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Hydrological and Runoff Formation Processes Based on Isotope Tracing During Ablation Period in the Third Polar Region

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Abstract: This study focused on the hydrological and runoff formation processes of river water in the source regions of the Yangtze river during different ablation episodes in 2016 and the ablation period from 2016 to 2018. The effects of altitude were greater for the river in the glacier permafrost area than for the mainstream and the permafrost area during the total ablation period in 2016. There was a significant negative correlation (at the 0.01 level) between precipitation and $\delta^{18}O$, while a significant positive correlation was evident between precipitation and d-excess. More interestingly, significant negative correlations appeared between $\delta^{18}O$ and temperature, relative humidity, and evaporation. A mixed segmentation model for end-members was used to determine the proportion of the contributions of different water sources to the target water body. The proportions of precipitation, supra-permafrost water, and glacier and snow meltwater for the mainstream were 41.70%, 40.88%, and 17.42%, respectively. The proportions of precipitation, supra-permafrost water, and glacier and snow meltwater were 33.63%, 42.21%, and 24.16% for the river in the glacier permafrost area and 20.79%, 69.54%, and 9.67%, respectively, for that in the permafrost area. The supra-permafrost water was relatively stable during the different ablation periods, becoming the main source of runoff in the alpine region, except for precipitation, during the total ablation period.

Keywords: River water, stable isotope, ablation period, source region, Yangtze River

1. Introduction

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Liquid precipitation, glaciers, snow, and permafrost in cold regions are important components of hydrological processes, serve as a key link in the water cycle, and are amplifiers and indicators of climate change (Yang et al., 2012; Chang et al., 2015; Li et al., 2016a; 2016b; 2018). They are not only important as the recharge sources of water in river basins but are also important resources to support regional development (Halder et al., 2015; Lafrenière et al., 2019). The runoff system in the source area of the Yangtze River consists of alpine glaciers, snow, frozen soil, and liquid precipitation. The temporal and spatial variations of runoff components are of great significance for water levels during wet and dry years in terms of ecological protection and the distribution of water resources (Wang et al., 2012; Pan et al., 2017; Mu et al., 2018). Therefore, studying changes in the composition of runoff and its hydrological effect in cold areas can not only consolidate theories on runoff research, prediction, and adaptation, but also have important practical significance for construction, industry, and agriculture in cold regions (Wang et al., 2009; 2017; Wang et al., 2019).

The stable isotope tracer technique has become an important research method in hydrology. In recent years, the response of hydrological processes to climate change in cold regions has become a hot topic in the field of global change, which has greatly promoted the application of the stable isotope and chemical ion tracing methods in the analysis of runoff in cold regions (Li et al., 2015; 2019; Qu et al., 2017; Zhu et al., 2019). Liu et al. (2004) systematically studied the contribution of glacier and snow

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meltwater to runoff in a cold area in Colorado, USA. It was found that the contribution of glacier and snow meltwater to runoff in spring was as high as 82%. Boucher and Carey (2010) systematically studied runoff segmentation in permafrost basins. Maurya et al. (2011) found that the average contribution of meltwater to runoff was 32% in typical glacial basins on the southern slope of the Himalayas. The application of the stable isotope tracer method in the analysis of runoff components in the cold regions of China has been relatively small. Gu and Longinelli (1993) first used $\delta^{18}O$ as a tracer in the Urumqi River in the Tianshan Mountains. The recharge water source can be separated into rainfall, snow meltwater, groundwater, and ice melt water. The results showed that groundwater and snow melt water were the major recharge sources of the Urumqi River in different periods and locations. Since then, Kong and Pang (2012) have studied the contribution of meltwater to runoff and its climatic sensitivity in two typical glacial basins in the Tianshan Mountains. The composition of runoff from the Tizinafu River in the Tianshan Mountains shows that the average contribution of snow melt water is 43% (Fan et al., 2015). The contribution of glacier and snow meltwater to runoff in the Baishui River in the Yulong Snow Mountains was 53.4% in summer (Pu et al., 2013). A study of the Babao River and the Hulugou basin in the Qilian Mountains showed that different water sources were fully mixed into groundwater before recharging rivers in this alpine cold region, and that the contribution of meltwater in the cryosphere to runoff in the cold region was as high as 33% (Li et al., 2014a; 2014b). Although these studies determined the contribution of precipitation and glacier and snow meltwater to

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runoff in the cold regions, they neglected the contribution of supra-permafrost water to runoff and its impact on hydrological processes (Prasch et al., 2013; Lutz et al., 2014). On the one hand, it increases the uncertainty of runoff analysis in the cold regions. On the other hand, it is difficult to comprehensively evaluate the impact of components on the runoff process and the hydrological effects in cold regions.

