Temporal and spatial variation characteristics of groundwater recharge in a small watershed in the Loess hilly region

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Abstract

Groundwater is an important water resource for the ecological restoration and the life and production of the inhabitants of the Loess hilly region. A quantitative exploration of groundwater recharge mechanism and the spatial-temporal variation pattern is the key for an effective evaluation of groundwater resources in this region. Based on a Bayesian model and a Sinusoidal model, the spatial-temporal distribution pattern of the water transmission time and the groundwater recharge ratio were investigated. The results showed that the transmission time of groundwater by precipitation and surface water were 443.16 d and 64.58 d, respectively, which yielded a recharge ratio of 29.22% and 70.78%, respectively. Surface water was the main recharge source of groundwater in this region. The values of the groundwater recharge ratio by precipitation in the rainy season and dry season were 32.83% and 25.60%, respectively. Groundwater recharge mainly occurred during the rainy season. From upstream to downstream of the small watershed, the groundwater recharge ratio by precipitation increased gradually, while the groundwater recharge ratio by surface water decreased. The spatial characteristics of groundwater recharge ratio were all nonetheless not obvious. Groundwater recharge mainly took place in the upstream region of the watershed, while the discharge took place in the downstream area. Groundwater recharge occurred mostly through a combination of piston flow and preferential flow. The findings of this study could provide a reference for the development, the utilisation and the protection of groundwater resources in small watershed in the Loess Hilly region.

1 Introduction

The surface water and groundwater resources are limited and unevenly distributed in time and space in the Loess hilly region, where the climate is predominantly arid and semi-arid. Even so, groundwater is, in some regions, the only freshwater source for the production and life of the inhabitants, such as drinking water and irrigation water (Xia et al., 2008). However, due to the insufficient precipitation and the high evapotranspiration in this area, groundwater recharge rate tends to be relatively low (Scanlon et al., 2010), while unreasonable abstraction of groundwater continues to occur. The overexploitation of groundwater compared to its renewal and recharge rate will cause the fast depletion of groundwater, thereby threatening the ecological restoration as well as the production and life of the residents. The sustainable management of groundwater resources must, therefore, requires an accurate quantitative analysis of groundwater recharge mechanism (Shen et al., 2015). It is nonetheless particularly difficult to provide a quantitative estimate of groundwater recharge given its relatively low rate in the region.Various methods have been used in previous studies to conduct an in-depth exploration of the groundwater recharge mechanism in this region. Zhu et al. (2009a; 2010b) quantitatively estimated the groundwater recharge ratio and the residence time of Wuding River Basin in the Loess Plateau, based on the water withdrawal analysis method. Gates et al. (2011) estimated the impact of land use on groundwater recharge in the Loess Plateau using a tracer method combining chloride ion, stable hydrogen and oxygen isotopes. They concluded that concentrated water infiltration in gullies and other low-lying areas was the main groundwater recharge mechanism in this region. Hui et al. (2015) evaluated the effect of reforestation on groundwater recharge in the Loess Plateau by applying the RHESSys model.

The hydrogen and oxygen isotope tracers have been widely used to examine groundwater recharge in arid and semi-arid regions due to the numerous advantages this technique presents (Emam et al., 2015; Qin et al.,2011). Amongst these advantages, these tracers do not interact with other substances in the water molecule migration process, they directly participate in groundwater circulation, they do not pollute the environment, and they can track long-term groundwater movements. Regional water cycle and the mixing process of multi-terminal water body could be traced by measuring δ D and $\delta\,^{18}$O in precipitation, soil water and groundwater in order for some of the main hydrological processes to be revealed, which include the precipitation composition, infiltration, evaporation, migration (Kendall; Tan et al., 2016). Peng et al.(2005) investigated the effect of vapour water from the continental evaporation on hydrogen and oxygen isotopes composition in precipitation based on hydrogen and oxygen isotope tracer method. Liu et al.(1995) explored the seasonal soil water movement in the top meter of undisturbed desert soil in the southern Arizona using δ D and $\delta\,^{18}$O, the results indicate repeated seasonal cyclic movement of soil water mainly occurred in the top layer of 60–80 cm. Several previous studies have applied the hydrogen and oxygen isotope tracer method in the groundwater research field. For example, the seasonal recharge pattern of the Huanlia river basin in Taiwan, China was quantitatively analysed by Yeh et al. (2014) using the hydrogen and oxygen isotope tracer technique. Earman et al. (2006) used these tracers to explore the groundwater recharge characteristic caused by snowmelt in the southwest of the United States. Thoma et al. (1979) calculated the amount of groundwater recharge by atmospheric precipitation through the analysis of the seasonal variation of δ ^{18}O in the atmospheric precipitation in Pelat dune, Israel. However, because of a lack of temporal water monitoring data of hydrogen and oxygen isotope, The mechanisms governing loess groundwater recharge in such a climatic and topographic environment still remain unclear (Tan et al., 2016). Existing studies in this field mainly focused on the analysis of groundwater source and recharge mechanism (Xiang et al., 2019; Tan et al., 2017; Zhi et al., 2017). Limited studies have focused on the spatial-temporal distribution characteristics of groundwater recharge in a small watershed of this region.

