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Contribution of cryosphere to runoff in the transition zone between the Tibetan Plateau and arid region based on environmental isotopes

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Abstract: As the transition zone between the Tibetan Plateau and the arid region, the Qilian Mountains are important ecological barriers and source regions of inland rivers in northwest China. In recent decades, drastic changes in the cryosphere have had a significant impact on the quantity and formation process of water resources in the Qilian Mountains. In this study, 2164 environmental isotope samples were used to quantify the runoff components of 11 major rivers in the Qilian Mountains and to investigate the influence of cryosphere changes on mountain runoff. The results showed that the mountain runoff mainly comes from the cryosphere belt, which contributes to approximately 82%、71%, and 80%, respectively, in the Hexi inland water system, upper stream of the Yellow River system, and Qinghai inland river system; the remaining amounts are contributed by precipitation in the vegetation belt. The maximum contribution ratio of glacier and snow meltwater to runoff occurred in May, but not in July and August, when the temperature was the highest. The important contribution of supra-permafrost water to runoff gradually increased from May to October and reached approximately 40% in some rivers in October.

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Cryosphere degradation in the Qilian Mountains after 90 years has caused a rapid increase in runoff, a change in the peak runoff time, and an increase in runoff in winter. These changes in hydrological processes bring opportunities and challenges to managing inland river water resources, and various adaptive measures to seek advantages and avoid disadvantages have been proposed. The findings from environmental isotope analysis provide insights into realizing harmony of life, agriculture, industry, and ecological water use.

Key Words: Runoff components; Stable isotope; Cryosphere degradation; Qilian mountains

1. Introduction

Characterizing how watersheds store and release precipitation as streamflow in a given region is the cornerstone of hydrology (Miller et al, 2021). Especially in the current context, freshwater resources around the world are under increasing stress, resulting from a changing climate and growing populations (Florke et al., 2018). Mountains are the principal component of the global water supply because they act as natural reservoirs of fresh water in the form of snow and glaciers. Numerous studies have shown that runoff from glacier discharge provides a valuable resource to downstream populations for domestic, agricultural, and other allied activities (Kriegel et al., 2013). Water shortage and low use efficiency make China thirst, and the loss of glaciers and wetlands in the western plateau will exaggerate this thirst in the future (Wang et al., 2006). Glacierized catchments in mountainous regions are generally headwater catchments, which are of great interest because of their complex runoff-generation processes and their important role in supplying water sources for downstream regions (Immerzeeleta 2010). In many headwater

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catchments, seasonal water availability is strongly dependent on cryospheric processes, and understanding these processes becomes even more relevant in a changing climate (IPCC, 2013). Permafrost in the Qinghai–Tibetan Plateau has experienced significant temperature increases and widespread degradation during the last several decades, and the trend of snow-covered areas has also been decreasing in the past 50 years (Yao et al., 2013). As a result, the runoff process undergoes significant changes in seasonal flow, flood peak discharge, and total runoff (Yang et al,. 2000). Therefore, it is very important to understand the source, processes, and mechanisms of runoff, particularly in seasonally arid mountainous areas, where snowmelt is vital for downstream human activities (Milly and Dunne, 2020) and for managing and sustaining water resources in a changing environment, particularly in mountainous areas of western China. However, runoff generation processes are complex and difficult to quantify, especially before an experimental investigation is conducted (Uhlenbrook et al., 2002)

Environmental tracers are commonly used tools to investigate hydrological processes. Stable isotopes in water (^{2}H and ^{18}O) are important components of natural water bodies and powerful tools for investigating the water cycle and hydrological processes. Although their natural abundance is low, they are highly sensitive to changes in their environment, can indicate the source, migration, and transformation of water, and are an ideal tracer for the water cycle (Gat, 1996; Bowen et al., 2019，Song et al., 2007). The stable isotope ratios of hydrogen and oxygen in water samples can provide essential information about water dynamics within a given watershed (Ruck et al., 2007). For inland river basins with widely distributed glaciers and permafrost areas, stable isotope tracing is particularly useful, as direct, continuous field observation of hydrological processes is extremely difficult

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because of the harsh environment (Cui and Li, 2015; Li et al., 2015). In the past few decades, isotopic tracers such as oxygen and deuterium isotopes have increasingly been utilized in conjunction with geochemical tracers and hydrometric measurements to separate flow pathways and to provide more information about temporal and geographic sources of runoff in temperate, humid, and arid environments (Hooper and Shoemaker, 1986; Li et al., 2016a, b, c). McDonnell et al. (1991) found that stream water in New Zealand was partially supplied by subsurface flow in a humid zone. Mortathi et al. (1997) reported that the average surface runoff and baseflow (pre-event) contributions were 30.3% and 69.7%, respectively, in the Amazon River. This method has been used to estimate the changes in glacier meltwater in many different regions. For example, the contribution of glacier and snow meltwater to runoff in spring was found to be as high as 82% in a cold area in Colorado, USA (Liu et al., 2004). These studies found that glacier changes have a significant impact on the runoff of important rivers in cold regions. Climate warming has also been significant in the cold regions of western China, where the annual average temperature has increased by 0.28°C/10 a during 1961–2016 (Li et al., 2019a), causing the glaciers in the study area to melt rapidly.

The Qilian Mountains are important ecological barriers and environmentally functional areas in Northwest China (Jia, 2012). They are not only the source region of the Hexi inland river system (HIRS), including the Shiyang, Heihe, and Shule River Basins, from southeast to northwest, but are also the source regions of the Qinghai inland river system (QIRS), including the Qinghai and Hala Lake Basins, and the upper stream of the Yellow River system (USYR). In the Qilian mountains, the glacier area was 2017.81 km^2 in 1956, 1761.3 km^2 in 1990, and 1597.1 km^2 in 2010 (Liu et al., 2003; Cao et al., 2010;

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Zhang et al., 2010a, 2010b; Wang et al., 2011; Pan et al., 2012; Sun et al., 2015a). The permafrost area has continuously decreased in the Tibetan Plateau over the past 50 years (Cheng et al., 2012). Drastic changes in the cryosphere are bound to have a significant impact on the quantity and formation process of water resources in the inland rivers of the Qilian Mountains, which are fed by glacial meltwater.

Against the background of climate warming and continuous retreat of the cryosphere, it is urgent that the runoff replenishment amount of the cryosphere and the runoff formation process in the study region are understood as the decision-making basis for the rational development and utilization of water resources in river basins. However, due to the lack of data and the difficulty of observation and sampling in cold regions, previous studies have focused on the statistical analysis of runoff and its associated influencing factors, and there is a lack of in-depth study on the mechanism of the temporal and spatial variations in runoff components from a microscopic point of view, while the quantification of the impacts of cryosphere meltwater on runoff in the Qilian Mountains remains ambiguous. The Danghe, Changma, Taolai, Heihe, Xiying, Nanying, Zamu, Jinqiang, Datong, Huangshui, and Buha Rivers were selected as the research objects in this study. The objectives were to: (a) understand the spatial and temporal differences of stable isotopes in various water bodies in the Qilian Mountains, (b) quantify the runoff components of major rivers using $\delta^{18}O$ and deuterium excess (d-excess) as a proxy in the Qilian Mountains, and (c) determine the impact of cryosphere degradation on water resources in inland river basins. The results of this study are helpful for the study of sources of streamflow and stream water fractions, and provide a more effective understanding of the internal hydrological processes in a depopulated alpine zone under the impacts of climate change.

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2. Materials and methods

2.1 Study region

The Qilian Mountains are located on the northeastern edge of the Tibetan Plateau, and consist of a series of NW trending parallel mountains and valleys, with latitudes of 36°N – 43°N and longitudes of 92°E –107°E (Fig. 1). The average annual temperature in the Qilian Mountains is -5.25 ~ 10.75°C. The average annual precipitation in the Qilian Mountains ranges from 34.23 mm to 493.97 mm and increases gradually from west to east (Lü et al., 2019). Rivers are widely distributed with radial drainage characteristics in the Qilian Mountains, and the Leng Longling Range divides all rivers into internal flow and outflow systems. The outflow rivers mainly include the Huangshui and Datong Rivers, which are located in the USYR. The inner flow is divided into three parts: the Qaidam Basin, Qinghai Lake Basin, and Hexi Corridor Basin.

Among them, the Danghe, Taolai, Heihe, Xiying, Nanying, and Zamu Rivers belong to the HIRS, and the Buha River belongs to the QIRS. The southern rivers of the Qilian Mountains mainly flow into the Qaidam Basin, while the northern rivers flow into the Hexi Corridor (Deng Shaofu, 2013). Generally, the annual distribution of surface runoff is consistent with the precipitation process and high-temperature season in the Qilian Mountains. Runoff and precipitation are concentrated in the warm season, mainly recharged by ice and snowmelt water and groundwater in spring and by precipitation in summer. The annual variation in runoff showed an obvious periodic trend (Wang Jinye,2006). The rivers in the Qilian Mountains are mainly fed by glacial meltwater. The region of water formation is the cryosphere belt, which contains glaciers, snow, and permafrost (Li et al., 2019b). According to the second glacier inventory of China, there are

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2859 glaciers in the Qilian Mountains, with a total area of 1597 km^2, and the total areas of glacier reserve and permafrost are 84.48×10^8 m^3 (Sun et al., 2015a), and 9.39×10^4 km^2 (Zhou et al., 2000), respectively. The inter-annual variation in runoff is small, but there is significant seasonal and daily variation. River runoff in the western and middle sections of the Qilian Mountains has increased significantly since 1980, whereas the eastern section has shown a slightly decreasing trend (Zhang et al., 2018).

2.2. Sample collection and analysis

In addition to river water samples, precipitation, glacier and snow meltwater, super-permafrost water, groundwater, and outlet river water were continuously collected in the Qilian Mountains, at the sampling sites shown in Fig. 1. The details of the samples are as follows:

River water (338). A sampling network of river water was established, including 11 sampling stations in the Qilian Mountains. The Danghe, Xiying, Taolai, Heihe, Nanying, Zamu, and Changma Rivers belong to the HIRS. Three samples were collected every month at the river outlets, and a total of 252 samples were collected from September 2018 to August 2019. The Datong, Huangshui, and Jinqiang Rivers belong to the USYR. Water from the river outlet was collected twice a month, and a total of 62 samples were collected from July 2017 to July 2018 (no samples were collected from the Jinqiang River in January, February, March, and December). Similarly, from August 2020 to August 2021, a total of 24 river water samples were collected from the Buha River in the QIRS.

Precipitation (1310). A total of 1310 groups of precipitation samples have been collected during 2012-2018. For more information, please refer to Gui et al. (2020).

Glacier and snow meltwater (96): The hydrochemical characteristics of glacier and

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snow meltwater in the cryosphere were analyzed. Samples were collected every half a month from May to October. The sampling time was 14:00 every day and the sampling location was in the hydrological section at the end of the glacier. During the sampling period, 84 glacier meltwater samples were collected from the end of Bayi Glacier, Shiyi Glacier, and the source glaciers of the Taolai, Shule, Danghe, Shiyang, and Datong Rivers, and 12 snow meltwater samples were also collected in Buha and Huangshui Rivers.

Supra-permafrost water (108). Supra-permafrost water is the most widely distributed type of groundwater and is mainly stored in the permafrost active layer. To determine the hydrochemical characteristics of supra-permafrost water in the study area, water samples were collected by comprehensive sampling from May to October in 2016 and 2018. The sampling was performed manually. First, a 2 m deep profile of the permafrost active layer was dug at each sampling point. Then, the water samples were immediately filtered through a 0.45 μm Millipore filtration membrane and poured into clean polyethylene bottles. During this period, 108 samples were collected from the Danghe, Changma, Heihe, Taolai, Shiyang, Datong, and Buha Rivers.

Groundwater (312): A total of 240 samples were collected weekly fromfive wells in the Danghe, Changma, Taolai, Heihe, and Shiyang Rivers of the HIRS within one hydrological year. Another 48 samples were collected twice a month in the same way from the Datong and Huangshui Rivers in the USYR. Finally, 24 samples were collected from the Buha River in the QIRS.

Hydrological data: Meteorological data for the Dang, Changma, Taolai, Heihe, Xiying, Nanying, Zamu, Datong, and Jinqiang Rivers were obtained the Hydrology and Water Resources Bureau of Gansu Province (HWRBGS). Runoff data for the Huangshui

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River are from Zhang et al. (2014) and for Buha River are from Liu et al. (2020). The specific information is given below.

2.3 Methods

2.3.1 sample testing

All kinds of water were carried out in the Key Laboratory of Eco-hydrology of Inland River Basin, Chinese Academy of Sciences to analysis of the hydrogen and oxygen stable isotopes. For the analysis stable isotopes of soil water, water was extracted from soil using a cryogenic freezing vacuum extraction system (LI-2000, Beijing Liga United Technology Co., Ltd., China), which can achieve complete extraction with high precision. Then the stable isotopes in the all kinds of water were measured using a liquid water stable isotope analyser (Model DLT-100, Los Gatos Research, Inc., Mountain View, CA, USA). The accuracies of $^{18}O/^{16}O$ and D/H were 0.2‰ and 0.5‰, respectively, which conform to the rule of valid digits for stable isotope analysis. The results were calibrated by Vienna Standard Mean Ocean Water (V-SMOW) and laboratory working standards. The final results were expressed in the form of micro-difference relative to V-SMOW:

$$\delta^{18}O(or\delta D)=\left[\frac{R_{\text{Sample}}}{R_{\text{V-Smow}}}-1\right]\times‰ \quad (1)$$

where R_{Sample} is the precipitation sample and $R_{V\text{-}Smow}$ is the ratio of oxygen or hydrogen stable isotope in VSMOW. The d-excess can be calculated by:

$$\text{d-excess}=\delta D-8\delta^{18}O \quad (2)$$

2.3.2 End-member mixing analysis

Hooper (2003) introduced the end-member mixing analysis (EMMA) using chemical/isotopic compositions in waters. The techniques involve graphical analyses, in

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which chemical and isotopic parameters are used to represent the designated end members. Tracer concentrations are constant in space and time. Essentially, the composition of the water changing can be considered as a result of intersections during its passage through each landscape zone. Tracers can be used to determine both sources and flow paths. The EMMA tracer approach has been a common method for analyzing potential water sources contributing to stream flow (Li et al, 2014a; 2016a). Here in a three end-member mass-balance mixing model is employed to calculate the contribution of up to three water sources in stream water, such as the following:

$$X_S=F_1X_1+F_2X_2+F_3X_3 \quad (3a)$$

$$Y_S=F_1Y_1+F_2Y_2+F_3Y_3 \quad (3b)$$

X and Y represent concentrations of two types of different tracers. In this study, $\delta^{18}O$ and deuterium excess were chosen for comparison. The subscripts represent stream water sample, and 1, 2, and 3 represent water from the respective contribution of three respective source waters (end members) to stream water. The fraction of each end-member is denoted by F. The solutions for F_1, F_2, and F_3 in regards to tracer concentrations in Eq. (3) can be given as:

$$F_1=[(X_3-X_S)/(X_3-X_2)-(Y_3-Y_S)/(Y_3-Y_2)]/[(Y_1-Y_3)/(Y_3-Y_2)-(X_1-X_3)/(X_3-X_2)] \quad (4a)$$

$$F_2=[(X_3-X_S)/(X_3-X_1)-(Y_3-Y_S)/(Y_3-Y_1)]/[(Y_2-Y_3)/(Y_3-Y_1)-(X_2-X_3)/(X_3-X_1)] \quad (4b)$$

$$F_3=1-F_1-F_2 \quad (4c)$$

This method has been used by previous study (Li et al.,2014b; 2015; 2016b). This study also used this method to evaluate the contribution of possible sources to the river water.