The source of the Yangtze River, which is a typical alpine frozen soil area, is an important ecological barrier and a protected water source in China (Liang et al., 2008; Li et al., 2017). The regional climate shows a significant warm and wet trend against the background of global climate change. Regional evapotranspiration increases because it is affected by this, and ice and snow resources exhibit an accelerating melting trend (Kang et al., 2007; Wang et al., 2019). The ground temperature of the permafrost increases, causing it to melt significantly. The active layer becomes thicker and degenerates remarkably (Shi et al., 2019). Given this background, the temporal and spatial patterns, mechanisms, and influences of precipitation, glacier and snow meltwater, meltwater in the active layer, and groundwater in the region undergo profound changes and impact runoff processes (Wu et al., 2015). These significant impacts and their hydrological effects on the entire basin have gradually become prominent.

In summary, due to the lack of data and the difficulty of observation and sampling in cold regions, current studies have paid more attention to the study of hydrological

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processes and water cycle characteristics at the watershed scale from the macroscopic point of view. However, there is a lack of in-depth study on the mechanism of the temporal and spatial variations of runoff components from the microscopic point of view, and the understanding of its hydrological effects is still in the exploratory stage. At present, although stable isotope tracer techniques have been applied to the analysis of runoff in cold regions, most of the current studies are limited to the assessment of the contribution and impact of glacier and snow melt water but neglect the significant role of liquid precipitation increase and melt water in the active layer. The results in a lack of systematic understanding of the hydrological effects of runoff composition changes in cold regions. Meanwhile, different types of tributaries in runoff-producing areas are the key to runoff-producing processes and are the main links to understanding hydrological processes in cold regions. It is urgent to develop an understanding of how runoff is produced. In addition, the current study of hydrological processes in the source area of the Yangtze River focuses on the variation in runoff itself and its response mechanism to climate change, lacking in-depth analysis of runoff components and its hydrological effects. Therefore, taking the source area of the Yangtze River as an example, we conduct a study into the temporal and spatial variations of isotopes in different tributary rivers under the background of climate warming and their influencing factors by using the methods of field observation, experimental testing, stable isotope tracing, and analytical modeling of end-element mixed runoff. Based on the conversion signals of stable isotopes in each link of the runoff process, this study further explores the hydraulic relations,

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recharge-drainage relations and their transformation paths, and the processes of each water body, and determines the composition of runoff, quantifies the contribution of each runoff component to different types of tributaries, and analyzes the hydrological effects of the temporal and spatial variation of runoff components. On the one hand, the research results can reveal the evolution mechanism of runoff in cold regions under the background of climate warming. On the other hand, it provides parameter support and a theoretical basis for the simulation and prediction of runoff changes in cold regions, and then provides a scientific basis for a more systematic understanding of the hydrological effects caused by underlying surface changes in cold regions, ultimately providing decision-making basis for the rational development and utilization of water resources in river basins.

2. Data and Methods

2.1 Study area

The source region of the Yangtze River is located in the hinterland of the Tibetan Plateau (Fig. 1). It is an important ecological barrier and water conservation region in China. The southern boundaries are the Tanggula Mountains and Sederi Peak, which contain the watersheds of the Nujiang River and the Lancangjiang River, respectively. The mean altitude reaches 4000 m above sea level with a decreasing elevation from west to east (Yu et al., 2013) that covers an area of approximately 138,000 km^2, ~7.8% of the total area of the Yangtze River Basin. Most tributaries start from glaciers, and form very dense drainage networks, such as those of the Chumaer River in the

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north, Tuotuohe River in the middle, and Dangqu River in the south (Pu, 1994). The glaciers in the study area are mainly distributed along the north-oriented slopes of the Tanggula Mountains and Sedir Mountains and the south-oriented slopes of the Kunlun Mountains, with a total area of 1496.04 km^2 (Yao et al., 2014). The permafrost has a thickness of 10 – 120 m, which accounts for 77% of the total basin area, and most surface soils are frozen during winter and thaw in summer, and active layer thicknesses range from 1–4 m (Gao et al., 2012). Annual average temperatures range from 3 – 5.5°C. The annual precipitation is 221.5 – 515 mm (Yu et al., 2014). The mean annual precipitation varies considerably over the reserve, and ~80% of the annual precipitation occurs during summer, with the highest precipitation occurring in August.

