Acta Geochim (2021) 40(2):176–183
https://doi.org/10.1007/s11631-021-00452-8

ORIGINAL ARTICLE

Estimation of evaporation losses based on stable isotopes of stream water in a mountain watershed

Zhongcong Sun[1] · Chaochen Hu[1] · Di Wu[1] · Guopeng Chen[2] · Xiaoqiang Lu[3] · Xueyan Liu[1]

Received: 18 August 2020 / Revised: 15 November 2020 / Accepted: 6 January 2021 / Published online: 15 February 2021

Abstract Water stable isotopes (δ^2H and δ^{18}O) can record surface water evaporation, which is an important hydrological process for understanding watershed structure and function evolution. However, the isotopic estimation of water evaporation losses in the mountain watersheds remains poorly explored, which hinders understanding spatial variations of hydrological processes and their relationships with the temperature and vegetation. Here we investigated δ^2H, δ^{18}O, and *d-excess* values of stream water along an altitude gradient of 2130 to 3380 m in Guan'egou mountain watershed at the east edge of the Qinghai-Tibet Plateau in China. The mean δ^2H ($-$ 69.6 ‰ $\pm$ 2.6 ‰), δ^{18}O ($-$ 10.7 ‰ $\pm$ 0.3 ‰), and *d-excess* values (16.0 ‰ $\pm$ 1.4 ‰) of stream water indicate the inland moisture as the major source of precipitation in study area. Water stable isotopes increase linearly with decreasing altitudes, based on which we estimated the fractions of water evaporation losses along with the altitude and their variations in different vegetations. This study provides an isotopic evaluation method of water evaporation status in mountain watersheds, the results are useful for further understanding the relationship between hydrological processes and ecosystem function under the changing climate surrounding the Qinghai-Tibet Plateau.

Keywords Water stable isotopes · Mountain watersheds · Water evaporation losses · Altitude effect · Rayleigh fractionation

1 Introduction

Terrestrial water evaporation is an important hydrological process that affects water balance and energy conversion in different landscapes (Edwards et al. 2015; Gibson et al. 1993; Skrzypek et al. 2015). Therefore, it is crucial to elucidate surface water evaporation losses and their spatiotemporal variations for a better understanding of regional environmental evolutions under global change (Chahine 1992; Fan et al. 2019; Yang et al. 2011).

While mountains cover only one-fourth of land surface, more than half of runoffs in the world originate from mountains (Körner 2007; Marston 2008). Hydrological processes in the mountain watersheds can influence biogeochemical processes of nutrients and their coupling with the water availability, which subsequently have implications for the carbon sequestration, vegetation succession, and climate on the continent (Edwards et al. 2015; Fan et al. 2019; McGuire and McDonnell 2007). However, the understandings of hydrological processes in the mountain watersheds are still limited due to insufficient information on the meteorology and the hydrology (Brown and Pasternack 2014; Fan et al. 2019; Wen et al. 2012; Wu et al. 2019a). Especially, heterogeneous terrain and climate

Supplementary Information The online version of this article (https://doi.org/10.1007/s11631-021-00452-8) contains supplementary material, which is available to authorized users.

✉ Xiaoqiang Lu
lxq@nies.org

✉ Xueyan Liu
liuxueyan@tju.edu.cn

1 School of Earth System Science, Tianjin University, Tianjin 300072, China

2 College of Forestry, Gansu Agricultural University, Lanzhou 730070, Gansu Province, China

3 Key Laboratory of Biosafety, Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing 210042, Jiangsu, China

can change water flow and discharge pathways, and subsequently influence water evaporation within the mixing and transformation between precipitation, snowmelt, surface runoff, and groundwater (Beria et al. 2018; Jiao et al. 2019; Wassenaar et al. 2011; Xing et al. 2015). Therefore, although it is well known that hydrological processes in mountain watersheds might vary with the altitude by the temperature effect (Li et al. 2016; Shen and Poulsen 2019; Wen et al. 2012), mechanisms of vertical variations of the water evaporation losses remain unclear in many mountain watersheds, which hindered the accurate estimations of the regional water evaporation fluxes and the understandings of effects of hydrological processes on ecosystem structure and function in responses to climate change (Fan et al. 2019; Wen et al. 2012).

Because of distinct fractionation effects during evaporation, signatures of water stable isotopes (δ^2H and δ^{18}O) are useful evidence on water sources and evaporation status (Cappa et al. 2003; Clark and Fritz 1997; Gat 1996; Gibson et al. 1993; McGuire and McDonnell 2007). The Global Meteoric Water Line (GMWL, $\delta^2H = 8\delta^{18}O + 10$) has been expressed by the regression relationship between δ^2H and δ^{18}O values of precipitation on the global scale (Craig 1961). Thus, the water δ^2H and δ^{18}O values, and the deuterium excess values (*d-excess* = $\delta^2H - 8\delta^{18}O$, Eq. 3) that mainly generated by the disequilibrium isotope fractionation of H and O could provide crucial information on moisture sources of precipitation (Dansgaard 1964; Tian et al. 2007; Yao et al. 2013). While plant transpiration and soil infiltration do not produce substantial isotope fractionation effect, the δ^2H, δ^{18}O, and *d-excess* values had been used to estimate water evaporation losses by combining with the isotopic fractionations in evaporation, and the isotopic mass balance of water input and output (Cui et al. 2017; Gibson et al. 2016, 1993; Gibson and Edwards 2002; Skrzypek et al. 2015). However, variations of isotope fractionation effects with the altitude by the temperature effect might raise uncertainties on the evaluation of land surface evaporation fluxes in the mountain regions (Wen et al. 2012; Yang et al. 2009).