Water transmission time refers to the time-lapse that water molecules have experienced from when they enter the small watershed system until they leave it. The transmission time could not only reveal some information about the water storage, the flow path and the water source but is also closely related to some of the internal hydrological processes in the watershed (Sivapalan, 2010; Mcguire et al., 2004). Numerous studies have investigated water transmission time in small watersheds. Asano et al. (2002) calculated the mean water transmission time of precipitation to groundwater in Rachdani region using the index of δ D, which was equivalent to a year. LEE et al. (2007) evaluated the water residence time at different depths of soil layers in Puji Island, South Korea, using deuterium surplus. Their results showed that the mean residence time at 30cm and 60-80cm depths were about 74 and 198 days, respectively. However, due to the Loess Plateau, China is predominantly covered by loess deposits ranging from 30 to 80 m in thickness (Wang et al., 2010), there is a slower groundwater recharge rate and the recharge period can be up to several decades, hundreds of years or even longer in the process of groundwater recharged by rainfall through unsaturated loess layers (Huang et al.,2013; Lin and Wei, 2006). Few studies have explored water transmission time in the Loess Hilly Region for relatively concealed water flow path and the insufficiency temporal monitoring data of isotope.

In this study, over 17 months in the Zhifanggou watershed and over 7 months in the Bangou watershed of stable D and O isotope composition monitoring were performed in precipitation, surface water and groundwater in the Loess hilly region. The results could provide a basis for the scientific research and rational development and utilisation of groundwater resources in this region. Therefore, the overall objectives of this study were threefold: (1) to analyze the spatial-temporal variation characteristics of hydrogen and oxygen isotopes in different water bodies at small watersheds in the Loess hilly region, and identify the main recharge sources of groundwater; (2) to quantitatively estimate the recharge ratio and the water transmission time of precipitation and surface water to groundwater in the small watershed; (3) uncover the temporal and spatial distribution model of groundwater recharge in small watershed of the Loess hilly region.

2 Materials and methods

2.1 study area

The study was conducted in the Zhifanggou watershed (36°43'-36deg46'N,109deg14'-109deg16'E) and the Bangou watershed (36deg46'-36deg44'N,109deg24'-109deg26'E), in Ansai county on the northern Loess Plateau of China (Fig. 1). The Zhifanggou watershed is the first branch of the lower reaches of the Xingzi River, a tributary of the Yanhe River. The area of the watershed is 8.27 km^2, with a narrow and long north-south direction. The watershed has a continental monsoon season climate. The mean elevation is 1425-1041 m, the annual mean temperature is 8.8 degC, the annual mean evaporation is 1463 mm, the annual mean precipitation is approximately 549.1 mm, which is unevenly distributed in the year and can vary considerably from one year to another. The land consists of loessial soil, mainly consisting of silt (0.002-0.05mm). The terrain is broken, and the density of the gully is 8.07 km/km^2. Groundwater mainly consists of water flowing in the quaternary alluvial aquifer and the fissured shallow weathering crust, with a mean depth of 13 m. The Bangou watershed (36deg46'-36deg44'N,109deg24'-109deg26'E) is located at 14.60 km east of the Zhifanggou watershed and belongs to the first-grade tributary of the Yanhe River. The watershed area is 6.56 km^2 with a mean elevation of 1268-1055 m and annual mean precipitation of approximately 534.7 mm. The soil type is mainly loessial, and the mean depth of the phreatic surface is 12 m. The climate type and the hydrogeological conditions of the Bangou watershed are similar to those of the Zhifanggou watershed, but its gully is cut deeper, and the aquifer is more fragmented.

2.2 sampling and analysis

The water sampling point of precipitation, surface water and groundwater were set up in each part of the gully head, upperstream, middlestream and downstream in the Zhifanggou watershed, respectively. Likewise, water sampling point of precipitation, surface water and groundwater were set up in each part of the upperstream, middlestream and downstream in the Bangou watershed, respectively. The elevation, the longitude and the latitude were recorded using a hand-held GPS. The specific sampling points were shown in Fig.1. Form June 2016 to October 2017, three water bodies in the Zhifanggou watershed were continuously sampled at intervals of 15 days. Similarly, three water bodies in the Bangou watershed were sampled from June April to October 2017 at similar intervals. Each sampling was repeated twice, and the samples were sent to the laboratory of water resources research institute, Xi'an University of Technology once the sample collections were completed. All samples were tested for δD and $\delta^{18}O$ using DLI-100 liquid isotope laser analyser LGR-LWIA (Los Gatos Research Inc., USA). Sampling methods for each water body were as follows:

Precipitation sampling: an open area was selected near each sampling point, and rain measuring cylinder with of type J16022 was set up to collect precipitation samples. About 8 milliliters of liquid paraffin oil was previously applied to the rainwater collector to prevent water evaporation. During sampling, the water below the paraffin oil layer was extracted with a 15 mL disposable syringe. The collected precipitation samples were filled in 10 ml brown glass reagent bottles, which were tightened and sealed with Membrane seal film. After the collection completed, the water collector was cleaned up, and the liquid paraffin oil reapplied. All the samples were refrigerated at 4 °C. The stable isotope was after that tested to ensure the reliability of the test results. According to statistics, 312 precipitation samples were collected during the experiment.