2.2 Sample Collection

This study mainly collects precipitation, glacier and snow melt-water, supra-permafrost water and river water to systematic analysis the recharge relationship between precipitation, glacier and snow melt-water, supra-permafrost water and river water in the source area of the Yangtze River. The specific sampling process is as follows:

River water: In order to analysis the spatial and temporal characteristic of stable isotope of river water in mainstream (25 samples) and major tributary (including river in glacier permafrost area (105 samples) and river in permafrost area (167 samples))

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in the study area, All of river water samples around the traffic routes in the source area of the Yangtze River were collected in initial ablation in 2016 (48 samples), ablation in 2016 (88 samples), end ablation in 2016 (45 samples), ablation in 2017 (55 samples) and ablation in 2018 (61 samples) (Fig.1).

Glacier and snow melt-water: This paper researched the hydrochemistry characteristic of melt-water in Cryosphere (Yuzhu peak Glacier, Geladandong Glacier and Dongkemadi Glacier) through collected water samples by fixed-point sampling from June to September in 2016 and 2017. The samples were collected once every 10 days at the glacier front during the ablation period. The sampling time is at 14 o'clock per day. The sampling location is in hydrological section at the end of the glacier.

Supra-permafrost water: Supra-permafrost water is the most widely distributed groundwater type in the SRYR, and it is mainly stored in the permafrost active layer (Li et al.,2018). The hydrochemistry characteristic of supra-permafrost water in the study area this paper collected water samples by comprehensive sampling from June to September in 2016 and 2018. The sampling process is manual operation. At first, a 2-m deep profile of the permafrost active layer was dug at each of the sampling points. Then, the collection of the water samples are immediately filtered with 0.45 um Millipore filtration membrane. Then, samples were poured the filtered into a clean polyethylene bottle.

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Precipitation: precipitation samples were collected at Zhimenda Hydrological Station (ZMD) at the mountain pass of the source area of the Yangtze River, Qumalai Meteorological Station(QML) in the middle reaches of the source area and Tuotuo River Meteorological Station(TTH) in the upper reaches of the source area. The sampling period extended from April 1, 2016 to October 31, 2018.

Before analysis, all samples were stored at 4ºC in a refrigerator without evaporation. Precipitation and surface water samples were analyzed for $\delta^{18}O$ and δD by means of laser absorption spectroscopy (liquid water isotope analyzer, Los Gatos Research DEL-100, USA) at the Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, CAS. The results are reported relative to the Vienna Standard Mean Ocean Water (VSMOW). Measurement precisions for $\delta^{18}O$ and δD were better than 0.5‰ and 0.2‰, respectively. Field measurements included pH, dissolved oxygen (DO), electrical conductivity (EC), and water temperature.

2.3 EMMA

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

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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:

$$X_S=F_1X_1+F_2X_2+F_3X_3 \quad (1a)$$

$$Y_S=F_1Y_1+F_2Y_2+F_3Y_3 \quad (1b)$$

In Eq. (1), 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 represents 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. (1) can be given as:

$$F_1 =[(X_3\text{-}X_S)/(X_3\text{-}X_2)\text{-}(Y_3\text{-}Y_S)/(Y_3\text{-}Y_2)]/[(Y_1\text{-}Y_3)/(Y_3\text{-}Y_2)\text{-}(X_1\text{-}X_3)/(X_3\text{-}X_2)] \quad (2a)$$

$$F_2=[(X_3\text{-}X_S)/(X_3\text{-}X_1)\text{-}(Y_3\text{-}Y_S)/(Y_3\text{-}Y_1)]/[(Y_2\text{-}Y_3)/(Y_3\text{-}Y_1)\text{-}(X_2\text{-}X_3)/(X_3\text{-}X_1)] \quad (2b)$$

$$F_3=1–F_1–F_2 \quad (2c)$$

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.

2.4 Uncertainty in hydrograph separation

The uncertainty of tracer-based hydrograph separations can be calculated using the error propagation technique (Genereux, 1998; Klaus & McDonnell, 2013). This approach considers errors of all separation equation variables. Assuming that the

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contribution of a specific streamflow component to streamflow is a function of several variables c1, c2, ⋯, cn and the uncertainty in each variable is independent of the uncertainty in the others, the uncertainty in the target variable (e.g.,the contribution of a specific streamflow component) is estimatedusing the following equation (Genereux, 1998; Uhlenbrook & Hoeg,2003):

$$W_{fx} = \sqrt{\left(\frac{\partial z}{\partial c_1} W_{c1}\right)^2 + \left(\frac{\partial z}{\partial c_2} W_{c2}\right)^2 + \cdots + \left(\frac{\partial z}{\partial c_n} W_{cn}\right)^2}, \quad (3)$$

where W represents the uncertainty in the variable specified in the ubscript. fx is the contribution of a specific streamflow component x to streamflow. The software package MATLAB is used to apply equation 3 to the different hydrograph separations in this study.

