Yuhong Liu[1,5]
Zhen Xu[2,5]
Fude Liu[3,5]
Lixin Wang[4]
Shuqing An[5]
Shirong Liu[6]

[1]Yantai Institute of Coastal Zone Research, CAS, Yantai, P. R. China
[2]State Power Environmental Protection Research Institute, Nanjing, P. R. China
[3]Key Laboratory of Water Resources and Environment of Shandong Province, Water Resources Research Institute of Shandong Province, Jinan, P. R. China
[4]College of Environment and Resources, Inner Mongolia University, Hohhot, P. R. China
[5]Laboratory of Forest Ecology and Global Changes, School of Life Science, Nanjing University, Nanjing, P. R. China
[6]The Institute of Forest Ecology, Environment and Protection, the Chinese Academy of Forestry, Beijing, P. R. China

Research Article

Analyzing Effects of Shrub Canopy on Throughfall and Phreatic Water Using Water Isotopes, Western China

Alpine shrub *Quercus aquifolioides* was selected to study the effects of shrub canopy on throughfall and phreatic water by analyzing the isotopic time series of precipitation, canopy throughfall and phreatic water and examining correlations among these series in Wolong Nature Reserve, Western China. Based on analysis of precipitation data in 2003, the local meteoric water line during the rainy season was $\delta D = 8.28 \times \delta^{18}O + 8.93$, and the primary precipitation moisture in this region originated from the Pacific Ocean in the summer. Stable isotope analysis showed that the main supply of throughfall and phreatic water was from precipitation, and the shrub canopy has an important effect on the processes of rainwater transmuted into throughfall and phreatic water. Moreover, the differences of δD and $\delta^{18}O$ values between rainwater and throughfall were relevant to rainfall. Due to interception of the shrub canopy, there had a response hysteresis of phreatic water to the various rainfall events, which was mostly 2 days, except that this hysteresis was $\leq$1 day when rainfall was $>$15 mm/day.

Keywords: Meteoric water line; *Quercus aquifolioides*; Response hysteresis; Stable hydrogen and oxygen isotope; Water–vapor interface

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1 Introduction

Regional hydrological cycles are closely linked with the prevailing climatic conditions and strongly associated with different vegetation coverage [1]. Plants play significant roles in hydrological processes by storing, releasing, or filtering the water through its root, stem and leaf systems. Changes in vegetation cover and structure such as variation in interception and transpiration have a significant impact on the hydrological cycle [2]. Hence, roles of vegetation are becoming an important focus in modern eco-hydrological studies.

The stable isotopes deuterium (D) and oxygen-18 (^{18}O) are very useful in studying the processes of hydrological cycle [3, 4], and have been widely utilized in precipitation studies on identifying moisture characteristics and origins [5–8]. The water stable isotope ratios can benefit for analyzing water flux variations through the ecosystem or plant individual [9–12], such as plant water use [13–16], stemflow, throughfall, and evaporation rate [17, 18]. At a large scale, the rain forest plays an important role in the regional hydrological cycle by stable isotope analysis [19]. Variations in the stable isotope composition of meteoric waters are used to identify different plant water sources [3, 20, 21], and plant water is mainly from the top 50 cm of the soil [13]. Moreover, Kubota and Tsuboyama studied how new water inputs (rainfall, throughfall and stemflow) affected the old water percentage within soil–root–plant system by using stable isotope method [17].

Correspondence: Dr. S. An, Laboratory of Forest Ecology and Global Changes, School of Life Science, Nanjing University, Nanjing 210093, P. R. China
E-mail: anshq@nju.edu.cn

In the Wolong Nature Reserve of Western China, vegetation protection has been practiced in this region for many years due to increased flooding risks potentially threatening the ecology security of this area. How do the structures and dynamics of alpine shrubs affect some regional hydrological processes in this alpine region? We selected the alpine shrub *Quercus aquifolioides*, which is a representative survivor of semiarid or arid flora of the Tethys, to investigate the effects of shrub canopy on throughfall and phreatic water by analyzing the isotopic time series of precipitation, canopy throughfall and phreatic water, and examining correlations among these series during the rainy season. The aims of this study were (1) to judge the origin of primary precipitation moisture, (2) to study relationships between precipitation and throughfall in the shrub canopy, and (3) to know the responses of phreatic water, which is an important water supply of topsoil and plant, to precipitation.

