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Water isotope technology application for sustainable eco-environmental construction: Effects of landscape characteristics on water yield in the alpine headwater catchments of Tibetan Plateau for sustainable eco-environmental construction

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ABSTRACT

Topography–climate–vegetation–runoff relationships are important issues in hydrological studies. In this paper, based on analyzing water isotope characteristics of river water, the influence of these variables on the relative contribution of rain to river water was investigated during one rain event in the Heishui Valley of the upper Yangtze River in China. During one rain event on August 19, 2005, a total number of 182 river water samples were collected at 13 sampling sites located along the principal river course and its tributaries. The analysis of water isotopes in the principal river course and its tributaries showed that new rain water and secondary evaporation precipitation caused great variation in values of δD and high d-excess increased with altitude. Based on calculations of two-component hydrograph separation using $\delta^{18}O$, the results showed that the biggest relative contribution of new rain to river water (43%) was found in tributary B, while the smallest contribution (less than 5%) was found in tributary I. According to stepwise linear regression analysis, topography (elevation and slope) was the most important factor affecting the contributions of new rain to river water. When only vegetation variables were considered in the regression model, alpine shrub coverage proved to be negatively correlated with the contributions of new rain to river water, while alpine meadow coverage was positively correlated with the contributions of new rain. This would imply that increasing the relative coverage of alpine shrubs in this mountainous region of China may decrease the risk of flooding.

1. Introduction

Rain–vegetation–runoff relationships are very important issues in hydrological studies and eco-environmental construction. Many studies have reported that changes in vegetation type, such as afforestation or deforestation, can affect water yield by altering evapotranspiration and redistribution of soil water, and infiltration characteristics of the ground surface (Bosch and Hewlett, 1982; Brown et al., 2005; Dou et al., 2013). The influence of vegetation change on water yield at relatively large scales has also been shown by both several modeling studies and different statistical methods (Zhang and Schilling, 1940; Sun et al., 2006). For example, Sun et al. (2006) showed that afforestation reduced annual water yield in the semi-arid Loess Plateau region. However, a contrasting view has also been reported: water yield is not so much influenced by vegetation change but more by characteristics of rain events, such as intensity (Niehoff et al., 2002), amount of rain water (Pizarro et al., 2006), and by topography (Welsch et al., 2001). These contrasting findings indicate the necessity of increasing our understanding of the effects of topography, climate and vegetation on water yield. Our paper aims to elucidate these effects by

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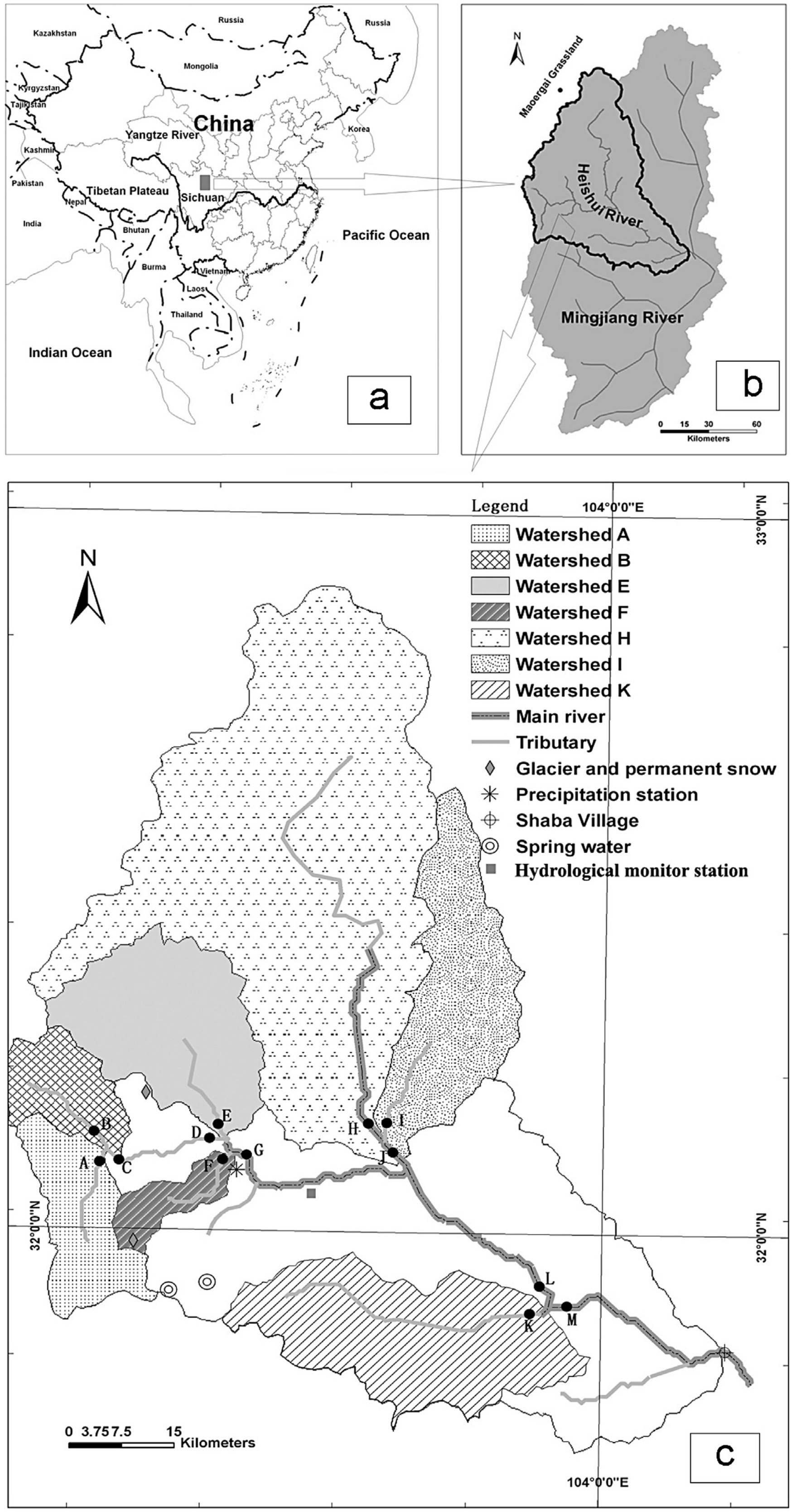