Surface water sampling: surface water sampling points were set up at the bottom of the gully, near the precipitation sample point. During the collection, the sample bottle was inserted 20 cm below the surface of the water to prevent the influence of evaporation fractionation. The collected surface water samples were filled in 10 ml brown glass reagent bottles, tightened and sealed with Membrane seal film. The samples were after that refrigerated at 4 , before the stable isotope was tested. According to statistics, 312 surface water samples were collected during the experiment.

Groundwater sampling: the sampling of groundwater consisted of withdrawing water from the bottom of a well up to the surface using a bucket, and quickly placing it in a cool place. The sampling and refrigeration methods were similar to those applied in the case of the surface water. Since there were only one groundwater well in the Zhifanggou watershed laocated in the mouth part of this watershed, which is used as a drinking water source, so as to only one groundwater sampling point was set up in the mouth of this watershed. A total of 76 groundwater samples were collected. In the case of the Bangou watershed, three groundwater sampling points were set up. The groundwater sample in upperstream corresponded to seepage water from the rock formation, and groundwater samples in the middlestream and downstream were from wells. A total of 56 groundwater samples were collected.

2.3 Analysis methods

2.3.1 Estimation of water transmission time

A large number of studies showed that the annual (seasonal) isotope characteristics of precipitation, surface water and groundwater followed a certain periodicity, which can be characterised by sinusoidal regression analysis of the following form:

$\delta=X+A*\cos(ct-\vartheta)$ (1)

where δ corresponds to δ D, δ ^{18}O or d-excess; X is the annual mean of δ D,δ ^{18}O or d-excess; C is the fluctuation frequency of δ D, δ ^{18}O or d-excess (0.017214rad·d^{-1}); T is the time, and ϑ is the lag time.

The mean water transmission time (T) in the water circulation system is as follows:

$T=C^{-1}[(A_{z2}/A_{z1})^{-2}-1]^{0.5}$(2)

Where A_{z1} is the amplitude of the input signal; A_{z2} is the amplitude of the output signal; C is the fluctuation frequency of δ D, δ ^{18}O or d-excess (0.017214rad·d^{-1}).

2.3.2 Quantitative estimation of groundwater recharge

The MixSIAR statistical package (Stock and Semmens, 2013) is a general Bayesian framework that was used to quantify the contributions of the different flows relative to the total groundwater recharge. It has been widely used in sourcing plant water, pollutants, soil carbon and in food-web studies. In this study, only two end members were considered: precipitation and surface water (as described in Section 3.1). As for groundwater, the water isotopes of different samples were considered independent consumers (input) as they were collected from different sites. The error structure was set to default, "Resid*Process" and the Markov Chain Monte Carlo length was set to "short" for better predictions of the probability distributions of the sources (e.g. precipitation and surface water). Because there was no prior information, the "Uninformative"/Generalist was selected in this framework. After running MixSIAR, a check diagnostic was conducted according to Stock and Semmens (2013) to confirm the validity of the output (contributions). Finally, the mean values of the runs were considered as the most likely proportions of contributions, and the standard deviation was considered as the uncertainty (Xiang et al., 2019)(Fig. 2).

3 Results

3.1 Spatial and temporal variation characteristics of hydrogen and oxygen isotopes in water

The values of the hydrogen and oxygen isotope characterisation from June 2016 to October 2017 for different water bodies in the Zhifanggou watershed are shown in Table 1. In different water bodies, the δ D and δ ^{18}O of groundwater was most depleted (-64.95, -9.04 the precipitation was most enriched (-52.12, -7.74 oxygen isotope characterisation values from April to October 2017 for the precipitation, the surface water and the groundwater in Bangou watershed are shown in Table 2. The hydrogen and oxygen isotopes of each water body in this watershed follow a similar lawpattern as in the Zhifanggou watershed, i.e. the precipitation isotope was the most abundant with the highest variation coefficient, while the groundwater isotope was the most depleted, with a relatively stable isotope.

At the same time, the hydrogen and oxygen isotopes in the different water bodies exhibited a certain spatial variability. In different parts of the Zhifanggou watershed, The δ D of precipitation in the upperstream was most depleted (-53.49

stream (-43.81precipitation in the downstream was most enriched(-36.11^{18}O of precipitation in the upperstream was most depleted(-7.72(-6.46downstream was most enriched(-5.43the downstream was most depleted (-62.55(-61.01water in the middlestream was most enriched (-57.55 ^{18}O of surface water in the downstream was most depleted (-8.46 head (-8.03 in the middlestream was most enriched (-7.64

On the other hand, the δ D of precipitation in the downstream of the Bangou watershed was most depleted (-39.85upperstream (-39.77^{18}O of precipitation in the middlestream was most depleted (-6.07 downstream (-5.83 of surface water in the upperstream of the Bangou watershed were most depleted (60.13, 7.63 the downstream (57.59, 7.16 ^{18}O of groundwater in the upperstream of the Bangou watershed were most depleted (-57.55, -7.93(-59.49, -7.44three water bodies were gradually enriched from upperstream to downstream in the watershed, but the difference was not significant. However, due to the influence of the watershed environment, the spatial characteristics of the hydrogen and oxygen isotopes in the surface water of the Zhifanggou watershed and the precipitation of Bangou watershed were not obvious.

