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Effects of land cover on variations in stable hydrogen and oxygen isotopes in karst groundwater: A comparative study of three karst catchments in Guizhou Province, Southwest China

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ABSTRACT

Studying the spatial and temporal variations of stable hydrogen and oxygen isotopic values (δD and $\delta^{18}O$, respectively) in precipitation and groundwater in catchments with different land cover is of great significance to understanding the hydrologic cycles within the catchments. This study is focused on three karst catchments, Banzhai, Chenqi and Dengzhanhe, in Guizhou Province, Southwest China, a region with a subtropical humid monsoon climate. We analyzed the spatial and temporal variations in the δD and $\delta^{18}O$ of precipitation and groundwater in these areas from September 2007 to September 2009. Local meteoric water lines (LMWLs) for the study areas and their relationships with groundwater were established. The seasonal variations of δD and $\delta^{18}O$ for both precipitation and groundwater were similar, being depleted in the heavier isotopomer in the rainy season and enriched in the heavier isotopomer in the dry season. The similarity of patterns between groundwater and precipitation indicates short groundwater residence times in the three catchments, typical of karst terrains. The isotopic values of the Banzhai catchment, which is covered by a thin soil layer beneath virgin forest floor, had the largest variation among the three catchments. The isotopic compositions of the Banzhai catchment groundwater were close to those of precipitation in the rainy season and responded rapidly to it, indicating that precipitation quickly recharges groundwater in this area. In comparison, in the Chenqi and Dengzhanhe catchments, the thicker soil layers and large numbers of paddy fields and dry lands in the catchments resulted in more intense evaporation, and therefore relatively higher isotopic values in the infiltration water. Consequently, the isotopic values of spring water in these two areas were higher and varied to a lesser extent in the rainy season than those of precipitation. The Rayleigh fractionation model based on the correlation between the deuterium excess (d) and evaporation was employed in this study. The model calculation results showed that the catchment evaporation was more intense in Dengzhanhe than in Chenqi, with 14 ± 1% and 6 ± 4% of the water evaporated in Dengzhanhe and Chenqi, respectively. The higher percentage of evaporation in Dengzhanhe was mainly due to the larger percentage of paddy fields in the catchment. In contrast, the effects of evaporation from free water surfaces or soil surfaces on groundwater in the virgin forest-covered Banzhai catchment were extremely weak. Based on the isotopic and high-resolution continuous meteorological and discharge data, the transpiration rates were estimated to be 78% for Banzhai, 10 ± 4% for Chenqi, and 24 ± 1% for Dengzhanhe, and the differences among these values are mainly attributed to differences in vegetation types in those areas. These results show that the variation in stable isotopes in groundwater can be used as a key index in evaluating the effects of different land cover changes and environmental changes on the water cycle in a catchment.

1. Introduction

The Southwest China karst region is one of the largest karst areas among the major concentrated karst regions in the world. A relatively large number of environmental issues have stemmed from the karst water cycle change caused by soil erosion, rocky desertification and vegetation degeneration. These latter environmental problems are closely related to human activities and different land uses. Land use plays

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an important role in catchment's water cycle. For example, different land uses can affect the hydrological process of a catchment, and can affect the catchment water balance through influencing evapotranspiration (Bronstert et al., 2002; Raymond et al., 2008). Due to special hydrogeological conditions in karst areas (e.g., less soil development, strong karst leakage, and etc., Ford and Williams, 2007), the factors that affect the catchment water cycle are varied and complex, which makes the processes of precipitation and runoff in karst catchments very complicated. Therefore, studying the water cycle pattern in karst regions under different land uses is of great significance to addressing regional environmental issues related to water cycle (Marfia et al., 2004).

In a catchment, atmospheric precipitation passes through the unsaturated zone and recharges groundwater. Soil, vegetation and lithology can all affect this recharge process (Clark and Fritz, 1997; Jasechko et al., 2013). Studying the response of groundwater to atmospheric precipitation can provide guidance for understanding the mechanism of the complex recharge processes in a catchment.

Since Craig (1961) and Dansgaard (1964) advanced the basic theory of water isotopes in the water cycle, δD and $\delta^{18}O$ have played important roles in studies of the water cycle. δD and $\delta^{18}O$ are extensively used in different scales of hydrological processes studies; commonly individual rainstorm, seasonal, and annual scales. Identifying the seasonal variations of δD and $\delta^{18}O$ in precipitation and groundwater can facilitate the evaluation of the mean groundwater residence time (Lindstrom and Rodhe, 1986; Ramspacher et al., 1992). Research in non-karst regions has shown relatively small seasonal variations of δD and $\delta^{18}O$ in groundwater which markedly diminished and lagged the seasonal variations in precipitation, indicating the groundwater residence time of generally more than one year (DeWalle et al., 1997). δD and $\delta^{18}O$ has also been used to examine rainstorm dynamics in catchments and then reflect the aquifer parameters under rainstorm conditions (Lyon et al., 2009). In this study, we will show that stable isotope responses in a karst terrain, on multiple scales, differ greatly from those in non-karst terrains.