3. Results

3.1 Temporal Variation

As shown in Fig. 2, there was significant difference in $\delta^{18}O$ and d-excess in the different ablation events in 2016 and total ablation from 2016 to 2018 for the different types of runoff. For the mainstream, the order of $\delta^{18}O$ for the different ablation periods was initial ablation (−10.31‰) > final ablation (−12.22‰) > total ablation (−13.51‰), while the order of $\delta^{18}O$ in ablation from 2016 to 2018 was total ablation in 2018 (−11.21‰) > total ablation in 2017 (−13.20‰) > total ablation in 2016 (−13.51‰). The order of d-excess for the different ablation periods and total ablation

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from 2016 to 2018 was: total ablation (13.57‰) > initial ablation (12.71‰) > final ablation (12.35‰) and total ablation in 2017 (14.62‰) > total ablation in 2016 (13.57‰) > total ablation in 2018 (10.81‰) (Fig. 2a, d). For the river in the glacier permafrost area, the order of $\delta^{18}O$ for the different ablation periods and the total ablation from 2016 to 2018 was the same as the mainstream order, but the values of $\delta^{18}O$ were different for the mainstream. The $\delta^{18}O$ values for the initial ablation in 2016, total ablation in 2016, final ablation in 2016, total ablation in 2017, and total ablation in 2018 were −9.92‰, −13.29‰, −10.82‰, −12.38‰, and −11.04‰, respectively. The order of d-excess for the different ablation periods and total ablation from 2016 to 2018 was: total ablation (14.24‰) > initial ablation (13.02‰) > final ablation (10.58‰) and total ablation in 2016 (14.24‰) > total ablation in 2017 (12.40‰) > total ablation in 2018 (10.49‰) (Fig. 2b, e). For the river in the permafrost area, the order of $\delta^{18}O$ for the different ablation periods and ablation from 2016 to 2018 was: initial ablation (−10.02‰) > final ablation (−11.65‰) > total Ablation (−12.53‰) and total ablation in 2018 (−11.17‰) > total ablation in 2017 (−11.99‰) > total ablation in 2016 (−12.53‰). This was the same as for the mainstream and the river in the glacier permafrost area. However, the order of d-excess for the river in the permafrost area was different than that for the river in the glacier permafrost area. This order, for the different ablation periods and ablation from 2016 to 2018, was as follows: final ablation (13.61‰) > total ablation (12.25‰) > initial ablation (9.97‰), and total ablation in 2017 (13.57‰) > total ablation in 2016 (12.25‰) > total ablation in 2018 (9.72‰) (Fig. 2c, f). In general,

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the $\delta^{18}O$ in the mainstream was more negative than those in the rivers in the glacier permafrost and permafrost areas. These results may be due to the fact that the highest runoff was for the mainstream and that the effects of dilution result in lower isotope values. However, the $\delta^{18}O$ in the river in the glacier permafrost area was more positive than those in the mainstream and the river in the permafrost area. The effect of evaporation could explain these results and the change in d-excess could also demonstrate the same.

3.2 Spatial Variation

To analyze the spatial variation of $\delta^{18}O$ based on the different ablation periods in 2016 and total ablation from 2016 to 2018, spatial interpolation of all river water samples in the study area was performed using ArcGIS. The results are shown in Fig. 3. The $\delta^{18}O$ value in the north-central region of the study area was more positive than those in other regions. In the southeastern part of the study area, especially the QML, ZMD, and Tanggula Mountains, the values were more negative during the initial ablation period. The area of positive ablation during the total ablation period, which was concentrated mainly in the northeast part of the study area, was larger than that during the initial ablation. The other regions, except some areas in the southwest, turned positive. The area of positive ablation was largest during the final of the different ablation periods in 2016; all areas, except some in the eastern region of the study area, were positive (Fig. 3). The area of positive ablation in the central and northern regions began to expand in 2017 compared to the area of total ablation in 2016. Furthermore, the area of negative ablation appears mainly in the southeastern and southwestern portions of the study area. However, the positive ablation area was also concentrated in the central and northern regions in 2018 and it was greater than it was in 2016 and 2017. Meanwhile, the negative ablation area appeared mainly in the southeastern and southwestern portions of the study area, but it was smaller than in 2016 and 2017. These results may be related to evaporation, possible recharge sources, or meteorological factors. These results were comprehensive and influenced by meteorological factors and the type and proportion of recharge sources. The evaporation effect was strong in the central and northern regions, which were also the major glacier and permafrost regions. The southeastern region was the downstream area where all runoff converged; thus, the dilution effect led to a more negative $\delta^{18}O$ here. Moreover, the Tanggula Mountains, with altitudes higher than those in other regions, were located southwest of the study area; thus, evaporation had a low influence on this region and the oxygen stable isotopes were more negative.

