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Hydrological cycle research by D & ^{18}O tracing in small watershed in the loess hilly region

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Abstract

The objective of this study was to determine the mechanisms of the hydrologic cycle in the loess area in China. Sixty eight water samples from precipitation, soil water of the 0 – 4 m layer, surface water in the valley, ground water (spring and well) were collected and the Deuterium (D) and Oxygen – 18 (^{18}O) of these water samples were analyzed to interpret the relationship among those waters in the watershed in the loess hilly region during 2005 – 2009. The results show that: the D & ^{18}O of precipitation in Yangou was consistent with that of Xi'an, apparently the north migration of water vapor in Xi'an; according to the correlations among the differential waters in D & ^{18}O, confirmed that precipitation recharge could account for most of the sources of valley flow, with part of the recharge water going to soil water recharge. The D & ^{18}O of groundwater were very close to that of precipitation, likely the soil preferential flow was dominant in groundwater recharge although the infiltration had a certain lag. Under the influence of rainfall and evaporation, the response of the soil moisture profile, and its D & ^{18}O profile were different. The soil moisture had the strong influenced layer in the 0 – 60 cm range, a weak impacted layer in 60 – 160 cm, and a stable layer below 160 cm. It was shown that the soil evaporation depth could be up to 160 cm because the D & ^{18}O changed in that depth. The study could increase our understanding of the magnitude and pattern of the hydrologic cycle, which should improve water resources management in the watershed scale.

Key Words: Hilly area in the Loess Plateau, Precipitation, Groundwater, Soil water, δD & $\delta^{18}O$

1 Introduction

In the process of hydrological cycle in precipitation, surface water, groundwater, soil water and plant water, Fractionation Effect caused the different contents of isotopes in those water bodies. According to the different contents of isotopes in different water bodies, the way and the amount of conversion could be researched (Zhang et al., 2006). In 1961, Craig, based on the statistics on isotopes of the global fresh water, firstly set up the Global Meteoric Water Line, called GMWL: $\delta D = 8\delta^{18}O + 10$ (Tian & Duan, 2007). In different regions, compared with Global Meteoric Water Line, the measured Meteoric Water Line had different degrees of deviation in the slope and the intercept, which reflected the origins of precipitation clouds in different areas, as well as, the difference in precipitation clouds of unbalanced levels of gas and liquid isotopes fractionation under the change of environmental

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conditions during migration (Yin et al., 2001). In order to quantize and compare these differences, Dansgaard (1964) defined the Surplus of Deuterium: $d = \delta D - 8\delta^{18}O$, and the average value of d in the global precipitation was 10. From then on, hydrogen and oxygen stable isotopes were widely used in researching Hydrological Cycle. With the majority of studies on precipitation (Zheng et al., 1983), rainfall infiltration (Wang & Liao, 2007; Tang & Feng, 2001), rainfall runoff response (Gu, 1995; 1992), the supply of groundwater (O'Driscoll et al., 2005; Xu & Chen, 2010), and the conversion in different water bodies (Gu, 1992; O'Driscoll et al., 2005; Revesz & Woods, 1990) at home and abroad, it was proven that the method of hydrogen and oxygen isotopes was feasible. From Xi'an to Yan'an in the Loess Plateau in China, the amount of annual precipitation reduced rapidly from 650 mm to 520 mm and the evaporation was intensive, which enhanced Fractionation Effect among vapor migration and facilitated Environmental Isotope Method to research Hydrological Cycle in this area.

In this research, Egg Mao Gully in Yangou in loess hilly region was selected as the object. Samples including rainfalls, soil water, surface water of valley, ground water (spring water, well water) would be collected and the D & ^{18}O of waters would be analyzed according to the observation materials of precipitation from April to September during 2005 to 2009. The relationship between rainfall, surface water and groundwater also would be argued, which would provide the research on the mechanism of hydrologic cycle in the Loess Plateau with some reference.

