zone (*Long*-Longitude, *Lat*-Latitude, *Alt*-Altitude, *T*-Air Temperature, *P*-Precipitation Amount, *h*-Relative Humidity)

Vegetation zone	Geographical parameter			Meteorological parametes			Number of samples	
	Long(°E)	*Lat*(°N)	*Alt*(m)	*T*(℃)	*P*(mm)	*h*(%)	Precipitation	Soil
Alpine Meadow	101°51'16"	37°33'28"	3637	-0.19	595.1	69.2	72	47
Coniferous Forest	101°53'23"	37°41'50"	2721	3.34	431.9	66.6	42	41
Mountain Grassland	102°00'25"	37°50'23"	2390	6.6	363.5	60.4	37	54
Deciduous Forest	102°10'56"	37°53'27"	2097	7.9	262.5	59.8	40	53

3.2 Sample determination

The analysis of δ^2H and $\delta^{18}O$ values of all the above water samples was completed using a liquid water isotope analyzer (DLT-100, Los Gatos Research, USA) in the stable isotope laboratory of Northwest Normal University. Before analyzing the isotope values of soil water, the soil water should be extracted from the collected soil samples by a low temperature vacuum condensation system (LI-2100, LICA United Technology Limited, China). During the analysis, both water sample and isotope standard sample were continuously injected 6 times. In order to avoid the memory effect of isotope analysis, we discarded the first two injection values ,used the average value of the last four times as the final value. The analysis results were expressed in thousandths of the Vienna Standard Mean Ocean Water (VSMOW):

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000‰ \quad (1)$$

Where the R_{sample} is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the sample, and the $R_{standard}$ is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in VSMOW. The test error of $\delta^{2}H$ value does not exceed ±0.6 ‰, and the test error of $\delta^{18}O$ value does not exceed ±0.2 ‰.

3.3 Analysis method

3.3.1 lc-excess

The linear relationship between $\delta^{2}H$ and $\delta^{18}O$ in precipitation and soil water is defined as LMWL and SWL, respectively, which is of great significance for studying evaporation fractionation of stable isotopes in the water cycle. Lc-excess in different water bodies can characterize the evaporation of different water bodies relative to local precipitation (Landwehr and Coplen, 2004).

$$\mathrm{lc-excess} = \delta^{2}\mathrm{H} - a \times \delta^{2}\mathrm{H} - b \tag{2}$$

where a and b are the slope and intercept of LMWL, respectively, and $\delta^{2}H$ and $\delta^{18}O$ are the isotopic values of hydrogen and oxygen in the sample. The physical meaning of lc-excess is expressed as the deviation degree between isotopic values in samples and LMWL, which indicates the non-equilibrium dynamic fractionation process caused by evaporation (Landwehr et al., 2014; Sprenger et al., 2017).

3.3.2 PET

Calculation of potential evapotranspiration based on Penman-Monteath equation (Allen et al., 1998):

$$\mathrm{PET} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u^2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u^2)} \tag{3}$$

where PET is the daily potential evapotranspiration (mm day^{-1}), R_n is net radiation (MJ m^{2} day^{-1}), G is soil heat flux density (MJ m^{2} day^{-1}), γ is humidity constant (kPa℃$^{-1}$), u_2 is the wind speed at a height of 2 m (m s^{-1}), T is the daily average temperature (℃), Δ is the slope vapor pressure curve (kPa℃$^{-1}$), e_a is the actual steam pressure (kPa) and e_s is saturated vapor pressure (kPa).

3.3.3 Soil water storage

Soil water storage is the thickness of water layer formed by all water in a certain soil layer, which is expressed by formula as follows:

$$S = R \times W \times H \times 10 \quad (4)$$

where S is soil water storage in a certain thickness layer (mm), R is soil bulk density (g cm^{-3}), H is soil thickness (cm), and W is soil weight moisture content in a certain thickness layer.

4. Results and analysis

4.1 Hydrological climate

PET and runoff are important indicators to reflect the dry-wet conditions of river basins. During the study period (April-October), the potential evapotranspiration was 872.8 mm, and the daily evapotranspiration ranged from 7.5 mm (July 14) to 0.9 mm (October 9) in Xiying River Basin, showing a fluctuating increase and decrease trend around July,. PET in April-July was higher than that in August-October. The input of summer precipitation and ice-snow melt water masked the strong evaporation, changed the negative correlation between runoff and PET, and led to the changing trend of runoff similar to PET. Total runoff during the observation period was 3.1× 10^9 m, accounting for 89% of the total annual runoff. The variation range of daily runoff was 286,848 m^3 (April 17) to 6,125,760 m^3 (July 13). Generally speaking, during the study period, the basin was drier before July than after July (Fig.2).