3. Results

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3.1 Characteristics of stable isotopes in different waters

3.1.1 Precipitation

The $\delta^{18}O$ of precipitation was characterized by pronounced seasonal variations, with maximum values in summer and minimum values in winter. The monthly average values varied from -21.62‰ to -5.15 ‰, with an annual average of -12.11‰. From January to December, $\delta^{18}O$ showed a trend of first increasing and then decreasing, with the maximum value occurring in June. Owing to the comprehensive influence of the water vapor source, temperature, precipitation, and other factors, the stable isotopes of precipitation fluctuate greatly during the year (Fig. 2a).

The HIRS is located on the northern slope of the Qilian Mountains, and the monthly average $\delta^{18}O$ in precipitation ranged from -21.26‰ to -5.03‰, with an annual average value of -12.21‰ (Fig. 2b). In the USYR and QIRS, located on the southern slope, the range of monthly average $\delta^{18}O$ values was -17.72‰–-3.85‰ and -27.32‰–-5.51‰, respectively, with annual average values of -10.53‰ and -11.57‰, respectively (Fig. 2). Compared with the HIRS and QIRS, the average value of $\delta^{18}O$ in the USYR was more positive. Different water vapor sources, climatic conditions, and topographic conditions resulted in obvious spatial and temporal differences in stable isotopes in precipitation in this study area.

3.1.2 Glacier and snow meltwater

Glacier and snow meltwater were collected from seven basins in the study area from May to October. As shown in Fig. 3, the mean $\delta^{18}O$ in glacier and snow meltwater of the Qilian Mountains was -9.61‰, which is significantly more negative than the corresponding river water. The seasonal fluctuation of glacier and snow meltwater was very small;

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although there were differences among several river systems, they were not significant. During the sampling period, the $\delta^{18}O$ of glacier and snow meltwater in the HIRS varied from -13.07‰ to -7.97‰, with an average value of -9.69‰. The $\delta^{18}O$ values of glacier and snow meltwater in the Danghe River, Changma River, Shiyi Glacier, Bayi Glacier, Taolai River, and Shiyang River were − -10.64‰, -9.31‰, -9.86‰, -9.77‰, -9.29‰, and -9.25‰, respectively. The mean $\delta^{18}O$ values of glacier and snow meltwater increased from west to east. In the USYR, the $\delta^{18}O$ of glacier and snow meltwater in the Datong River was -10.24‰ to -8.06‰, with a mean value of -9.54‰. In general, from May to October, fluctuations in $\delta^{18}O$ were small, and the weak time variation first increased and then decreased, with the maximum value appearing in August and the minimum value in May. In the QIRS, the $\delta^{18}O$ of glacier and snow meltwater in the Buha River ranged from -11.69‰ to -8.26‰, with a mean value of -9.24‰. These $\delta^{18}O$ values in the QIRS were more positive than those in the HIRS and USYR system and fluctuated greatly during the study period.

The $\delta^{18}O$ values of glacier and snow meltwater were relatively stable during the sampling period and did not show any obvious temporal variation. The maximum $\delta^{18}O$ values in the HIRS, USYR system, and QIRS occurred in May, August, and July, respectively, while the minimum values were in June, May, and August, respectively. The time that maximum and minimum values of $\delta^{18}O$ occurred in the three river systems was not consistent, which may be closely related to the start time of glacier and snow melting and storage. The d-excess of glacier and snow meltwater also showed no obvious seasonal characteristics during the sampling period. The d-excess in the HIRS, USYR system, and QIRS ranged from 19.33‰ to 22.06‰, 14.17‰ to 22.90‰, and 11.38‰ to 11.57‰, with mean values of 21.53‰, 17.42%, and 11.47‰, respectively.

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3.1.3 Supra-permafrost water

Supra-permafrost water is groundwater that exists mainly in the permafrost active layer, which is an important part of the runoff in cold regions (Li et al.,2016a). The $\delta^{18}O$ value of supra-permafrost water was significantly more positive than those of glacier and snow meltwater (Fig. 4). This is because, during the study period, the supra-permafrost water was subjected to higher temperatures causing intense evaporation. In the HIRS, the mean $\delta^{18}O$ values in supra-permafrost water were -7.16‰ to -6.49‰, with an average of -6.69‰. The $\delta^{18}O$ of supra-permafrost water in the Heihe River was the most stable, with almost no fluctuation from May to October. The Danghe River showed slight fluctuations, with the maximum value in September. In the Shiyang River Basin, $\delta^{18}O$ values were negative from May to June, positive from July to August, and negative from September to October, whereas in the Changma River they were generally positive, with a maximum of -5.12‰ in June and a minimum of -7.15 ‰ in October. In the USYR system, the $\delta^{18}O$ of supra-permafrost water ranged from -7.61‰ to -6.87‰, with an average value of -7.34‰. Values in the Datong and Huangshui Rivers of the USYR system are quite different, those for the Datong River being relatively positive with an average value of -6.34‰, while the Huangshui River were relatively negative, with an average value of -8.34‰. In the Buha River of the QIRS, $\delta^{18}O$ values were relatively stable, and the weak temporal variation showed peaks in June and September. In conclusion, the $\delta^{18}O$ in the supra-permafrost water of the three river systems was generally positive and did not show obvious temporal variation. This phenomenon can be explained by the following two reasons: First, supra-permafrost water is mainly stored in the active layer of the permafrost, and under the strong evaporation from soil and vegetation, the stable isotope concentration wouldbe unbalanced

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through the influence of dynamic fractionation. Second, the supra-permafrost water is replenished by a mixture of precipitation, snow and ice meltwater, and subsurface ice meltwater, resulting in random fluctuations in stable isotope concentrations. The range of d-excess values for the supra-permafrost water for the corresponding river systems was 10.03‰~17.69‰、13.56‰~15.73‰、11.43‰~14.87‰, respectively，with mean values of 13.36‰, 14.29‰ and 12.93‰, respectively (Fig. 4).

3.1.4 River water

As shown in Fig. 5, the $\delta^{18}O$ of river water in all basins in the study area was relatively stable, which is different from that of precipitation in this area and has significant seasonal variation characteristics. The $\delta^{18}O$ values of different river systems in the Qilian Mountains were relatively stable and did not show obvious seasonal variation, although there were some differences. The range of $\delta^{18}O$ values was -8.75‰–-8.27‰, -8.97‰–8.53‰, -8.15‰–7.26‰, and -9.47‰–7.96‰ for the entire Qilian Mountains, HIRS, USYR system, and QIRS, respectively, with corresponding mean values of -8.49‰, -8.72‰, -7.79‰ and -8.49‰. Although $\delta^{18}O$ value in rivers was relatively stable, there were slight variations from the annual mean value among the different river systems, with USYR > QIRS > HIRS (Fig. 5a).

The maximum monthly mean values of $\delta^{18}O$ in the HIRS, USYR, and QIRS were in September, February, and October, respectively, while the minimum monthly mean values were in May, July, and June, respectively. In the HIRS, the $\delta^{18}O$ of river water in the Shule River in the western segment fluctuated greatly compared with the three rivers in the Shiyang River Basin in the eastern segment. For example, in the Danghe River, in May and October, $\delta^{18}O$ was less than -11‰, while in February, it was more than -9‰, with an average value of -9.97‰, which was generally negative. The $\delta^{18}O$ in the river water of the Heihe River, located in the middle Qilian Mountains, was positive, with an annual average of -7.75‰ and -6.79‰ in April.

In conclusion, because of the long distance from west to east in the HIRS, the $\delta^{18}O$ values of different rivers varied greatly. In terms of average values, the Heihe River Basin in the middle reaches was the greatest, followed by the Shiyang River Basin in the eastern part, while the Shule River Basin in the western part was significantly negative. In the USYR system, except for the Jinqiang River, the river water $\delta^{18}O$ values of the Huangshui and Datong Rivers were relatively positive, with mean values of -7.76‰ and -7.58‰, respectively. The $\delta^{18}O$ values of river water in the Jinqiang River were relatively negative, with large fluctuations. In the QIRS, because of the large extent of uninhabited areas, sampling was conducted only in the Buha River, where the $\delta^{18}O$ ranged from -9.47‰ to -7.96‰, with a mean of -8.59‰. In terms of its weak seasonal variation, the maximum occurred in October and the minimum occurred in June.

The mean d-excess values in the Qilian Mountains, HIRS, USYR system, and QIRS were 13.63‰, 13.78‰, 13.56%, and 20.20%, respectively. According to monthly mean values, USYR < HIRS < QIRS. In HIRS, the d-excess value ranged from 8.52‰ to 16.15‰. Except for the Dang River, the annual variation in the other rivers was small. In the USYR, the d-excess value in the Jinqiang River was more positive than those of the Datong and Huangshui Rivers (Fig. 6).

The differences in stable isotopes in river water reflect differences in recharge sources and recharge processes in different river systems. If river water is only supplied by precipitation, its stable isotope composition should be closer to the stable isotope variation

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of precipitation. However, there is a significant difference between $\delta^{18}O$ in river water and precipitation, which indicates that the potential recharge source of these three river systems is precipitation.

3.1.5 Groundwater

Variations in the stable isotopes in groundwater were highly consistent with those of river water; the annual fluctuation was small, and there was no obvious time variation. The $\delta^{18}O$ of groundwater in the Qilian Mountains ranged from -8.99‰ to -8.50‰, with a mean value of -8.76‰. In the HIRS, USYR system, and QIRS, the $\delta^{18}O$ variation ranges were -9.01‰–8.43‰, -9.37‰–8.43‰, and -9.12‰–7.60‰, respectively, corresponding to mean values of -8.78‰, -8.83‰, and -8.55‰ (Fig. 7). The temporal variations in $\delta^{18}O$ values in river water and groundwater in the study area were highly consistent, which confirms that precipitation and supra-permafrost water may be transformed into groundwater runoff and then into recharge. The $\delta^{18}O$ concentration of groundwater was more negative than that of river water, which indicates that the evaporation effect of groundwater was relatively weak compared with that of river water. On the other hand, the mutual transformation relationship and frequent exchange processes between them were confirmed. In alpine desert zones, sparse vegetation, large soil particles, and high permeability are conducive to the infiltration of precipitation, snow, and ice melt water, which can be converted into groundwater, thus replenishing runoff.

3.2 Relationships of stable isotopes between river water and various water sources

The isotopic relationship between river water and various water sources is shown in Fig.8. The local meteoric water line (LMWL) of the Qilian Mountains was $\delta D = 7.99\delta^{18}O + 14.57$ ($R^2 = 0.96$), and $\delta^{18}O$ was clearly higher in summer and autumn but lower in winter

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and spring (Gui et al., 2020). The glacier and snow meltwaters are distributed in the center of the LMWL and slightly deviate from it, while the supra-permafrost water is mainly distributed below the LMWL, and its value, which is positive is mainly affected by strong evaporation. The stable isotopic compositions of river water and groundwater were close to the LMWL, and their values were between those of precipitation, glacier and snow meltwater, and supra-permafrost water, indicating that river water was fed by all of these sources of water. At the same time, the distribution of river water and groundwater showed a hydraulic connection. The local evaporation lines (LEL) of the Qilian Mountains, HIRS, USYR system, and QIRS were $\delta D = 5.19\delta^{18}O - 8.35$ ($R^2 = 0.55$, $P < 0.01$), $\delta D = 5.96\delta^{18}O - 2.77$ ($R^2 = 0.72$, $P < 0.01$), $\delta D = 5.44\delta^{18}O - 6.37$ ($R^2 = 0.79$, $P < 0.01$) and $\delta D = 3.72\delta^{18}O - 15.67$ ($R^2 = 0.58$, $P < 0.01$). The corresponding $\delta^{18}O$ and δD values at the intersection of the LEL and LWML were (-8.19‰, -50.84‰), (-8.54‰, -53.68), (-8.21‰, -51.04‰), and (-7.08‰, -42.01‰), respectively, which were very close to the corresponding mean values of $\delta^{18}O$ and δD in groundwater (-8.76‰,-52.10‰), (-8.78‰,-52.54‰), (-8.83‰,-53.02‰), and (-8.55‰,-48.07‰). This indicates that various types of water in the study area are converted to groundwater and then resupplied by river water.