The temporal variation characteristics of the hydrogen and oxygen isotopes in different water bodies of the Zhifanggou watershed are shown in Fig. 3. The hydrogen and oxygen isotopes of the precipitation exhibited the largest variation over time, and their δ D andδ ^{18}O were the most enriched in May (-19.45, -3.11-14.26surface water were relatively stable from June to December 2016, and the fluctuations mainly occurred within the period January - August 2017. Their δ D and δ ^{18}O were the most enriched in May (-19.45, -3.11(-71.86, -9.39). The hydrogen and oxygen isotopes of the groundwater were relatively stable, with a δ D and δ ^{18}O the most abundant in August (-61.15, -8.16the most depleted in March (-67.54There was a lag time between the depletion peak of groundwater and the peak of precipitation and surface water, indicating that the groundwater recharge process by precipitation and surface water was mainly through piston flow, with a lower recharge rate and longer recharge period (Tan et al., 2016). The temporal evolution of the hydrogen and oxygen isotopes in the three water bodies of Bangou watershed is shown in Fig. 4. The depletion peaks of the precipitation, the surface water and the groundwater appeared in October in all cases. This indicates that there may be preferential flow channels for water flow in this watershed. Hence, precipitation could recharge groundwater faster, which induced a shorted recharge period. Therefore, there was a possibility that the piston flow and the preferential flow could jointly recharge groundwater in the Loess Hilly region (Xiang et al., 2019; Tan et al., 2017).

At the same time, the d-excess of the precipitation in the two watersheds was analysed. The results showed that the d-excess of the precipitation from June to October remained smaller than 10means that the precipitation water vapour mainly originated from marine air mass. Also, the d-excess from November to May exceeded 10indicated that the precipitation was mainly attributed to the continental air mass.

3.2 Analysis of groundwater recharge source

The relationship between the hydrogen and oxygen isotopes in the case of the precipitation in the Zhifanggou watershed was fitted for two periods, as shown in Fig. 5-a. The first period extended from November to May and the second period extended from June to October, The equation of the precipitation line wereδ D=7.50δ ^{18}O+10.14, R^2=0.98 andδ D=7.84δ ^{18}O+5.64,R ^{2}=0.96, in the first period and in the second period, respectively. The gradient of the precipitation line was smaller than that of the global atmospheric precipitation line (δ D=8δ ^{18}O+10). Most of the groundwater hydrogen and oxygen isotope points fell on the precipitation fitting line from June to October. Away from the part of the surface water points that fell in the region where the groundwater was located, the rest of points were located at the lower right of the precipitation fitting line. The results indicated that the precipitation from June to October was the main recharge source for the surface water and the groundwater, and there was a possibility that surface water and groundwater could recharge each other. And the points of the surface water and the groundwater were all still located at the lower right of this line from November to May. This indicates that the surface water and the groundwater could be recharged by precipitation in this period, but its hydraulic connection with surface water and groundwater was weaker than during the period from June to October.

The fitting equation of the hydrogen and oxygen isotopes for the precipitation in Bangou watershed were$\delta D=7.42\delta^{18}O+8.11$ ($R^2=0.99$) and$\delta D=6.72\delta^{18}O-2.62$ ($R^2=0.96$), from April to May and from June to October, respectively. The values of the gradient of these two lines were smaller than that of the global precipitation line. The points of the groundwater and the surface water were both located at the lower right of the precipitation fitting line from June to October, which indicate that the precipitation in this period was the main recharge source for the surface water and the groundwater in Bangou watershed. The region where the locations of the surface water and the groundwater points were coincident indicated that the connection between groundwater and surface water was closer in this period than during the period June-October. Also, this demonstrates that the mutual recharge of surface water and groundwater was more frequent.

3.3 Water transmission time

Sinusoidal fitting was performed for the hydrogen and oxygen isotopes in different water bodies of the Zhifanggou watershed in the period June 2016 - October 2017, as shown in Fig. 6. The results of δ D fitted showed that amplitudes of the precipitation and the groundwater were respectively 18.60precipitation to groundwater estimated by the model was 510.06 d. Based on the results of δ ^{18}O fitted, the transmission time of the precipitation to groundwater was 376.25 d (Table 3). Therefore, the mean transmission time of the precipitation to groundwater was 443.16 d. Table 4 shows the transformation time between surface water and groundwater in different parts of the watershed. The fitting results of δ D provide evidence that the transformation time of surface water to groundwater was 77.14 d, 55.37 d and 65.53 d, in the gully head, upperstream and middlestream, respectively. Also, the estimated result for the transformation time based on $\delta^{18}O$fitted was 64.68 d, 60.13 d and 63.88 d, in the gully head, upperstream and middlestream, respectively. Threrfore, the mean transmission time of surface water to groundwater was 70.91, 57.75 and 64.71 d in the gully head, the upperstream and the middlestream, respectively. The mean transmission time of surface water to groundwater in this watershed was 64.58 d, which was about 15% of the transmission time of the precipitation recharge to groundwater. In the downstream, the surface water was recharged by the groundwater. Based on the fitting results ofδ D and δ D^{18}O, the transmission time of surface water recharged by groundwater were 55.26 and 49.53 d, respectively. The mean transmission time value was 51.10 d. This show that the downstream was the main groundwater discharge area in the small watershed. At the same time, the time of groundwater discharge to the surface water was similar to the time of surface water recharge to groundwater. This indicates that there might be a similar channel through which the groundwater and the surface water could recharge each other simultaneously.