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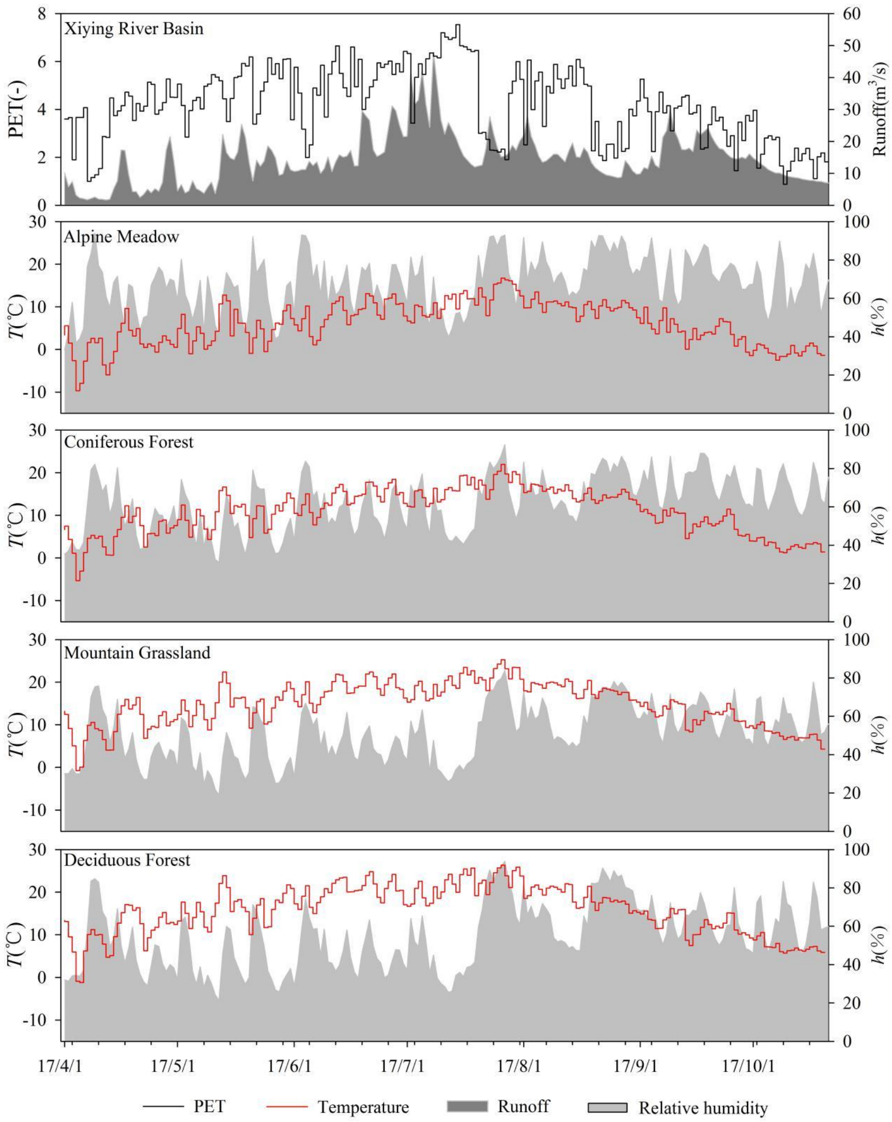

Fig. 2 Climatic and hydrological conditions of Xiying River basin and its vegetation zones

To explore the differences in the natural environment in different vegetation zones, air temperature, atmospheric humidity, and precipitation were used to indicate each research site's heat and moisture conditions. Hilltop is a typical Alpine Meadow zone, with a daily average temperature of 6.1℃, ranging from -9.7℃ (April 5) to

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16.8℃ (July 27). The average daily humidity was 68.2%, with little difference in different periods. There were 72 precipitations in the vegetation zone during the observation period, with total precipitation of 534.3 mm, which was relatively evenly distributed in each month. In the Coniferous Forest zone, the average daily temperature during the study period was 10.9℃, ranging from -5.4℃ (April 5) to 22.0℃ (July 27). The average daily humidity was 62.5%, and the precipitation was 400.6 mm, mainly concentrated from early August to late September. Close to the foothills is the Mountain Grassland zone, with a daily average temperature of 14.9℃, ranging from -0.7℃ (April 5) to 25.3℃ (July 27). The average daily humidity was 51.1%, and the precipitation of the vegetation zone during the observation period was 327.2 mm, mainly from late July to mid-August. During the observation period, the average daily temperature at the Deciduous Forest zone was 15.8℃, ranging from -1.2℃ (April 6) to 26.3℃ (July 27). The average daily humidity was 54.7%, and the total precipitation was 250.6 mm, which was concentrated in the month from late July to late August. To sum up, the heat of the four vegetation zones was AM<CF<MG<DF and the moisture condition was AM > CF > MG > DF (Fig. 2 and Fig. 3).