The δ^2H and δ^{18}O values of surface water flows generally increased with decreasing altitudes in the mountain watersheds (Hren et al. 2009; Ren et al. 2017; Wen et al. 2012; Wu et al. 2019a), which was mainly related to the gradual depletion of ^{2}H, ^{18}O in precipitation during the moisture condensation and rain out with decreasing temperatures according to the Rayleigh equation (Jiao et al. 2019; Shen and Poulsen 2019). However, it remains unclear whether and how the altitude effects of surface water flow isotopes in a mountain watershed were controlled by the variation of water evaporation losses (Shen and Poulsen 2019; Yang et al. 2011). Therefore, the estimation of water evaporation losses from surface water flows with the altitude in a mountain watershed by using water stable isotopes has important implications for understanding regional water balance and its responses to climate change in mountain ecosystems (Gibson and Reid 2010; Jasechko et al. 2013; Skrzypek et al. 2015).

Basing on the above context, this study analyzed the δ^2H, δ^{18}O, and *d-excess* values of stream water and its variations along an altitude gradient in the Guan'egou mountain watershed of western China. Our objectives are: (1) to explore the major water recharge source, and how abiotic and biotic traits in the watershed scale influence the isotopic variations of stream water. (2) to estimate the fractions of water evaporation losses and their variations with the altitude, temperature, and vegetation. The information can enrich the knowledge of hydrological processes in mountain watersheds, and the application of water isotopes in ecological processes.

2 Materials and methods

2.1 Study area

The study was conducted in the Guan'egou watershed of Tanchang county, Gansu province at the east edge of the Qinghai-Tibet Plateau (QTP) in China (104°19′ E ~ 104°24′ E, 34°03′ N ~ 33°53′ N) (Fig. 1a). The total area of the study watershed covers nearly 350 km^2 with a range of altitude from 1780 to 4154 m (Fig. 1b). The climate in the study watershed is dominated by a temperate continental climate where the mean annual temperature (MAT) and mean annual precipitation (MAP) are nearly 9.3 °C and 640 mm, respectively. The air temperature varied with the altitude in the study watershed and showed an estimated vertical lapse rate of 0.53 °C/100 m (Li and Xie 2006). The stream water originates from Mt. Leigu, which has the highest altitude of 4154 m, and flows through the vegetations of heath and meadow (> 3400 m), spruce-fir forest (3000 ~ 3400 m), mixed broadleaf-conifer forest (2500 ~ 3000 m) and broadleaf forest (< 2500 m) with the decreasing altitude (Wang 2016). The information of dominant plant species in those vegetations along the altitude is listed in Table S1. The lakes and shoals are distributed in low mountain valleys.

The Guan'egou watershed is one of many ecological hotspot areas around the QTP in China, where the mountain ecosystems generally sensitively respond to climate change (Meng and Liu 2013, 2016; Zhang et al. 2010). Especially, distinct altitude gradient and associated vegetation succession in the study watershed provide a natural experiment for exploring the variations of water evaporation losses with the changing climate and vegetation.