3.4 recharge ratio of groundwater

Based on the Bayesian model, the mean groundwater recharge ratio by precipitation and surface water in Zhifanggou watershed were respectively 34.7% and 65.3%, from June 2016 to October 2017. From April to October 2017, the groundwater recharge ratio by precipitation and surface water in the Bangou watershed were 17.2% and 82.8%, respectively. In the Bangou watershed, the groundwater recharge ratio by precipitation was 22.5%, 6.8% and 14.1%, in the upperstream, middlestream and downstream, respectively (Fig. 7a). The groundwater recharge ratios by surface water were 77.5%, 93.2% and 85.9% in the upperstream, middlestream and downstream, respectively (Fig. 7b). The groundwater recharge ratio by precipitation in the gully head, upperstream, middlestream and downstream of the Zhifanggou watershed were 33.3%、32.7%、46.0% and 10.6%, respectively (Fig. 7a), and the recharge ratio by surface water were 66.7%、67.3%、54.0% and 89.4%, respectively (Fig. 7b). The groundwater ratio by precipitation from the upstream to the downstream in the small watershed gradually decreased, while the recharge ratio by surface water increased. These results show that the upperstream of the small watershed was the main recharge area of groundwater by perciputation. But there were two phenomenons that the groundwater ratio by precipitation in the middlestream of Bangou watershed decreased sharply compared with oter parts, and the ratio increased sharply in the middlestream of Zhifanggou watershed compared with other parts of the watershed. This phenomenon might be related to the regional situation such as topography and vegetation, and the location of the sampling points in the middlestream.

The study period from June to October was classified as rainy season since the d-excess value of precipitation was less than 10period from January to May was classified as a dry season. The groundwater recharge ratio by precipitation and surface water in Zhifanggou watershed were estimated in the periods June-October and November- May(Fig. 8). Similarly, the groundwater recharge ratio by precipitation and surface in the Bangou watershed were estimated in the periods June-October and April-May, as shown in Fig. 8. In the rainy season (June-October), the values of the groundwater recharge ratio by precipitation were 37.65% and 28.00% in the Zhifanggou watershed, and the Bangou watershed, respectively (Fig. 8a), and the corresponding ratios by surface water were 62.35% and 72.00%, respectively (Fig. 8b). In the dry season (January-May), the values of the groundwater recharge ratio by precipitation were 24.60% and 8.30% in the Zhifanggou watershed, and Bangou watershed, respectively (Fig. 8a), and the corresponding ratios by surface water were 75.40% and 91.70%, respectively (Fig. 8b). In the rainy season, the values of the groundwater recharge ratio by precipitation were 1.53 and 3.37 times greater than in the dry season, for the Zhifanggou watershed and the Bangou watershed, respectively. These results evidence that the rainy season was the main season in which groundwater was recharged through precipitation. Also, the groundwater in the dry season was mainly recharged by surface water, where the ratio was about 1.21 and 1.27 times greater than in the rainy season, in the Zhifanggou watershed and the Bangou watershed, respectively.

4 Discussion

4.1 Spatial and temporal variation characteristics of hydrogen and oxygen isotopes in water

In this study, the hydrogen and oxygen isotopes of groundwater were the most depleted in the three water bodies, but the hydrogen and oxygen isotopes of the precipitation, which is one of the main water recharge sources for groundwater (Joshi et al.,2018; Maria et al.,2007), were the most enriched. This phenomenon might be related to the amount effect of the hydrogen and oxygen isotopes in rainfall (Yeh et al., 2011; Yamanaka et al.,2004; Dalai et al.,2002) (Fig. 9). The annual frequency of occurrence of short-duration light rains in the Loess Plateau could reach up to 86.70%, with relatively small rainfall and a large quantity of isotope. While the annual rainfall frequency of medium and heavy rains with large rainfall and little isotope was only 13.30%, which made the hydrogen and oxygen isotopes of the precipitation relatively abundant. Liu et al. (2009), Oiro et al. (2018) and Grismer et al. (2000) all found that groundwater recharge generally occurred after heavy rains and continuous rainfall, thereby implying that the probability of groundwater being recharged by heavy rain was greater. In this study, the δ D and δ ^{18}O of the heavy precipitation were respectively -85.12more depleted than the values for groundwater (-64.95hydrogen and oxygen isotopes gradually approached those of the groundwater due to the combination of evaporation fractionation and the mixing of previous enriched soil water during the infiltration process of precipitation into the soil to recharge groundwater (Natalie et al.,2016). At the same time, Earman et al. (2006) found that the groundwater recharge ratio by snowmelt could reach 40% to 70% in the southwestern United States, while more than 50% of the groundwater recharge in Norway taken place during snowmelt (French et al.,2004), although snowfall only accounts for 25% to 50% of the annual precipitation. This indicates that snowfall in winter may also produce greater recharge to groundwater. In this study, the mean values ofδ D and δ ^{18}O in snowfall were -95.08% and -14.11%, respectively, which were more depleted than those of groundwater. Groundwater isotopes had become the most depleted of the three water bodies under the combined recharge of heavy rains and snowfall with depleted isotopes.