4.2 Time variation of water stable isotopes in different vegetation zones

Influenced by different water sources and complex weather conditions in the precipitation process, the isotopic composition of precipitation in four vegetation zones was obviously different during the study period. The mean values of δ^2H and δ^{18}O in Alpine Meadow were -73.1‰±36.3‰ (-163.9‰~13.7‰) and -10.0‰±4.3‰ (-23.1‰~-1.3‰), respectively. The average values of δ^2H and δ^{18}O of Coniferous Forest were -42.0‰±37.2‰ (-117.8‰~13.0‰) and -7.1‰±4.7‰ (-17.4‰~-0.1‰), respectively. The average values of δ^2H and δ^{18}O of Mountain Grassland were -37.4‰±30.5‰ (-103.1‰~4.2‰) and -5.9‰±3.9‰ (-15.1‰~-0.9‰), respectively. The average values of δ^2H and δ^{18}O of Deciduous Forest were -31.8‰±42.8‰ (-110.2‰~23.2‰) and -5.8‰±5.5‰ (-15.2‰~3.2‰), respectively. The maximum isotopic values of the four vegetation zones appeared on August 4 (Alpine Meadow),

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August 10 (Coniferous Forest), August 7 (Mountain Grassland) and August 13 (Deciduous Forest), respectively, which were 7 days, 13 days, 10 days and 16 days behind the local maximum temperature. In addition, the atmospheric precipitation isotopes of the four vegetation zones had similar time variations: from April to August, the fluctuation of δ^2H and δ^{18}O increased, reached the maximum in mid-August, and then gradually decreased (Fig. 3).

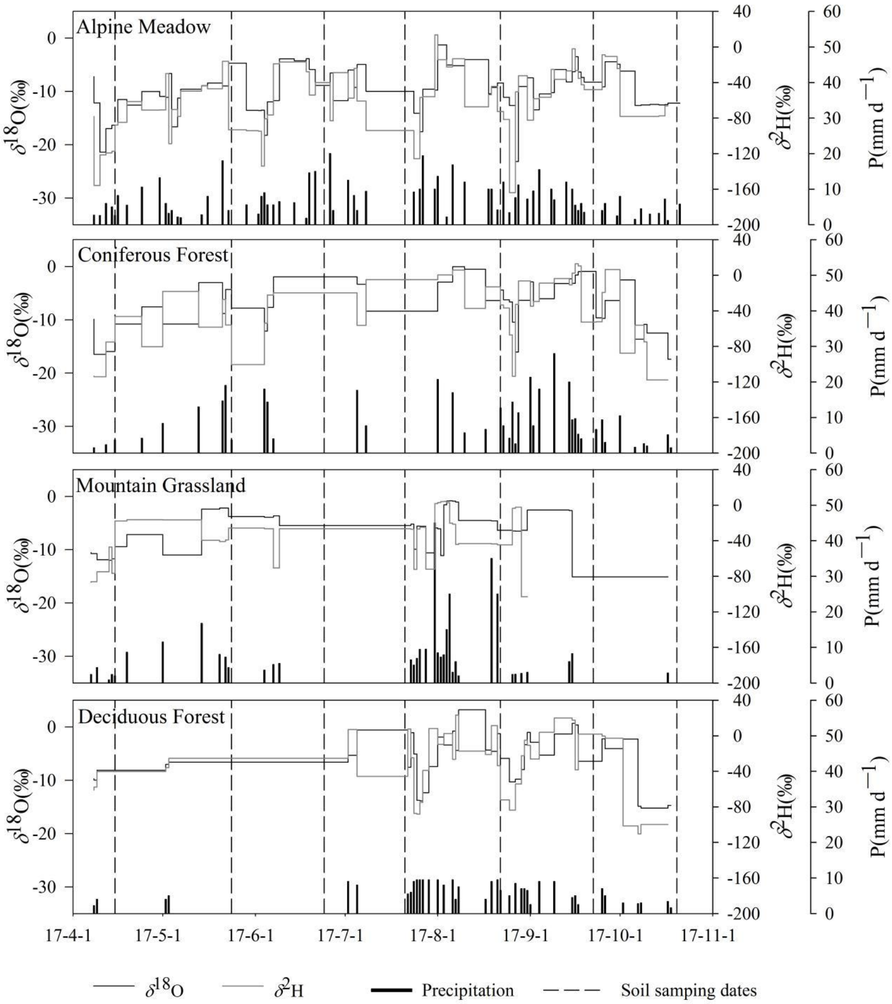

Fig. 3 Time series of rainfall and isotope characteristics in different vegetation zones in Xiying River Basin, with dotted lines indicating the date of soil water sampling

