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Understanding recharge in soil-groundwater systems in high loess hills on the Loess Plateau using isotopic data

Hongbing Tan*, Zihao Liu, Wenbo Rao, Ben Jin, Yudong Zhang

School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China

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ABSTRACT

The topography on the eastern and western sides of the Liupan Mountains (northwestern China) is characterized by hilly and gully loess deposits with elevations above 1000 m. This study aims to uncover the mechanisms governing loess groundwater and soil water recharge in these relatively arid to semiarid higher loess hills on the basis of temporal soil profiles. The results show that during the four monitoring periods, the distinct variations of soil water and Cl contents in soil water at different times in the upper parts of loess profiles, particularly the increasing water content after the rainy season above 7.5 m, indicate that temporal precipitation can at least infiltrate to 7.5 m in depth. These variations attenuate as depth increases. Discernable variations in $\delta^{18}O$ and $\delta^{2}H$ values in soil water can also be identified at different times and even in deeper parts of the soil profiles. However, based on the average values in the steady-state hydrologic layer (SSL) in the soil profiles, very small temporal variations in average $\delta^{18}O$ and $\delta^{2}H$ values in the soil water in the SSL are observed if the analytical uncertainties of $\delta^{2}H$ and $\delta^{18}O$ are considered. The $\delta^{18}O$ and $\delta^{2}H$ values in groundwater show relatively similar temporal fluctuations as the average values of soil water in the SSL at the same times. They are also close to the local weighted average annual precipitation. Groundwater sampled in May 2013 revealed elevated tritium concentrations in both the monitoring well and the springs or wells. The monitoring well displays a lower tritium isotope content (2.26 TU), and others show higher contents in lower areas. The radio-carbon 14 isotope in the monitoring well also shows a lower content of approximately 25.95 pmC. Thus, it can be inferred that in a general year, temporal precipitation can rapidly infiltrate and reach the depth (below 7.5 m) of the loess profile through various preferential conduits, preventing the water from evaporating near the surface. Then, the soil water slowly percolates downwards, mimicking a piston-like flow, and finally recharges groundwater. These dual flow modes that exist inside loess deposits are the main mechanisms that maintain soil water and relatively abundant groundwater resources.

1. Introduction

The loess hills on the eastern Liupan Mountains (Northwest China) rise several hundreds over the surrounding plains and reach elevations of up to 1000 m. The region's climate is arid-semiarid monsoon influenced, with uneven seasonal precipitation (Dong et al., 2015). In detail over 80% of the annual precipitation occurs during the summer. The mechanisms governing loess groundwater and soil water recharge in such a climatic and topographic environment still remain unclear.

Generally, precipitation largely evaporates during high summer temperatures, with not enough water available to recharge the groundwater if the precipitation event infiltrates through the upper loess layers too slowly (Gehrels et al., 1998). However, the very limited winter precipitation is less likely to be the source water for soil water or groundwater recharge. Liu et al. (2010) suggested that significant soil water recharge generally does not occur beyond 2–3 m; however, in wet years, the wetting depth of infiltrating rainwater may exceed 2 or even 3 m, and amounts that infiltrate below this depth may become significant. Some studies have accepted that rapid preferential recharge through macro-pores or conduits is the main recharge mechanism for groundwater in loess aquifers in the Loess Plateau (Yan and Wang, 1983; Yasuda et al., 2013). However, most studies think that the preferential recharge mainly dominates in the root zone (Gazis and Feng, 2004) and below the root zone, the soil water movement is dominated by diffuse flow (Gehrels et al., 1998). Some studies also suggested that rainfall can infiltrate and recharge groundwater through unsaturated loess layers via the so-called piston infiltration mode where the recharge period can be up to several decades, hundreds of years or even longer (Zimmermann et al., 1967; Yan, 1986; Zhang et al., 1990; Lin and Wei, 2006; Huang et al., 2013). Chen et al. (2012) proposed a

* Corresponding author.
E-mail address: tan815@sina.com (H. Tan).

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new idea, suggesting that groundwaters beneath loess layers may originate from deep confined aquifers discharging upward. The recharge source water may originate from outside of the Loess Plateau and is likely located in an area of higher elevation. This may help explaining the depleted H and O isotopes in some groundwater samples. In our previous study of precipitation and groundwater in hilly and gully regions of the Loess Plateau, O and H isotope compositions in groundwater from most areas were found to vary with temporal means of precipitation, suggesting that rapid recharge also exists in some loess aquifers (Tan et al., 2016). However, because of a lack of temporal soil water monitoring data, none of these previous studies was able to determine the infiltration mechanisms in the higher loess hills.

In summary, these previous studies show varying mechanisms regarding the recharge of abundant groundwater in loess aquifers. In particular, the presence of abundant groundwater in loess aquifers on top of some hills with elevations above 1000 m on the Loess Plateau should be scientifically determined. In this study, over two years of stable H and O isotope composition monitoring were performed in soil- and groundwater samples in a loess deposit hill (over 1700 m above sea level) on the eastern side of the Liupan Mountains. The analysis focused on the following goals: 1) determining whether local precipitation is the dominant recharge source of soil water and groundwater; 2) describing the temporal stable isotopic variation characteristics of soil water at different profile depths and in groundwater; and 3) assessing the replenishment period of soil water and groundwater.