At the same time, the hydrogen and oxygen isotopes of the rainfall have an elevation effect (Peng et al., 2016; Campani et al.,2012) (Fig.9). The precipitation isotopes in the upperstream with the higher elevation were more depleted, and the isotopes in the downstream area with the lower elevation were more enriched. In the process of surface water flowing from the gully head to the downstream, evaporation fractionation occurred and caused the hydrogen and oxygen isotopes to become gradually enriched (Lu et al., 2012). This finding is in agreement with the results reported by Song et al. (2009) in the Chabagou watershed. Under the combined recharge of precipitation and surface water, the hydrogen and oxygen isotopes of groundwater were also depleted in the upperstream and enriched in the downstream (Ho J C et al., 2004). However, the difference of the water hydrogen and oxygen isotopes was not significant among the different parts.

4.2 Temporal characteristics of groundwater recharge

The groundwater recharge by precipitation was affected by the stratigraphic structure of the study area (Ndlovu et al., 2016; Adrian et al., 1989). Tang et al. (2016) found that the rock formations in the Ansai area of China were mainly composed of clastic feldspathic sandstones, and the rock layers were filled with hydrophilic substances with high viscosity such as chlorite. The rock formation in this region was relatively broken due to the strong brittleness of feldspar sandstone. The thinner the rock formation, the more the fracture develops (George et al., 2009). The rock formations in the Zhifanggou watershed were mostly thin-layered (Fig. 1f). The rock fissures were relatively developed, and the soil layer in some areas was relatively shallow. In case of large precipitations, the water could easily penetrate the loess layer and enter the groundwater aquifer along the rock fissures (Zhu et al., 2010), which provides a possibility for groundwater recharge by precipitation. According to the studies of Xiaolu et al. (2018) and Zhu et al. (2010), the infiltration depth of precipitation and the groundwater recharge ratio by precipitation were allpositively correlated with the precipitation. Precipitation from June to October accounted for 88% of the total annual precipitation in the Loess Plateau, which was the time when most moderate and heavy rains occurred. In this study, precipitation and groundwater were more closely related in the rainy season, and the groundwater ratio was 7.23% higher than that in the dry season (Dvory et al., 2016). Groundwater recharge season occurred mainly during the rainy season (Machiwal et al., 2012). The precipitation was scarce from November to May, and the groundwater was mainly recharged by snow melting in some areas (Wang et al.,2017; Diodato et al.,2013). Groundwater recharge by precipitation in this season was smaller, and the connection between groundwater and precipitation was weaker. These findings are similar to those reported by Yeh et al. (2014) in the Hualien River watershed, Taiwan, China.

Gullies in the small watershed of the loess plateau were formed under the long-term undercut erosion and scour of the flowing water (Descloitres et al.,2003). The gully cuts through the loess and penetrates the bedrock weathering zone (Guyassa et al.,2017; Orazulike et al.,1988). Local gullies even cut through weathering zones into fresh rocks to form deep grooves. Undercutting of rock strata destroyed the underground aquifers in some areas, causing groundwater to leak out and recharge surface water (Unland et al.,2014). When the surface water resource was abundant with a high water level, it could enter the underground aquifer through the fault zones, so that surface water and groundwater could recharge each other (Borman et al.,2014; Almanaseer et al.,2012). The response mechanism of groundwater to precipitation and surface water was also closely related to the shape of the gully (Demisachew et al., 2018). The gully shape of Bangou watershed was a narrow and deep with steep slopes on both sides, which was approximately a "V" the type of shape. Most of the precipitation was concentrated into the gully in the form of runoff in a short time. The surface water could then recharge groundwater through the fracture surface of the aquifer. The gully shape of the Zhifanggou watershed was wide and shallow with gentle slopes on both sides, which was approximately a "U" type of shape. The contact time between the runoff and the surface soil was longer, which made water to be stored in the soil and recharge groundwater through vertical infiltration. Due to the sedimentation at the bottom of the gully, surface water needs to penetrate the alluvium to recharge groundwater through the aquifer fracture zones (King et al., 2015).

4.3 Spatial variation characteristics of groundwater recharge

In this study, the groundwater recharge ratio by precipitation was gradually decreased from upperstream to downstream, while the recharge ratio by surface water increased gradually (Egusa et al,2016). The main reason was that the gully shape in the upperstream is narrow with a larger uncut plateau area and relatively gentle geomorphic type, the precipitation mostly enters the soil in the form of infiltration (Li, et al,2008). Moreover, most of the terraces are located in the upstream, which greatly increased the recharge capacity of soil water and groundwater by precipitation (Arnáez et al,2015; Gates et al,2011). So a larger groundwater recharge ratio by precipitation appeared in the upperstream. There was little surface water in the upperstream due to the smaller catchment area (Orlova et al.,2014; Egusa et al.,2016). The groundwater recharge ratio by surface water was thus relatively smaller in this area. In the downstream, because of the maturity gully shape with increased gully proportion and seriously damaged the aquifer, and the abundant surface water resources given for the relatively larger catchment area, the groundwater could be recharged quickly by surface water through the fractures of the aquifer (Sun et al.,2016). Therefore, the groundwater recharge ratio by surface water was higher in downstream. On the other hand, due to the most geomorphology had a steeper slope in this area, the most precipitation lost in the form of runoff and less infiltrated into the soil. Therefore, the groundwater recharge ratio by precipitation was smaller in downstream. This result is consistent with that reported by Zhang et al. (2016) in the Grand River basin in Michigan, U.S. However, this process of groundwater recharge by surface water occurred at the time of abundant surface water resources in downstream. According to the analysis of the water transmission time, the process of surface water recharged by groundwater was relatively common in downstream (Santos et al.,2010; Zhang et al.,2016). This is because there was a lower water level of surface water for the deeper gully shape in the downstream. The groundwater of shallow aquifer, which originated from vertical infiltration of precipitation, could subsequently recharge surface water through the surface fractures.