2 Research methodology

2.1 *The description of research area*

The Yan'gou Watershed in Shaanxi, China, is located between latitudes N36°28′00″ and N36°32′00″ and between longitudes E109°20′00″ and E109°35′00″. The watershed is in the center of the hill-and-gullied loess areas and has a total area of 46.88 km^2. The main gully is 8.6 km long. The geomorphology is very complicated with many gullies resulting in various types of land utilization, e.g. farming on steep slopes, animal grazing, forestry, etc. The average temperature is 9.8℃. The average annual precipitation is 546.9 mm, and 70% of the annual precipitation occurs from June to September. And the annual average evaporation on water surface is 1, 100 mm. The testing field was sited mainly in Egg Mao Gully, one gully of Yangou. The area of Egg Mao Gully is 0.32 km^2 with 0.6 km long and 82 m level difference, which is covered by 1.8 – 100 m -depth loess. According to the data from oil drilling, as the boundary with groundwater basin, the spring water and well water are basically consistent with the surface basin landscape. In this watershed, parent material is loess. Hilly area and gully region are mainly covered by new loess and secondary loess which are the primary cultivated soil. Cultivated loessial soils occupies over 90% in this area, which owns some characteristics, such as, uniform grain composition, a loose and porous structure, vertical joints, the similar properties to the parent material, and without any feature like zonal of soil profile characteristics. Loessal soil is made up of sand clay (42.34% – 58.83%), pink clay (27.96% – 42.48%), and clay (9.36% – 15.18%). In this experiment, the measurement of soil water is based on loessal soil.

2.2 *Samples collection and analysis*

The distribution of water samples in this experiment is shown in Fig. 1. When the rainfall was over 10mm in rainy season, all of water in rain gauge should be collected after raining and the water samples were collected, too. According to the weather forecasts, the water samples of well water, spring water and gully water were collected before raining, and after raining samples of those should be collected several times in fixed interval again.

The water samples of soil water: before and after raining, 300 g soil was sampled from different depth of soil horizon profile from 0 to 300 cm in terraces. And soil samples were put into 500 ml plastic bottles and sealed in order to avoid isotopes exchange with outside. Those soil samples were taken into laboratory and Revesz's Toluene Azeotropic Distillation Method was used to extracting soil water. Through distilled indoor, all water samples were collected.

Put 10 – 20 ml water of every sample into the 20 ml glass bottles with seal-packing. Remove the water samples

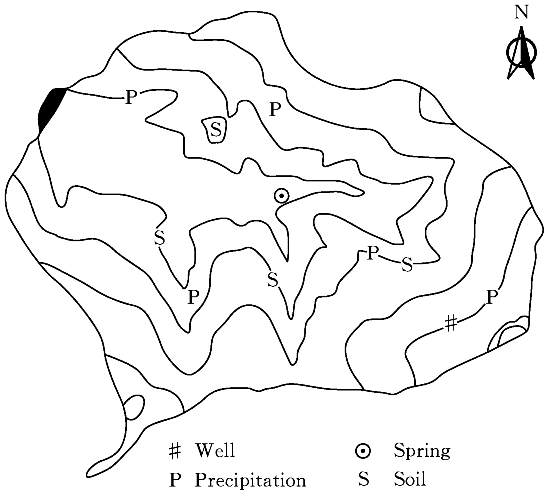

Fig. 1 Location of water samplings in Egg Mao gully

which were not closely related to rainfall events, and the number of water samples used in this study was 68, including 11 rainfall samples, 23 soil water samples, 10 spring water samples, 8 well water samples and 16 gully water samples. The distilled soil water was sealed in 20 ml glass bottles, too.

3 Analysis and discussion

3.1 *Consistency analysis on the δD & $\delta^{18}O$ of rainfall between Yangou and Xi'an*

The average value of δD & $\delta^{18}O$ of precipitation in Yangou and Xi'an (1985 – 1992), standard deviations and value ranges were shown in Table 1. The data of hydrogen and oxygen isotopes of Xi'an precipitation came from GNIP (Global Network of Isotopes in Precipitation).

In Table 1, the range of δD & $\delta^{18}O$ of precipitation in Xi'an had totally contained that in Yangou. The collected rainfall in Yangou almost occurred from June to October. Compared with the structure of rainfall isotopes in Xi'an in the same months during 1985 – 1992, the range in Yangou was fundamentally as the same as that in Xi'an, while the δD & $\delta^{18}O$ of precipitation were smaller. This phenomenon showed that precipitation in Yangou derived from the north migration of water vapor of Xi'an, and the δD & $\delta^{18}O$ fell down from clouds during migration, which caused that the heavy isotopes of precipitation in Yangou was less than that in Xi'an. This analysis tallied with the fact that the water vapor of Yangou came from Xi'an.