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The monthly variation of soil water isotope records the signal of precipitation input and evaporation. The low temperature environment of Alpine Meadow and abundant and uniform precipitation events made the monthly mean values of δ^2H and $\delta^{18}O$ change little and were most depleted than other vegetation belts. Despite this, SWlc-excess of most samples in this station was still negative, and there were different degrees of evaporation in the process of precipitation penetrating the soil and mixing with original pore water, among which evaporation fractionation was stronger in July (-11.5‰, lc-excess) and October (-14.9‰, lc-excess). Evaporation fractionation of soil water isotopes in Coniferous Forests was more intense. Soil water isotopes of Coniferous Forest gradually changed seasonally. From April to July, precipitation was scarce, the temperature rose, and the isotopes of soil water was gradually enriched on the surface, reaching the peak value of the observation period in July (-29.5‰, δ^2H; -2.1‰, $\delta^{18}O$), and continuous rainfall input from late July to mid-August resulted in soil water isotopes depletion. SWlc-excess was an obvious fractionation signal opposite to the trend of isotope change, reaching the lowest value (-26.3‰) in the sampling period in July, and the change of air temperature and precipitation controlled the evaporation intensity. From April to July, the isotopic value of surface soil water in Mountain Grassland was higher ($\delta^{18}O$ was greater than zero), and SWlc-excess was lower than -30‰. During this period, evaporation and fractionation of shallow soil water were intense. Similar to the Coniferous Forest, the input of heavy precipitation from late July to mid-August led to the depletion of soil water isotopes. There was only sporadic rainfall in Deciduous Forest from April to July, and the soil water isotopes were gradually enriched on the surface and reached its peak in June when there was no rainfall event (-18.2‰, δ^2H; 0.2‰, $\delta^{18}O$), and then became depleted. In addition, due to the influence of Xiying Reservoir and vegetation coverage, the isotopic enrichment degree of soil water in this vegetation zone was lower than that in Mountain Grassland. As the most intuitive form of water change, GWC (gravimetric water content) was always at a low value in July, when the evaporation was the strongest, and it was most obvious in shallow soil (Fig. 4).

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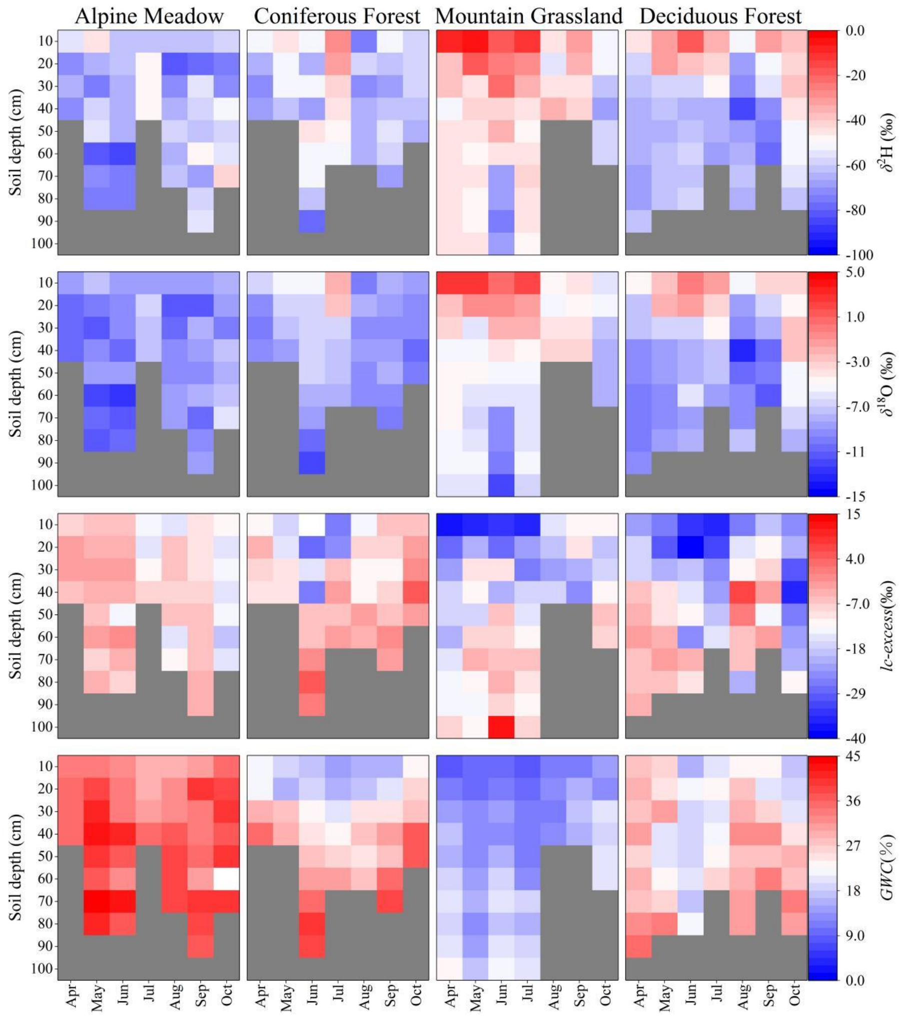

Fig. 4 Heat map of soil depth profile of δ^2H, $\delta^{18}O$, lc-excess and GWC in different vegetation zones, and the layer lacking measurement is indicated by deep color

4.3 Spatial variation of water stable isotopes in different vegetation zones

Isotope data of precipitation and soil water obtained from different vegetation zones were shown in the double isotope diagram (Fig. 5). In the Alpine Meadow observation station, the secondary evaporation was low due to low temperature, low cloud bottom height, and low air saturated water vapor loss. In addition, the monsoon caused strong convective precipitation at the station. Therefore, the slope (8.35) and intercept (23) of LMWL were higher than GMWL. The slope of LMWL in the other

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three vegetation zones was lower than GMWL, and gradually decreased with altitude decrease. This was mainly because in arid areas, with the decrease of altitude, the secondary evaporation under clouds was strengthened, and the strong evaporation will lead to the decrease of intercept. The δ2H and δ18O of soil water in each vegetation zone mostly fall in the lower right of LMWL, indicating that atmospheric precipitation was the main supply source of soil water, subject to different degrees of soil water evaporation. With the decrease of altitude, the soil water evaporation became stronger and stronger, except soil in Deciduous Forest. On the one hand, the vegetation coverage of this site was higher. On the other hand, Xiying Reservoir enhanced the regional air humidity and slowed down the local water vapor circulation driving force.