The transmission time of groundwater recharge by precipitation was longer than that by surface water. Due to the gully bottom area where the surface water existed performed a lower elevation and cutting into the bedrock, the groundwater could recharged with a short path through passing through the silted soil layer at the bottom of the gully or directly getting into the cracks of the rock layer (Zhi et al., 2017; Broxton et al., 2009). Most of the precipitation nonetheless infiltrated in the gully slope and the platform not cut by water flow as the gully area was only about 9% of the watershed. Also, the water that infiltrated into the soil could enter the underground aquifer with a longer flow path through the thick loess aeration zone (Dewalle et al., 1997).

Meanwhile, the recharge process of surface water to groundwater was closely related to the topography and the geomorphology (Zhi et al., 2017). The groundwater recharge ratio in the middlestream of the Bangou watershed was much higher than the mean value of this watershed, accounting for 93.2%. Since groundwater sampling well in the middlestream is located at the bottom of the gully and is close to the surface water, the groundwater was recharged by surface water. The groundwater recharge ratio by precipitation in the Zhifanggou watershed was much higher than the mean value of this watershed, accounting for 46.0%. Given the ideal condition of precipitation infiltration in the soil caused by the good vegetation conditions in the middlestream (Gates et al.,2011; Jayawickreme et al.,2008). There is a large distribution of woodland with well soil pores in deep soil, making the precipitation could recharge groundwater more quickly. Meanwhile, the surface water was smaller, and the recharge capacity of surface water to groundwater was consequently weakened, whereas, the recharge capacity by precipitation was relatively enhanced.

5 Conclusion

Stable isotopes (δD and δ^{18}O) of precipitation, surface water, and groundwater were used to determine the groundwater recharge mechanism and the spatial-temporal variation pattern in the Loess hilly region. The hydrogen and oxygen isotopes of precipitation was most enriched, followed by surface water and then groundwater(this having the most depleted isotopes). The hydrogen and oxygen isotopes of the three water bodies were all gradually enriched from the gully head to the downstream in the small watershed. The transmission time of the precipitation and surface water to groundwater were 443.16 d and 64.58 d, respectively; and the corresponding groundwater recharge ratio were 29.22% and 70.78%, respectively. The main recharge source of groundwater in the Loess hilly region was surface water. The connection between precipitation and groundwater in the rainy season was stronger than that in the dry season, and the ratios of recharge were 32.83% and 25.60%, in the rainy and dry season, respectively. The groundwater recharge ratio by precipitation in upstream was larger than downstream. Meanwhile, the recharge ratio by surface water in upstream was smaller than the downstream. At the same time, the main recharge area for groundwater was located upstream in the small watershed of loess hilly region, while the main discharge area for groundwater was located downstream.