2 Methods

2.1 Study area

The Wolong Nature Reserve is located in the Wenchuan County, Sichuan Province, China (102°52′–103°24′; 30°45′–31°25′N) and on the southeast slope of the Qionglai Mountain, a transition zone from the Sichuan Basin to the Tibet Plateau. The typical geomorphic features of this region are high mountains and deep valleys [22]. The Nature Reserve was established in 1963, aiming to protect subalpine and alpine ecosystems, and endangered animal species, especially the panda.

Additional corresponding author: Dr. F. Liu,
e-mail: fudeliu2005@163.com

The Wolong Nature Reserve belongs to the sub-humid temperate zone, and is alternately influenced by a monsoon climate including East Asian monsoons (April to August) and Indian monsoons (September to October). The rainy season is from May to October. The annual average temperature, precipitation and relative humidity are 8.9°C, 888 mm, 80%, respectively [22, 23].

This study was carried out at the Balang Mountain near the Wolong Ecological Station. On the south slope of the Balang Mountain, a dominative vegetation type is the alpine shrub *Q. aquifolioides*, one of climax communities distributing from altitude 2700 to 3800 m [22]. This community has only two layers including the shrub layer and the herbage layer. The coverage of alpine shrub *Q. aquifolioides* generally ranges from 60 to 80% and the height of them usually from 2 to 5 m. The herbage coverage is less than 15%. The agrotype is mountain brown dark coniferous forest soil, a sort of Cambisols, the soil texture is loam clay composed mainly of silt (average 40%) and gravel (20–30%), the soil thickness is about 70 cm. Plot A (altitude 3070 m, 30°51.810′ N; 102°58.147′ E), plot B (altitude 2930 m, 30°51.845′ N; 102°58.286′ E), plot C (altitude 2830 m, 30°51.782′ N; 102°58.364′ E), and two surface exits of phreatic water including SI (altitude 3030 m, 30°51.845′ N, 102°58.171′ E) and SII (altitude 2790 m, 30°51.850′ N, 102°58.531′ E) were chosen on this slope. All plots are distributed in the alpine shrub *Q. aquifolioides*, the LAI of which in plot A, plot B, and plot C is 2.03, 1.98, and 2.57, respectively.

2.2 Collection of precipitation, canopy throughfall and phreatic water

The rain collector was installed in the weather station of the Wolong Ecological Station. The rainwater in the collector was stored and sealed immediately in the special plastic bottles after precipitation events. During the sampling period, there were 21 rainfall samples collected totally.

When a rain event occurred, the canopy throughfall and phreatic water samples were consecutively collected for at least 5 days. Consecutive precipitation was considered as one rain event. According to occurrence of precipitation events, samples were collected in the three periods: sampling group I (from July 28 to August 6, 2003), sampling group II (from August 10 to 20, 2003 and sampling group III (from August 30 to September 6, 2003, broke down because of snow). Because of the heavy rain on August 15, we did not collect water samples on that day. We also collected water samples solely on August 25, 2003. Canopy throughfall samples were collected from the collectors with a radius of 0.16 m in plot A, plot B, and plot C. In each plot, throughfall waters from three collectors were mixed as one water sample. There were 13 throughfall samples collected totally at each of plot A, plot B, and plot C. Phreatic water samples were collected from two surface exits SI and SII (Fig. 1). There were 29 phreatic water samples collected totally at each of SI and SII. In order to reduce influences of transpiration, the collection processes were finished before 10 a.m. on each sampling day. All the samples were collected from July 24 to September 8, in 2003.