3.3 Components of outlet runoff

End-member mixing analysis (EMMA) was used to determine the contribution ratio of different water sources to runoff. The results of the above analysis show that there were significant spatio-temporal variations in d-excess and $\delta^{18}O$ concentrations in the river and its supplementary components; therefore, $\delta^{18}O$ and d-excess were selected as tracers for analysis because this combination provides a reasonable separation of sources. In the three river systems of the Qilian Mountains, Jinqiang River, and Huangshui River in the QIRS,

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there were no glaciers in the upper reaches; therefore, the binary segmentation model was adopted to calculate the supply source (Fig. 9h and 9j). For the remaining rivers, precipitation, supra-permafrost water, and glacier and snow meltwater were taken as three end-members, and the recharge sources were calculated (Fig. 9). The results showed that precipitation was the main recharge source of seven rivers in the HIRS (Fig. 9a-g), and its contribution ratios to the Danghe, Changma, Taolai, Heihe, Xiying, Nanying, and Zamu Rivers was 65%, 51%, 69%, 59%, 75%, 80%, and 79%, respectively. More than half of the runoff in the HIRS was contributed by precipitation; it increased from west to east, and in the Nanying and Zamu Rivers in the eastern part of the Qilian Mountains was as high as 80%. This is consistent with the spatial distribution characteristics of higher precipitation in the east and lower precipitation in the west. In addition to precipitation, supra-permafrost water was an important recharge source for the HIRS. The contribution of supra-permafrost water to Danghe, Changma, Taolai, Heihe, Xiying, Nanying, and Zamu Rivers was approximately 21%, 33%, 20%, 33%, 19%, 15%, and 16%, as the third end-member; the corresponding glacier and snow meltwater contributed approximately 14%, 16%, 11%, 8%, 6%, 5%, and 5% to runoff, respectively. Contrary to the spatial distribution trend of the precipitation contribution, the contribution ratio of glacier and snow meltwater showed a decreasing trend from west to east. This was mainly related to the storage and distribution of glaciers in the Qilian Mountains, in terms of glacier area and ice storage: Shule River Basin > Heihe River Basin > Shiyang River Basin (Sun et al., 2015b).

Compared with the HIRS, the contribution of glacier and snow meltwater to the runoff in the USYR was clearly low, and, among the three rivers, only the Datong River was weakly replenished by glacier and snow meltwater. The contribution ratios of precipitation,

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supra-permafrost, and glacier and snow meltwater to Datong River were 63%, 35%, and 2%, respectively. Jinqiang River was mainly replenished by precipitation and groundwater, which contributed 30% and 70%, respectively, while Huangshui River was mainly replenished by precipitation and supra-permafrost water, which contributed 83% and 17%, respectively. Located in the QIRS, the Buha River was mainly replenished by precipitation, supra-permafrost,and glacier and snow meltwater, with the contributions of the three end-members to the runoff is 58%, 40%, and 2%, respectively.

Studies have shown that runoff in inland river basins in China is mainly derived from precipitation in mountainous areas, supra-permafrost, and glacier and snow meltwater (Kang et al, 2008； Zhou et al., 2000). Li et al. (2016c) determined that the elevation of mountain runoff is approximately 3,500 m, according to the elevation effect of $\delta^{18}O$ in the precipitation of the Qilian Mountains, which is 0.18‰/100 m. These facts show that the water resources of the Qilian Mountains mainly originate from the upper reaches of the mountain area. Because the permafrost boundary is 3600 m in the Qilian Mountains (Zhou et al., 2000) and the altitude at which the river flows from the mountains in the USYR and QIRS is higher, with 3700 m as the boundary, the mountainous area was divided into the cryosphere belt and the vegetation belt. Then EMMA was used to calculate the contributions of the cryosphere and vegetation belts to mountain runoff from the three major water systems in the Qilian Mountains.

For HIRS, the $\delta^{18}O$ values in the precipitation of the cryosphere and vegetation belts were -9.02‰ and -7.32‰, respectively. Calculation using a binary mixed segmentation model showed that the contribution ratio of the cryosphere belt to HIRS reached 82% (consisting of precipitation, glacier and snow meltwater, and supra-permafrost water at

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50%, 9%, and 23%, respectively); the remaining 18% was contributed by precipitation in the vegetation belt below 3600 m.

Similarly, the $\delta^{18}O$ values in the precipitation in the cryosphere and vegetation belts in the USYR were -10.74‰ and -8.42‰, respectively. The contribution ratio of the cryosphere belt was 71% of runoff (consisting of precipitation, glacier and snow meltwater, and supra-permafrost water at 43.5%, 24%, and 3.5%, respectively) and that of the vegetation belt was 29%. In the QIRS, the $\delta^{18}O$ values in the precipitation of the cryosphere and vegetation belts were -12.29‰ and -8.95‰, respectively. Calculation using the binary mixed segmentation model showed that the cryosphere belt to the runoff was 80% (consisting of precipitation, glacier and snow meltwater, and supra-permafrost water at 38%, 2%, and 40%, respectively) and that of the vegetation belt was 20% (Fig. 10, 11).

3.4 Hydrological processes

The runoff process in the Qilian Mountains occurs mainly from May to October and is influenced by glacier and snow meltwater, precipitation, and freezing and thawing processes in different ways in different months Therefore, monthly runoff components can be segmented according to the daily isotope values from May to October (Fig. 12). In May, the temperature and precipitation gradually increases, causing the glacier, snow, and permafrost active layer to melt gradually. Snowmelt runoff increases with increasing temperature and, together with precipitation, replenishes the river. Snow meltwater and supra-permafrost water in the surface layer are blocked by the frozen layer, which directly merges into river recharge runoff and becomes an important part of the spring runoff. This is also the main reason for spring floods in inland rivers. As shown in Fig. 12, the contribution of snow and glacier and snow meltwater to river runoff in all three river

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systems was largest in May. At this time, the contribution of glacier and snow meltwater in the HIRS, USYR system, and QIRS to runoff is approximately 16%, 3%, and 7%, respectively, which is significantly higher than the average level of the entire growing season. As temperatures continue to rise and precipitation continues to increase in June, the snow melts rapidly, but reserves are dwindling. With the thawing of the soil at the top of the permafrost active layer, the contribution of supra-permafrost water to runoff is further enhanced, but precipitation still plays a leading role. At this time, the contribution of precipitation in the HIRS, USYR system, and QIRS to runoff from mountains was 73%, 64%, and 72%, respectively.

In July and August, temperatures and precipitation are at their highest, the melting depth of the active layer of permafrost further increases, and the water absorption is enhanced; thus, the precipitation and surface water can be quickly transformed into groundwater in the active layer of permafrost. In steep terrains, it rapidly replenishes runoff in the form of spring water, whereas in relatively flat terrains, it directly replenishes runoff in the form of groundwater, which becomes an important part of runoff in cold regions. At this time, the contribution of supra-permafrost water to runoff further increases. However, at this time, on the one hand, the snow has completely melted; on the other hand, the massive increase in rainfall has an absolute leading role in runoff, especially in August, when the contribution ratio of precipitation to the Huangshui and Zamu Rivers was as high as 90%. Although the glacier and snow meltwater flows remained unchanged, the total flow at this time was larger than that in May and June, resulting in a lower contribution ratio of glacier melt water.

From September to October, the temperature and precipitation began to drop, and the saturated active layer of permafrost began to release water; the contribution of supra-permafrost water to runoff was at its highest level in a year, especially in October, with more than half of the runoff in many rivers coming from supra-permafrost water, including Changma River (57%), Heihe River (59%), Datong River (57%), and Buha River (65%) (Fig. 12). However, the contribution of glacier and snow meltwater remained high because of the significant decrease in overall runoff and the relative decrease in precipitation. In conclusion, from May to October, the runoff of the Qilian Mountain is dominated by precipitation, and it plays an absolutely dominant role from July to August. However, with the thickening of the permafrost active layer, the contribution ratio of the permafrost active layer to runoff from May to October increases. The contribution ratio of glacier and snow meltwater to runoff in the Qilian Mountains is relatively low overall, and the highest valueoccurs in May, whereas the contribution ratio is relatively low in July-August when the temperature is relatively high.

From the above analysis, it can be seen that precipitation has an absolute replenishment effect on rivers in the Qilian Mountains. In some rivers, precipitation contributed more than 80% of the runoff. Except for the Jinqiang River, which mainly relies on groundwater, more than half of the recharge sources of the other rivers are precipitation. In the HIRS, the contribution of precipitation to runoff increased from west to east. In Shule River in the western section of the Qilian Mountains, the contribution of precipitation to runoff was between 50% and 65%, in the Heihe River Basin, located in the middle of the Qilian Mountains, the contribution was approximately 60%-70%, and at the Shiyang River in the eastern part of the Qilian Mountains, it was approximately 75%-80%. This regional difference was mainly caused by spatial distribution differences in

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precipitation. The spatial distribution of precipitation in the Qilian Mountains gradually increases from west to east. The contribution of precipitation to runoff was slightly lower in the USYR system and QIRS than the HIRS.

4. Discussion

4.1 Contribution of the cryosphere to runoff under changing environments

4.1.1 Contributions of glacier and snow meltwater to runoff

Glacier and snow meltwater are an important part of runoff in alpine mountains in western China. Different types and sizes of glaciers have different sensitivities to climate change that lead to significant differences in their production and confluence processes. In the Bai Shui River in the Yulong Mountains, the two-component mixing model showed that an average of 53.4% of runoff came from glacier and snow meltwater during the wet season (Pu et al., 2013). Maurya et al. (2011) found that the average contribution of meltwater to runoff is 32% in typical glacial basins on the southern slope of the Himalayas, while in the western Himalayan region, the glacier and snow meltwater contribution has been estimated to be 35% to 50% of the river discharge (Laskar et al., 2018). The results suggested that the fraction of glacier and snow meltwater input over the total stream flow ranged from 84.50 to 86.52% in Hailuogou watershed on the eastern slope of Mount Gongga, China (Meng et al.,2013). In the Hengduan Mountains, hydrograph separation analysis showed that the contribution to runoff from glacier and snow meltwater varied from 63.8% to 92.6% (Liu et al., 2008). The contribution of glacial melt to the annual runoff varied greatly among the basins, with approximately 22.3%, 25.2%, 34.6%, and 79% for the source regions of the Mekong, Salween, Brahmaputra, and Indus, respectively （Zhang et al., 2013）. In the source regions of the Yangtze River, meltwater accounted

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for 23% of river water at the TTH station from June 2016 to May 2018, while the corresponding value at the ZMD station was 17% (Li et al, 2020). In the USYR, the contribution of snow and ice meltwater to runoff was approximately 23%. In the Kunlun Mountains, the average contribution of meltwater to runoff in the Tizinafu River was 43% (Fan et al., 2015), and in Urumqi River, it was 14.7%, while in Kumalak River, the contribution was more than 57% (Kong et al., 2012; Sun et al.,2015c) (Fig. 13).

The contribution of glacier meltwater to mountain runoff showed significant spatial differences. As solid reservoirs, glacier retreat will inevitably lead to a reduction in total water resources. Glacial meltwater and its contribution to runoff in cold basins is controlled by the number, size, area ratio, and storage capacity of glaciers in the basin. Glacier meltwater runoff increases when the glacier is degraded and then tends to decrease as the glacier area decreases (Chen et al., 2012). During 1960-2019, the Qilian Mountains showed an overall warming trend with an average annual temperature rise of 0.319°C/a (Ye et al., 2022). Under the influence of global warming, glaciers have become shorter, narrower, and thinner, and statistical results showed that the glacier area of the Qilian Mountains in 1987, 1991, 1997, 2001, 2007, 2013, and 2018 was 2080.39 km^2, 1939.12 km^2, 1805.65 km^2, 1691.13 km^2, 1619.26 km^2, 1531.21 km^2, and 1,442.09 km^2, respectively. During 1987-2018, the glacier area was in continuous retreat, at an average annual rate of 1.34% during 1987 - 2001 and 0.87% during 2001 - 2018 (Wang et al., 2020). The massive retreat of glaciers will inevitably have a large impact on glacial meltwater runoff.

4.1.2 Contribution of permafrost to runoff

In cold watersheds, winter precipitation is solid and cannot directly recharge rivers, so winter runoff mainly comes from groundwater. In the long term, the active layer of

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permafrost is also a solid water source, and permafrost degradation will lead to thickening of its active layer, which in turn will cause an increase in the permafrost water storage capacity and groundwater volume, ultimately causing changes in the hydrological processes and seasonal structure of runoff in cold regions. Permafrost is widely distributed in the Qilian Mountains, which are mainly characterized by steep topography, sparse vegetation, and cold climate, and it plays an important role in the exchange of surface and groundwater within the basin as well as in the intra-annual distribution (Cheng and Wu,2007; Li et a, 2014a). On the one hand, the increased depth of the active layer of permafrost reduces the depth of the water barrier, thereby reducing direct runoff, and on the other hand, as the active layer deepens, the frozen water stored in the active layer will be released, thereby recharging runoff. It can be seen that the effect of temperature on runoff is a complex interaction of various factors (Ding et al, 1999).

The spatial and temporal distributions and hydrothermal characteristics of different types of permafrost differ to some extent, which leads to significant differences in hydrological processes. The above analysis confirms that supra-permafrost water is also an important part of the runoff from the Qilian Mountains. In some months, its contribution to runoff from the mountains can reach more than 60%. The contribution of supra-permafrost water to runoff from mountains shows obvious spatiotemporal characteristics. In terms of time, the contribution ratio gradually increases from May to October, and the largest contribution ratio appears in October. In terms of spatial distribution characteristics, the contribution is significantly higher in the Datong River of the USYR system and the Buha River of the QIRS than in the HIRS. This is mainly related to the spatial distribution and thickness of the permafrost. In the Qilian Mountains, the average contribution of supra-

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permafrost water to runoff from May to October is 10%-40%, while in the source region of the Yangtze River in China, due to the widespread distribution of permafrost, the contribution is generally over 40% (Li et al.,2020).

4.2 Hydrological effects of cryospheric change

4.2.1 Runoff changes

Numerous studies have shown that under global warming, glacier degradation and precipitation have continued to increase in the study area, resulting in a significant increase in runoff in the Qilian Mountains since 1990 (Li et al., 2019a, b; Cao et al.,2010; Bie et al., 2013). Therefore, the runoff variation after 1990 in the study area was analyzed. As shown in Fig. 14, from 1990 to 2020, the seven rivers in the HIRS all showed an increasing trend. The increasing rates of runoff in the Danghe, Changma, Taolai, Heihe, Xiying, Nanying, and Zamu Rivers were 0.16×10^8 m^3/10a, 2.7×10^8 m^3/10a, 0.48×10^8 m^3/10a, 2.6×10^8 m^3/10a, 0.36×10^8 m^3/10a, 0.04×10^8 m^3/10a, and 0.01×10^8 m^3/10a, respectively. Accordingly, the peak runoff of the seven rivers appeared in 2019 (5.057×10^8 m^3), 2017 (17.43×10^8 m^3), 2018 (7.82×10^8 m^3), 2017 (23.31×10^8 m^3), 2019 (4.416×10^8 m^3), 1993 (1.738×10^8 m^3), and 2003 (3.542×10^8 m^3), respectively (Fig. 14).