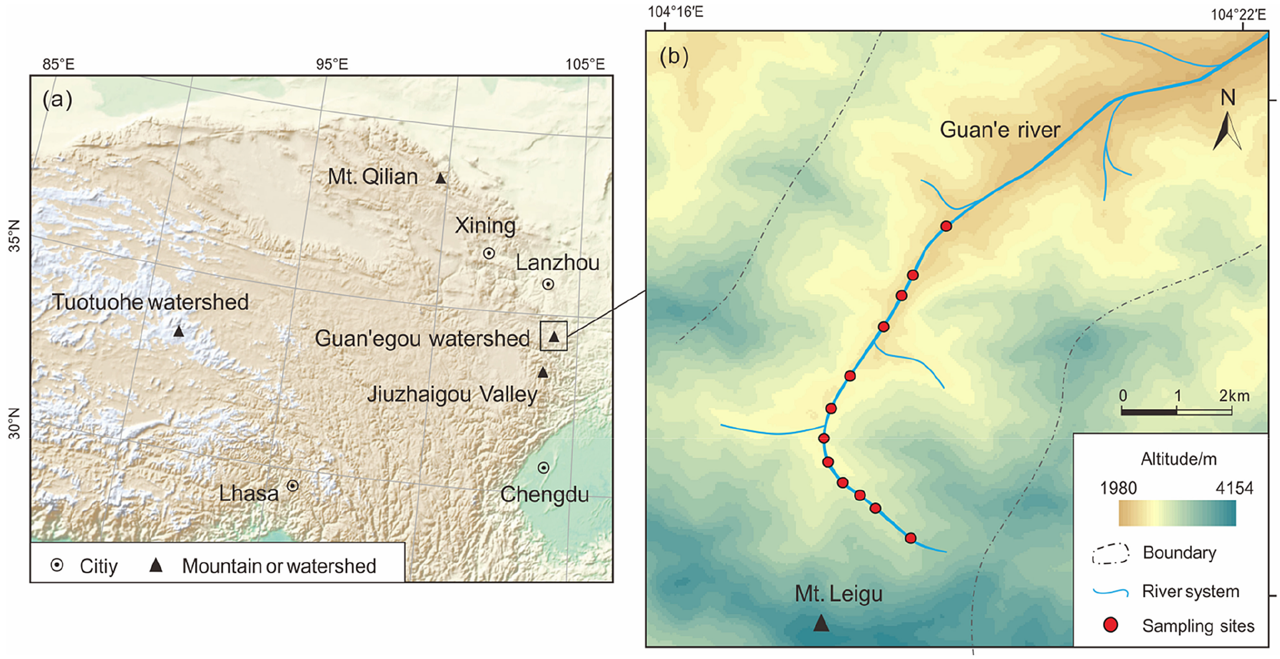

Fig. 1 Location of Guan'egou watershed and sampling sites of stream water

2.2 Stream water sampling and isotope analyses

In September of 2018, stream water was sampled at twelve sites with different altitudes from the north slope of Mt. Leigu (3380 m) to the downstream (2130 m). In each site, the stream water was slowly filled into the glass head-space vials crimp-sealed with butyl septa (W224110-185, Wheaton, USA). The sample vials were taken back to the laboratory in a cooling bag and preserved at 4 °C till laboratory analyses. Water temperature, pH, electrical conductivity (EC), and concentrations of dissolved oxygen (DO) of stream water were measured in the field by using a multiparameter water quality monitor (YSI professional plus, Xylem, USA). The geographic information of longitude, latitude, and altitude was recorded by a GPS at each site. The air temperature at each site was estimated by mean air temperature on the sampling day in Tanchang county (16 °C at the altitude of 1750 m, cited from China Meteorological Data Service Center (http://data.cma.cn), and the local vertical lapse rate of air temperature (0.53 °C/100 m) (Li and Xie 2006).

Stream water was transferred and filled up into vials (1.5 mL) in the laboratory before isotopes analyses. δ^2H and δ^{18}O values of stream water were analyzed by using the method of high-temperature pyrolysis, and element analyzer coupled with a gas stable isotope mass spectrometer (Flash 2000HT-MAT 253, Thermo Scientific GmbH, Germany) (Gehre and Strauch 2003). Briefly, the water samples were pyrolyzed to H_2 and CO with the presence of reactive carbon at a high temperature (> 1400 °C) in the element analyzer, then their isotopic compositions (^{2}H/^{1}H and ^{18}O/^{16}O values) were measured in the gas stable isotope mass spectrometer after gas chromatographic separation in a constant temperature. Water stable isotopes were then expressed as δ^2H and δ^{18}O values (‰) (Clark and Fritz 1997).

$$\delta^2\mathrm{H} = \left[\left({}^2\mathrm{H}/{}^1\mathrm{H}\right)_{\mathrm{sample}} / \left({}^2\mathrm{H}/{}^1\mathrm{H}\right)_{\mathrm{standard}} - 1\right] \times 1000, \tag{1}$$

$$\delta^{18}\mathrm{O} = \left[\left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{sample}} / \left({}^{18}\mathrm{O}/{}^{16}\mathrm{O}\right)_{\mathrm{standard}} - 1\right] \times 1000, \tag{2}$$

where the Vienna Standard Mean Ocean Water (V-SMOW) is used as the standard. Water isotope standards of GBW04458 (δ^2H = − 1.7 ‰, δ^{18}O = –0.15 ‰), GBW04459 (δ^2H = − 63.4 ‰, δ^{18}O = − 8.61 ‰), and GBW04460 (δ^2H = − 144.0 ‰, δ^{18}O = − 19.13 ‰) were measured in the same way as stream water samples for data calibrations. Analytical precisions of δ^2H and δ^{18}O values were ± 0.5 ‰ and ± 0.2 ‰ based on triplicate sample analyses, respectively. Then, the *d-excess* values were calculated as following (Dansgaard 1964):

$$d - excess = \delta^2\mathrm{H} - 8\delta^{18}\mathrm{O}, \tag{3}$$

the uncertainties of calculated *d-excess* values were ± 0.3 ‰.

3 Results

The δ^2H, $\delta^{18}O$, and *d-excess* values of stream water in the Guan'egou watershed ranged from − 66.9 ‰ to − 77.1 ‰ (mean ± SD = − 69.6 ‰ ± 2.6 ‰), − 11.4 ‰ to − 10.3 ‰ (mean ± SD = − 10.7 ‰ ± 0.3 ‰), and 13.5 ‰ to 18.1 ‰ (mean ± SD = 16.0 ‰± 1.4 ‰), respectively (Fig. 2). The stream water line (SWL) was defined as the linear regression that fitted between the δ^2H and $\delta^{18}O$ values of stream water ($\delta^2H = 7.65\delta^{18}O + 12.28$, $N = 12$, $R^2 = 0.72$). Both δ^2H and $\delta^{18}O$ values of stream water increased with decreasing altitude and increasing air temperature in the study watershed (Fig. 3a, b), showing the enrichment rates of 0.61 ‰ /100 m and 0.07 ‰ /100 m, respectively.

4 Discussion

4.1 Recharge source of stream water

Because isotopic signatures of surface water basically follow those of precipitation (Meng and Liu 2013, 2016; Ren et al. 2017), the meteoric water line (MWL) that fitted by δ^2H and $\delta^{18}O$ values can trace the recharge source of surface waters (Kong et al. 2019). The study watered is located at the transition area of the east edge of the QTP, the Loess Plateau, and Qinling mountains in China (Fig. 1a) (Wang 2016). So far, isotopic surveys of precipitation in and near the study watershed remain very limited. The Jiuzhaigou Valley is geographically closest to our study watershed and has a very similar altitude range (2000–4000 m) (Fig. 1b). The similarity in the climate and landform provides a good opportunity for comparison of precipitation isotopes between these two mountain watersheds (Yin et al. 2000). Therefore, the similar slope and intercept values between the SWL of the study watershed with the MWL ($\delta^2H = 7.86\ \delta^{18}O + 15.07$; $N = 22$, $R^2 = 0.98$) of Jiuzhaigou Valley obtained in September indicated that the stream water in the study watershed was mainly recharged by precipitation at the same period (Fig. 2) (Meng and Liu 2013, 2016; Yin et al. 2000; Wu et al. 2019a).