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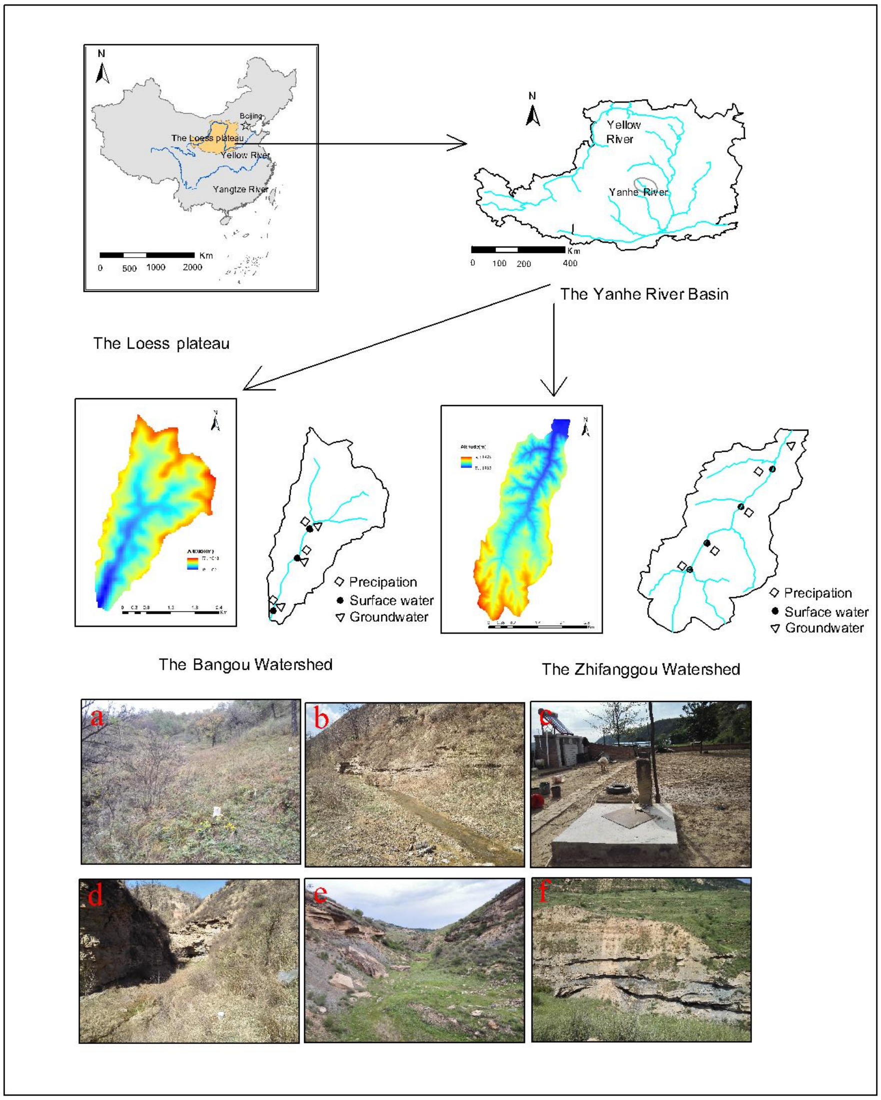
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The Zhifanggou Watershed
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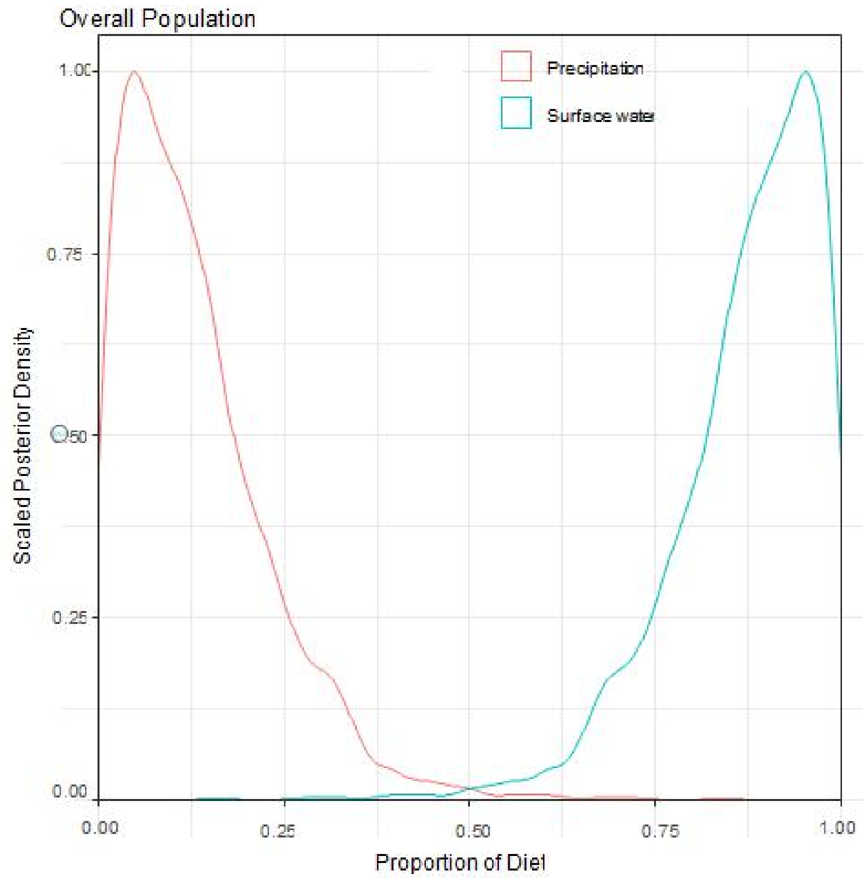

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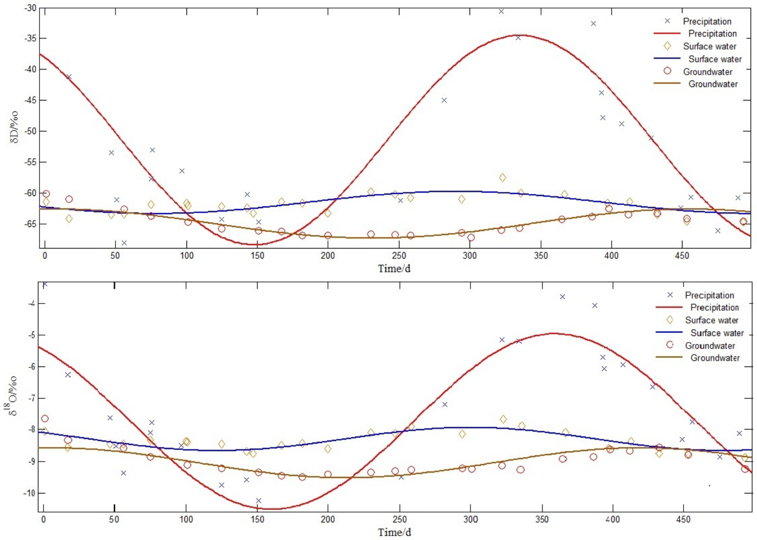

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