In the USYR system, the runoff of Datong and Huangshui Rivers still showed an increasing trend, with rates of 1.3×10^8 m^3/10a and 1.55×10^8 m^3/10a, respectively. The runoff of the Jinqiang River showed a decreasing trend, but the speed was very slow, at only -0.08×10^8 m^3/10a. In summary, after 1990, runoff from the Qilian Mountains generally showed an increasing trend, and similar studies have shown that global warming has increased runoff from rivers that are heavily affected by glacier recharge. Based on annual runoff data from 1951 to 2000, the results show that the runoff of most rivers in

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western China has been increasing (Ye et al., 2006), especially since 1980. The runoff from mountains in Xinjiang has increased significantly, with a maximum increase of 40% (Ding et al., 2020).

4.2.2 Seasonal structure of runoff

The seasonal patterns of runoff have also changed over the past 30 years. For example, the time of maximum monthly runoff in some rivers is changing. As shown in Fig. 15, except for the Danghe and Changma Rivers, the runoff peaks of the other five rivers have all changed in the HIRS. From 1990 to 2020, the time of peak runoff in the Heihe River was delayed from July to August, but in the other six rivers, it advanced from August to July. This was closely related to the mass melting of the glaciers. Glacier meltwater runoff is mainly influenced by two factors: temperature and the size of the glacier's reserves and area. In the context of global warming, the climate of northwest China was warm and dry from the end of the Little Ice Age to the 1980s and began to change to warm and humid around 1990 (Shi et al., 2003). The results showed that the warming of the annual mean temperature in the Qilian Mountains from 1991 to 2016 was twice as much as that in 1961-1990, making the ablation period in the Qilian Mountains longer (Li et al.,2019b). This caused the glacier snowpack to start melting earlier and combine with heavy precipitation to form a flood season. Regardless of whether the peak runoff was advanced or retarded, it was still concentrated in July and August in the HIRS. The peak runoff of the Jinqiang River in the USYR moved from August to September (Fig. 15).

4.2.3 Winter runoff increases

Global warming has caused a temperature rise and active layer thickening of the permafrost in the Qinghai-Tibet Plateau of China (Cheng et al., 2007). Monitoring results

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show that the permafrost has been continuously degraded in the past few decades, and statistical model estimations show that the thickness of the active layer along the Qinghai-Tibet Highway has increased significantly from 1981 to 2018, with an average change rate of 19.5 cm/10 a, and much of the underground ice that had been trapped near the upper boundary of the permafrost has melted (Zhao et al, 2010; Li et al.,2012). The distribution of permafrost in Qilian Mountains in the 1960s, 1970s, 1980s, 1990s, the first decade of the 21st century, and 2010-2015 were 0.61 × 10^4 km^2, 0.58 × 104 km^2, 0.57 × 10^4 km^2, 0.50 × 10^4 km^2, 0.42 × 10^4 km^2, and 0.43 × 10^4 km^2, respectively (Chen et al., 2019). Permafrost degradation increases the infiltration rate of the soil, resulting in the weakening or even loss of the water barrier effect of the permafrost layer. In summer, an increase in the depth of permafrost thaw increases the recharge of groundwater from precipitation, while some underground ice melts and the area of the thaw zone expands, thus increasing the recharge of winter runoff (Clark et al.,2001; Niu et al,2011).

The winter runoff (total runoff in January, February, and December) of some rivers in the Qilian Mountains increased after 1990. For example, the winter runoff of the Changma River in the HIRS was 0.759 × 10^8 m^3 in 1990-2000, 1.175 × 10^8 m^3 in 2001-2010, and 1.250 × 10^8 m^3 in 2011-2020, representing an increase of approximately 25%. The winter runoff of the Heihe River was 1.114 × $10^8$$m^3$ in 1990-2000, 1.225 × 10^8 m^3 in 2001-2010 and 1.320 × 10^8 m^3 in 2011-2020, representing an increase of approximately 18.5%. Similarly, winter runoff increased by approximately 6% and 57% in the Nanying and Zamu Rivers, respectively. A similar situation occurred in the USYR (Fig. 15). The winter runoff of the Datong River was 1.432 × 10^8 m^3 in 1990-2000, 1.629 × 10^8 m^3 in 2001-2010, and 2.280 × 10^8 m^3 in 2011-2020, representing an increase of approximately 59%. This is

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mainly because permafrost degradation has led to further weakening of the permafrost water barrier, thereby changing the groundwater reservoir storage capacity and drainage paths. At the same time, glacier melt hasaccelerated, resulting in more glacier meltwater and rainfall mixing to recharge groundwater and subsequent monthly runoff in the form of baseflow (Chen et al.,2019). Similar results have been reported for other cold regions of the world. For example, analysis and simulation of runoff change showed that, owing to the decline of permafrost and a change in the thawing process, the winter runoff in European parts of Russia has increased significantly by as much as 50%-120% (Kalyuzhnyi et al.,2012). In a typical basin of the Northern Slope of the Himalayas during the cold period (from November to March of the following year), the runoff increased by different amounts, especially in January, and increased by 67% in the last 10 years compared with the previous 10 years (Zhang et al., 2006) Studies on rivers in the Qinghai-Tibet Plateau, Tianshan Mountains, northeast China, and other regions of China have found that permafrost degradation leads to increased winter runoff, which is consistent with the trend of frozen soil degradation over time（Huang et al,2008; Liu et al,2006; Gong et al,2006; Liu et al,2003）

4.3 Implications for water resources management

Water resources are a key factor limiting the development of the arid zone in northwest China. In these regions, water resources mainly come from the surrounding mountains; therefore, changes in mountain runoff will directly affect socioeconomic activities (Ye et al., 2008). According to the above study, 82%, 71%, and 80% of the runoff in the HIRS, USYR system, and QIRS come from the cryosphere belt above 3600/3700 m altitude in the Qilian Mountains. Kang et al. (2008) also confirmed that the contribution ratio of the

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cryosphere belt to mountain runoff in the HIRS was 83%, based on water balance.

These facts indicate that the water resource security of inland river basins in China is highly dependent on the stability of the cryosphere belt. The severe retreat of the cryosphere after 90 years has changed the characteristics of runoff, such as a rapid increase in volume, a change in the peak time, and an increase during winter. More seriously, as the glacier shrinks and its area decreases, the amount of glacial meltwater is bound to decrease at some point in the future, which is called the inflection point of the glacial meltwater increase to decrease, also known as the peak of glacial meltwater (Ding et al，2020). These changes will pose challenges to water security in the future. Model predictions also indicate future glacial meltwater reductions of approximately 34%, 62%, and 74% by the end of the 21st century under the RCP2.6 (low), RCP4.5 (medium) and RCP8.5 (high) discharge scenarios (Zhang et al., 2012b; Zhao et al., 2019). Under such a changing background of water resources, Gansu and Qinghai provinces, which depend on the Qilian Mountains for water supply, will also actively adjust their water-use strategies. From 2010 to 2019, the total utilization of water resources in these provinces showed a downward trend. Among them, the agricultural irrigation and industrial water consumption showed a downward trend, while the water consumption for forestry, husbandry, fishery, livestock, comprehensive living, and ecological environment showed an upward trend. The structure of water use in Gansu and Qinghai is still dominated by agricultural water, which accounts for more than 70% of the total water consumption, whereas ecological water use remains less than 10％ (Hou et al., 2021).

In conclusion, runoff from the Qilian Mountains has shown a pronounced increasing trend in recent decades, and the runoff composition has changed to some extent.

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However, it is predicted that the contribution of meltwater to runoff will decrease significantly in the future as glaciers melt substantially. This will lead to reduced runoff in basins where glacial meltwater contributes more to runoff.

Changes in runoff and its composition have resulted in many opportunities. For example, increased runoff means that there are more water resources to use and in winter it means that the uneven distribution of runoff during the year can be effectively alleviated. More importantly, it provides good conditions for ecological restoration and protection in arid areas. However, sudden increases in runoff and changes in runoff peaks indicate an increased risk of flooding. At the same time, the increase in runoff in winter does not match the main period of use for local production and living, and the utilization efficiency of this part of the water resource is not high. More importantly, an increase in runoff may not be sustainable. In the future, with the continuous decrease in glacier area and numbers, the amount of runoff from glacier and snow meltwater will decrease, which is likely to lead to a decrease in runoff from mountains, bringing great loss to local economic and social development. Based on the current situation of water resources, the following suggestions are proposed (Fig. 16):

(1) Strengthen the capacity for water storage and release by designing water supply and flood control projects. Because of the restrictions on economic and social conditions, development ideas, and water resource conditions at that time, water conservancy projects such as reservoirs built in the early years have been unable to some extent to meet and cope with the current situation of increasing mountain runoff. Therefore, it is necessary to continually improve regional water supply and flood control capacity. On the one hand, it is necessary to consider storing more water for use in the dry season, and on the other hand,

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it is necessary to strengthen the awareness and ability to cope with flood disasters and flexibly respond to changes in water resources.

(2) Redistribute water resources over time according to actual water use. In the oasis areas that depend on the water resources of the Qilian Mountains, the water use structure is mainly agricultural; however, agricultural activities have relatively fixed amounts and times, and their requirements often cannot completely adapt to the situation of natural water supply, especially in the current context of increased winter runoff. On the one hand, the increased runoff in winter can be stored for use in the dry season through water conservancy projects and other measures. On the other hand, agricultural irrigation methods can be adjusted appropriately, such as replacing winter irrigation with spring irrigation.

(3) Strengthen regional communication and cooperation to reallocate water resources. Although the runoff from mountains has generally shown an increasing trend in recent decades in the study area, this is not uniform in space, and some regions even show negative growth, which leads to a more uneven distribution of water resources in space. To better adapt to this situation, each region should build and improve the inter-basin water transfer project according to the actual situation, adjusting the remaining water resources efficiently to realize the optimal allocation of water resources.

(4) Accelerate the reform of water-saving agriculture and actively address the impact of glacier and snow meltwater on agriculture. It is predicted that with the continuous decrease in glacier reserves, the contribution from glacier and snow meltwater to runoff from mountains will decrease in the future, which will significantly reduce runoff where glacier and snow meltwater is the main recharge source. To deal with the impact of water resource reduction on agriculture, on the one hand, we should vigorously promote water-

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saving irrigation; on the other hand, we should promote drought-resistant tillage and cultivation methods. By applying various measures to seek advantages and avoid disadvantages, the harmony of life, agriculture, industry, and ecological water use can be realized.

5. Conclusions

Based on the isotopic data of 1310 precipitation, 338 river water, 96 glacier and snow meltwater, 108 supra-permafrost water, and 312 groundwater samples, the present study quantified the runoff components of 11 major rivers in the Qilian Mountains and investigated the influence of cryosphere changes on runoff from mountains. It was found that the stable isotopes of various water bodies in the Qilian Mountains varied significantly in time and space. The stable isotope of precipitation was characterized by pronounced seasonal variations of -12.11‰. The stable isotopes of river water and groundwater in the study area were relatively invariable, unlike that of precipitation, which showed significant seasonal variation. The annual mean values of $\delta^{18}O$ of river and groundwater in the Qilian Mountains were -8.49‰ and -8.76‰, respectively. while for glacier and snow meltwater, it was -9.61‰, which is significantly negative compared with that of river water. Because of the effects of evaporation, the $\delta^{18}O$ value of supra-permafrost water was significantly more positive than that of glacier and snow meltwater.

The stable isotope relationships of various waters showed that the river water was fed by precipitation, glacier and snow meltwater, and supra-permafrost water. EMMA was used to determine the contribution ratios of different water bodies to runoff. The calculations showed that precipitation was the main recharge source of seven rivers in the HIRS, the contribution ratios to Danghe, Changma, Qiaolai, Heihe, Xiying, Nanying, and Zamu

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Rivers being 65%, 51%, 69%, 59%, 75%, 80%, and 79%, respectively. Supra-permafrost water was also an important recharge source for the HIRS. The contribution of supra-permafrost water to Dang, Changma, Taolai, Heihe, Xiying, Nanying, and Zamu Rivers was approximately 21%, 33%, 20%, 33%, 19%, 15%, and 16%, respectively. As the third end-member, the corresponding glacier and snow meltwater contributed approximately 14%, 16%, 11%, 8%, 6%, 5%, and 5% to runoff, respectively. In the USYR system, the contribution of glacier and snow meltwater to the runoff was clearly low, the contribution ratios of precipitation, supra-permafrost, and glacier and snow meltwater to Datong River being 63%, 35%, and 2%, respectively. Jinqiang River was mainly replenished by precipitation and groundwater, which contributed 30% and 70%, respectively, while Huangshui River was mainly replenished by precipitation and supra-permafrost water, which contributed 83% and 17%, respectively. Located in the QIRS, the Buha River was mainly replenished by precipitation, supra-permafrost, and glacier and snow meltwater, with the contributions of these three end-members to the runoff being 58%, 40%, and 2%, respectively.

Runoff in the inland rivers of the Qilian Mountains is mainly derived from the cryosphere belt. Calculations using a binary mixed segmentation model showed that the contribution ratios of the cryosphere belt to mountain runoff in the HIRS, USYR system, and QIRS were 82%, 71%, and 80%, respectively. Cryospheric changes have changed the hydrological processes in the Qilian Mountains. After the 1990s, the runoff from the Qilian Mountains generally increased rapidly, the peak time of runoff changed, and runoff showed an increasing trend in winter. These changes in hydrological processes provide both opportunities and challenges, and requires various measures to exploit advantages and avoid disadvantages so as to achieve harmony in ecological, living, and production water use.

Code/Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study. We will not share our data until all relevant results are completed.

Author Contributions

Gui Juan led the write-up of the manuscript with significant contribution. Zongxing Li developed the research and designed the experiments. Qi Feng collected the water samples and analysed the data. All authors discussed the results and contributed to the preparation of the manuscript.

Competing interests

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

References:

Bie Q, Qiang W, Wang C, et al, 2013.Monitoring Glacier Variation in the Upper Reaches of the Heihe River Based on Remote Sensing in 1960-2010. Journal of Glaciology and Geocryology, 35(3):574-582 (In Chinese).

Bowen, G. J., Cai, Z., Fiorella, R. P., and Putman, A. L., 2019. Isotopes in the water cycle: regional-to global-scale patterns and applications, Annu. Rev. Earth Planet. Sci., 47, 453–479.