2.3 Stable isotopic analysis

One microliter sub-sample was taken from each water sample for hydrogen and oxygen stable isotope analysis by the isotope ratio mass spectrometer (Finnigan Delta X^{plus}, Thermo-Finnigan Instrument Inc., Germany). Hydrogen or oxygen isotopic composition can be expressed by Eq. (1):

$$\delta D \text{ or } \delta O = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000‰ \quad (1)$$

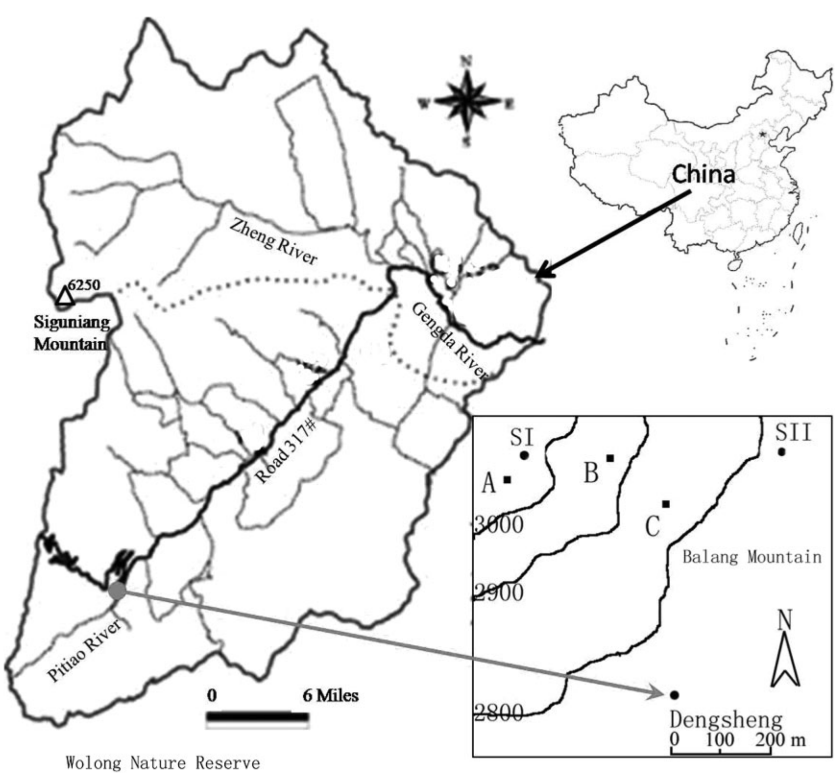

Figure 1. Map of the Wolong ecological station and sampling sites. The station is located in the Dengsheng of the Wolong Nature Reserve. A, B, and C were the sampling sites of canopy throughfall. SI and SII were the sampling sites of two surface exits of phreatic water.

where R_{sample} and $R_{standard}$ are hydrogen or oxygen stable isotopic compositions ($^2H/^1H$ or $^{18}O/^{16}O$) of the samples and standard water (standard mean ocean water). The analytical precision for $\delta^{18}O$ and δD is 0.3 and 3.0‰, respectively.

2.4 Data analysis

The deuterium excess (*d*-excess) was calculated by $d = \delta D\text{-}8\ \delta^{18}O$ [24], which tested the deviation of the given data point from the line with a slope 8 going through VSMOW. According to GNIP Maps and Animations (http://isohis.iaea.org) [25], the weighted *d*-excess of July, August and September in the Wolong Nature Reserve varies from 0 to 8‰, and the weighted *d*-excess of November and December is <-4‰. Hence the precipitation data with *d*-excess >-4‰ was used to draw the local meteoric water line (LMWL) during the sampling period.