Quantifying water cycle processes (e.g., runoff, evaporation and transpiration) in a catchment is often difficult, because evapotranspiration consists of both physical evaporation from surfaces and biological transpiration (Telmer and Veizer, 2000). Globally, research on the quantification of evapotranspiration has been mostly focused on arid and semiarid regions. In China, similar research is mainly concentrated on the north region, whereas very few studies have examined southern regions, where the climate is warm and humid and the vegetation is dense (Schlesinger and Jasechko, 2014). There are three main approaches used to study evapotranspiration: field measurement, models, and isotopic methods (Sutanto et al., 2014). Field measurement methods are mainly based on physical parameters related to evaporation process such as humidity, wind speed, and solar radiation. The eddy covariance (EC) method is the most commonly used field measurement method. While the EC method is relatively accurate for fixed points, it may be problematic when applied to a larger scale (e.g., catchment scale) (Telmer and Veizer, 2000). In addition, some physical parameters involved in the EC method are relatively difficult and costly to acquire. Modeling is an extension of field measurement methods but requires validation and correction against measured data in practical applications. The introduction of isotopic methods has significantly advanced quantitative research on water cycles in catchments without high-accuracy meteorological instrument measurements (Telmer and Veizer, 2000). The conventional method for determining evaporation in a catchment is based on difference of δD and $\delta^{18}O$ between groundwater and meteoric precipitation. First, the initial isotopic composition of groundwater in the catchment is determined. The initial composition is usually taken as the values at the intersection point of the evaporation and meteoric water lines of the catchment (Kendall and Caldwell, 1998). The amount of evaporation can then be calculated (Gonfiantini, 1986; Telmer and Veizer, 2000; Lee and Veizer, 2003). However, the δD and $\delta^{18}O$ in large catchments may have relatively large variation. A more powerful derivative stable isotope parameter, deuterium excess (d), is unrelated to the isotopic composition of precipitation but instead is related to its sources and subsequent processes. For this reason, waters with different δD and $\delta^{18}O$ may exhibit the same d value (Clark and Fritz, 1997; Huang and Pang, 2012). Moreover, the d in a catchment reflects degree of evaporation: the more intense evaporation is, the lower d value is (Dansgaard, 1964). While the d value and δD and $\delta^{18}O$ values are all related to evaporation, the d value is more stable and conducive to the investigation of evaporation in a catchment than the δD and $\delta^{18}O$ values.

The three catchments of Banzhai, Chenqi and Dengzhanhe in Guizhou, Southwest China, each under different land uses, were selected as the study areas in this project. Precipitation and groundwater samples were collected during two consecutive hydrological years (September 2007 through September 2009). This study reveals the δD and $\delta^{18}O$ variation patterns of karst groundwater under these different land uses and demonstrates the dynamics of water cycle processes in karst catchments.

2. General information about the study areas

Banzhai Catchment: Situated in the Maolan National Karst Forest Nature Reserve in Libo County, Guizhou, the Banzhai catchment (107°55′–108°05′E, 25°12′–25°15′N, Fig. 1) is part of the Liujiang River system in the Pearl River Basin and encompasses an area of approximately 19 km^2 (Fig. 2). This catchment has a multi-year (30 years)

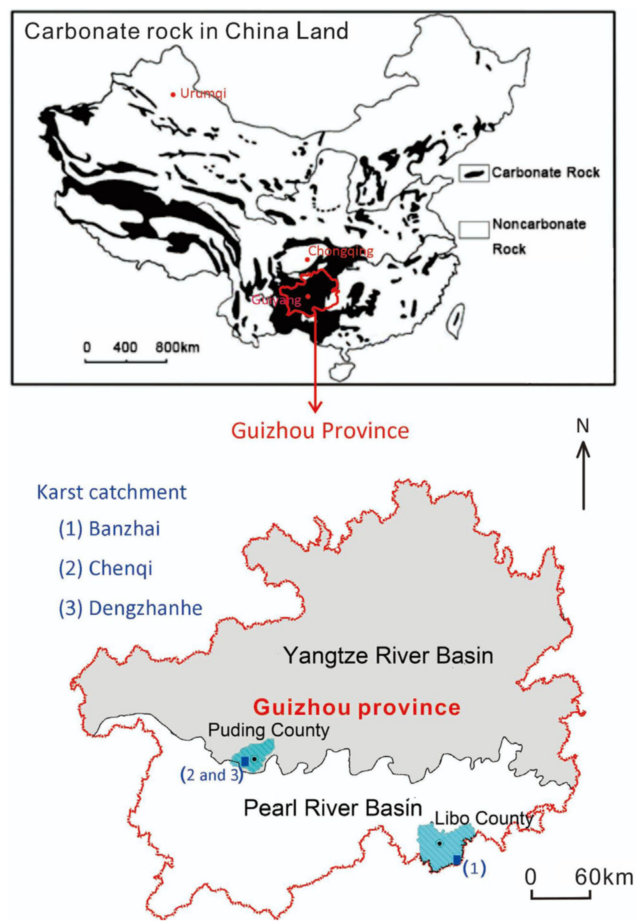

Fig. 1. The location map of study area. Figure above shows the location of Guizhou Province in China. In the Guizhou map (down), the locations of Chenqi and Dengzhanhe karst catchments (Zhao et al., 2015), and Banzhai karst catchment (Zeng et al., 2016) are shown.

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