Because precipitation *d-excess* values can indicate recycled moisture, precipitation derived from arid inland moisture generally had higher *d-excess* values than that

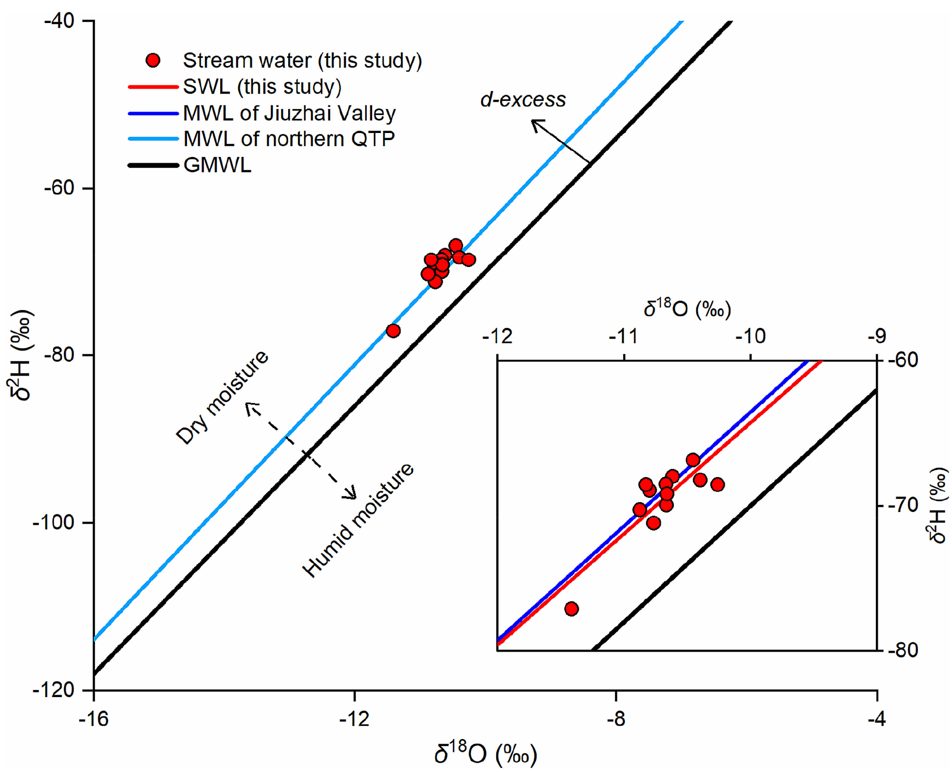

Fig. 2 Distributions of δ^2H and $\delta^{18}O$ values of stream water in Guan'egou watershed, and a comparison of stream water δ^2H and $\delta^{18}O$ values with the meteoric water line (MWL) of northern Qinghai-Tibet Plateau (QTP). The stream water line (SWL) in the Guan'egou watershed ($\delta^2H = 7.65\delta^{18}O + 12.28$; $N = 12$, $R^2 = 0.72$) and meteoric water line (MWL) of Jiuzhaigou Valley in September ($\delta^2H = 7.86\delta^{18}O + 15.07$; $N = 22$, $R^2 = 0.98$) (Yin et al. 2000) were showed and compared; the MWL of northern QTP was represented by local MWL that obtained in Tuotuohe area ($\delta^2H = 7.86\delta^{18}O + 15.07$; $N = 22$, $R^2 = 0.98$) (Tian et al. 2001b); Different deviations of MWLs from the GMWL represent a dry or humid moisture source (dashed arrows); solid arrow represents the increasing trend of *d-excess* values

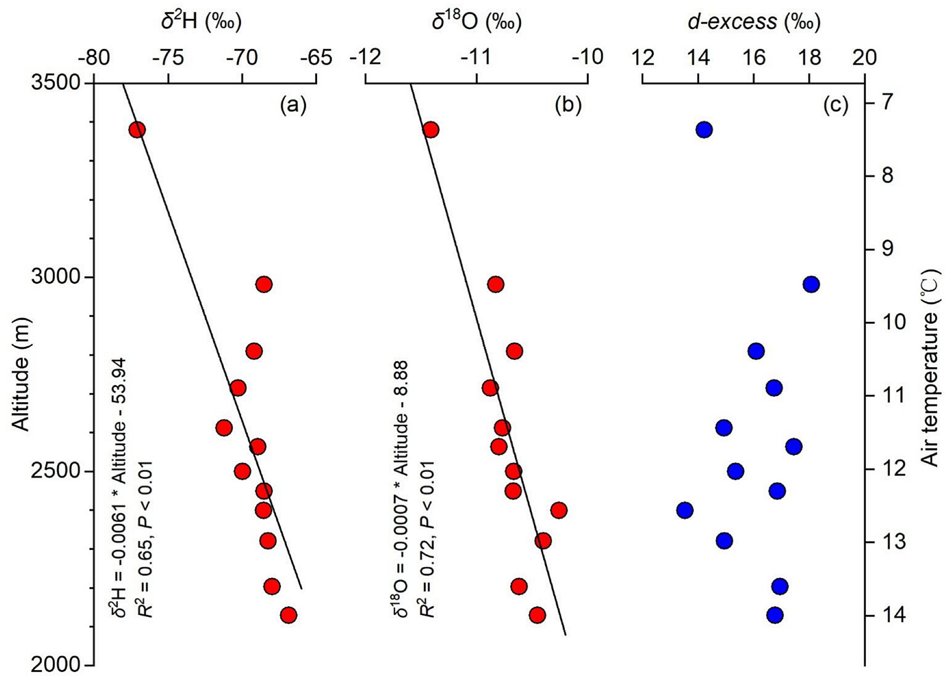

Fig. 3 Variations of δ^2H (**a**), δ^{18}O (**b**) and *d-excess* (**c**) values of stream water with the altitude (H) and the estimated air temperature (T) in the Guan'egou watershed