End-member mixing models can calculate contributions of different water sources when the isotope value of each water source can be determined [11, 26]. During the sampling period, the rainfall event of August 15, 2003 (14.8 mm/day) was used to calculate its contribution in sequential 5 days (August 16–20) since there had few rainfalls from August 14 to 20 except for August 15. Two-source mixing model with single isotope is used to calculate the contributions of two sources, as follows:

$$\delta t = f_A\delta_A + (1 - f_A)\delta_B \tag{2}$$

where δ_t is a mixing value of the isotope values (δ_A and δ_B) of source A and B; f_A is the contribution of source A, which is obtained by Eq. (3):

$$f_A = \frac{\delta_t - \delta_B}{\delta_A - \delta_B} \tag{3}$$

Kendall correlation analysis (bivariate process) was used to assess the correlations between two data sets. The effects of independent variables on dependent variables were evaluated by both correlation coefficient and significance. Independent-samples *t*-test and one-way ANOVA were used to compare discrepancies of two data sets and three data sets, respectively. When ANOVA results were significant, multiple comparisons were used to decide which treatment was better among three data sets by using the Tukey HSD test. All the statistical analyses were carried out by using the statistical package for the Social Sciences (SPSS Version 12.0 for Windows).

3 Results

3.1 Stable isotopic compositions of precipitation

The δD values of the precipitation ranged from −56.5 to −156.2‰, while the $\delta^{18}O$ values ranged from −8.6 to −17.7‰ (Tab. 1). Most of *d*-excess values were below the global average value 10‰. Twenty-one rainwater samples were divided into precipitation stage I (July 24–August 31, 2003; *d*-excess >-4‰, $n = 16$) and precipitation stage II (September 1–8, 2003; *d*-excess <-4‰, $n = 5$), which were described by the following Eqs. (4) and (5). The line from Eq. (4) was defined as the LMWL (Fig. 2).

$$\delta D = 8.28\delta^{18}O + 8.93 (r^2 = 0.91,\ n = 16) \tag{4}$$

Table 1. Isotopic compositions of precipitation, canopy throughfall, and phreatic water

Samples	Parameters	Mean ± SD	Minimum	Maximum
Precipitation stage I	δD (‰)	−86.0 ± 5.4	−136.4	−56.5
	$\delta^{18}O$ (‰)	−11.5 ± 0.6	−16.6	−8.6
	d-excess (‰)	5.8 ± 1.7	−3.9	14.8
Precipitation stage II	δD (‰)	−146.2 ± 4.4	−156.2	−133.5
	$\delta^{18}O$ (‰)	−16.8 ± 0.4	−17.7	−15.4
	d-excess (‰)	−12.0 ± 1.0	−14.3	−9.3
Phreatic water of SI	δD (‰)	−79.9 ± 1.5	−83.8	−77.1
	$\delta^{18}O$ (‰)	−10.6 ± 0.5	−11.6	−9.2
Phreatic water of SII	δD (‰)	−76.3 ± 2.5	−80.3	−67.9
	$\delta^{18}O$ (‰)	−10.2 ± 0.4	−11.1	−9.4
Throughfall	δD (‰)	−100.4 ± 28.7	−156.9	−52.6
	$\delta^{18}O$ (‰)	−12.6 ± 2.9	−17.7	−7.9

Stage I was from July 24 to August 31, 2003 and stage II was from September 1 to 8, 2003.