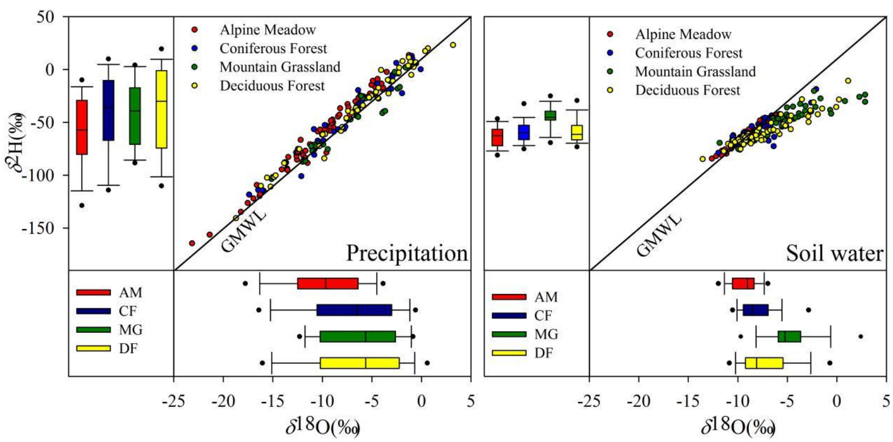

Fig. 5 Double isotope diagram of precipitation (left) and soil water (right) isotope data of four vegetation zones. In the box plots, the box represents 25%-75% percentile, the line in the box represents median (50th percentile), the required line indicates 90th and 10th percentile, and the point indicates the 95th and 5th percentile.

During the study period, compared with soil water in Alpine Meadow and Coniferous Forest, the isotopic value of soil water in Mountain Grassland and Deciduous Forest was relatively enriched, the lc-excess was smaller and deeper into the middle and lower soil layers, and the GWC was relatively low. Because of the

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difference in vegetation types and the influence of reservoirs, this change did not have the elevation effect completely. Although the elevation was low, the soil water of Deciduous Forest had more depleted isotopic characteristics and higher soil moisture than Mountain Grassland in most samples (Fig. 4).

Soil profiles obtained from different vegetation zones can reflect the evaporation signals of water. Low temperature natural environment made Alpine Meadow soil less affected by dynamic fractionation (lc-excess > -20 ‰), and GWC was at a high value (GWC > 25%) during the whole study period. The surface soil water of Coniferous Forest was easily affected by climate, and had higher isotopic composition (-29.5‰, δ^2H; -2.1‰, δ^2H) and lower lc-excess (-26.3). With the increase of soil depth, the fractionation signal gradually weakened, δ^2H and δ^{18}O became depleted, and soil water content gradually increased. Isotopes of soil water in Mountain Grassland and Deciduous Forest were enriched in surface soil layer due to fractionation. Especially in the Mountain Grassland, the average values of δ^2H and δ^{18}O in 0-10cm soil layer were as high as -24.4‰ and -1.2‰, respectively, and SWlc-excess was lower than 25‰, even close to 40‰ in some samples. Evaporation signal can easily penetrate deep soil, which made the GWC value of all sampling activities at this site lower than 20% (Fig.6).

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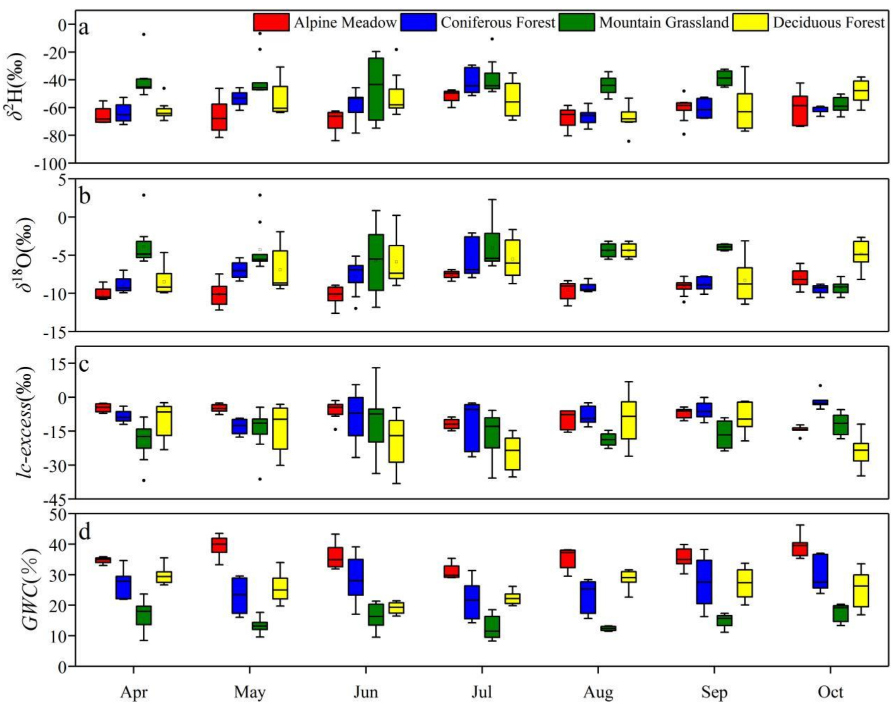