Fig. 1. Map of the sampling sites. (a) The location of the Minjiang valley in western China; (b) the location of the Heishui Valley within the Minjiang Valley; (c) the distribution of sampling sites in the Heishui Valley. Sampling sites C, D, G, J, L and M were situated in the confluences; sampling sites A, B, E, F, H, I and K in the tributary watersheds. The location of the precipitation station is also indicated.

investigating rain-vegetation-runoff relationships in the Heishui Valley in China. The Heishui Valley, the upper watershed of the Yangtze River, was chosen because the Yangtze River is the longest river in China, harbouring 1/3 of China's fresh water (Varis Vakkilainen, 2001; Wang et al., 2006) and is now the foundation of the rapid economic growth of middle and eastern China. Increased flooding risks potentially threaten the economic development and security of this area (Jiang et al., 2004; Wang et al., 2006) and a better understanding of rain contributions to river water may decrease the risk of flooding in this area.

The Heishui Valley has climatic, soil, vegetation and hydrological characteristics representative of the Minjiang Valley in the upper Yangtze River catchment, which makes it an ideal subject for the study of the interaction between the hydrological dynamics and landscape characteristics in this region. However, due to the remote location of our sampling sites within seven tributaries in the Heishui Valley it is not easy to use traditional methods to monitor hydrological processes of the different tributaries. Yi et al. (2008) successfully used a coupled isotope tracer (stable hydrogen (δD) and oxygen (δ^{18}O) isotopes) to characterize input water to lakes in remote regions assuming conservative behavior for both isotopes during mixing and evaporative enrichment. However, due to time-series isotopic sampling limit (Yi et al., 2008) we undertook this study using a more conventional dual-tracer approach. This technique enables the distinction of precipitation variability from evaporation effects (Gibson et al., 2005) and identifies temporal and spatial variability of the isotope signatures in this region during the dry and wet season (Liu et al., 2008a,b). The objectives of our study are: (1) to study causes of temporal and spatial variation of the water isotopes δD and δ^{18}O during one rain event, (2) to clarify whether topography, P/AET or vegetation coverage is the most important factor in affecting the relative contribution of new rain to river water, (3) to emphasize roles of vegetation coverage in mitigating flooding processes, assumed that effects of topography and climate factors are excluded in stepwise linear regression models, because in practice topography and climate factors are not easily controlled by humans.

2. Study area

The Yangtze River has an upper course of 4511 km and an upper catchment area of about 1.0×10^6 km^2. One of the most important tributaries in the upper course of Yangtze River is the Minjiang River, which is located within the transition region between the Tibetan Plateau and the Sichuan Basin (Pu, 2000; Li et al., 2003). The Heishui River is the largest tributary of the Minjiang River and stretches 122 km from the Ruoergai Grassland to the Shaba village (Fig. 1). The average annual temperature in the Heishui Valley is 9 °C and the average annual rainfall is 833 mm (Liu et al., 2008b). The climate is monsoonal and is affected by two atmospheric circulations. A westerly dry circulation from the Atlantic Ocean prevails during winter, and southwesterly wet monsoons enter into this region from the Indian Ocean during summer (Zhang et al., 2002).

The Heishui Valleys are formed by the effects of the rivers and fold, uplift and fracture of the earth crust through the Indosinian movement, the Yanshan movement and the Himalayan orogeny. Being located in the southeastern rim of the Tibetan plateau, the Heishui valley falls in elevation from northwest to southeast. The northwestern mountain ridge is over 4500 m above sea level (a.s.l.). The highest mountain ridge is more than 5400 m a.s.l. in the southwest of the Heishui Valley (Zhang et al., 2002; Chen and Chen, 2003). Thus, the plateau mountain topography is in the northwest and the mountain valley topography is in the south of the area. The main rocks include muscovite granite, biotite diorite, granite, phyllite, slate, shale and sandstone (Sichuan Vegetation Editing Committee, 1980). Seven different vegetation types and five soil types are distributed along the altitude gradient (Table 1) (Jiang, 1994, 2004; Zhuang et al., 1995; Zhang et al., 2002; Chen and Chen, 2003).

3. Methods

3.1. Field water sampling

According to the records of precipitation amount in August from 1996 to 2000 in the Heishui meteorological station, there was a total of 81 precipitation events happened. By computing, precipitation amount less than 5 mm, precipitation amount between 5 mm and 10 mm and precipitation amount more than 10 mm occupied 60%, 28%, 12% of 81 precipitation events, respectively. Therefore, we chose one precipitation event (precipitation amount between 5 mm and 10 mm) on August 2005 to study different catchment characteristics how to affect variation of tributary water.

Based on field experiment design, thirteen sampling sites along the principal river course of the Heishui River and its tributaries were selected (Fig. 1c). Six sites (C, D, G, J, L, and M) were situated along the principal river course and seven sites (A, B, E, F, H, I, and K) in the tributaries. Water samples from two rain storms were collected by rain gauge at the Heishui precipitation station (32°03.00′N, 102°35.4′E) at an altitude of 2400 m above sea level (a.s.l.). The first storm ("old rain") began at 23:00 on August 14, 2005 and lasted for 7 h, during this time a total of 10 mm of rain fell and was collected. The second storm ("new rain") began at 21:00 on August 19, 2005 and lasted for 4 h, during this time a total of 6 mm of rain fell and was collected. At each of our sampling sites, one river sample (pre-event water) was collected on August 17, 2005 before the new rain event and a total of 13 sequential samples were collected to measure dynamics of river water for 24 h from 21:00 on August 19 to 21:00 on August 20 in 2005. In addition, seven samples of spring water at two sampling sites (Fig. 1c) were

Table 1
Vegetation types with their characteristic species and corresponding soil types along the altitudinal gradient in the Heishui Valley.