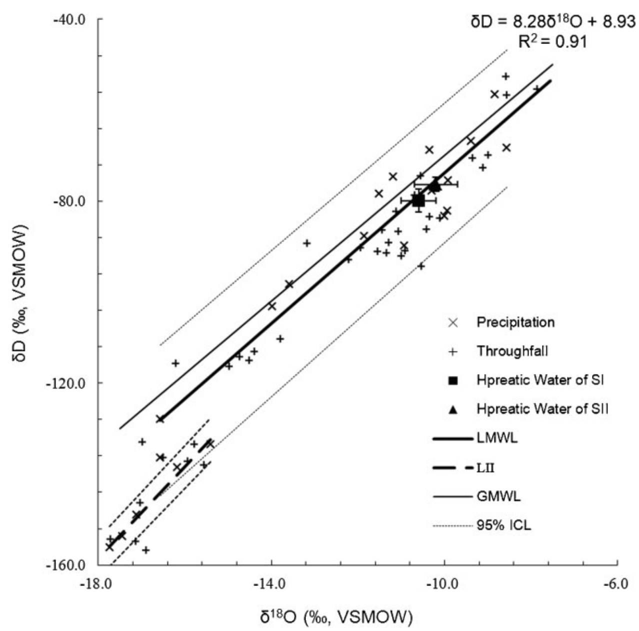

Figure 2. The local meteoric water line (LMWL), canopy throughfall and phreatic water during the rainy season in 2003 showed in the space of $\delta^{18}O$ versus δD. Global meteoric water line (GMWL) of Craig [30] and δD-$\delta^{18}O$ regression line of precipitation stage II (LII) were also plotted. ICL meant individual confidence level.

And that of stage II can be described by Eq. (5):

$$\delta D = 10.07\delta^{18}O + 22.72 (r^2 = 0.99,\ n = 5) \tag{5}$$

3.2 Analyzing relationships between canopy throughfall and rainfall

The $\delta^{18}O$ values of throughfall water varied from −7.9 to −17.5‰, and the δD from −52.6 to −156.9‰ (Tab. 1). Kendall correlation analysis showed that water isotope values of throughfall water were negatively correlated with rainfall (for δD: $r = -0.288$, $p = 0.006$; for $\delta^{18}O$: $r = -0.309$, $p = 0.003$; Fig. 3).

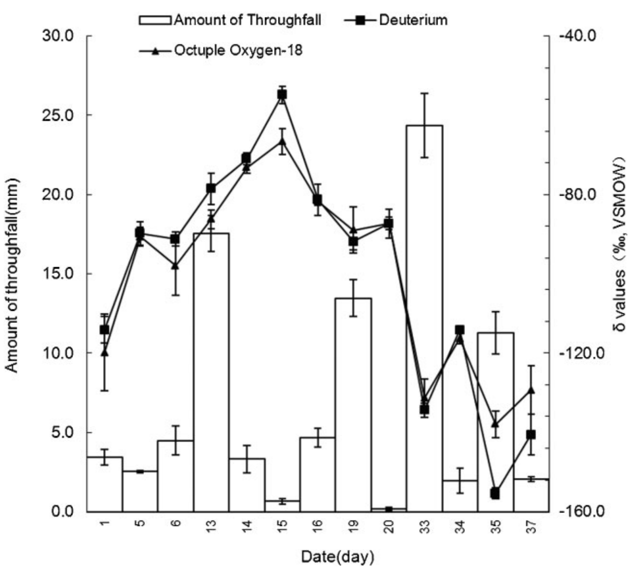

Figure 3. Relationship between amount of throughfall and its stable isotope values along with time. The first day was July 29, 2003. The throughfall of August 10 was a gather of the rain events during August 9–10, 2003.

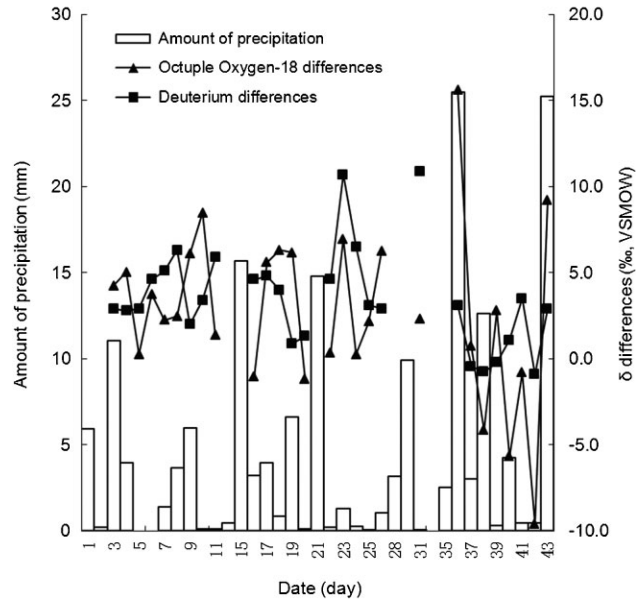

Figure 4. Relationship between the amount of precipitation and tracer differences between phreatic waters and precipitation along with time. The first day was July 26, 2003.