derived from warm and humid marine moisture (Froehlich et al. 2008; Li et al. 2015; Liu et al. 2007; Tian et al. 2001b), which causes deviations of isotopic distributions from the GMWL (Fig. 2). Especially, in the Qinghai-Tibet Plateau (QTP), higher *d-excess* values of precipitation in northern areas were mainly attributed to the dominance of inland moisture, rather than the marine monsoon (He and Richards 2016; Liu et al. 2007; Tian et al. 2001a; Zhou et al. 2007). Therefore, the differences of observed δ^2H and δ^{18}O distributions of stream water from the GMWL might exclude the dominance of marine monsoon moisture in precipitation (Liu et al. 2007, 2010; McGuire and McDonnell 2007) (Fig. 2). Similar isotopic distributions of stream water in our study watershed with the precipitation in northern QTP areas such as the Tuotuohe area revealed that the inland moisture from the continental monsoon or local recycled vapor at the end of the rainy season (Tian et al. 2001a, 2001b) (Fig. 2; Fig. S1). These results highlighted an effective diagnose of the moisture source of precipitation in semi-arid areas by combining distributions of water isotopes with the *d-excess* values (Kong et al. 2019; Li et al. 2020; Pfahl and Sodemann 2014; Tian et al. 2007).

4.2 Estimation of water evaporation losses of stream water

Both δ^2H and δ^{18}O values of stream water in the study watershed showed distinct altitude effects (Hren et al. 2009; Ren et al. 2017). However, the observed lapse rates of δ^2H and δ^{18}O values with increasing altitude were lower than those of surface water flows in the QTP (Ren et al. 2017; Wen et al. 2012; Wu et al. 2019a; Yang et al. 2009). Such differences were mainly caused by the low precipitation at the end of the rainy season (Fig. S1) when the mixing of different moisture sources might have generated the altitude decoupling of air mass and terrains (Wen et al. 2012; Yang et al. 2009; Yao et al. 2013). Previously, the evaporation has been found to enhance the altitude effect of river δ^{18}O values at regional scales but has often been neglected at watershed scales (Wu et al. 2019a; Yang et al. 2009). In our study watershed, however, the water evaporation losses played an important role in regulating the variations of stream water isotopes with the altitude (Wu et al. 2019b).

Because stream water isotopes were controlled by isotopic compositions of precipitation and evaporation isotope effects, the altitude effects of stream water isotopes could reflect water distillation processes (Edwards et al. 2015; Wu et al. 2019a, 2019b). Assuming a transient equilibrium state of the water–vapor interface during the evaporation, the fractionation factor could be only related to temperature (Skrzypek et al. 2015; Wassenaar et al. 2011). In another word, we aimed to estimate the water losses of the equilibrium evaporation processes to reflect their variations along the altitude gradient. While the kinetic fractionation of ^{2}H is larger than that of ^{18}O in evaporation, the δ^{18}O value of stream water is better to estimate the equilibrium water evaporation losses (Luz et al. 2009). The δ^{18}O values of stream water at the highest altitude (denoted as H_0, where the temperature is T_0) and lower altitudes (denoted as H_n, where the temperature is T_n) can be considered as those of initial and residual water. Accordingly, each water equilibrium evaporation process could be described as the following open-system Rayleigh equation (Wassenaar et al. 2011) (Eq. 4).

$$\delta^{18}O_n + 1 = (\delta^{18}O_0 + 1) \times (1 - E_n)^{(\alpha n - 1)}, \quad (4)$$

where $\delta^{18}O_0$ and $\delta^{18}O_n$ values are $\delta^{18}O$ values of stream water at the altitude of H_0 and H_n, respectively. The E_n is the fraction of water evaporation losses (%). The α_n is the equilibrium isotope fractionation factor and was estimated by the following equation (Clark and Fritz 1997; Gat 1996; Majoube 1971).

$$10^3 \ln\alpha_n(^{18}O) \approx \left(1.137 \times 10^6\right) / T_e^2 - 415.6 / T_e - 2.0667, \quad (5)$$

where T_e is the air temperature (in Kelvin) of the water–vapor interface and is estimated as the mean air temperature between the altitudes of H_n and H_0.

The calculated E_n values based on Eq. 4 ranged between 4.97% –10.44%, reflecting distinct vertical differences of water evaporation losses in the study watershed (Kong et al. 2019; Wu et al. 2019a). Moreover, the E_n values increased with the altitude lapses ($\Delta H_n = H_0 - H_n$) and the temperature increments ($\Delta T_n = T_n - T_0$) ($P < 0.01$; Fig. 4). This revealed the importance of temperature variations for shaping the heterogeneity of hydrological processes in mountain ecosystems (Guo et al. 2016; Yao et al. 2013). The calculating results and findings are useful for water budget estimations in mountain areas, which should be integrated into water balance models (Fan et al. 2019; Jasechko et al. 2013).

The vegetation is a key factor affecting water evaporation losses at the landscape scale (Jiang et al. 2004). We found that the increments of E_n values differed with the vegetation (Fig. 4; Table S1), water evaporation losses showed a mean rate of 1.36%/100 m in the subalpine spruce-fir forest at the upper mountain, 0.31%/100 m in the mixed broadleaf-conifer forest at the middle mountain, 0.61%/100 m in the broadleaf forest at the lower mountain. Although the equilibrium evaporation that dominated by temperature was partly hypothetical. the result reflected the differences of vegetation in restricting soil water evaporation potentially due to different litter compositions and tree canopy sizes (Edwards et al. 2015; Jiang et al. 2004). Among vegetations along the altitude gradient, the higher plant diversity in the broadleaf forest and mixed broadleaf-conifer forest than that in the spruce-fir forest could also promote soil water retention (Table S1) (Kammer et al. 2013; Sundqvist et al. 2013; Wu et al. 2014). Meanwhile, water evaporation losses can affect the vegetation succession by altering local precipitation (Zhang et al. 2010). Our results highlighted that vegetation and hydrological processes can interact in influencing the structure and function of mountain ecosystems.