Cao, B., Pan, B.T., Gao, H.S., et al, 2010. Glacier variation in the lenglongling range of eastern Qilian mountains from 1972 to 2007. J. Glaciol. Geocryol. 32 (2), 242–248 (In Chinese).

Chen Rengsheng, Zhang Shiqiang, Yang yong et al,2019. Effects of cryospheric changes on runoff in cold regions of western China. Science Press.

Chen Rensheng, Qing Wenwu, 2012. Liu Sshiyin, et al. The relationship between runoff and ground temperature in glacierized catchments in China.Environmental Earth Science, 65: 681-687． . (In Chinese)

Cheng G, Wu T. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. J Geophys Res, 2007, 112: F02S03.

Cheng, G.D., Wu, T.H., 2007. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet plateau. J. Geophys. Res. 112 (F_2), 93–104

Cheng, W.M., Zhao, S.M., Zhou, C.H., et al, 2012. Simulation of the decadal permafrost distribution on the Qinghai-Tibet Plateau (China) over the past 50 years. Permafr. Periglac. Process, 23 (4), 292–300.

Clark ID, Lauriol B, Harwood L, et al, 2001.Groundwater contributions to discharge in a permafrost setting, Big Fish River, NWT, Canada. Arctic Antarctic and Alpine Research, 33(1):62-69

Cui, B.L., Li, X.Y., 2015. Runoff processes in the Qinghai Lake Basin, Northeast Qinghai-Tibet Plateau, China. Insights from stable isotope and hydrochemistry, Quarter, Inter,pp. 1–10

Deng Shaofu, 2013. Impacts of climate change on vegetation in Qilian mountains from 2000 to 2011. Lanzhou university. (In Chinese).

Ding Yongjian, Zhang Shiqiang, 2020. Chen Rensheng. Cryospheric Hydrology: Decode the Largest Freshwater Reservoir on Earth. Bulletin of Chinese Academy of Sciences,(35) 4：414-424 (In Chinese).

Ding Yongjian，Ye Baisheng，Liu Shiying 1999. Effect of Climatic Factors on Streamflow in the Alpine Catchment of the Qilian Mountains. Acta Geography sinica，54(5), 0375-5444.

Fan YT, Chen YN, Li XG, et al, 2015. Characteristics of water isotopes and ice-snowmelt quantification in the Tizinafu River, north Kunlun Mountains, Central Asia. Quaternary International. 380:116-122.

Florke, M., Schneider, C., McDonald, R.I., 2018. Water competition between cities and agriculture driven by climate change and urban growth. Nat. Sustainability 1 (1), 51–58.

Gat, J. R, 1996. Oxygen and hydrogen isotopes in the hydrologic cycle, Annu. Rev. Earth Pl. Sc., 24, 225–262,.24.1.225.

Gong Tongliang, Liu Changming, Liu Jingshi, 2006. Hydrological response of Lhasa River to climate change and permafrost degradation in Xizang．Acta Geographica Sinica,

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

61(5): 519-526 (In Chinese).

Gui Juan, Li Zongxing, Feng Qi, et al,2020. Environmental effect and spatiotemporal pattern of stable isotopes in precipitation on the transition zone between the Tibetan Plateau and arid region. Science of the Total Environment,141559.

Hooper RP, Shoemaker CA. 1986. A comparison of chemical and sotopic hydrograph separation. Water Resources Research 22(10):1444–1454.

Hooper, R. P., 2003. Diagnostic tools for mixing models of stream water chemistry, Water Resour. Res., 39, 1055

Hou Yuanbing，Li Changchun，Nie Yan, et al,2021. Analysis on decoupling effect and driving factors between water resources utilization and economic growth in Gansu Province. Water Resources and Hydropower Engineering, 1-15

Huang Yuying，Liu Jingshi，Shang Sichen，et al., 2008. Study on monthly runoff volume in winter，frozen earth and climate change in the Keriya River Basin in the Kunlun Mountains. rid Zone Research, 5(2):174-178 (in Chinese)

Immerzeel, W. W., Van Beek, L. P., and Bierkens, M. F. 2010. Climate change will affect the Asian water towers, Science, 328, 1382–1385

IPCC: Summary for Policymakers. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, United Kindom and New York, NY, USA, 2013.

Jia W, 2012. Temporal and Spatial Changes of Precipitation in Qilian Mountains and Hexi Corridor during 1960-2009. Acta Geographica Sinica, 67(5): 631-644. (In Chinese)

Kalyuzhnyi I L, Lavrov S A, 2012. Basic physical processes and regularities of winter and spring river runoff formation under climate warming conditions. Russian Meteorology

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

and Hydrology, 37(1): 47-56.

Kang, E.S., Chen, R.S., Zhang, Z.H., et al., 2008. Study on mountainous hydrology and ecology in inland basins of China. Adv. Earth Sci. 23, 675–681 (In Chinese).

Kong YL, Pang ZH, 2012. Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge. Journal of Hydrology,434:121-129.

Kriegel, D., Mayer, C., Hagg, W., et al., 2013. Changes in glacierisation, climate and runoffin the second half of the 20th century in the Naryn basin, Central Asia. Glob. Planet. Change 110, 51–61.

Laskar AH, Bhattacharya SK, Rao DK, et al,2018. Seasonal variation in stable isotope compositions of waters from a Himalayan river: Estimation of glacier melt contribution. Hydrological Processes,32(26):3866-3880.

Li R, Zhao L, Ding Y J, et al, 2012. Temporal and spatial variations of the active layer along the Qinghai-Tibet highway in a permafrost region. Chin Sci Bull, 57: 4609−4616. (In Chinese)

Li Zongxing, Feng Qi, Li Jianguo et al, 2015. Environmental significance and hydrochemical processes at a cold alpine basin in the Qilian Mountains. Environmental Earth Sciences, 73: 4043-4052.

Li Zongxing, Feng Qi, Liu Wei et al, 2014a. Study on the Contribution from Cryosphere to Runoff in the Cold Alpine Basin: A Case Study of Hulugou River Basin in the Qilian Mountains. Global and Planetary Change, 122 (2014) 345-361.

Li Zongxing, Feng Qi, Liu Wei, Wang Tingting, et al, 2014b**.** Study on the contribution from cryosphere to runoff in the cold alpine basin: a case study of Hulugou river basin in the Qilian Mountains. Global and Planetary Change, 122: 345-361.

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

Li Zongxing, Feng Qi, Q J Wang, et al, 2016c.Contribution from frozen soil meltwater to runoff in an in-land river basin under water scarcity by isotopic tracing in northwestern China. Global and Planetary Change, 136 (2016), 41-51.

Li Zongxing, Feng Qi, Wang Yamin, et al, 2016a. The effect of sub-cloud evaporation on the $\delta^{18}O$ of precipitation in Qilian Mountains and Hexi corridor, China. Sciences in Cold and Arid region, 8(05):378-387.

Li Zongxing, Feng Qi, Yong Song, et al,2016b. Stable isotope composition of precipitation in the south and north slopes of Wushaoling Mountain, northwestern China. Atmospheric Research. 182 (2016) ,87-10.

Li Zongxing, Gui Juan, Wang Xufeng, et al, 2019b. Water resources in inland regions of central Asia: Evidence from stable isotope tracing. Journal of Hydrology, 570: 1-16.

Li Zongxing, Li Zongjie, Feng Qi, et al,2020. Runoff dominated by supra-permafrost water in the source region of the Yangtze river using environmental isotopes. Journal of Hydrology, 582, 124506: 1-20.

Li, Zongxing, Qi, Feng, Li, Zongjie, et al., 2019a. Climate background, fact and hydrological effect of multiphase water transformation in cold regions of the Western China: a review. Earth Sci. Rev. 190, 33–57.

Liu FJ, Williams MW, Caine N, 2004. Source waters and flow paths in an alpine catchment, Colorado Front Range, United States. Water Resources Research,40(9).

Liu J, Hayakawab N, Lub M， et al, 2003. Hydrological and geocryological response of winter streamflow to climate warming in North east China. Cold Regions Science and Technology,37: 15-2

Liu Jingshi, WeiWenshou, Huang Yuying, et al., 2006. Hydrological response of

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

winter streamflow to climate change and permafrost degradation in Manas Watershed，Tianshan Mountains. Journal of Glaciology and Geocryology. 28(5):656-662． (in Chinese)

Liu Xiaoyuan, LiuYang, Wang Fang, 2020. An Analysis of Runoff Evolution Law in Qinghai Lake Basin in the Past 60 Years. China's rural water and hydropower, (11): 1-13. (In Chinese)

Liu YH, Fan NJ, An SQ, et al,2008. Characteristics of water isotopes and hydrograph separation during the wet season in the Heishui River, China. Journal of Hydrology, 353(3-4):314-321.

Liu, S.Y., Sun, W.X., Shen, Y.P., et al, 2003. Glacier changes since the little ice age maximum in the western qilian Shan, Northwest China, and consequences of glacier runoff for water supply. J. Glaciol. 49 (164), 117–124

Lü Yuemin, Li Zongxing, Feng Qi, et al, 2019. Analysis of extreme temperature changes in Qilian Mountains in the past 60 years. Plateau Meteorology, 38(5): 959-970. (In Chinese)

Maurya, A.S., Shah, M., Deshpande, R.D., Bhardwaj, R.M., Prasad, A., Gupta, S.K., 2011. Hydrograph separation and precipitation source identification using stable water

McDonnell, J.J., Stewart, M.K., Owens, I.F.,1991. Effect of catchment-scale subsurface mixing on stream isotopic response. Water Resource Research 27, 3065–3073.

Meng YC, Liu GD, 2013. Stable isotopic information for hydrological investigation in Hailuogou watershed on the eastern slope of Mount Gongga, China. Environmental Earth Sciences,69(1):29-39.

Miller SA, Mercer JJ, Lyon SW, et al. 2021. Stable isotopes of water and specific conductance reveal complimentary information on streamflow generation in snowmelt-

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

dominated, seasonally arid watersheds. Journal of Hydrology, 596.

Milly, P.C.D., Dunne, K.A., 2020. Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. Science (80-.) 367, 1252–1255.

Mortathi, J., Moraes, J.M., Rodrigues, J.C., Victoria, R.L., Martinelli, L.A., 1997. Hydrograph separation of the Amazon River using ^{18}O as an isotopic tracer. Scientia Agricola 54 (3), 167–173.

Niu Li, Ye Baishneg, Li Jing et al.,2011. Effects of permafrost degradation on hydrological processes in typical basins in northwest China. Science in China: Earth Sciences, 41(1) 85-92.

Pan, B., Cao, B., Wang, J., Zhang, G., Zhang, C., Hu, Z., et al., 2012. Glacier variations in response to climate change from 1972 to 2007 in the western lenglongling mountains, northeastern tibetan plateau. J. Glaciol. 58 (211), 879–888.

Pu, T., He, Y.Q., Zhu, G.F., Zhang, N.N., Du, J.K., Wang, C.F., 2013. Characteristics of water stable isotopes and hydrograph separation in Baishui catchment during the wet season in Mt. Yulong region, south western China. Hydrol. Process. 27 (25),3641–3648.

Ruck, L., Mayer, B., 2007. Isotope hydrology of the Oldman River basin, southern Alberta, Canada. Hydrological Process 21, 3301–3315.

Shi, Yafeng, Shen, Yongping, Li, Dongliang, Zhang, et al, 2003. Discussion on the present climate change from warm-dry to warm-wet in northwest China. Quat. Sci. 23 (2), 152–164 (in Chinese)

Song Xianfang, Liu Jian rong, Sun Xiao min, et al., 2007. Establishment of Chinese Network of Isotopes in Precipitation (CHNIP) based on CERN. Aavance in Earth Science, 22(7): 738-747. (In Chinese)

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

Sun C J, Weihong L, Yaning C, et al, 2015c. Isotopic and hydrochemical composition of runoff in the Urumqi River, Tianshan Mountains, China. Environmental Earth Sciences, 74(2):1521-1537.

Sun, C.J., Chen, Y.N., Li, X.G., Li, W.H, 2015a. Analysis on the stream flow components of the typical inland river, Northwest China. Hydrological Sciences Journal, 61 (5): 970-981.

Sun, Meiping, Liu, Shiyin, Yao, Xiaojun, Guo,Wuanqin, Xu, Junli, 2015b. Glacier changes in the Qilian Mountains in the past half century: based on the revised First and Second Chinese Glacier Inventory. Acta Geograph. Sin. 70 (9), 1402–1414 (In Chinese)

Uhlenbrook S, Frey M, Leibundgut C, et al, 2002. Hydrograph separations in a mesoscale mountainous basin at event and seasonal timescales. Water Resources Research, 38(6).

Wang Jinye,2006. Study of Mechanism and Process of Water Transmission on Resource Conservation Forests Ecosystem in Qilian Mountains. Central South University of Forestry and Technology (In Chinese).

Wang Yingzheng, Li Jia, Wu Lixin, et al, 2020. Using remote sensing images to monitor the glacier changes in Qilian Mountains during 1987 – 2018 and analyzing the impact factors. Journal of Glaciology and Geocryology, 42(2):344-356 (In Chinese).

Wang, S., Zhang, M., Wang, Z., et al., 2011. Glacier area variation and climate change in the chinese tianshan mountains since 1960. J. Geogr. Sci, 21 (2), 263–273.

Wang, Z.S., Zhou, C.F., Guan, B.H., Deng, Z.F., Zhi, Y.B., Liu, Y.H., Xu, C., Fang, S.B., Xu, Z., Yang, H.B., Liu, F.D., Zheng, J.W., Li, H.L., An, S.Q., 2006. The headwater loss of the western plateau exacerbates China's long thirst. Ambio 35, 271.

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

Yang zhenniang, Liuxinren, zeng Qunzhu, et al, 2000. Hydrology in cold regions of China. Science Press. (In Chinese).

Yang zhenniang,Liu xinren, Zeng Qunzhu, et al,.2000. Hydrologic process in cold regions of China. Beijing, Science Press, 2000:1-105.

Yao T, Masson-Delmotte V, Gao J, et al, 2013. A review of climatic controls on δ18O inprecipitation over the Tibetan Plateau: Observations and simulations. Reviews of Geophysics,51 (4): 525-548.

Ye Baisheng, Chen Peng, Ding Yong jian, et al, 2008. Discharge Changes of the Eight Large Rivers in East Asia during the Last More Than100Year. Journal of glaciology and geociology, 30(4),556-561.