Vegetation type	Altitude (m a.s.l.)	Dominant plant species	Soil type
(1) Arid shrublands	2300–2400	*Aophora viciifolia,Cotinus coggvria* and *Lucium chinense*	Alluvium and mountain gray cinnamon soil
(2) Deciduous broadleaved forest	2400–2600	*Quercus liaotungensis* and *Betula davurica*	Mountain cinnamon soil
(3) Mixed broadleaved and coniferous forest	2600–2900	*Picea asperata*, *Pimus tabulaeformis* and *Quercus liaotungensis*	Mountain cinnamon soil
(4) Subalpine coniferous forest	2900–3800	*Abies fabric* and *Picea asperata*	Mountain brown soil
(5) Alpine shrub	3800–4000	*Spiraea alpine* and *Lonicera litangensis.*	Mountain brown soil
(6) Alpine meadow	4000–4500	*Kobresiap ygmaea* and *Carex alpine*	Alpine meadow soil
(7) Hillside and mountaintop	>4500	Few herbaceous and fruticous plants present	Alpine cold desert soil

Table 2
Topography and vegetation coverage characteristics of the studied sub-watersheds. *P* is mean annual precipitation and AET is mean actual evapotranspiration during 1950–2000.

Watershed	Location of sampling site (E/N)	Area (ha)	Altitude (m asl)	Slope (°)	Subalpine forest coverage (%)	Alpine meadow coverage (%)	Alpine shrub coverage (%)
A	102°45.89′/32°06.12′	30,205.6	3801.8	16.2	35.5	44.1	10.4
B	102°45.92′/32°06.17′	21,590.2	4042.9	18.9	23.2	52.9	12.1
E	102°55.62′/32°09.44′	60,342.0	4022.6	17.3	19.6	56.6	13.0
F	102°55.88′/32°06.38′	11,625.5	3747.5	17.7	33.0	43.6	11.5
H	103°11.99′/32°06.26	250,121.8	3785.6	12.6	20.6	48.1	15.9
I	103°12.28′/32°06.41	59,580.8	3477.7	15.1	43.1	33.2	10.5
K	103°25.96′/31°53.8′	76,033.0	3531.5	22.8	25.3	53.2	15.6

Table 3
Spatial distribution of maximum (MAX), minimum (MIN) and mean (AVE) annual precipitation (*P*) and actual evapotranspiration (AET) in the studied watersheds.

Watersheds	A		B		E		F		H		I		K	
Parameters	*P*	AET	*P*	AET	*P*	AET	*P*	AET	*P*	AET	*P*	AET	*P*	AET
MAX (mm)	720	680	720	680	800	740	800	760	760	750	720	680	720	710
MIN (mm)	640	570	680	510	680	570	680	670	640	510	640	450	640	520
AVE (mm)	696	642	700	599	715	627	717	700	684	566	692	546	665	643

also collected on August 21, 2005, four samples were taken at an altitude of 3600 m a.s.l. and three samples at an altitude of 3700 m a.s.l. In total, 191 water samples were collected.

3.2. Measurement of water isotopes

The analyses of the stable hydrogen (δD) and oxygen (δ^{18}O) isotopes were carried out by a Gas Bench II and MAT-253 mass spectrometer (Finnigan MAT, Bremen, Germany) in the Key Laboratory of Atomic Resources and Environment, East China Institute of Technology, China. The accuracy of the measurements was ±1‰ for δD, and ±0.1‰ for δ^{18}O. The final results of δD and δ^{18} were expressed as the relative to the value for standard mean ocean water (SMOW), respectively:

$$\delta^{18}\mathrm{O} = \frac{[(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{sample}} - (^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{SMOW}}]}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{SMOW}}} \times 10^3‰ \quad (1)$$

$$\delta\Delta = \frac{[\left((\mathrm{D/H})_{\mathrm{sample}} - \mathrm{D/H}\right)_{\mathrm{SMOW}}]}{\left(\mathrm{D/H}_{\mathrm{SMOW}} \times 10^3‰\right)} \quad (2)$$

In this study, the water samples were analysed in a random order and analytical errors of δD and δ^{18}O of each sample was less than ±1‰ and ±0.1‰, respectively.

3.3. Data analysis

Contributions of new rain to river water at various times within the seven tributaries were calculated by the two-component model described below:

$$Q_t \times C_t = Q_e \times C_e + Q_p \times C_p \quad (3)$$

$$Q_e + Q_p = Q_t \quad (4)$$

Q was the discharge, *C* was the concentration of the stable isotope tracer, and the subscripts *t*, *e* and *p* referred to total, event, and pre-event water components, respectively (Pinder and Jones, 1969). In our study, the concentration of the stable oxygen (δ^{18}O) isotope was used in Eq. (3), and *t* was total flood water at different times, *e* was the new rain water on August 19, 2005 and *p* was river water before this new rain event.