5 Conclusions

Stable isotopes and *d-excess* values of stream water in a mountain watershed around the QTP revealed precipitation dominated by inland moisture from the continents or local water vapor as the main recharge source. Stable isotopes of stream water increased distinctly with decreasing altitudes,

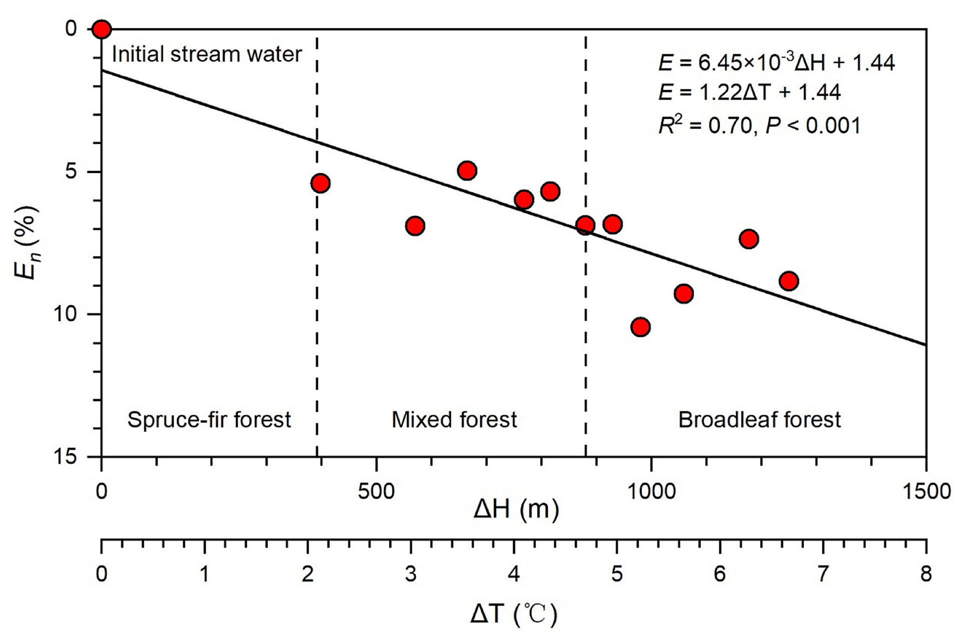

Fig. 4 Variations of water evaporation losses (E_n) with the altitude lapses (ΔH) and temperature increments (ΔT) of stream water in the Guan'egou watershed. The red-filled circles represented the water evaporation losses (E_n) in different altitude lapses (ΔH) and temperature increments (ΔT); the initial stream water (E_0 = 0, ΔH = 0, ΔT = 0) was showed; the dashed lines represented the boundaries of vegetations at different altitudes; The mixed forest is the abbreviation of the broadleaf-conifer forest

which indicated the variations of water evaporation losses along the altitudes. A Rayleigh isotope model based on water δ^{18}O values was established to estimate the fractions of water evaporation losses, which increased with the decreasing altitude and increasing temperature. Moreover, the increments of fraction values differed among vegetation types. This study provided useful hydrogeochemical information of surface waters in mountain watersheds to better understand relationships between hydrological processes, climate, and vegetation surrounding the QTP region.

Acknowledgements We thank the assistance and support by Tanchang County People's Government, Forestry Bureau of Tanchang County, and Guan'egou National Forest Park on the field work. This study was supported by National Natural Science Foundation of China (No. 41730855), State Key Project of Research and Development Plan (2016YFA0600802).

Compliance with ethical standards

Conflict of interest We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

References

Beria H, Larsen JR, Ceperley NC, Michelon A, Vennemann T, Schaefli B (2018) Understanding snow hydrological processes through the lens of stable water isotopes. WIREs Water. https://doi.org/10.1002/wat2.1311

Brown RA, Pasternack GB (2014) Hydrologic and topographic variability modulate channel change in mountain rivers. J Hydrol 510:551–564. https://doi.org/10.1016/j.jhydrol.2013.12.048

Cappa CD, Hendricks MB, DePaolo DJ, Cohen RC (2003) Isotopic fractionation of water during evaporation. J Geophys Res. https://doi.org/10.1029/2003jd003597

Chahine MT (1992) The hydrological cycle and its influence on climate. Nature 359:373–380. https://doi.org/10.1038/359373a0

Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis Publishers, New York

Craig H (1961) Isotopic variations in meteoric waters. Science 133:1702–1703. https://doi.org/10.1126/science.133.3465.1702

Cui J, Tian L, Biggs TW, Wen R (2017) Deuterium-excess determination of evaporation to inflow ratios of an alpine lake: Implications for water balance and modeling. Hydrol Process 31:1034–1046. https://doi.org/10.1002/hyp.11085

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436–468. https://doi.org/10.3402/tellusa.v16i4.8993

Edwards PJ, Williard KW, Schoonover JE (2015) Fundamentals of watershed hydrology. J Contemp Water Res Educ 154:3–20. https://doi.org/10.1111/j.1936-704X.2015.03185.x

Fan Y et al (2019) Hillslope hydrology in global change research and earth system modeling. Water Resour Res 55:1737–1772. https://doi.org/10.1029/2018wr023903

Froehlich K, Kralik M, Papesch W, Rank D, Scheifinger H, Stichler W (2008) Deuterium excess in precipitation of Alpine regions - moisture recycling. Isotopes Environ Health Stud 44:61–70. https://doi.org/10.1080/10256010801887208

Gat JR (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. Annu Rev Earth Planet Sci 24:225–262. https://doi.org/10.1146/annurev.earth.24.1.225