When the precipitation influenced by intense evaporation emerged the dynamic Fractionation Effect, the surplus of Deuterium was decreasing (Aragu et al., 1998; Zhang & Wu, 2009). According to the definition of Surplus of Deuterium (Dansgaard, 1964), the range of surplus of Deuterium of precipitation in Yangou during June-October was −8.33–14.63, and the average value was 5.91 which was less than that in Xi'an. This phenomenon illustrated there was an intense evaporation in Yangou during June – October.

3.2 *The relationship and the characteristics of D and ^{18}O in different waters*

What was shown in Table 1 was the heavy isotopes eigenvalues in those five water bodies. Because of the differences caused by evaporation fractionation, there was a significant difference in the contents of heavy isotopes in those water bodies, and the contents of δD & $\delta^{18}O$ from low to high were rainfall, spring water and well water, gully water, and soil water. There was a little difference in the range of δD & $\delta^{18}O$ of spring water and well water, which stated clearly that they had the similar recharge sources. The average value was close to those of rainfall in Yangou, and it indicated that the precipitation was the dominant direct recharge of groundwater and the infiltration was not affected by the absorbing exchange between rain and soil. That is to say, the recharge of soil preferential flow was dominant. The value range of gully water was similar to that in rainfall, which showed the hydraulic relationship between rainfall and gully water was intimate but less close than that of spring water and well water. The value range of gully, spring and well water were approximate, which indicated that there were some recharge relationships between surface water and groundwater. The δD & $\delta^{18}O$ of gully water was a little more than that of well water and spring water, which may resulted from the recharge of interflow that enriched heavy isotopes.

According to the second observation data of rainfall and weighting water, the average values of δD & $\delta^{18}O$ of rainfall in Yangou were −70.37‰ and −9.53‰ respectively.

Table 1 **Characteristics of δD & $\delta^{18}O$ of different water bodies**

Water body	δD (‰)				$\delta^{18}O$ (‰)				Observation number
	Average	Standard deviation	Min	Max	Average	Standard deviation	Min	Max	
Soil water	−23.42	24.68	−54.29	35.35	0.6	4.69	−5.54	12.34	23
Gully water	−64.74	15.12	−98.67	−49.66	−8.35	2.31	−13.8	−5.94	16
Spring water	−68.26	2.94	−75.67	−65.22	−8.85	0.51	−9.76	−8.06	10
Well water	−68.58	2.75	−72.51	−64.4	−8.77	0.75	−9.66	−7.29	8
Rainfall	−70.37	24.76	−108.07	−19.76	−9.53	3.32	−14.75	−4.24	11
Average rainfall of Xi'an	−48.29	24.76	−122.7	0.8	−7.27	3.11	−17.02	−1.1	60
Rainfall of Xi'an from Jun. −Oct.	−51.34	23.36	−101.5	0.8	−7.57	2.87	−14.27	-1.1	29

3.3 *The recharge of soil water after rainfall*

Fig. 2 showed the heavy isotopic composition and soil water content in different depths (0 – 300 cm) of terraces from 28th May, 2009 to 12th June, 2009. There was 22.7 mm rainfall on 27th May, 2009, and the δD & $\delta^{18}O$ of rainfall were −61.93‰ and −7.91‰; and there was 12.2 mm rainfall on 7th June, 2009.