Just as with the spatial distribution of $\delta^{18}O$, there was a significant spatial distribution of d-excess in the study area (Fig. 4). Compared to the spatial distribution of $\delta^{18}O$, the d-excess in the central and northern regions were lower than those in the other regions. However, d-excess was higher in the latter, especially in the southwestern regions and in the southeastern regions during the initial ablation period. The lower area begin to expand during the total ablation period in 2016, while the central and northeastern regions and the Tanggula Mountains were greater. Meanwhile, the negative ablation

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area continued to expand during the final ablation period; ablation was greater only in the southeastern part of the study area. However, all regions exhibited high ablation, especially in the Tanggula Mountains, except for areas in the eastern region where the ablation was low during the ablation period in 2017. Moreover, the lower ablation regions appeared mainly in the central and southeastern regions of the study area; values were higher in the other regions, especially in the Tanggula Mountains and the northeast. The spatial distribution of d-excess also confirmed the spatial distribution of the oxygen stable isotope because evaporation resulted in the enrichment of isotopes and led to a reduction in d-excess.

In general, the influence of evaporation on the isotope and d-excess was only manifested in some places, such as the central and northern parts of the study area, in the initial ablation and the total ablation periods. However, the influence of evaporation on the isotope and d-excess was manifested in most places, except the southeast of the study area. Meanwhile, these results also indicated that there may be a hysteresis for the influence of meteorological factors on isotopes and d-excess. On the one hand, river water was the result of the final convergence of various recharge sources that include precipitation, supra-permafrost water, and glacier and snow meltwater. On the other hand, meteorological factors directly affected the main recharge sources of river water.

As shown in Fig. 6, there was a significant difference in the variation of $\delta^{18}O$ and d-excess with altitude for the mainstream, the river in the glacier permafrost area, and the river in the permafrost area of the study area. For the mainstream, the oxygen stable isotope showed a decreasing trend, with increases in altitude, during the ablation periods in 2016 and 2018. In other words, the altitude effect only appeared in the total ablation periods during these two years and had values of −0.16‰/100 m ($p < 0.05$) and −0.14‰/100 m ($p < 0.05$), respectively. However, $\delta^{18}O$ showed an increasing trend with an increase in altitude during the initial and final ablation periods in 2016 and total ablation period in 2017. The anti-altitude effects of the initial and final ablation periods in 2016, and total ablation period in 2017, were 0.11‰/100 m ($p < 0.05$), 0.13‰/100 m ($p < 0.01$), and 0.04‰/100 m ($p < 0.05$), respectively. d-excess showed a decreasing trend during the initial and final ablation periods in 2016 and a significant increasing trend in the total ablation period from 2016 to 2018. For the river in the glacier permafrost area, $\delta^{18}O$ showed a decreasing trend with increase in altitude during the total ablation periods in 2016 and 2018, but the ablation in 2018 was not significant. The altitude effect was −0.66‰/100 m ($p < 0.05$) and −0.15‰/100 m ($p > 0.05$), respectively, during the former two periods. Moreover, a significant anti-altitude effect of 0.47‰/100 m ($p < 0.05$), 0.67‰/100 m ($p < 0.05$), and 0.97‰/100 m ($p < 0.05$), appeared in the initial and final ablation periods in 2016 and total ablation period in 2017, respectively. Just as with the mainstream, d-excess showed a decreasing trend in the initial and final ablation periods in 2016 and an increasing trend in the total ablation from 2016 to 2018. For the river in the permafrost area, $\delta^{18}O$ showed a decreasing trend with an increase in altitude in the initial ablation period and total ablation period in 2016, with an altitude effect of −0.38‰/100 m ($p < 0.05$) and −0.12‰/100 m ($p > 0.05$), respectively. However, $\delta^{18}O$ showed an increasing trend with increase in altitude in the final ablation period in 2016 and the total ablation periods in 2017 and 2018, with an anti-altitude effect of 0.21‰/100 m ($p < 0.05$), 0.01‰/100 m ($p > 0.05$), and 0.68‰/100 m ($p < 0.05$), respectively. d-excess showed an increasing trend with increase in altitude in the initial and final ablation periods in 2016 and total ablation periods in 2016 and 2017. However, d-excess also showed a decreasing trend with increase in altitude in the total ablation period in 2018.