Ye Baisheng, Ding Yong jian Yang Daqing, 2006. Regional Parttens of Climate Change in Northwest China during the Last 50 Years Viewed from Annual Discharge Change. Journal of glaciology and geocryology, 28(3):307-311.

Ye Weilin，Huang Yuhan，Zhou Ziqiang，et al,2022. Temporaland spatial variations of air temperature in the Qilian Mountains during the past 60 years. Science Technology and Engineering, 22(4): 1344-1353.

Zhang Dedong, Zhao Qing, 2018. Hydrological variability of runoff sequences from major rivers in the Qilian Mountains. Water Planning and Design Water, (8): 1672-2469. (In Chinese)

Zhang Fei, Liu Jingshi, Gongtong Liang,2006. Winter runoff processes in typical alpine permafrost region, Himalayas. Advances in Earth Science,21(12):1333-1338.

Zhang LL, Su FG, Yang DQ, et al, 2013. Discharge regime and simulation for the upstream of major rivers over Tibetan Plateau. Journal of Geophysical Research-

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

Atmospheres,118(15):8500-8518.

Zhang Shiqiang, Ye Baisheng, Liu Shiyin, et al,2012a. A modified monthly degree-day model for evaluating glacier runoff changes in China：part II：application. Hydrological Processes, 26(11):1697 - 1706. (In Chinese)

Zhang Tiaofeng，ZhuXide，Wang Yongjian, et al.,2014. The Impact of Climate Variability and Human Activity on Runoff Changes in the Huangshui River Basin. Resources Science, 36(11):2256-2262. (In Chinese)

Zhang, R., Fang, H., Zhao, F., 2010a. The evolution of existing glaciers in the past 30 years in the Qinghai Tibet Plateau. Remote Sens. Land Resour. B11, 49–53 (In Chinese).

Zhang, R., Fang, H., Zhao, F., Zeng, F., 2010b. Remote sensing survey of existing glacier in Qinghai Tibet Plateau. Remote Sens. Land Resour. B11, 45–48 (In Chinese).

Zhang, Y., Shangguan, S., Jing, D., et al., 2012b. Thinning and shrinkage of laohugou no.12 glacier in the western qilian mountains, China, from 1957 to 2007. J. Mt. Sci. 9(3), 343–350

Zhao Lin, Ding Yongjian, Liu Guangyue, et al, 2010. Estimates of the Reserves of Ground Ice in Permafrost Regions on the Tibetan Plateau. Journal of glaciology and geocryology, 32(1) 1-9. (In Chinese)

Zhao Qiudong，Ding Yongjian，Wang Jian，et al, 2019. Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the glacier inventory data and observed streamflow. Journal of Hydrology，2019，573:60-81.

Zhou, Y., Guo, D., Qiu, G., Cheng, G, 2000. Geocryology in China. Science Press, Beijing

https://doi.org/10.5194/egusphere-2022-620
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Tables:

Table 1 Hydrological data of various basins in Qilian Mountains

Table 1

Drainage	River	Station	Period	Source
	Danghe River	Dangchengwan	1990-2020	HWRBGS
	Changma River	Changma Bao	1990-2020	HWRBGS
	Taolai River	Jiayuguan	1990-2020	HWRBGS
HIRS	Heihe River	Yingluoxia	1990-2020	HWRBGS
	Xiying River	Jiutiaoling	1990-2020	HWRBGS
	Nanying River	Nan ying	1990-2020	HWRBGS
	Zamu River	Zamusi	1990-2020	HWRBGS
	Datong River	Tiantang	1990-2020	HWRBGS
USYR	Jinqiang River	Wushengyi	1990-2020	HWRBGS
	Huangshui River	Minhe	1990-2010	Zhang et al,.2014
QIRS	Buha River	Buha River	1990-2016	Liu et al,.2020

Figures:

Fig.1 Location of (a): study region (1. Danghe river; 2. Changma river; 3. Taolai river; 4. Heihe river; 5. Xiying river; 6. Nanying river; 7. Zamu river; 8. Datong river; 9. Huangshui river;10.Jinqiang river; 11.Buha river) and (b): sampling site

Fig.2 Temporal variation of $\delta^{18}O$ in precipitation in Qilian Mountains

Fig.3 Temporal variation of stable isotopes in glacier and snow meltwater in Qilian Mountains

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Fig.4 Temporal variation of stable isotopes in supra-permafrost water in Qilian Mountains

Fig.5 Temporal variation of $\delta^{18}O$ in the outflow river in the Qilian Mountains

Fig.6 Temporal variation of d-excess in outlet river in Qilian Mountains

Fig.7 Stable isotope characteristics of groundwater in Qilian Mountains

Fig. 8 Relationships of stable isotopes between river water and various water in (a) Qilian mountains, (b) HIRS, (c) USYR, (d) QIRS

Fig. 9 Mixing diagram using the mean values of $\delta^{18}O$ and d-excess for river water Qilian mountains

Fig. 10 Mixing diagram using the mean $\delta^{18}O$ and d-excess values for the outlet runoff in (a): HIRS;(b): USYR and (c): QIRS

Fig. 11 Conceptual model of the contribution of cryosphere belt and vegetation belt to runoff in (a): Hexi inland river system;(b): Upper stream of yellow river system;(c) Qinghai inland river system

Fig. 12 Contribution rate from runoff components to monthly runoff

Fig. 13 Contribution of glacier and snow meltwater to runoff in alpine regions of China

Fig. 14 Annual variation of runoff after 1990 in Qilian mountains

Fig. 15 Seasonal variation of runoff after 1990 in hexi inland river system: (a) Danghe River; (b) Changmahe River; (c) Taolai River; (d) Heihe River; (e) Xiying River; (f) Nanying River and; (g)Zamu River

Fig. 16 Conceptual model of runoff change, water resource effect and countermeasures under global warming in the Qilian Mountains

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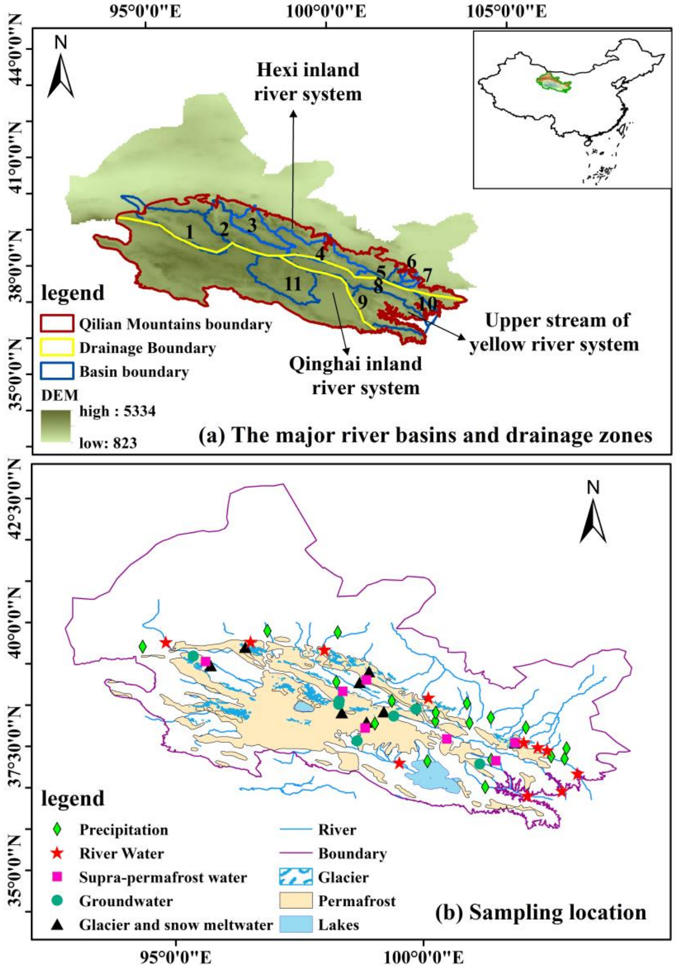

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1105 Fig.1

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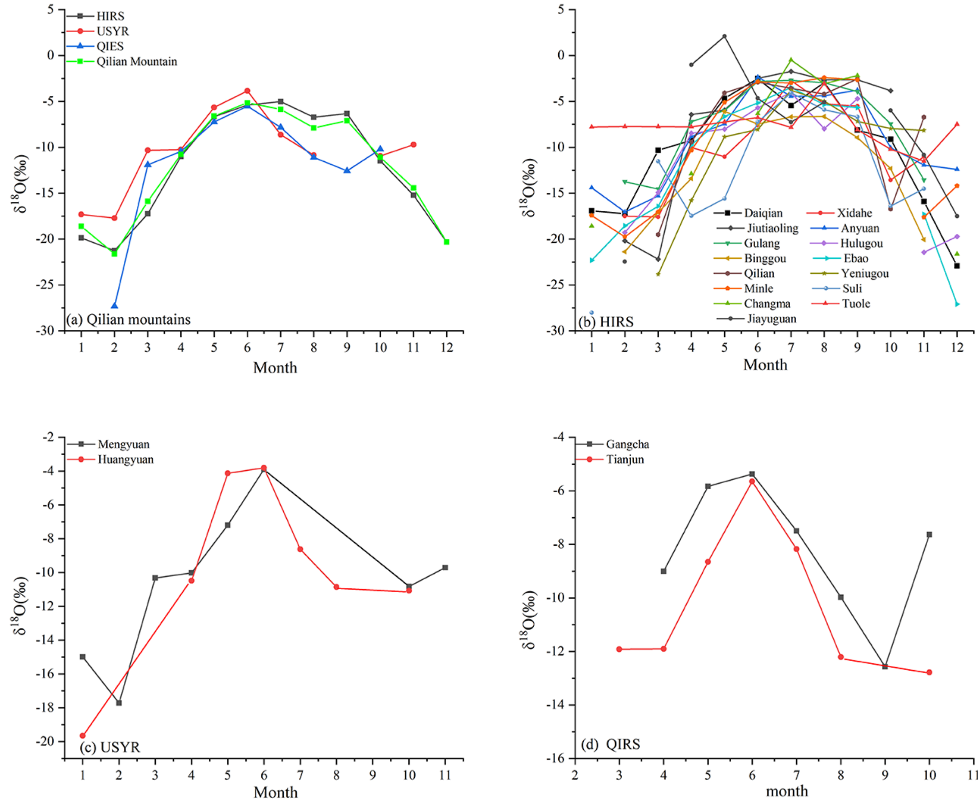

Fig.2

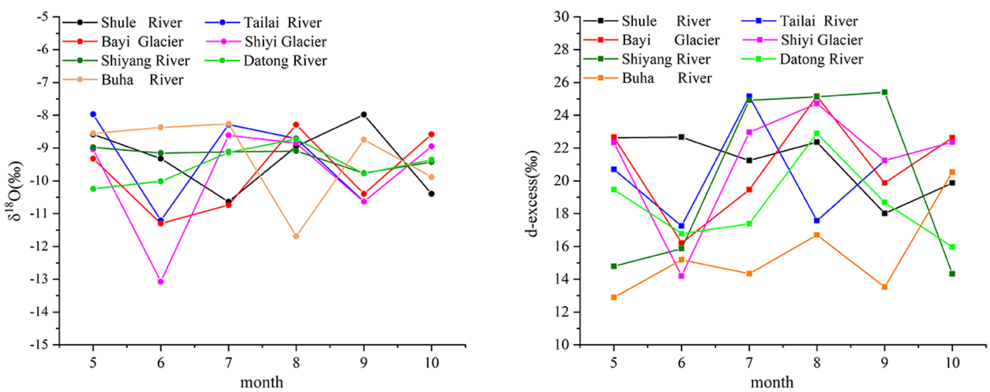

Fig.3

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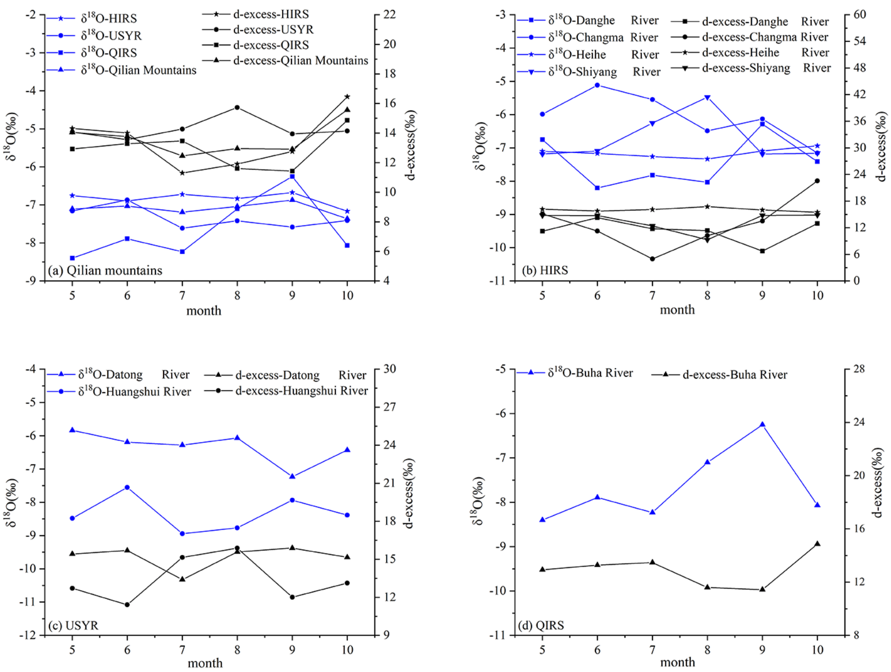