As shown in Fig. 2, soil water content of surface soil (0 – 10 cm) was all lower, while the δD & $\delta^{18}O$ of soil water were higher. It indicated that the surface soil evaporation was intensive and that the heavy isotopes were enriched quickly in soil water by evaporation fractionation. In the depth of 20 cm, the heavy isotopes in soil water were depleted apparently because the evaporation fractionation decreased after the precipitation recharge, and the water content reached the peak on 28th May. In the depth of 30 cm, the δD & $\delta^{18}O$ increased and there was a high value of soil water content. Some studies (Zhang et al., 2003; Gong et al., 2005) showed that the plough pan of cultivated loessial soils was about 20 – 40 cm underground, having poor water permeability and the declining infiltration rate. So when the rainfall infiltrated to this layer (about 30cm), continued infiltration rate become slower, which led to water retention, and then more water joined the water from upper layers, so the δD & $\delta^{18}O$ raised. The infiltration rate decreased with the increasing depth, which caused that there was a declining trend in soil water content and intensity of evaporation in 30 – 60 cm, and the δD & $\delta^{18}O$ in 30 – 50 cm also showed a decreasing trend. In Fig. 2(c), the soil water contents on 2 different days in 60 cm were similar, and it indicated that the rainfall on 27th had not infiltrated to 60 cm before measuring on 28th May. Secondly, there was a decrease in soil moisture in 60 – 160 cm in the later period, while the δD & $\delta^{18}O$ raised more obviously than before [Fig. 2(a) and Fig. 2(b)]. And it was believed that this range (60 – 160 cm) was the weak evaporation layer and the effect of evaporation fractionation was clearer because this layer had less water. The δD & $\delta^{18}O$ in 160 – 300 cm had little change in each of two moments, and there was also no change in soil moisture, so this layer may be the stable layer.

In the profiles of δD and $\delta^{18}O$ [Fig. 2(a) and Fig. 2(b)], the changed trend of the δD & $\delta^{18}O$ of soil water in different depth among 0 – 50 cm was no difference between 28th May and 12th, June. The curve of 12th June was the right movement of the curve of 28th May, which showed that the δD & $\delta^{18}O$ of soil water were enriched obviously because of the evaporative fractionation. In Fig. 2(c), the soil moisture in 0 – 50 cm on 12th June was much less than that on 28th, May. And the heavy isotopes of soil water were enriched under the supporting of evaporative fractionation. In the depth of 60 – 160 cm, soil moisture was less than that on 8th May. At the same time, Fig. 2(a) and Fig. 2(b) showed that the δD & $\delta^{18}O$ were enriched. Below 160 cm, soil moisture, the δD & $\delta^{18}O$ all remained stable during measuring. It inferred that the precipitation recharge and the evaporation occurred in the depth of 0 – 60 cm, 60 – 160 cm was the weak evaporation layer, and the stable layer was below 160 cm. In term of the δD & $\delta^{18}O$ of soil water, the soil layer could be divided into two parts: the affected layer (0 – 160 cm) and the weak affected layer (below 160 cm).