In summary, the altitude effect mainly appeared during ablation, whether it was in the mainstream, the river in the glacier permafrost area, or the river in the permafrost area. The altitude effects were higher for the river in the glacier permafrost area than for the mainstream or the river in the permafrost area during the ablation period in 2016. Meanwhile, the anti-altitude effect of the river in the glacier permafrost area was higher than that of the other areas. The $\delta^{18}O$ during the initial and final ablation periods in 2016 showed a significant anti-altitude effect for the mainstream and the river in the glacier permafrost area; a significant altitude effect appeared during the initial ablation period for the river in the permafrost area. These results may be due to the comprehensive influence of possible recharge sources and different recharge proportions caused by the influence of meteorological factors.

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3.3 Evaporation Line

The variations in the location of the evaporation line for river water during the different ablation periods in 2016 and the total ablation periods from 2016 to 2018 are shown in Fig. 6. The slope and intercept of the LEL for river water showed an increasing trend from the initial to final ablation periods in 2016. The LEL in the initial ablation period was $\delta D = 6.59\delta^{18}O - 3.60$ ($p < 0.01$) and it was $\delta D = 6.88\delta^{18}O - 1.37$ ($p < 0.01$) during the total ablation period. The LEL during the final ablation period was $\delta D = 7.39\delta^{18}O + 5.88$ ($p < 0.01$). These results indicate that the effect of evaporation on the stable isotopes in river water gradually weakened from the initial ablation to the final ablation periods. The slope and intercept of the LEL of river water during the total ablation period in 2017 were lower than those in 2016. The LEL during the total ablation period in 2017 was $\delta D = 6.59\delta^{18}O - 3.63$ ($p < 0.01$). However, whether the slope or the intercept of LEL of river water in 2018 was higher than that in 2016 and 2017, with the LEL was: $\delta D = 7.63\delta^{18}O + 5.82$ ($p < 0.01$). This phenomenon showed that the influence of evaporation on stable isotope levels was greatest during the total ablation period in 2017, followed by that in 2016. In general, the lower slope and intercept indicate that the water body was affected by evaporation or non-equilibrium dynamic fractionation. This conclusion could also explain the results of this study.

3.4 Recharge Sources

The distributions of δD and $\delta^{18}O$ for river water in the different types of water, among supra-permafrost water, glacier snow meltwater, and precipitation, are shown in Fig. 8 the different ablation periods in 2016 and ablation from 2016 to 2018. The results of the distribution of δD and $\delta^{18}O$ of river water indicate the possible recharge sources of river water. However, the δD and $\delta^{18}O$ of river water, supra-permafrost water, glacier snow meltwater, and precipitation exhibited little change during the initial ablation in 2016 (Fig. 7a, b). This phenomenon suggests that precipitation may be the major recharge sources for river water during the initial ablation. A plot of δD versus $\delta^{18}O$ for river and supra-permafrost water, glacier snow meltwater, and precipitation is shown in Fig. 8c. The δD and $\delta^{18}O$ values of glacier and snow meltwater from above the LMWL are the most negative compared to other water bodies. The stable isotope of supra-permafrost water was relatively more positive, located below the LMWL, confirming the influence of strong evaporation. The stable isotope of river water was close to the LMWL, and its concentration value was between precipitation, glacier and snow meltwater, and supra-permafrost water, reflecting that river water was recharged and affected by multi-source water in the study area. Moreover, the distribution of river water, glacier and snow meltwater, and supra-permafrost water also indicated that there was a hydraulic relationship between the source and target in the different ablation periods in 2016 and ablation from 2016 to 2018.

The mixed segmentation model of the end-member is used to determine the contribution proportions of different water sources to the target water. Owing to the two stable isotope concentrations in different water bodies have significant spatial and temporal differences, which can effectively distinguish different water bodies and their mixing relationships. The d-excess and $\delta^{18}O$ are used as tracers of the mixed segmentation model of the end-elements. As shown in Fig. 8, according to the locations of the different types of water (mainstream, glacier permafrost area river, and permafrost area river) and the distance from other water bodies (precipitation, glacier and snow meltwater, and supra-permafrost water), which reflected the mixed recharge of three water bodies, supra-permafrost water was the first end element, precipitation was the second end element, and glacier and snow meltwater was the third end element in the initial ablation in 2016. However, the possible recharge sources of the mainstream, the glacier permafrost area river, and the permafrost area river were different (Fig. 8), as the different runoffs likely have different recharge sources and different recharge proportions. Overall, the source of the permafrost area river was mainly the supra-permafrost water, with similar levels of precipitation in the different periods of ablation in 2016 and the total ablation from 2016 to 2018. The permafrost area river had the least contribution from the glacier and snow meltwater, indicating that the supra-permafrost water was the major recharge source for the permafrost area river followed by precipitation, and the recharge proportions also exhibited the same trend. As the source of the glacier permafrost area river was the same as the permafrost area river, the permafrost area river was dominated by the supra-permafrost water, followed by precipitation and then glacier and snow meltwater. However, the glacier permafrost area river comprised glacier and snow

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meltwater more so in the total ablation period than in other periods. Compared with the permafrost area river and the glacier permafrost area river, the mainstream was governed by the supra-permafrost water in the initial ablation period while containing nearly equal proportions of supra-permafrost water and precipitation in the final ablation period. However, the mainstream received significant contributions from all three end members in the total ablation period from 2016 to 2018 and particularly in 2017.