Gehre M, Strauch G (2003) High-temperature elemental analysis and pyrolysis techniques for stable isotope analysis. Rapid Commun Mass Sp 17:1497–1503. https://doi.org/10.1002/rcm.1076

Gibson JJ, Birks SJ, Yi Y (2016) Stable isotope mass balance of lakes: a contemporary perspective. Quaternary Sci Rev 131:316–328. https://doi.org/10.1016/j.quascirev.2015.04.013

Gibson JJ, Edwards TWD (2002) Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. Global Biogeochem Cy 16: 10–1–10–14. https://doi.org/10.1029/2001gb001839

Gibson JJ, Edwards TWD, Bursey GG (1993) Estimating evaporation using stable isotopes: quantitative results and sensitivity analysis for two catchments in Northern Canada: paper presented at the 9th Northern Res. Basin Symposium/Workshop (Whitehorse/Dawson/Inuvik, Canada - August 1992). Hydrol Res 24:79–94. https://doi.org/10.2166/nh.1993.0015

Gibson JJ, Reid R (2010) Stable isotope fingerprint of open-water evaporation losses and effective drainage area fluctuations in a subarctic shield watershed. J Hydrol 381:142–150. https://doi.org/10.1016/j.jhydrol.2009.11.036

Guo X, Wang L, Tian L (2016) Spatio-temporal variability of vertical gradients of major meteorological observations around the Tibetan Plateau. Int J Climatol 36:1901–1916. https://doi.org/10.1002/joc.4468

He S, Richards K (2016) Stable isotopes in monsoon precipitation and water vapour in Nagqu, Tibet, and their implications for monsoon moisture. J Hydrol 540:615–622. https://doi.org/10.1016/j.jhydrol.2016.06.046

Hren MT, Bookhagen B, Blisniuk PM, Booth AL, Chamberlain CP (2009) δ^{18}O and δD of streamwaters across the Himalaya and Tibetan Plateau: implications for moisture sources and paleoelevation reconstructions. Earth Planetary Sci Lett 288:20–32. https://doi.org/10.1016/j.epsl.2009.08.041

Jasechko S, Sharp ZD, Gibson JJ, Birks SJ, Yi Y, Fawcett PJ (2013) Terrestrial water fluxes dominated by transpiration. Nature 496:347–350. https://doi.org/10.1038/nature11983

Jiang H et al (2004) The influence of vegetation type on the hydrological process at the landscape scale. Can J Remote Sens 30:743–763. https://doi.org/10.5589/m04-033

Jiao Y, Liu C, Gao X, Xu Q, Ding Y, Liu Z (2019) Impacts of moisture sources on the isotopic inverse altitude effect and amount of precipitation in the Hani Rice Terraces region of the Ailao Mountains. Sci Total Environ 687:470–478. https://doi.org/10.1016/j.scitotenv.2019.05.426

Kammer PM, Schöb C, Eberhard G, Gallina R, Meyer R, Tschanz C (2013) The relationship between soil water storage capacity and plant species diversity in high alpine vegetation. Plant Ecol Divers 6:457–466. https://doi.org/10.1080/17550874.2013.783142

Kong Y, Wang K, Li J, Pang Z (2019) Stable isotopes of precipitation in China: a consideration of moisture sources. Water. https://doi.org/10.3390/w11061239

Körner C (2007) The use of "altitude" in ecological research. Trends Ecol Evol 22:569–574. https://doi.org/10.1016/j.tree.2007.09.006

Li Q, Xie Z (2006) Analyses on the characteristics of the vertical lapse rates of temperature, taking Tibetan Plateau and its adjacent area as an example. J Shihezi Univ (Nat Sci) 24:719–723 **(in Chinese with English abstract)**

Li Z et al (2016) Contributions of local terrestrial evaporation and transpiration to precipitation using δ^{18}O and D-excess as a proxy in Shiyang inland river basin in China. Glob Planet Change 146:140–151. https://doi.org/10.1016/j.gloplacha.2016.10.003

Li ZJ, Li ZX, Song LL, Ma JZ (2020) Characteristic and factors of stable isotope in precipitation in the source region of the Yangtze River. Agr Forest Meteorol. https://doi.org/10.1016/j.agrformet.2019.107825

Li Z et al (2015) Can monsoon moisture arrive in the Qilian Mountains in summer? Quat Int 358:113–125. https://doi.org/10.1016/j.quaint.2014.08.046

Liu Z, Tian L, Yao T, Yu W (2007) Seasonal deuterium excess in Nagqu precipitation: influence of moisture transport and recycling in the middle of Tibetan Plateau. Environ Geol 55:1501–1506. https://doi.org/10.1007/s00254-007-1100-4

Liu Z, Tian L, Yao T, Yu W (2010) Characterization of precipitation $\delta^{18}O$ variation in Nagqu, central Tibetan Plateau and its climatic controls. Theor Appl Climatol 99:95–104. https://doi.org/10.1007/s00704-009-0125-x

Luz B, Barkan E, Yam R, Shemesh A (2009) Fractionation of oxygen and hydrogen isotopes in evaporating water. Geochim et Cosmochim Acta 73:6697–6703. https://doi.org/10.1016/j.gca.2009.08.008

Majoube M (1971) Oxygen-18 and deuterium fractionation between water and steam (in French). J Chim Phys PCB 68:1423–1436

Marston RA (2008) Land, life, and environmental change in mountains. Ann Assoc Am Geogr 98:507–520. https://doi.org/10.1080/00045600802118491

McGuire K, McDonnell J (2007) Stable isotope tracers in watershed hydrology. Blackwell Publishers, Boston