Fig. 6 the differences of δ^{2}H, δ^{18}O, lc-excess and GWC in different vegetation zones in each sampling

5. Discussion

5.1 Soil water storage capacity of different vegetation belts in arid headwaters area

As the temperature decreases rapidly with the increase of height, the precipitation and humidity increase to a certain extent, and the vegetation shows a strip-like alternation approximately parallel to the contour line, forming zonal vegetation with obvious differentiation(Yin et al., 2020). The dry-wet conditions of different vegetation zones restrict the soil water storage capacity in the basin. The rainfall decreased, the temperature rose, the groundwater level dropped and the soil water storage capacity was weak during the replacement of vegetation zones to low altitudes (Coussement et al., 2018; Kleine et al., 2020). The soil water storage capacity of Alpine Meadow with low temperature and rainy weather was obviously higher than that of other vegetation zones. The soil water storage capacity (0-40 cm)

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of each sample during the study period exceeded 165 mm, with little difference between months and no obvious change between months. With the decrease of altitude, the monthly difference of dry-wet conditions in each vegetation zone gradually became obvious. With the increase of summer temperature, the environment became dry, and the soil water storage capacity weakened (Sprenger et al., 2017). The soil water storage capacity of Coniferous Forest began to decrease in April, and the water storage capacity of 0-40 cm reached the minimum value (101.2 mm) in July. The change in temperature and precipitation was the main reason for the monthly difference (Dubber and Werner, 2019). Although there was a certain water storage capacity in Coniferous Forest with some water transpiration loss, the soil water storage capacity in this vegetation zone was not strong. The water storage capacity of Mountain Grassland soil was lower than that of other vegetation zones. The continuous dry and warm weather in spring and summer led to the water storage capacity of 0-40 cm soil being lower than that of 100 mm every month. Particularly, drought stress leads to insufficient soil moisture, making it difficult to maintain plant demand, resulting in sparse vegetation and large-scale exposed surface soil, which further accelerates surface water loss. The continuous rainfall from the end of July prevented the further development of drought, and the input of water gradually restored the soil water storage capacity (Kleine et al., 2020). Deciduous Forest had similar hydrothermal conditions with Mountain Grassland, but the soil porosity of forest land is obviously larger than that of barren land, and its permeability was better than that of barren land. Rainwater was sent to the ground through roots and turned into groundwater. Forest was a reservoir with strong water storage and soil conservation capacity (Sprenger et al., 2019). The water storage capacity of 0-40 cm soil sampled every time in Deciduous Forest was higher than that in 100 mm soil. In addition, the water content of 0-40 cm soil layer in each vegetation zone increased with the deepening of the soil layer, and the water storage capacity of surface soil was weak. The difference of soil properties will also lead to more water stored in the middle and lower soil with higher clay content (Heinrich et al., 2019) (Fig. 7).

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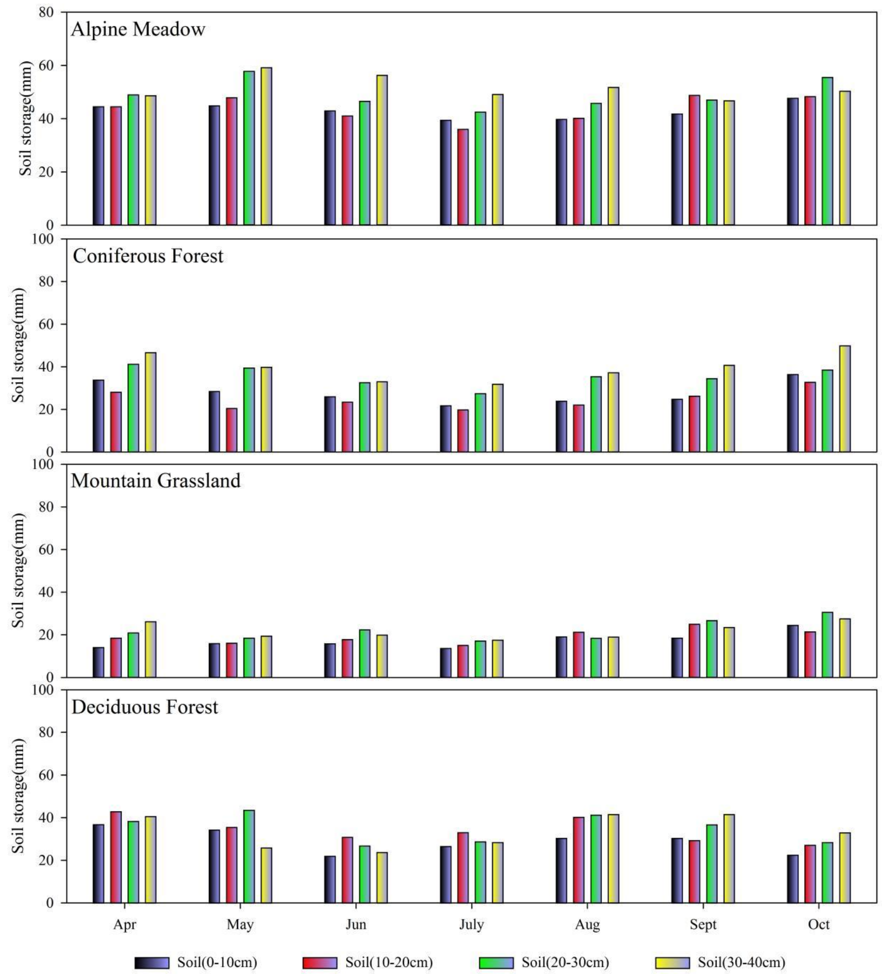