The average δ^{18}O of rain water (C_{wd}) within each of the seven watersheds was calculated by Eq. (5) (Liu et al., 2008b), as

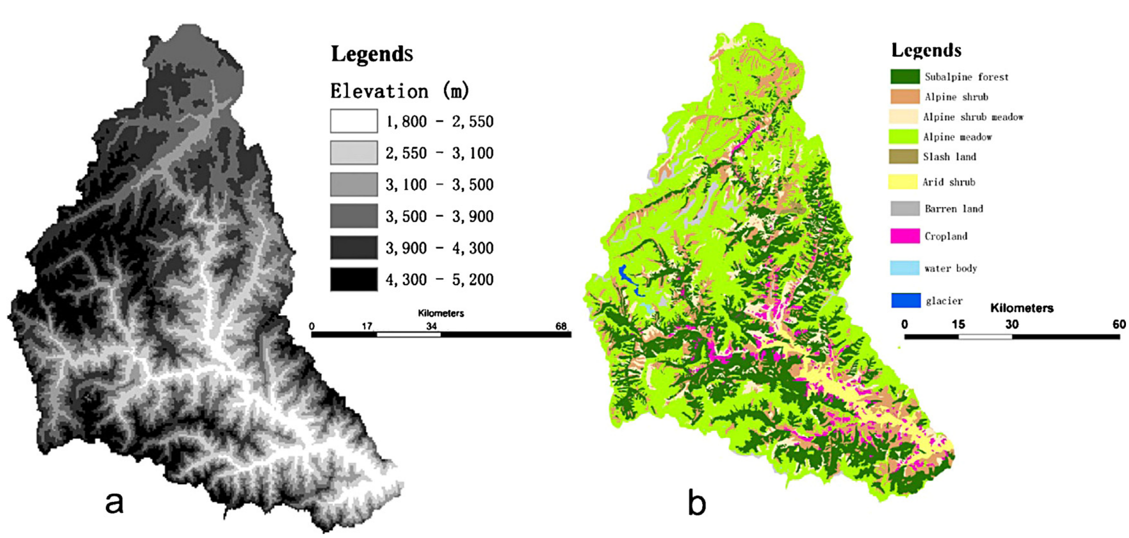


Fig. 2. Topography (a) and vegetation types (b) in the Heishui Valley.

described below:

$$C_{wd} = C_{ave} + \frac{(H_{wd})}{H_0} \times \Delta C \quad (5)$$

where C_{ave} was $\delta^{18}O$ values of the collected rain water at the Heishui precipitation station, H_{wd} was the average altitude of each of seven watersheds (Table 2) and H_0 was the altitude of collected new rain sample from the Heishui precipitation station. ΔC was -0.2 ± 0.04‰ (Liu et al., 2008a), which is the rate of decrease in $\delta^{18}O$ with each 100 m increase in altitude in the Heishui Valley. In this experiment, $\delta^{18}O$ and δD of the first storm ("old rain") were -106.69 ± 0.50, -13.55 ± 0.09 and that of the second storm ("new rain") were -117.99 ± 0.42, -14.7 ± 0.03.

In order to study effects of topography, climate and vegetation on runoff during rain events, 10 parameters were chosen to represent these variables. This selection was based on expert experience and their importance in topography, climate and vegetation in this mountainous region. The selected parameters included four related to topography (location of sampling site, area, altitude, slope), two related to climate (mean precipitation (P), mean evapotranspiration (AET)) and three related to vegetation coverage (subalpine forest coverage, alpine shrub coverage, alpine meadow coverage) (Tables 2 and 3). Topography, P/AET and vegetation coverage parameters of the seven studied sub-watersheds were computed by the following methods: the topography parameters of the seven watersheds (Fig. 2a) were obtained by a digital elevation model and the Hydro model of ArcView from Environmental Systems Research Institute (ESRI) of America. Our study areas form one part of the Minjiang Valley, as such, maximum, minimum and mean annual precipitation (P) and actual evapotranspiration (AET) were computed according to spatial distribution of P and AET in the Minjiang Valley (Jiang et al., 2004). Coverage of each vegetation type was obtained by the optimal iterative unsupervised classification (OIUC) method (Jiang et al., 2004) based on distinct natural vegetation types distributed along various altitudes in the Heishui valley (Jiang, 1994; Zhuang et al., 1995). The classification (Fig. 2b) was carried out by using Landsat 7 TM satellite images acquired on 10 July 2002. The accuracy of the vegetation classification was calculated to be 92% for the whole area, assessed by field validation and previously published ancillary spatial database (Jiang et al., 2004).

Stepwise linear regression models (Verma et al., 1983) were run to determine the most important variable(s) among the ten variables (Tables 2 and 3) affecting the relative contribution of new rain to river water. All statistical tests were done using the Statistical Package for Social Science (SPSS) 14.

4. Results

4.1. Water isotope characteristics of different tributary water during one rain event in summer

Based on visual observation (Fig. 3), the values of river water samples falling above the local meteoric water line (LMWL: $\delta D = 9.3\ \delta^{18}O + 25.9$ reported by Liu et al. (2008a)) may be divided into two groups: elevated group 1 considered only of samples from tributary B; and elevated group 2 consisted of some samples from tributary H, I, and K. The two groups were able to be described by fitted lines with the following equations: group 1 $\delta D = 9.3\ \delta^{18}O + 52.9$ ($p < 0.01$); group 2 $\delta D = 9.3\ \delta^{18}O + 38.5$ ($p < 0.01$) (Fig. 3). Most of the river water samples D, E, F, G, L, M and some of the river water samples A, C were distributed around the old rain water sample, while some of the river samples B, C were distributed around the water sample of new rain, as showed that new and old rain waters were the main source of these river waters. While most of the water samples H, I, J, K were far from the new and old rain water samples, indicating they were not supplied directly by the two recent event rains.

All δD and $\delta^{18}O$ values of the spring water samples were similar to that of the old rain water sample, which indicated that the main source of spring water was from the old rain water. Since springs are one of the main paths supplying the river in this region, spring water consisting of old rain water should be thought of as the major source of river water in August.

The initial glacier melt water in spring was located between group 2 and LMWL. Because later glacier melt water in summer had lower d-excess than initial glacier melt water, water samples in group 2 and 1 with higher d-excess were not supplied by glacier melt water.