The δD-δ^{18}O points of throughfall were scattered around the lines described by Eqs. (4) and (5) (Fig. 2), as showed that throughfall came mainly from the local precipitation. Based on Eq. (2), throughfall occupied about 63.4% of rainwater when rainfall was $<$5 mm/day, about 78.3% when rainfall was between 5 and 20 mm/day and about 95.4% when rainfall was $>$20 mm/day.

3.3 Analyzing relationships between phreatic water and rainfall

The δD and δ^{18}O values of phreatic water varied from −67.9 to −83.8‰ and from −9.2 to −11.6‰ (Tab. 1), respectively, which were distributed along the LMWL (Fig. 2). This indicated phreatic water was mainly supplied by rainwater.

Based on Fig. 4, there had a temporal hysteresis in δD and δ^{18}O values of phreatic water response to the different rainfall events. When rainfall was $<$5 mm/day, δD and δ^{18}O differences between phreatic water and rain water did not change obviously, however, this difference would occur if there were similar rainfall events occurred continuously. When rainfall was between 5 and 15 mm/day, the differences decreased obviously on the second day. If rainfall was $>$15 mm/day, the time of isotopic hysteresis was 1 day or even less.

By δ^{18}O value calculation, the contributions of August 15 rainwater were 8.8, 69.2%, 55.8, 18.6, and 0% to SI phreatic waters from August 16 to 20, respectively. For SII of phreatic water, the contributions were 35.5, 40.0, 69.8, 32.9, and 10.5%, respectively.

4 Discussion

4.1 Formation of local precipitation and its origin

The deuterium excess offers a method to characterize spatial-temporal variations of different air masses during their movements [4, 5, 7, 27]. The deuterium excess is not changed significantly within cloud processes, and usually considered within the formation of precipitation (http://isohis.iaea.org) [28]. In stage I, precipitation moisture in the Dengsheng was carried by East Asian monsoons (April–August), showing origin of moisture was from the Pacific Ocean and formed raindrops that directly fell to earth immediately. In stage II affected by Indian monsoons (September–October), precipitation fell as snow in higher alpine area with low-temperature and during this phase there were more heavy isotopes enriched [3]. And then the remanent raindrops with poorer water isotopes fell onto the relatively lower alpine region of the Dengsheng [29]. The GNIP Maps and Animations [25] also showed that the weighted *d*-excess of July, August and September in Wolong varied from 0 to 8‰. Therefore, samples in stage I were chosen to plot the LMWL during the summer and used to trace the origins of different water.

All the δ^{18}O and δD values in precipitation distributed along the global meteoric water line (GMWL), defined by $\delta D = 8\ \delta^{18}O + 10$ [30]. The δD and δ^{18}O of precipitation in rainy seasons became lower gradually when clouds move to inland from the coast [31, 32]. The line represented by Eq. (4) was approximately in paralleled with the GMWL and the smaller *y*-intersection showed a relatively low level of *d*-excess in precipitation moisture (Fig. 2). This further provided a proof that precipitation moisture in this region during the rainy season came mainly from the ocean.

4.2 Effects of canopy throughfall on soil erosion

Vegetation types were very important in reducing soil erosion and changing hydraulic conductivity [33, 34], and rainfall amount is the primary cause of affecting soil erosion [35]. In this study, when rainfall was $<$5 mm/day, throughfall occupied 63.4% of rainwater. The dry canopy kept most of rainwater. When rainfall ranged from 5 to 20 mm/day, contribution of rainwater to throughfall was 78.3%. The collected throughfall was composed of both the rainwater changed by shrub canopy and the unchanged rainwater. When rainfall was $>$20 mm/day, the contribution of rainwater to