Meng Y, Liu G (2013) Stable isotopic information for hydrological investigation in Hailuogou watershed on the eastern slope of Mount Gongga, China. Environ Earth Sci 69:29–39. https://doi.org/10.1007/s12665-012-1931-5

Meng Y, Liu G (2016) Isotopic characteristics of precipitation, groundwater, and stream water in an alpine region in southwest China. Environ Earth Sci. https://doi.org/10.1007/s12665-016-5697-z

Pfahl S, Sodemann H (2014) What controls deuterium excess in global precipitation? Clim Past 10:771–781. https://doi.org/10.5194/cp-10-771-2014

Ren W, Yao T, Xie S, He Y (2017) Controls on the stable isotopes in precipitation and surface waters across the southeastern Tibetan Plateau. J Hydrol 545:276–287. https://doi.org/10.1016/j.jhydrol.2016.12.034

Shen H, Poulsen CJ (2019) Precipitation $\delta^{18}O$ on the Himalaya-Tibet orogeny and its relationship to surface elevation. Clim Past 15:169–187. https://doi.org/10.5194/cp-15-169-2019

Skrzypek G, Mydłowski A, Dogramaci S, Hedley P, Gibson JJ, Grierson PF (2015) Estimation of evaporative loss based on the stable isotope composition of water using *Hydrocalculator*. J Hydrol 523:781–789. https://doi.org/10.1016/j.jhydrol.2015.02.010

Sundqvist MK, Sanders NJ, Wardle DA (2013) Community and ecosystem responses to elevational gradients: processes, mechanisms, and insights for global change. Annu Rev Ecol Evol Syst 44:261–280. https://doi.org/10.1146/annurev-ecolsys-110512-135750

Tian L et al (2007) Stable isotopic variations in west China: A consideration of moisture sources. J Geophys Res-Atmos. https://doi.org/10.1029/2006jd007718

Tian L, Yao T, Numaguti A, Duan K (2001a) Relation between stable isotope in monsoon precipitation in southern Tibetan Plateau and moisture transport history. Sci China Ser D 44:267–274. https://doi.org/10.1007/bf02911996

Tian L, Yao T, Sun W, Stievenard M, Jouzel J (2001b) Relationship between δD and $\delta^{18}O$ in precipitation on north and south of the Tibetan Plateau and moisture recycling. Sci China Ser D 44:789–796. https://doi.org/10.1007/bf02907091

Wang Y (2016) Study on geoheritage landscape features and formation of Guan'egou Geopark. Chengdu University of Technology, Gansu province, China Sichuan Province **(in Chinese with English abstract)**

Wassenaar LI, Athanasopoulos P, Hendry MJ (2011) Isotope hydrology of precipitation, surface and ground waters in the Okanagan Valley, British Columbia, Canada. J Hydrol 411:37–48. https://doi.org/10.1016/j.jhydrol.2011.09.032

Wen R, Tian L, Weng Y, Liu Z, Zhao Z (2012) The altitude effect of $\delta^{18}O$ in precipitation and river water in the Southern Himalayas. Chinese Sci Bull 57:1693–1698. https://doi.org/10.1007/s11434-012-4992-7

Wu GL, Zhang ZN, Wang D, Shi ZH, Zhu YJ (2014) Interactions of soil water content heterogeneity and species diversity patterns in semi-arid steppes on the Loess Plateau of China. J Hydrol 519:1362–1367. https://doi.org/10.1016/j.jhydrol.2014.09.012

Wu H et al (2019a) Spatial and temporal variability of stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) in surface waters of arid, mountainous Central Asia. Hydrol Process 33:1658–1669. https://doi.org/10.1002/hyp.13429

Wu H, Wu J, Song F, Abuduwaili J, Saparov AS, Chen X, Shen B (2019b) Spatial distribution and controlling factors of surface water stable isotope values ($\delta^{18}O$ and $\delta^{2}H$) across Kazakhstan, Central Asia. Sci Total Environ 678:53–61. https://doi.org/10.1016/j.scitotenv.2019.03.389

Xing B, Liu Z, Liu G, Zhang J (2015) Determination of runoff components using path analysis and isotopic measurements in a glacier-covered alpine catchment (upper Hailuogou Valley) in southwest China. Hydrol Process 29:3065–3073. https://doi.org/10.1002/hyp.10418

Yang K, Ye B, Zhou D, Wu B, Foken T, Qin J, Zhou Z (2011) Response of hydrological cycle to recent climate changes in the Tibetan Plateau. Clim Change 109:517–534. https://doi.org/10.1007/s10584-011-0099-4

Yang X, Xu B, Yang w, Qu D, Lin P, (2009) Study of altitudinal lapse rates of $\delta^{18}O$ in precipitation/river water with seasons on the southeast Tibetan Plateau. Chin Sci Bull 54:2742–2750. https://doi.org/10.1007/s11434-009-0496-5

Yao T et al (2013) A review of climatic controls on $\delta^{18}O$ in precipitation over the Tibetan Plateau: Observations and simulations. Rev Geophy 51:525–548. https://doi.org/10.1002/rog.20023

Yin G, Fan X, Guo J, Yang J (2000) Isotope tracer on water cycle system in Jiuzhaigou, Sichuan. Acta Geograp Sinica 55 **(in Chinese with English abstract)**

Zhang W et al (2010) Using stable isotopes to determine the water sources in alpine ecosystems on the east Qinghai-Tibet plateau, China. Hydrol Process 24:3270–3280. https://doi.org/10.1002/hyp.7754

Zhou S, Nakawo M, Sakai A, Matsuda Y, Duan K, Pu J (2007) Water isotope variations in the snow pack and summer precipitation at July 1 Glacier, Qilian Mountains in northwest China. Chinese Sci Bull 52:2963–2972. https://doi.org/10.1007/s11434-007-0401-z