Altitude effects were obvious in distribution of river samples along the LMWL: river samples B with the highest altitude of 4046 m were located at the bottom part of the LMWL, river samples D, E, F, A, C, K, L, M with higher altitude from 3531 to 4022 m were distributed in the middle part, and river samples I with the lowest altitude of 3477 m were lain on the upper part. Moreover, the locations of group 1 and 2 also displayed altitude effects.

4.2. Spatial and temporal variation of δD, $\delta^{18}O$ and d-excess within the seven tributaries and their confluence

The spatial and temporal variations of δD and $\delta^{18}O$ within the tributaries and their confluences during one rain event were shown in Fig. 4. Most of the $\delta^{18}O$ values from the confluence sites C, G, J, M were distributed between that of their tributaries, whereas for δD this trend was only observed for confluence site G. These results indicated that there were differences existing in hydrological processes within the seven sub-watersheds. A decrease of the isotope content relative to their initial value was observed, which was more or less expressed in the different sampling sites, and this phenomenon meant that some new rain water entered into the rivers and mixed with original river water after this new rain event. Based on Fig. 5, large positive d-excess offset occurred within tributary B, H, K and confluence J. Moreover, for d-excess more than 10, d- excess in tributary B was higher obviously than in tributary H, K and confluence J, and their temporal variation presented linear trends that were consistent with the fitting lines of group 1 and 2 in Fig. 3. This d-excess offset was attributed possibly to relatively local humidity and temperature.

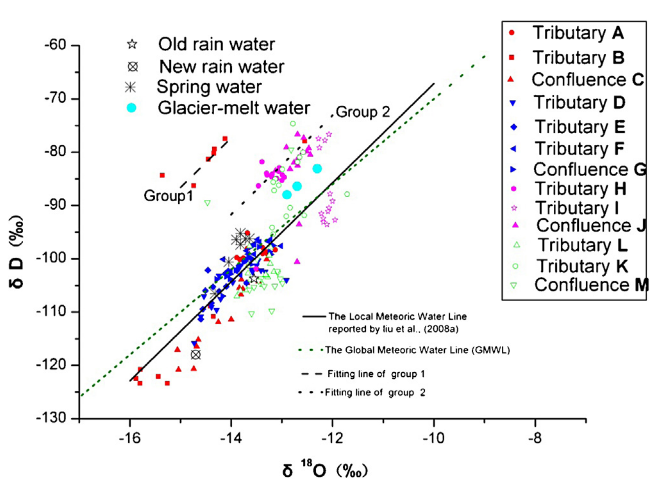


Fig. 3. Distribution of the hydrogen (δD) and oxygen ($\delta^{18}O$) values of rain water, river water, and spring water along the local meteoric water line (LMWL: $\delta D = 9.3\ \delta^{18}O + 25.9$ reported by Liu et al. (2008a)).

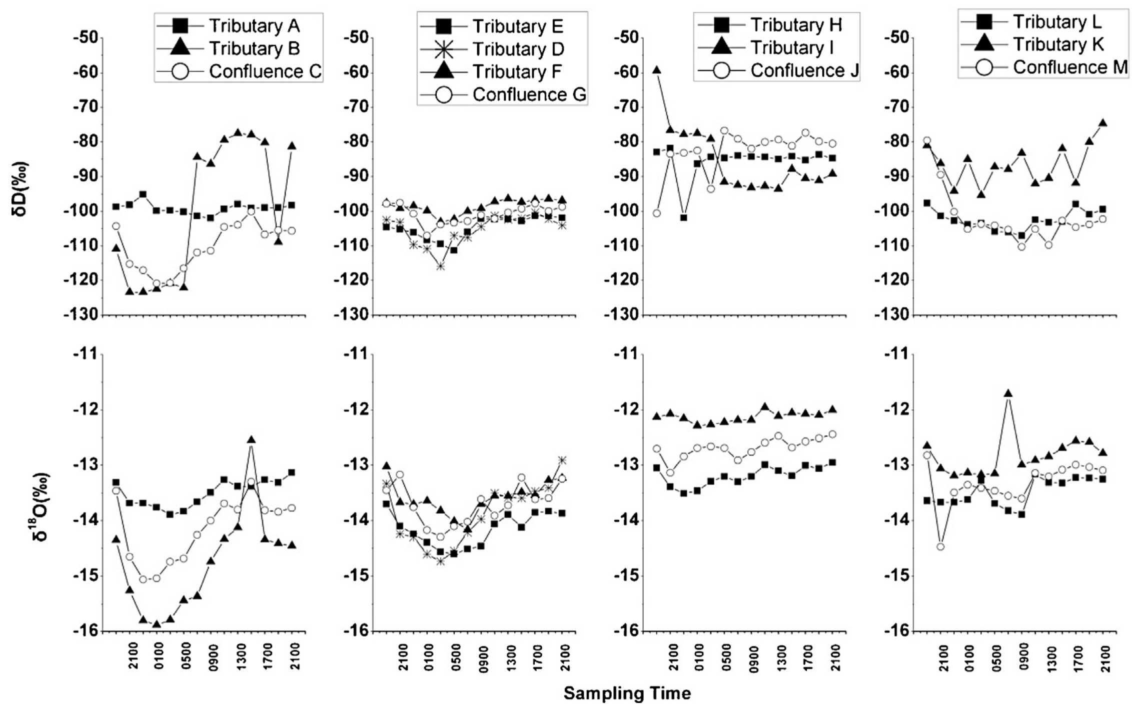
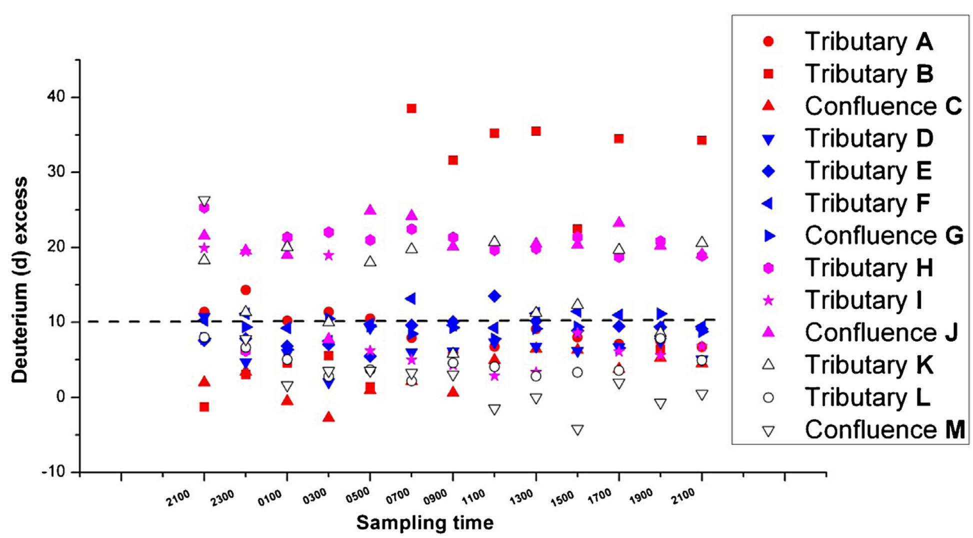