Fig.4

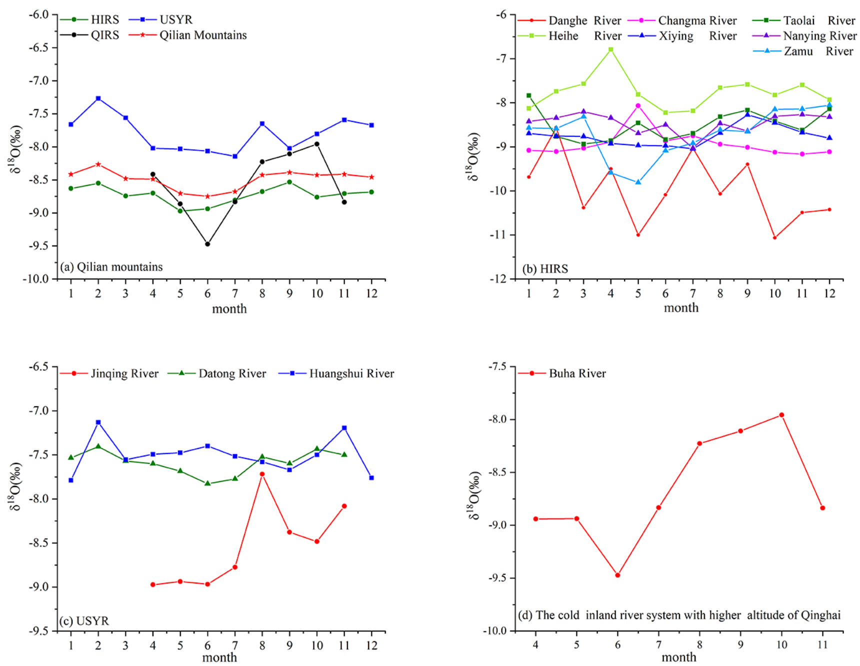

Fig.5

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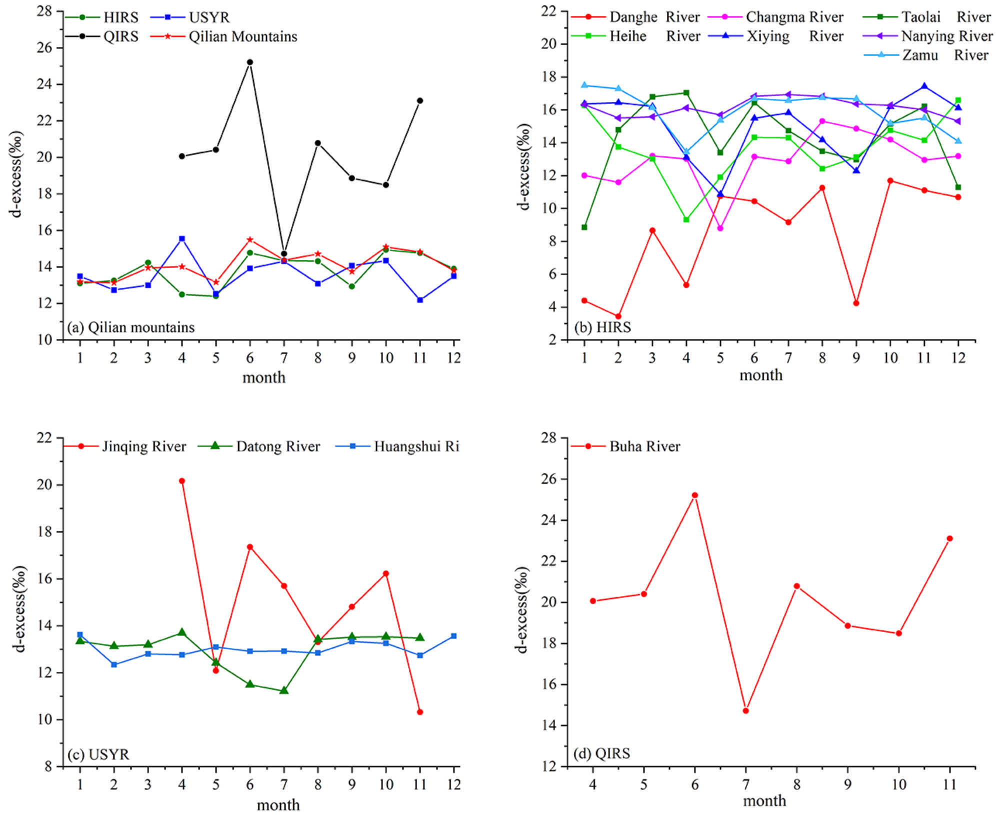

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1116 Fig.6

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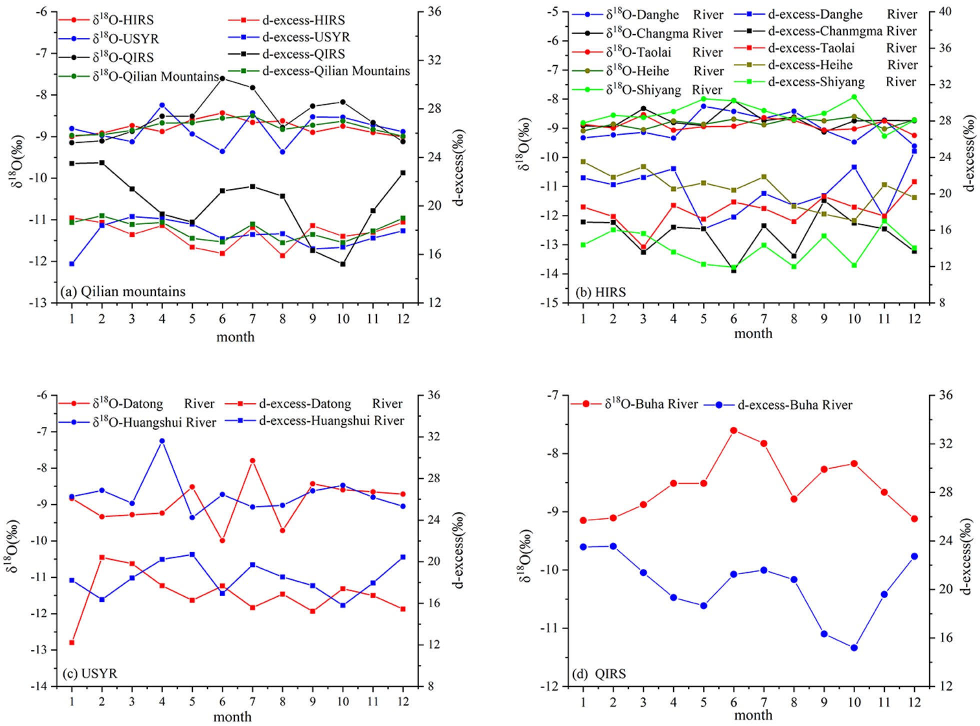

Fig.7

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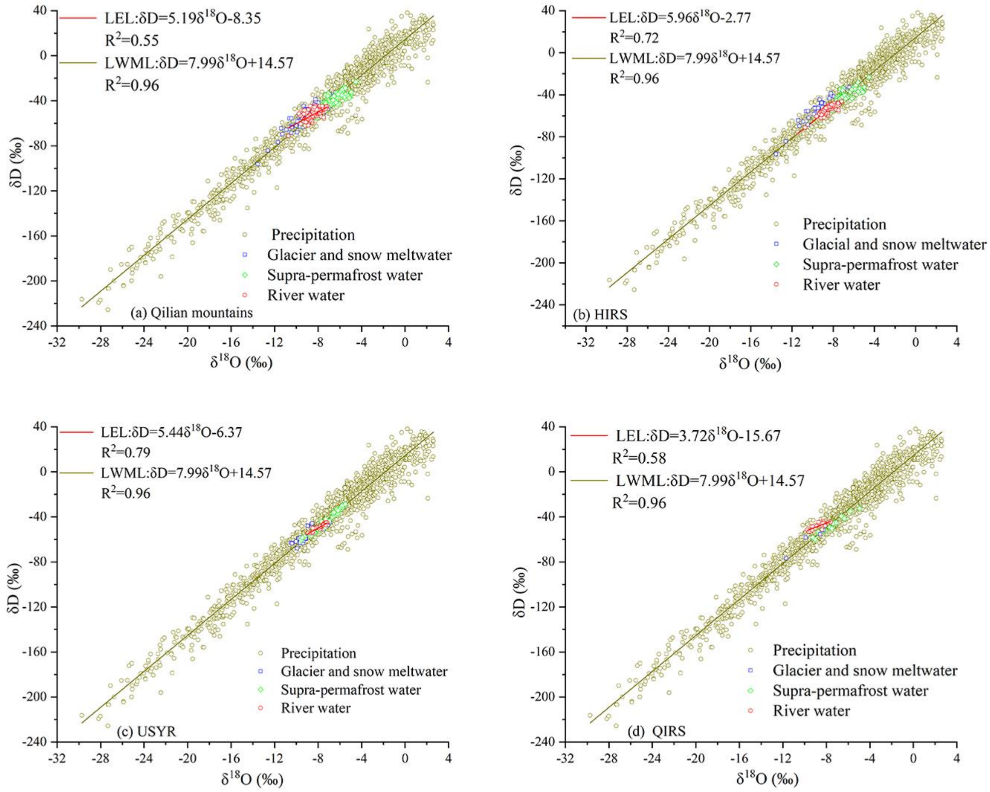

Fig. 8

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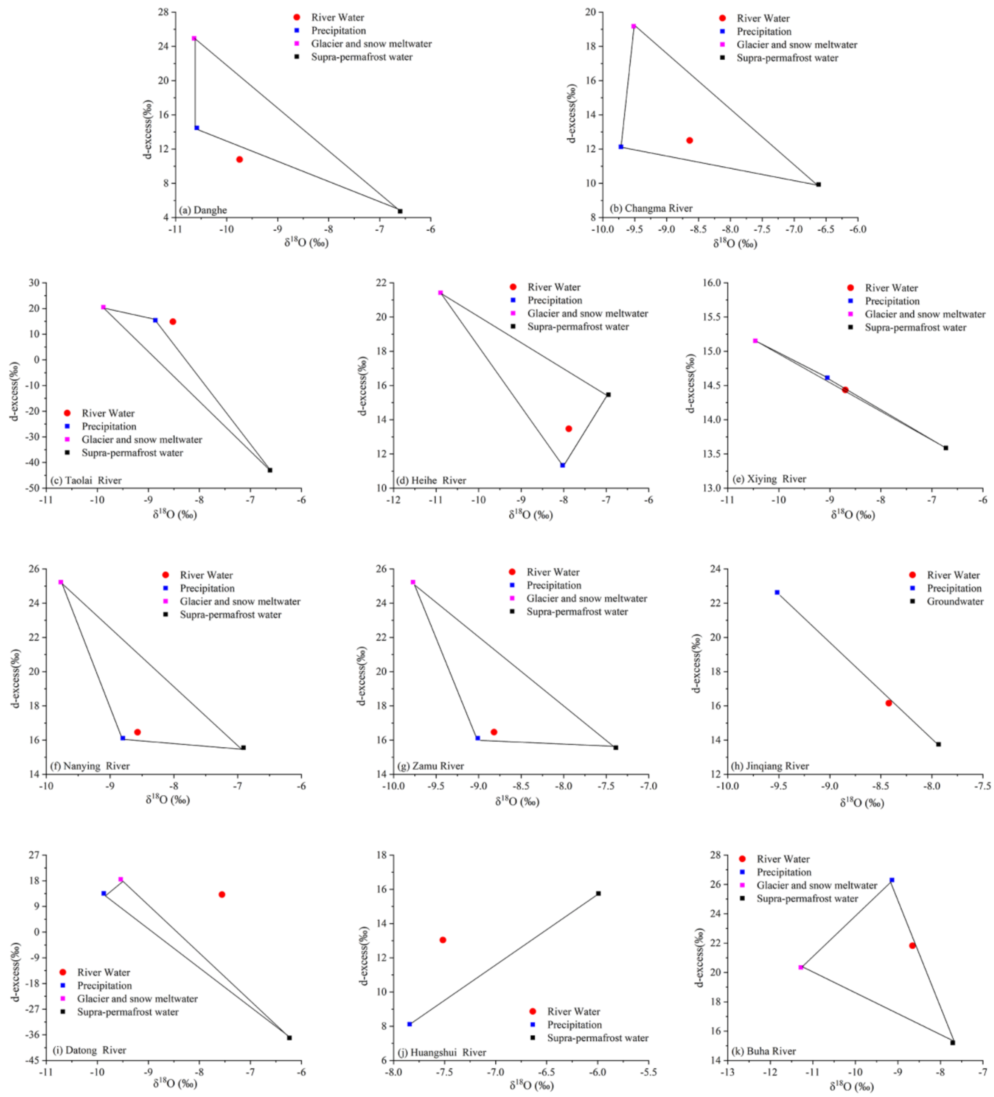

Fig. 9

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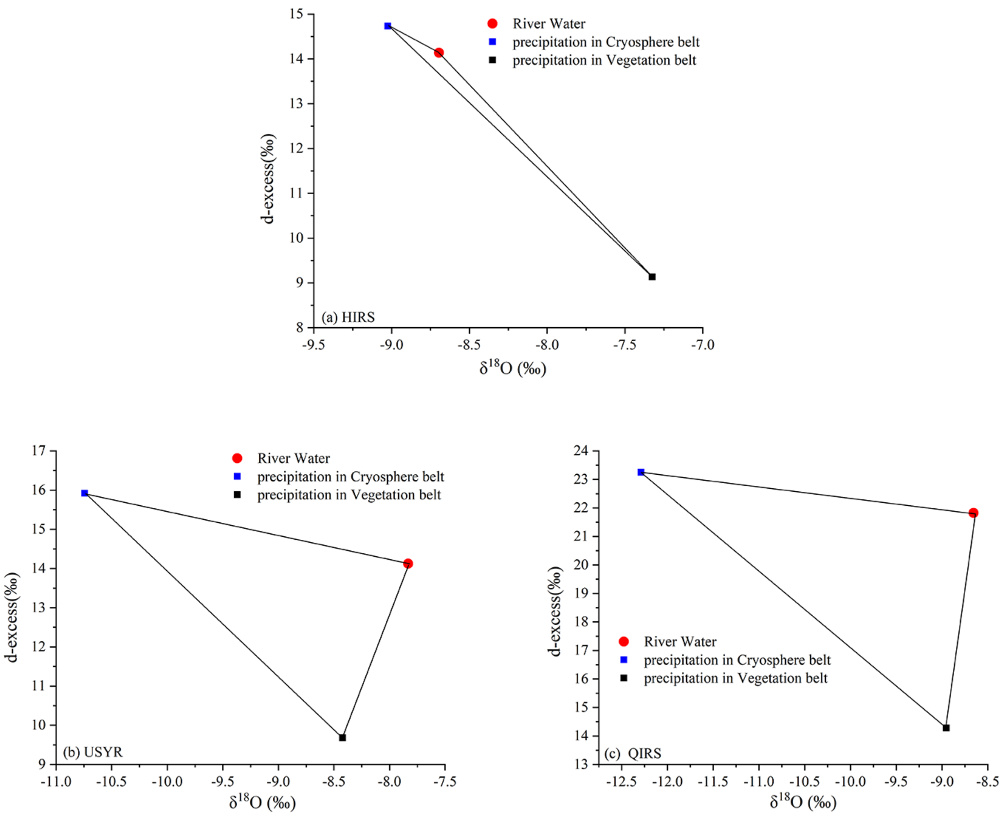