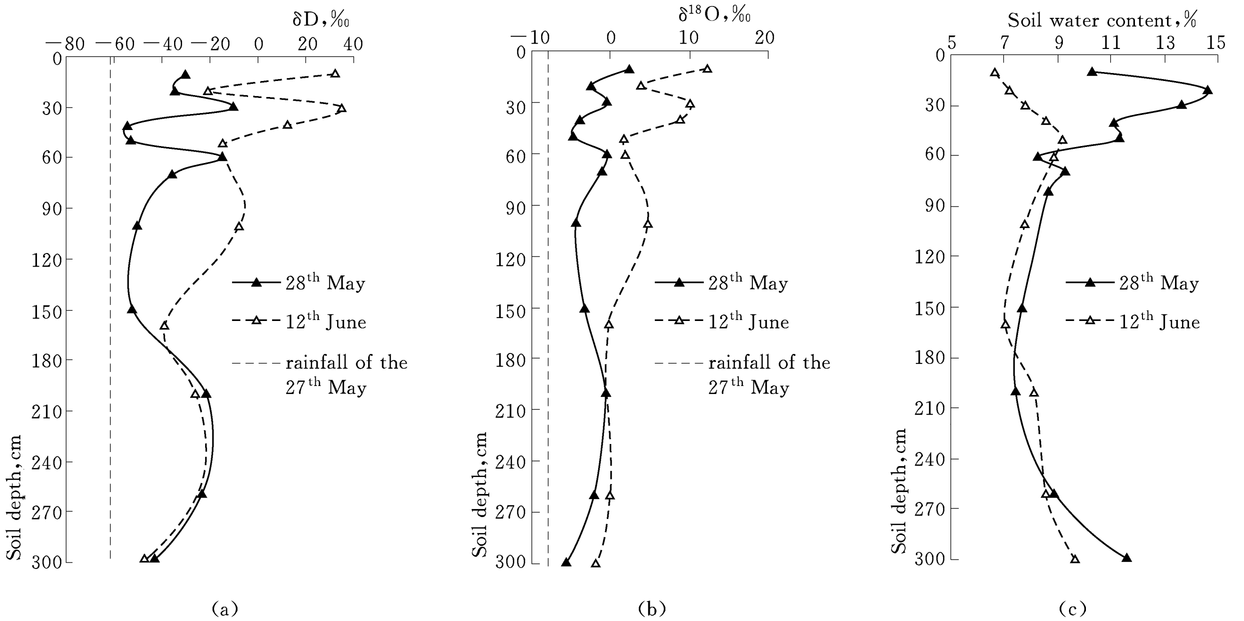

Fig. 2 The δD & $\delta^{18}O$ profiles of soil water and soil water content profile in 2009

3.4 *The precipitation recharge of groundwater*

In Fig. 3, water sampling points of groundwater were near to the LMWL, which indicated they were from atmospheric precipitation. However, those points deviated from the LMWL to some degree, and most of them were located in the bottom right of the LMWL. It showed that the rainfall was evaporating and fractionating in the process of precipitation recharge. The changed trend of composition of stable hydrogen and oxygen isotopes in groundwater (spring water and well water) could be fitting with a straight line: $\delta D = 4.25\ \delta^{18}O - 31.073$ and $R^2 = 0.5402$. That was the evaporation line of groundwater. Its slope and intercept were all smaller than those of the LMWL, which reflected the climate characteristics of Yangou, the small rainfall and strong evaporation. The water sample

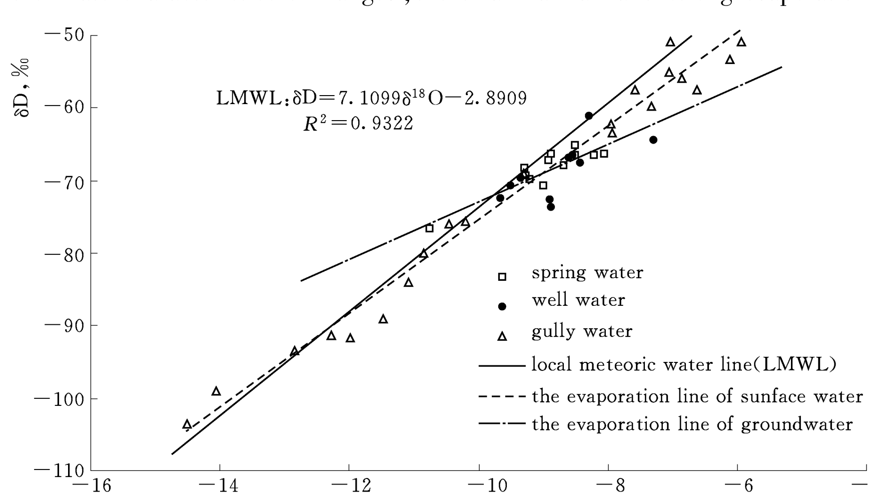

Fig. 3 Relationships between δD & $\delta^{18}O$ for precipitation, surface water and groundwater in Yangou Watershed

points near to the intersection of the evaporation line and the LMWL formed the characteristics of hydrogen and oxygen isotopes of rainfall at the beginning of groundwater formation (Zhai et al., 2011). In the intersection, the δD & δ^{18}O were −73.32‰ and −9.94‰ respectively, which were closer to that of the rain in Yangou (about −70.37‰ and −9.53‰). And it instructed further that the recharges of spring water and well water were closely related to rainfall from June to October in Yangou.

The ranges of spring water and well water were small and there was a significant difference while compared with the rainfall in same period. It showed that although the groundwater accepted rainfall, this recharge was not a rapid process and certainly lagging to some extent. The δD & δ^{18}O of well water on 16th, 20th and 25th Aug. decreased slightly but increased on 1st Sep., which indicated well water received recharge by some depleted water bodies during 16th to 25th Aug. At the same time and before, the rainfall on 24th July was more and the heavy isotopes were depleted to those on 20th and 25th Aug. So it was deduced that spring water was recharged by rainfall in 24th July during 16th to 20th Aug. and this retardation time was almost 23 – 27 d. Dang et al. (2011) had researched the relationship between rainfall and spring flow in Yangou and found that the retardation time of spring water respond to rainfall was about 22 – 30 d, which was consistent with the result in this article. In Table 2, the δD & δ^{18}O of well water on 29th July and rainfall on 24th July was similar to those of well water on 8th Sep. and rainfall on 3rd Sep. The intervals were all 5 d. Dang et al. (2011) also found that the time that the well water respond to rainfall was approximately 7 – 10 d, which was also consistent. But because of the shortage of observation data of well water, the specific time that well water respond to rainfall need further investigation.