Fig. 4. The temporal variation of hydrogen (δD) and oxygen ($\delta^{18}O$) values in the tributaries and their confluences.



4.3. Contributions of new rain to river water within the seven watersheds

By calculation of two-component hydrograph separation using $\delta^{18}O$, the relative contributions of new rain to river water were shown in Fig. 6. The biggest relative contribution of new rain to river water (almost 43% at about 4 h after the start of the rain event) was found in sub-watershed B. In contrast, tributary I had the smallest contribution (not exceeding 5%) to river water. Generally, humped back-shaped curves were observed within each sub-watershed: increased contributions of new rain to river water after the start of the new rain event till maximum contribution and then gradually decreasing contributions over time. The trend and duration of the rain water contributions differed among the seven watersheds as a result of differences in their landscape and climate characteristics.

In addition, the maximum contributions of new rain water to river water at site G was from 14% to 18% calculated by $\delta^{18}O$ while at similar times the maximum contribution was about 10% calculated by flow amount recorded at the Heishui hydrological monitor station (Fig. 1). This meant our results could be applied in analyzing influence of different factors on contributions of new rain to river water.

4.4. Influence of different factors on contributions of new rain to river water

Of the ten variables (Tables 2 and 3) to account for temporal variability in the relative contributions of new rain to river water included in the stepwise regression model, the topographical parameters, especially elevation and slope, were the most important predictors, explaining almost 27% of temporal variation

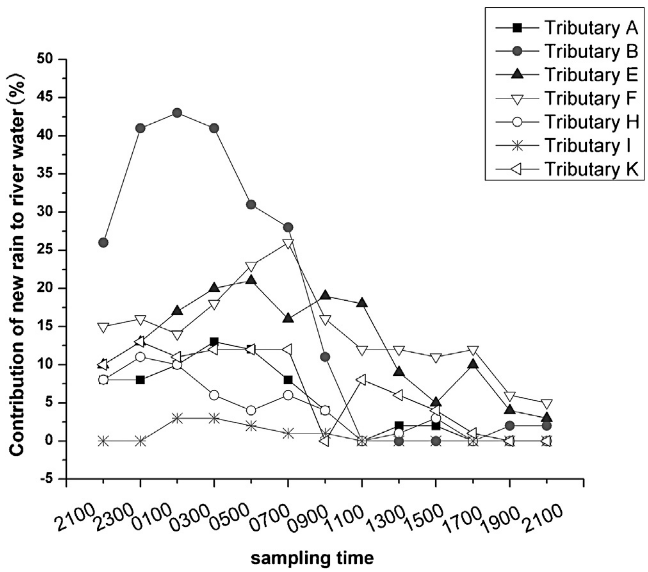


Fig. 6. Contributions of rain to river water in the seven watersheds calculated by stable oxygen isotope ($\delta^{18}O$).

of contributions. The relationships with elevation and slope were linear and positive with contribution of new rain to river water indicating that more new rain water was discharged to the rivers with increasing elevation and slope, as described by Eq. (6):

$$\text{Contributionofnew rain to river water at differernt time} = 0.898 \times (\text{Meadow}) - 2.0.65 \times (\text{Shrub}) - 6.649(R = 0.43, p < 0.001) \quad (6)$$

Moreover, by linear fitting between contributions of new rain and elevation or slope, Fig. 7 showed clearly that elevation and slope were positively correlated with contributions of new water, respectively and the slopes of the two fitting lines (0.02 for elevation; 0.8 for slope) were similar to the slopes of elevation and slope in Eq. (6). This further proved that contributions of new rain were affected by elevation and slope in the mountainous regions.

In the Eq. (6), *P*/AET and vegetation variables did not play a role in explaining new rain contributions to river water when all parameters were entered in the regression analysis. In this stepwise regression model, elevation/slope, *P*/AET and vegetation coverage variables showed some correlation, therefore, when elevation/slope was used to describe contributions of new rain water to river water, roles of *P*/AET and vegetation coverage variables were obscured. However, when topography variables were excluded in regression analysis, climate variables (*P* and AET) were more important than vegetation coverage variables in affecting contributions of new rain water ($p < 0.001$). Therefore, it was obvious that topography and climate parameters played more important roles than the vegetation coverage parameters in controlling contributions of new rain water to river water.