Fig. 7 Monthly variation of soil water storage in 0-40cm soil layer of different vegetation zones

5.2 "Memory" effect of isotope signals on soil water migration in different vegetation zones

Isotopic signals can evaluate the effects of dry-wet conditions in different vegetation zones on soil water transport. After rainfall, the variability of isotope signal at a certain soil depth can identify the seepage way of water (Peralta-Tapia et al., 2015). During the study period, the soils of Alpine Meadow and Coniferous Forest were seasonally frozen and thawed all the year-round, and the isotope difference of

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soil isotope profile was small, and precipitation mainly penetrated into the soil in the form of plug flow. Preferential infiltration showed high variability of isotopic signal (Brodersen et al., 2000), and rainwater in Mountain Grassland and Deciduous Forest flowed into deep soil rapidly through soil matrix through exposed soil fissures and roots. Water movement and mixing in the unsaturated zone can be observed in the space-time variation of isotope within 1 meter of the soil profile. In addition, the dynamic changes of lc-excess in soil profiles of different vegetation zones reflected the evaporation signals caused by drought during the study period. Particularly in low altitude areas, soil evaporation in spring and summer and insufficient precipitation during drought were the main driving forces leading to isotopic enrichment in the surface soil of Mountain Grassland and Deciduous Forest (Kleine et al., 2020). Alpine Meadow and Coniferous Forest zone were rich in rainfall. After a short period of weak evaporation, the soil will be rewetted by the next rainfall. The Mountain Grassland and Deciduous Forest zone had only sporadic precipitation from mid-May to late July, and the soil moisture evaporates rapidly. With the decrease of air temperature and the occurrence of continuous precipitation after July, the soil was re-wetted after two months of drought, and both vegetation zones showed the replacement and mixing of soil water isotope and precipitation. There were commonalities in soil moisture changes in different vegetation zones characterized by more enriched isotopes, stronger evaporation signal, and lower moisture content in shallow soil. With the increase of soil depth, isotope was gradually depleted, and evaporation signal was gradually weakened until it disappeared. The evolution of isotopes, lc-excess, and GWC in unsaturated soil showed the differences among different vegetation zones. From high altitude to low altitude, the isotopic value of the surface gradually enriched and the evaporation signal increased. The low vegetation coverage on the Mountain Grassland made the evaporation front penetrate deeper into the soil layer, and there was still an obvious evaporation signal below 70 cm of the surface (Fig. 4). The results showed that the storage of soil and groundwater in this area was seriously insufficient, which reflected the incomplete rewetting of the basin at the end of the study. In addition, lower soil water storage capacity will make the remaining soil water have a stronger Rayleigh fractionation effect (Zimmermann et al., 1966; Barnes and Allison, 1988). Similar evaporation signals have been found in the Mediterranean and arid climate regions (Sprenger et al., 2016b; McCutcheon et al., 2017). Evaporation signal only exists in the surface soil in humid areas, and there is no significant difference between lc-excess and 0 in the soil layer below 20cm (Sprenger et al., 2017). We observed the isotopic drought signal (lc-excess) and the "memory" effect of soil rewetting caused by precipitation input and mixing in different vegetation zones during the whole study period. The continuous separation of soil moisture reflected different soil and climate attributes and formed different hydrological paths.