The recharge proportions of precipitation, supra-permafrost water, and glacier and snow meltwater at different altitudes are depicted in Fig. 9, from the mixed segmentation model of the three end-members during the ablation periods mentioned above. The recharge proportions of the three end members in the ablation periods were significantly different. This may be due to the different effects of the runoff recharge sources in different ablation periods, as well as the significant differences in recharge and drainage relationships in the different ablation periods. The recharge proportions of precipitation in the initial ablation in 2016, total ablation in 2016, final ablation in 2016, total ablation in 2017, and total ablation in 2018, obtained by calculating the average contribution proportion from each altitude, were 28.71%, 44.41%, 44.60%, 42.53%, and 51.03%, respectively. Meanwhile, the recharge proportions of supra-permafrost water in the initial ablation in 2016, total ablation in 2016, final ablation in 2016, total ablation in 2017, and total ablation in 2018 were 55.38%, 36.51%, 40.21%, 37.56%, and 28.87%, respectively. The recharge proportions of glacier and snow meltwater in the initial ablation in 2016, total ablation in 2016, final ablation in 2016, total ablation in 2017, and total ablation in 2018 were 15.91%, 19.08%, 15.19%, 19.90%, and 20.09%, respectively. The recharge proportion of precipitation decreased with increase in altitude in the initial ablation, while the proportion of supra-permafrost water and glacier and snow meltwater exhibited an increasing trend with increase in altitude. However, the recharge proportion of the supra-permafrost water was higher than that of precipitation or glacier and snow meltwater, and also showed a decreasing trend from low to high altitude in the final ablation in 2016. The proportion of glacier and snow meltwater increased with increase in altitude, but the recharge proportion of supra-permafrost water was stable with the change in altitude in the final ablation in 2016. The trend of precipitation and glacier and snow meltwater for the total ablation was the same as that for the initial and final ablation. However, the recharge proportion of precipitation was higher than the proportion of supra-permafrost water and glacier and snow meltwater in the ablation period. Meanwhile, the recharge proportion of glacier and snow meltwater in ablation was higher than that in the initial and final ablation period. In general, the recharge of supra-permafrost water to runoff was stable, whether in the different ablation periods in 2016 or the total ablation from 2016 to 2018. However, the proportion of supra-permafrost water was relatively low, mainly due to the larger runoff during the ablation period.

Using the approach shown in Equation (3), the uncertainty originating from the variation in the tracers of components and measurement methods could be calculated

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separately (Uhlenbrook & Hoeg, 2003; Pu et al., 2013). According to the calculations made using Equation (3), the uncertainty was estimated to be 0.07 for the three - component mixing model in the study region. The uncertainty terms for supra-permafrost water accounted for more than 50.0% of the total uncertainty, indicating that the $\delta^{18}O$ and δD variations of supra-permafrost water accounted for the majority of the uncertainty. Although there is some uncertainty for hydrograph separation, isotope-based hydrograph separations are still valuable tools for evaluating the contribution of meltwater to water resources, and they are particularly helpful for improving our understanding of hydrological processes in cold regions, where there is a lack of observational data.

4. Discussions

4.1 Meteorological Factors

To further explain the reason for the variation in temporal and spatial characteristics of stable isotopes and LEL, this study includes the analysis of the monthly change in precipitation, temperature, relative humidity, and evaporation during the sampling period (from January 2016 to December 2018). The results are shown in Fig. 10. The average of the precipitation was 371.9 mm during the sampling period, and the precipitation in the total ablation period accounted for 78.87%. The average of the temperature, relative humidity, and evaporation during the sampling period were −1.42 °C, 52.20%, and 4.14 mm, respectively. However, the average of the temperature, relative humidity, and evaporation during the total ablation period were

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8.04 °C, 66.47%, and 5.57 mm, respectively.