Interestingly, when topography and climate variables were not considered in regression analysis, alpine meadow and alpine shrub coverage variables proved to be significantly correlated with the contributions of new rain water to river water. Alpine meadow coverage was positively correlated with new rain contributions to river water, which meant that increased alpine meadow coverage led to lower retention of new rain water and greater discharge of new rain water. In contrast, increased alpine shrub coverage led to higher rain water retention and lower contributions of new rain to river water (Eq. (7)). Subalpine forest coverage had no effect on new rain contributions during this rain event.

$$\text{Contribution of new rain to river water at different time} = 0.898 \times (\text{Meadow}) - 2.0.65 \times (\text{Shrub}) - 6.649(R = 0.43, p < 0.001) \quad (7)$$

5. Discussions

5.1. Analyzing reasons of large d-excess offsets

Generally, river water samples supplied by rain water are distributed along the GMWL (Clark and Fritz, 1997). However, in this study, some river samples were located above the LMWL with large positive d-excess offsets. In similar region adjacent to this study area, a study undertaken near the PiTiao River in the Wolong Nature Reserve, Cui et al. (2009) found that a large part of rain at the alpine meadow was derived from secondarily evaporated water by deuterium (d) excess analysis, and fog line ($\delta D = 7.9\ \delta^{18}O + 37.99$) formed by secondarily evaporated water paralleled the rainy season local meteoric water line of the alpine meadow (rsLMWL, $\delta D = 7.9\ \delta^{18}O + 34.28$). Ingraham and Matthews (1990) also reported a similar finding like Cui' that Kenya Mountain fog contained water that was recycled terrestrially by evapotranspiration and these fog water data points were distributed above the local meteoric water line. Therefore, the elevated distribution of some samples in our study above the LMWL can be described as being supplied by secondarily evaporated water. However, why were there two fitting lines within river water samples above the LMWL? This occurrence can be described by differing altitudes between the sites. Group

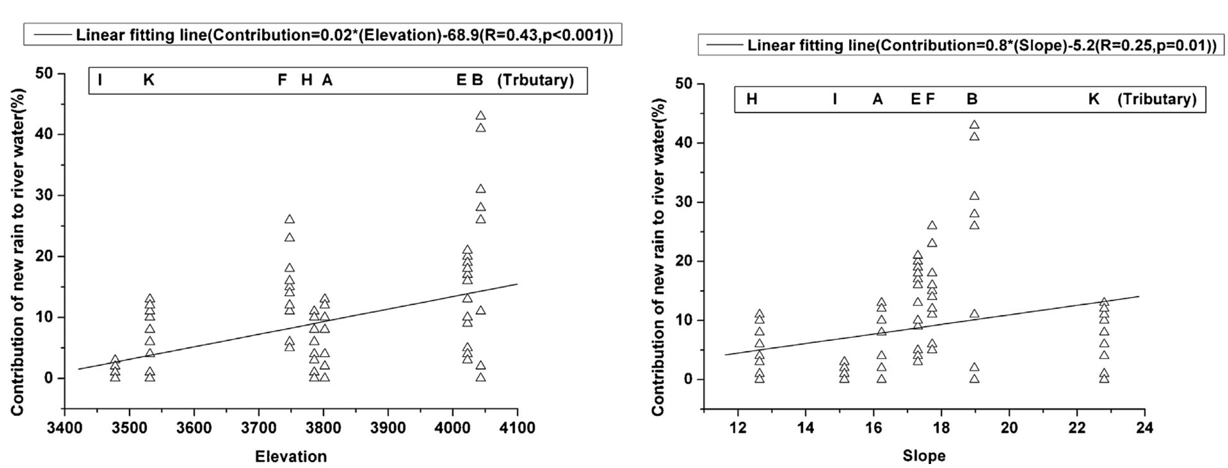


Fig. 7. Relationships between altitude/slope and contributions of new rain to river water.

1 was composed of data from tributary B, and the group 2 was composed of data from tributaries H, I, K. Based on comparison of altitude, the altitude of tributary B was obviously higher than that of tributaries H, I, K (Table 2), hence altitude effects played an important role in formation of secondary evaporation. Cui et al. (2009) found an abrupt rise of d excess values was correlated with elevation. Our study findings also reflect this phenomenon. Moreover, further by analyzing relationships of d-excess and altitude (Fig. 8), d-excess with about and above 20 increased with altitude while there was no apparent relationship between altitude and d-excess with about and below 10. Based on study results of Tibetan Plateau from Bershaw et al., (2012), d-excess in our region was about 11 and caused mainly by Indian Monsoon in summer, while relatively high d-excess was possibly affected by Mediterranean or westerly derived vapor (Karim and Veizer, 2002; Tian et al., 2005, 2007; Hren et al., 2009) or local environmental conditions (Cui et al., 2009; Bershaw et al., 2012). Therefore, river water of d-excess with about 11 in this study was caused by Indian Monsoon, while high d-excess should be attributed to local environmental conditions, especially secondary evaporation precipitation that significantly supplied tributaries B, H, I, K at a certain time. Boronina et al. (2005) found enrichment generally affects δD values less than $\delta^{18}O$ values during evaporation fractionation. As a result, variation of $\delta^{18}O$ was affected less than that of δD. In this study, evaporation at different humidities was the main factors affecting variation of δD and $\delta^{18}O$ or high and low d-excess (Hren et al., 2009). Therefore, the oxygen isotope values are more stable and have a better predictive capacity. Based on this premises, $\delta^{18}O$ values of mixed water should almost distribute between the values of its tributaries, and then it is a reliable