5.3 Understanding of watershed runoff and water resources management

Climate warming and the spatiotemporal imbalance of water resources interfere with the ecological-water balance of different vegetation zones in inland river source areas (Liu et al., 2015). The growth of plants mainly depends on the water stored in shallow soil layer (Amin et al., 2019). Drought reduces the water storage of soil, inhibits the growth of plants and leads to the decrease of stomatal conductance of plants, finally causing plant death due to lack of water or carbon (Li et al., 2020). In recent years, dry and hot summers have become more common. Understanding the soil water and hydrological process of the unsaturated zone in basin areas using the stable isotopic method is very important for formulating ecological restoration and water resources management strategies in vulnerable areas under the background of climate warming (Kleine et al., 2020). The management of watershed runoff and water resources in different vegetation zones should be based on local hydrological and climatic conditions, and the influence of human activities should also be considered. The Alpine Meadow vegetation zone has steep terrain. Abundant precipitation and glacier snow provide sufficient water for unsaturated zone soil and easily form slope runoff when rainfall intensity or snowmelt intensity exceeds the infiltration capacity of ground soil. Some of the infiltration water is incompletely lost,

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which becomes underground runoff, so runoff includes surface and underground runoff. With the global warming in recent years, despite the increase of runoff, the glacier area is shrinking, the ice and snow reserves are decreasing, and regional climate regulation is weakened. In addition, the waste from mining activities will pollute glaciers and even lead to the deterioration of water quality in the process of runoff formed by rainfall and melting water of ice and snow. As a natural reservoir, although the transpiration of plants is strong in the drought period, the soil water storage capacity of the forest is still higher than that of other vegetation-covered soils under the same climate conditions (Sprenger et al., 2019). The Coniferous Forest belt is located on the mountainside, with a large slope on the ground. The continuous heavy precipitation from late summer will form surface runoff and flow into Xiying River, and some water will seep into the soil layer to supply underground runoff. There is little rainfall in the Deciduous Forest zone, and the terrain of this vegetation zone is gentle. After rainfall reaches the ground, it is not easy to form slope runoff, but easy to seep into the soil to replenish groundwater. In the arid period of Mountain Grassland, the evaporation is strong, the water storage is less, and the groundwater is buried deeply. After one rainfall, the water storage in the basin is not saturated, and all the infiltration water is lost, making it difficult to form underground runoff. Only when only a few rainfall intensity is greater than infiltration intensity, the over-infiltration rain will occur, forming surface runoff. The soil moisture content in this region is extremely low, and the growth of plants is inhibited, resulting in the unsustainability of ecosystem services and agricultural and pastoral land. In order to effectively improve and manage water resources in arid headwaters areas, it is necessary to explore the heterogeneity among different vegetation zones and deeply understand the runoff generation mechanism of different vegetation zones in watershed runoff generation areas. According to the current situation of climate, hydrology, and social economy in the basin, scientific and reasonable management policies should be formulated according to local conditions for different ecological-hydrological contradictions and extended to more areas.

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6. Conclusion

This work provides further insights into the movement and mixing of soil water in different vegetation zones in arid headwaters areas. Dry-wet conditions were the key factors that restrict soil water storage capacity in different vegetation zones. Rainfall decreased, temperature rose, groundwater level dropped, and soil water storage capacity weakened in the vegetation zone change to low altitude. The water storage capacity of the surface soil of each vegetation zone was weak, and more water was stored in the middle and lower soil with higher clay content. During the study period, the dynamic changes of lc-excess in soil profiles of different vegetation zones reflected the evaporation signals caused by drought. Soil evaporation in spring and summer and insufficient precipitation during drought were the main driving forces leading to isotopci enrichment in surface soil. In low altitude vegetation zone, the high temperature made evaporation front penetrate deeper into soil layer, and there was still obvious evaporation signal below 70 cm of the surface. Soil water isotopes and GWC record the process of soil rewetting caused by precipitation input and mixing. Alpine Meadow and Coniferous Forest zones were rich in rainfall. After a short period of weak evaporation, the soil will be rewetted by the next rainfall. There was only sporadic precipitation in Mountainous Grassland and Deciduous Forest belt from mid-May to late July. After July, the drop in temperature and continuous precipitation made the soil wet again after two months of drought. The Mountain Grassland and Deciduous Forest zone had only sporadic precipitation from mid-May to late July. With the decrease of air temperature and continuous precipitation after July, the soil was re-wetted after two months of drought. In addition, the Alpine Meadow and Coniferous Forest zones had a steep slope and humid climate, which was easy to form surface runoff and underground runoff in the rainy season and ice and snow melting period. Low-altitude vegetation zone with flat terrain had dry climate and scarce precipitation, and part of the water seeped into the middle and lower layers of soil to accumulate or replenish groundwater, so it wasn't easy to form slope flow. This research are helpful to understand the hydrological process of different vegetation areas, and give managers to formulate scientific and reasonable water resources, animal husbandry and mining area management policy decision support.

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Author Contribution statement

Guofeng Zhu and Leilei Yong conceived the idea of the study; Yuanxiao Xu and Qiaozhuo Wan analyzed the data; Zhigang Sun and Leilei Yong were responsible for field sampling; Zhuanxia Zhang participated in the experiment; Lei Wang participated in the drawing; Leilei Yong wrote the paper; Liyuan Sang and Yuwei Liu checked and edited language. All authors discussed the results and revised the manuscript.

Additional Information

Competing Interests: The authors declare no competing interests.