2. Description of the study area

2.1. Geography

The study area is located on the eastern side of the Liupan Mountains in northwestern China (Fig. 1). The landscape is characterized by high rolling hills and steeply incised valleys with thick loess deposits. The climate is dominated by arid-half arid and monsoon climate zones. Generally, precipitation is dominated by summer rainfall, with over 80% of annual total precipitation. Additionally, snowfall seems to be insignificant in the hydrologic budget. The average precipitation from 1951 to 2014 at Pingliang Meteorology Station was 480 mm/year (Fig. 2). The precipitation during the rainy season in 2013 was the highest observed since records have been kept at the meteorological station. Records from weather stations show that the annual total precipitation was 760.0 mm in Pingliang in 2013, which is 31.4% higher than the average total value (480.0 mm). By contrast, the annual total precipitation was 478.5 mm in 2012 and 585.1 mm in 2014. In conclusion, the year 2013 was an unusual wet year, 2012 a relatively dry and 2014 an average precipitation year.

2.2. Hydrogeology

The study area lies in catchment area of the Jing river which is a tributary to the Huang He (Yellow River). A larger branch of Jing River named Xie River flows from north to southeast at the foot of the studied hills, which rises > 200 m over the river plain. The studied hill deposits are mainly composed of Upper Pleistocene Malan Loess and Middle Pleistocene Lishi Loess. The thickness of the loess strata is generally over 30 m, with a range from 30 to > 100 m. The loess is interposed with several layers of palaeo-soils that developed between the loess depositions. Their thicknesses range from < 1 m to over 3 m. With respect to palaeo-soils or red clay strata, the Upper Malan Loess is coarse with high porosity. Thus, shallow loess groundwater is mainly developed in the Upper Malan Loess strata and the underlying palaeo-soils or red clay strata generally act as aquiclude layers. The thickness of the Malan Loess strata in these hills is generally 10 m to 30 m. On the loess deposit hills, microtopography features such as vertical fissures, macro-pores, sinkholes, solution passages and sinks can be observed. These topographic features are commonly developed in regional scale in hill and gully regions of the Loess Plateau. In particular, at the top of and halfway up the hills, sinkholes that are generally over 1 m in diameter and > 5 m deep can be widely observed (Fig. 3). Previous studies suggested that they act as good conduits and allow heavy precipitation to rapidly reach deep strata (Yan and Wang, 1983).

Despite the controversy about the runoff and discharge of groundwater in loess aquifers in the higher hills of the Loess Plateau, their groundwater recharge source is most likely be controlled by local precipitation as all rivers in the area lie below the aquifer more than several hundreds meters. Further it seems to be unlikely for groundwater in these hills to derive from the nearby Liupan Mountains as they are divided from them by the deep north-south running valley of the Jing River. The total precipitation in Liupan Mountains and the loess hills is similar. The precipitation and springs from both sides of Liupan Mountains may contribute to the groundwater discharge to the lower valleys. However, they seem unlikely to discharge to the groundwater of the higher loess hills on the other side of the Jing River valley. In such a case the deep circulating confined groundwater from Liupan Mountains would have to move upwards through thick red clays and several layers of palaeo-soils (both characterized by very low permeability) to recharge the shallow loess aquifer in the top of the higher loess hills, rather than discharging directly to lower valleys and gullies. An important reason is that most gullies surrounding the loess hills are usually dry. Runoff only occurs after heavy rain or storm events and flows into these gullies.

2.3. Description on monitoring site

In the first field campaign, a representative site named Xiegou village in Pingliang city was selected as a long-term monitoring station. This site shows no influences by human activities. The site is covered with grass and is located near the top of a hill at an elevation of 1724 m (several hundred meters higher than the surrounding valleys and river plains). Beneath this hill, shallow groundwater developed in loess aquifers and seems to be unusually abundant. However, there are no perennial flows in the lower valleys, suggesting that there is no deep confined groundwater upwelling and discharge. The landform is gently sloped, with slope angles < 10°. Some drinking water wells are distributed around the site at distances of over 100 m. These wells provide abundant water yields for local residents, who drink the water and pipe it for agricultural uses. According to older local residents, perennial shallow groundwater in the loess aquifers is relatively abundant. The water table is generally < 20 m below the surface. At the lower flank of the hills, some deep drill wells (e.g. Wanlong sample site; sample No WL) with > 30 m depth were drilled for the local workshop industry (e.g. brick manufacturing). In this depth a thick red clay layer acts as a good aquiclude layer for the deeper aquifers.

3. Sampling and analysis

The Xiegou (XG) site in Pingliang was selected as the temporal monitoring station in this study (Fig. 1). Soil samples were collected using a hollow-stem hand auger. Cores were generally collected approximately 10 to 11 m below the surface to determine the soil water infiltration and percolation. Unfortunately, due to the groundwater table depth of nearly 20 m or even more, not all cores reached the groundwater table using hand augers. From field observations of loess profiles in a nearby valley, the Malan Loess strata are over 10 m thick. Pedogenic features of the sampled Malan Loess at the sample site were small fissures, wormholes and plant root systems and a thin interlayer of weak palaeo-soils in the upper strata approximately 7.5 m below the surface. And therefore soil water percolation generally allows the water to reach the groundwater table in > 10 m depth. During the monitoring periods, soil profile samples were collected before the rainy season in May (after experiencing a long dry season) and two months after the end of the rainy season in November. Samples were collected in 2013