5.2. Effects of topography, P/AET and vegetation coverage on contributions of rain to river water

Variation in the amount of runoff at the outlet of watersheds can be affected by many factors (Cognard-Plancq et al., 2001) such as the amount and intensity of precipitation, the area of the watershed, soil characteristics, and vegetation cover (Llamas, 1993; Pizarro et al., 2006). However, our study showed that there was a sequence of importance among topography, *P*/AET and vegetation coverage variables that determined the effects of contributions of new rain to river water in the Heishui Valley. Slope and elevation were the most important factors of these variables. Moreover, our results showed that with increasing elevation and slope, contributions of new rain to river water would increase. Many studies also have reported that topography was very important in driving water flow during storm events, and that elevation gradients largely controlled hydrologic

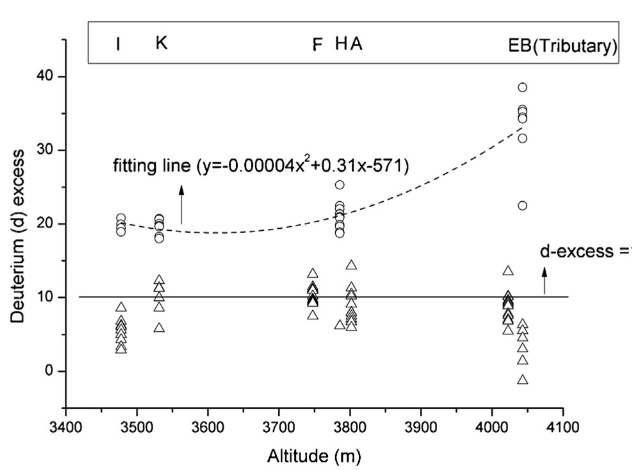


Fig. 8. Relationships between altitude and deuterium (d) excess of river water samples.

pathways and subsurface soil moisture distributions especially in steep, headwater catchments (Welsch et al., 2001; Beven and Kirkby, 1979; Siebert et al., 1997; Liu et al., 2012). Furthermore, topography can also control the spatial patterns of surface water distribution, soil water properties and soil moisture in mountainous areas (Ambroise, 1995). Our work supports the conclusions that elevation and slope affect contributions of new rain to river water in our study region by controlling hydrological pathways and different water distribution.

If topography plus *P*/AET variables were not considered in our regression analysis since they are physical characteristics of watersheds and uneasily changed in the practice of managing watershed ecology and hydrology, some vegetation coverage variables proved to have a significant effect on the contributions of new rain to river water. This is an interesting result and worth some attention in the future management of watersheds. At first our results may appear to differ to those of Pizarro et al. (2006). Their study reported that peak flows were more highly dependent on precipitation amounts and were not correlated with variation of vegetation coverage. However, this conclusion was not seriously contradicted by our results, because we found the effects of vegetation coverage on contributions of new rain to river water were weaker than that of precipitation (e.g., *P*/AET analysis). Although topography and climate played more important roles than vegetation coverage in affecting contributions of new rain to river water, the roles of vegetation coverage should not be ignored during management of watersheds because in practice, different vegetation coverage could be controlled by humans (Lin et al., 2012). In our study, the roles of different vegetation coverage in affecting contributions of new rain to river water varied: increasing alpine shrub coverage could decrease contributions of new rain, and the opposite was true for alpine meadow coverage. In this region, alpine shrub mainly exists on the south slopes and at lower altitudes than alpine meadow, whereas subalpine forests are distributed on the north slopes with the lowest altitude (Sichuan Vegetation Editing Committee, 1980; Jiang et al., 2004). The soil in alpine shrub was not easily saturated as significant evaporation occurred on southern slopes and the water holding capability of alpine shrub canopy was higher than that of alpine meadow canopy (Sichuan Vegetation Editing Committee, 1980), preventing a lot of rain from reaching the soil. Moreover, we further found that alpine shrub utilized shallow soil water from new rain water easily (Liu et al., 2011). Therefore, less new rain water entered river channel, as a result alpine shrub coverage negatively affected the contributions of new rain to river water. In contrast, alpine meadow was mainly distributed at relatively higher altitudes (Sichuan Vegetation Editing Committee, 1980; Jiang et al., 2004), and the soils where this vegetation grow have relatively less water holding capacity and a lower rate of evaporation of soil water (Cui et al., 2009). The low water holding capacity of the soil where alpine meadow occurs can be largely attributed to the inability of alpine meadow to increase soil organic matter, improve soil structure, decrease soil bulk density, and enhance soil porosity (Chang et al., 2003). As a result, the shallow soils of alpine meadow allow new water to easily enter into the subsurface water. Therefore, alpine meadow coverage would increase the contributions of new rain to river water (Wang et al., 2010), as was found in our study. It is important to consider different vegetation coverage and its various hydrological functions in management of watersheds, especially in decreasing risk of flooding, as was described by toposequences of ecosystems resulting from climate and vegetation altitudinal zonation (Ambroise, 1995). In thefuture, we should consider the different and important roles of alpine shrub coverage and alpine meadow coverage in adjusting contributions of different rain to river water.

6. Conclusions

During one rain event, water isotope characteristics of river water and relationships between topography, *P*/AET, vegetation coverage variables and contributions of new rain to river water were studied within the seven sub-watersheds of the Heishui Valley. By comparing $\delta^{18}O$ and δD values of the collected water samples, we could establish that in the middle of summer river water was mainly supplied by a combination of old rain water and new rain water. Our results of regression analysis also showed that topography, especially elevation and slope, played the most important roles in affecting the contributions of new rain to river water. However, alpine shrub proved to be able to retain much more new rain water than alpine meadow when only vegetation coverage factors were considered. This difference was due to two factors. Firstly, the effects of evaporation on water from soils of alpine shrub were higher. Secondly, the water holding capability of alpine shrub canopy was higher than that of alpine meadow. Both of these factors combined to reduce contribution of new rain to river water in alpine shrub. Subalpine forest was found to have no effects on the contribution of new rain to river water. Therefore, our study implied that increasing alpine shrub coverage would produce a buffer for new rain water flowing to river and could decrease risk of flooding in this region during summer.

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