Table 2 Characteristics of δD and δ^{18}O of precipitation, surface water and groundwater in 2007

Rainfall				Gully water			Spring water			Well water		
Date	Rainfall (mm)	δD (‰)	δ^{18}O (‰)	Date	δD (‰)	δ^{18}O (‰)	Date	δD (‰)	δ^{18}O (‰)	Date	δD (‰)	δ^{18}O (‰)
7-24	83.66	−79.63	−10.89	7-26	−77.27	−10.51						
7-27	84.84	−108.07	−14.75	7-28	−90.75	−11.91						
7-29	2.3			7-29	−98.67	−13.80				7-29	−72.51	−9.66
8-9	3.19			8-8	−62.17	−7.95	8-16	−66.65	−8.21			
8-29	40.06			8-19	−63.41	−7.93	8-20	−69.41	−9.27			
8-31	11.28	−104.05	−14.30	8-26	−69.09	−9.31	8-25	−75.67	−9.76			
9-1	13.56						9-1	−68.23	−9.28			
9-2	18.04											
9-3	5.74	−78.37	−11.63									
9-6	20.70	−58.81	−8.81	9-8	−84.06	−11.08				9-8	−70.79	−9.50
9-13	1.83											

3.5 *The precipitation recharge of surface water*

In Fig. 3, water sampling points of groundwater were near to the LMWL, which indicated they were almost from atmospheric precipitation. Set up the linear relation between δD & δ^{18}O of gully water, and there was an evaporation line of surface water: $\delta D = 6.4509\delta^{18}O - 10.899$ and $R^2 = 0.9797$. Its slope and intercept (7.1099, −2.8909) were lower than those of the LMWL, which illustrated that rainfall was also evaporating and fractionating when recharging surface water. The δD & δ^{18}O of gully water on 26th July, 2007 were similar to those of rainfall on 24th July (Table 2), and it showed that most of the gully water on 26th, July came from the rainfall on 24th July. Under the influence of rainfall (84.84 mm) which was depleted with heavy isotopes on 27th July, the δD & δ^{18}O of gully water on 28th and 29th were decreasing closely to those of rainfall on 27th. It stated that, at the same time, the effect on valley flow by rainfall on 24th reduced slightly. Instead, the effect by rainfall on 27th increased. It showed that the valley flow was influenced dominantly by rainfall during this period. Dang et al. (2011) also found that there was an excellent response between surface runoff and rainfall in Yangou.

4 Results

Analyzing the characteristics of δD & $\delta^{18}O$ of rainfall in Yangou and Xi'an, it showed that the moisture source in Yangou was as the same as that in Xi'an and derived from the north migration water vapor of Xi'an. Under the influence of evaporating during migrating, the slope and intercept of the LMWL in Yangou were all lower than those in Xi'an.

After analyzing the characteristics of heavy isotopes in those five water bodies, it was found that the direct recharge of groundwater and surface water were affected dominantly by the rainfall in Yangou, with little soil water under evaporation and fractionation. That was to say, soil preferential flow was leading the recharge of groundwater. With the recharge by some soil water, the gully water was almost from rainfall, too.

There was a certain lag in the recharge of precipitation to groundwater, and the response time from spring water and well water to rainfall was about 23 – 27 d and 5 – 7 d, which was influenced by the depth of groundwater level.

The migration of rainfall on the soil profile could be divided into three parts: the strong influenced layer (0 – 60 cm), the weak influenced layer (60 – 160 cm), and the stable layer (below 160 cm). And the δD & $\delta^{18}O$ on soil profile could be divided into two parts: the fractionation layer (0 – 160 cm) and non-fractionation layer (below 160 cm).

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