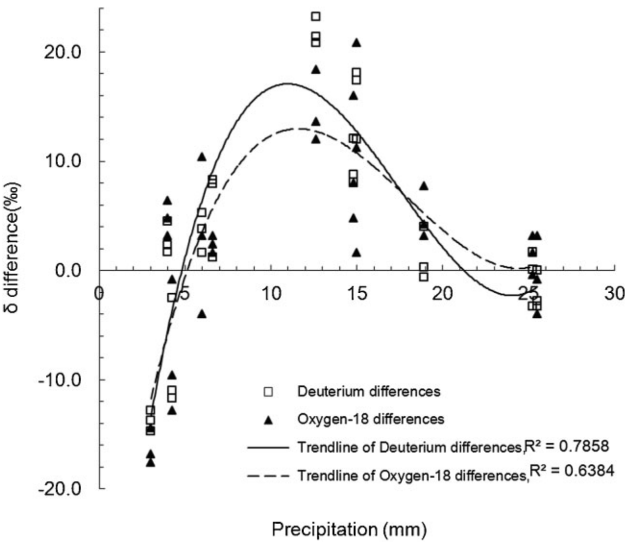

Figure 5. Tracer differences and its trend lines between rainwater and throughfall varying with rainfall.

throughfall was 95.4%, indicating the throughfall came mainly from the rainwater passing through the shrub canopy. Lee and Heo [35] proved that annual rainfall erosion was positive with annual precipitation. Therefore, the ability of the *Q. aquifolioides* shrub canopy in retention and reservation of precipitation decreased and soil erosion increased with throughfall amount increasing.

With increasing of rainfall, there were two physical processes controlling the isotope exchange between rainwater and throughfall (Fig. 5). The points below *x*-axis indicated heavy isotopes abundance in throughfall caused by the evaporation in dry canopy. The points above *x*-axis indicated the indigence of heavy isotopes in throughfall because higher humidity induced more heavy isotopes to exchange from water to vapor and caused dilution of heavy isotopes in water [36] and this made throughfall depleted in heavy isotopes. Both depleting and enriching heavy isotope processes made the curves of Fig. 5 arrive at its inflexion at *x*-axis with about 11 mm/day precipitation. Hence the 11 mm/day of precipitation was the maximum, at which shrub canopy could keep its ability of retention and reservation of precipitation normally. In this region, because most of rainfall were <10 mm/day (Fig. 4), shrub canopy was very important in decreasing the amount of throughfall and risks of soil erosion produced by throughfall.

4.3 Effects of shrub canopy throughfall on phreatic water generation

In ecosystems, vegetation canopy could adjust spatial distribution of incident rainfall and its throughfall different with open rainfall would affect generation of subsurface water [37]. In this study, there had a temporal hysteresis in the δD and $\delta^{18}O$ differences of phreatic water and rainwater response to rainfall, and this δD and $\delta^{18}O$ difference was negative with the relevant rainfall. This indicated that recharge of phreatic water was affected by characteristics of rain events. Moreover, the rate of phreatic water recharge also depends on the type of vegetation cover [38] and precipitation. In our study site, high coverage of *Q. aquifolioides* shrub prevented the direct supply of rainwater to phreatic water because of canopy retention and reservation. The contributions of August15 rain further proved that the rainwater occupied a great proportion of phreatic waters after the rainfall event. Hence different rainfall events and vegetation cover could affect isotopic compositions of phreatic water but the effect was slowly and inconspicuous. Hopp and McDonnell [37] reported that the effects of fine-scale throughfall patterns were less important than that of open rainfall, subsurface topography and variable soil depths on generation of subsurface water, which was consist with our results.

5 Conclusions

During the rainy season, water stable isotopic characteristics of precipitation approved that primary precipitation moisture in this region was originated from the Pacific Ocean. The shrub canopy had obvious effects on the processes of rainwater transmuted into throughfall. The differences of δD and $\delta^{18}O$ values between rainwater and throughfall varied with rainfall, and the rainwater changed by shrub canopy occupied less and less part of throughfall with increasing of rainfall. There had a temporal hysteresis in phreatic water response to rainfall, the δD and $\delta^{18}O$ differences of which were negative with the relevant rainfall.

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