Fig. 10

https://doi.org/10.5194/egusphere-2022-620
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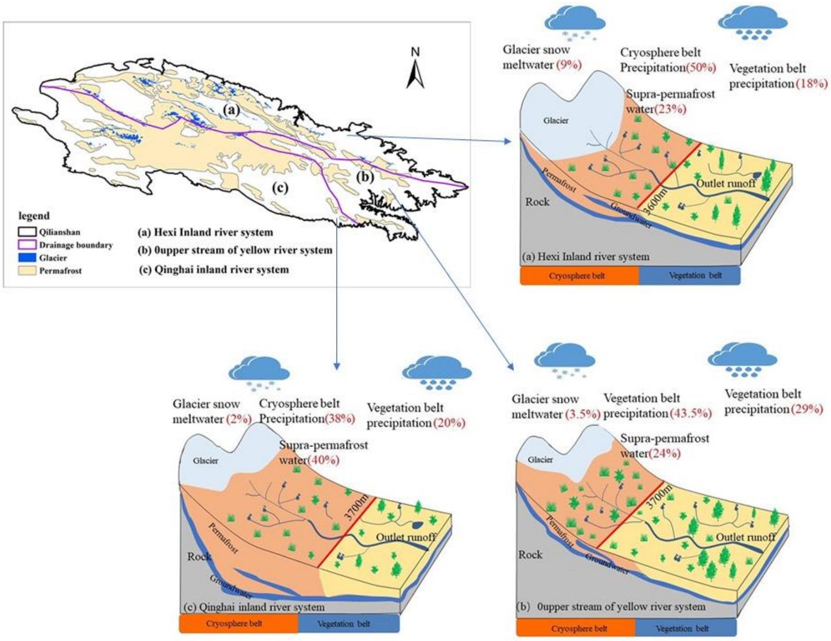

Fig. 11

https://doi.org/10.5194/egusphere-2022-620
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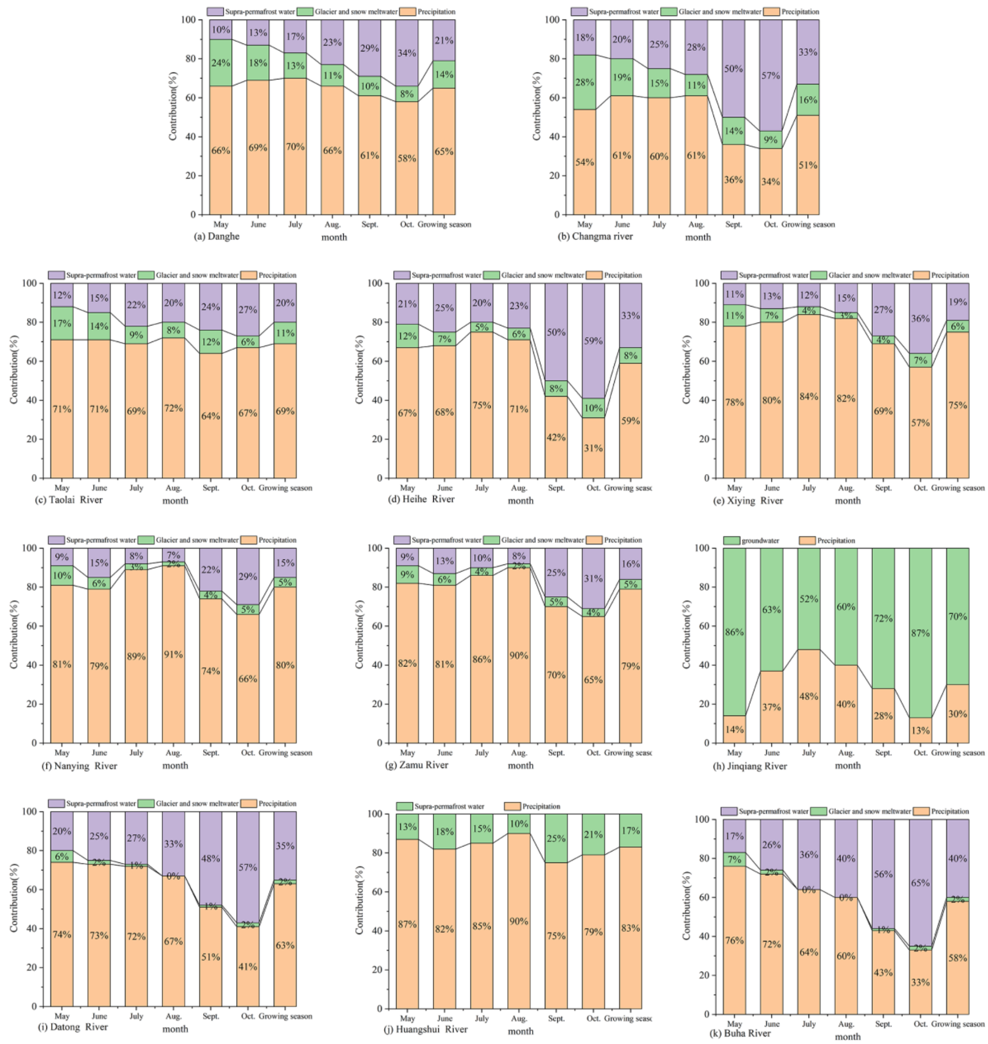
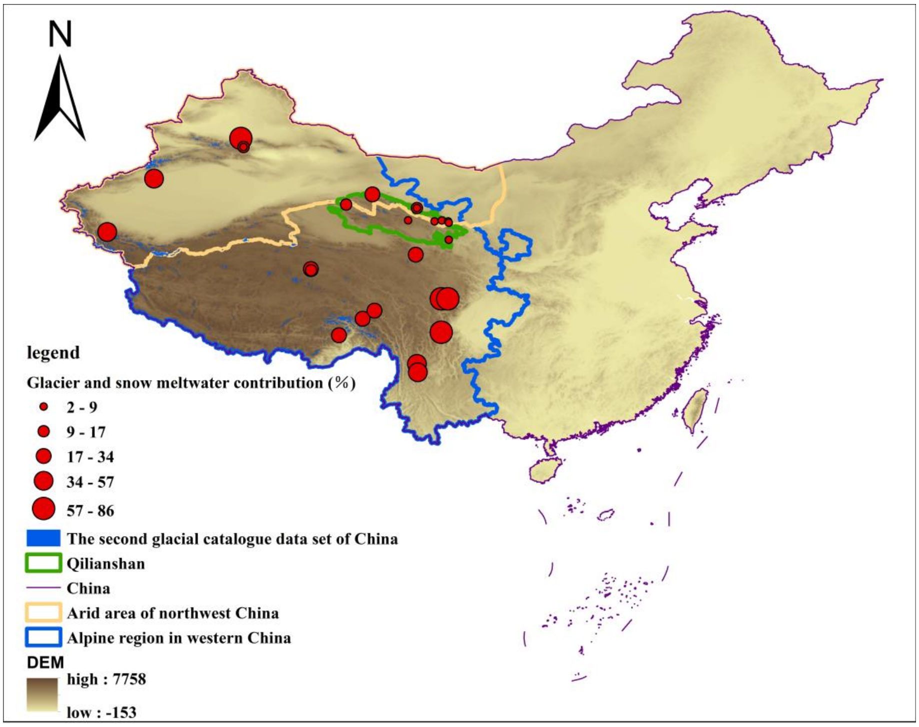


Fig. 12

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

1129 

1130 Fig. 13

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

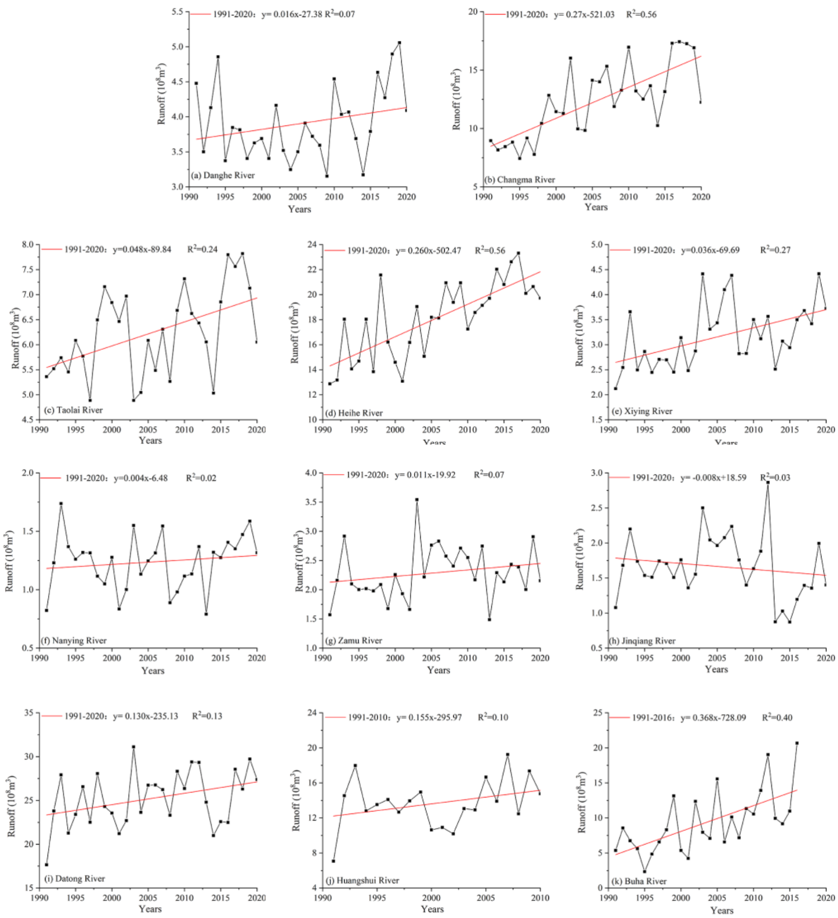


Fig. 14

https://doi.org/10.5194/egusphere-2022-620
Preprint. Discussion started: 29 July 2022

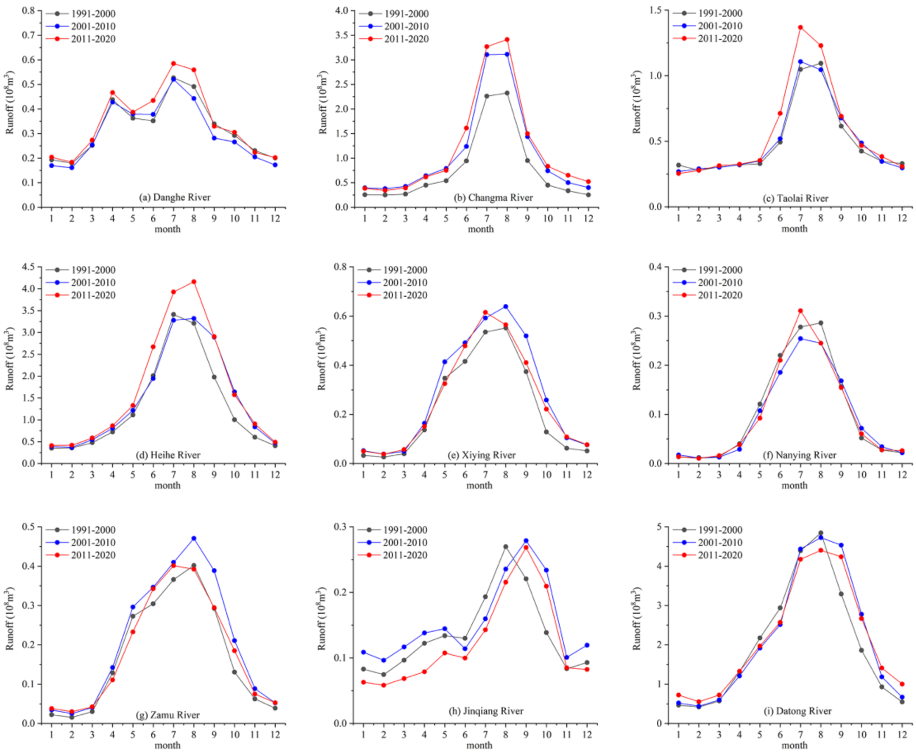


Fig. 15

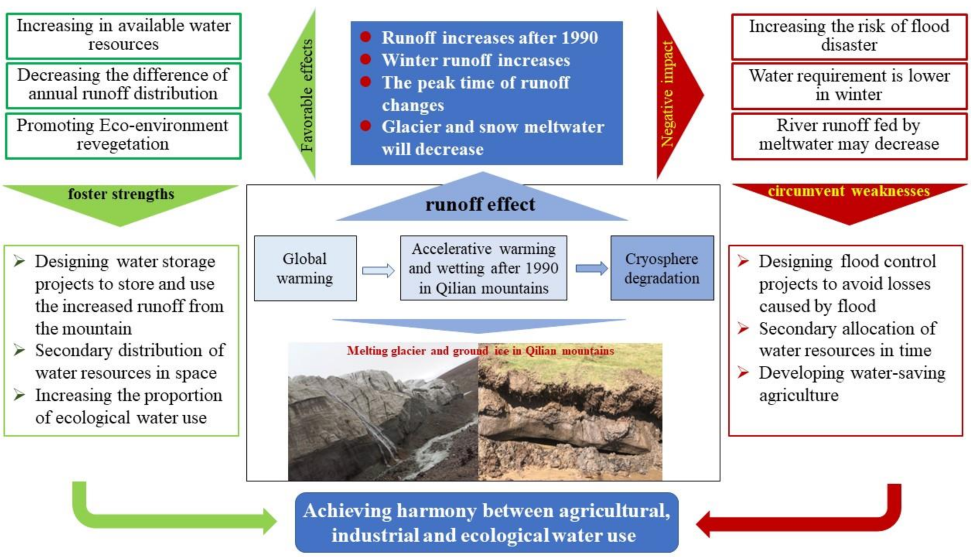


Fig. 16