More importantly, the precipitation during the initial, total, and final ablation periods in 2016, and the total ablation periods in 2017 and 2018, were 50.40 mm, 107.90 mm, 42.90 mm, 70.60 mm, and 119.00 mm, respectively. For precipitation, the isotope levels tend to decrease with the increase in rainfall; Precipitation is also the major source of water for all water bodies (Maurya et al., 2011; Pu et al., 2013; Li et al., 2014b; 2015; 2016a; 2018; Pan et al., 2017) and, in general, more precipitation resulted in a greater dilution effect. A more negative $\delta^{18}O$ appeared in the total ablation period in 2016 whether in all three study areas given the change in $\delta^{18}O$ (Fig. 2). This result showed that dilution does not only play an important role in the precipitation effect; it also affects river water. However, the dilution effect was also significant when precipitation was the major recharge source for river water (Abongwa and Atekwana, 2018; Li et al., 2015).

Temperature for the initial, total, and final ablation periods in 2016, and the total ablation periods in 2017 and 2018, were 6.82 °C, 9.58 °C, 3.77 °C, 9.47 °C, and 11.09 °C, respectively. For atmospheric precipitation, the lower the temperature was, the higher the condensation degree of water vapor exhibited and the lower the isotope content in precipitation. Therefore, there is a positive correlation between the stable isotope and temperature in precipitation (Li et al., 2016a). However, the influence of temperature on the stable isotope of river water was not significant from the variation in river water isotope during the different ablation periods. However, the variation trend of the stable isotope of river water in the total ablation period from 2016 to 2018 was similar to that for the change in temperature. Meanwhile, the variation trend of d-excess can also be confirmed by this analysis (Fig. 2).

Relative humidity in the initial ablation, total ablation, and final ablation periods in 2016 and the total ablation periods in 2017 and 2018 were 60.07%, 63.16%, 70.57%, 63.39%, and 63.48%, respectively. When the relative humidity is low, the dynamic fractionation increases and the slope decreases, and vice versa. The variation trend of the slope of the LEL for the different ablation periods in 2016 was the same as that for the change in relative humidity (Fig. 6). Meanwhile, the intercept of the LEL for the different ablation periods in 2016 also showed the same trend.

Evaporation in the initial ablation, total ablation, and final ablation periods in 2016 and total ablation periods in 2017 and 2018 were 6.69 mm, 6.96 mm, 4.02 mm, 6.48 mm, and 6.02 mm, respectively. The stable isotopes of hydrogen and oxygen in river water are comprehensively affected by the evaporation process, runoff change, precipitation recharge, glacier and snow meltwater recharge, supra-permafrost water, and evaporation loss in cold regions. During the process of evaporation, lighter water isotopes are separated preferentially from the surface of water while heavier isotopes are enriched in the remaining water body. Evaporation enriches the oxygen and hydrogen stable isotopes and reduces excess deuterium (Li et al., 2015; 2018). The trend in the oxygen isotope in the total ablation periods from 2016 to 2018 was the same as that for the change in evaporation (Fig. 2). Meanwhile, the spatial distribution of $\delta^{18}O$ and d-excess also responded to this change (Fig. 3, 4).

To further analyze the influence of meteorological factors on the stable isotope, the correlation analysis between meteorological factors and the monthly value of $\delta^{18}O$ and d-excess, which showed continuous observations at two fixed-point stations was analyzed (Table 1), and the results are shown in Table 1. There was a significant negative correlation between precipitation and $\delta^{18}O$ at the 0.01 level (2-tailed), while a significant positive correlation between precipitation and d-excess was also present. More interestingly, just as with precipitation, a significant negative correlation appeared between $\delta^{18}O$ and temperature, relative humidity, and evaporation, with coefficients of −0.671, −0.555, and −0.636, respectively. Meanwhile, a significant positive correlation occurred between d-excess and temperature, relative humidity, and evaporation, with coefficients of 0.602, 0.524, and 0.533, respectively. This results indicated that the direct influence of meteorological factors on stable isotopes of river water was significant and definite.

Hydrogen and oxygen isotope compositions in river water are the result of the combined effects of the isotopes making up present in precipitation, glacier and snow meltwater, and supra-permafrost water as well as evaporative fractionation (Li et al., 2015). The main influential hydrometeorological factors include precipitation,

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temperature, relative humidity, and evaporation. On the whole, river water isotopes were not influenced by a single factor; instead, they were based on the comprehensive influence of many factors in the cold regions. The influence of meteorological factors on different types of river water (mainstream, rivers in glacier permafrost areas, and rivers in permafrost areas) showed that apart from their directly influences, each factor indirectly affected the river water recharge source. This indirect influence was mainly felt on precipitation, glacier, snow, and permafrost.

4.2 Hydrological processes

To systematically quantify the main recharge sources of different types of runoff in the alpine regions, the possible sources and recharge proportions of runoff of different types in different ablation periods were deeply analyzed by using the mixed segmentation model of the three end-members in this study. The conceptual model map of the recharge form and proportion of the river water in the different ablation periods is shown in Fig. 11.

For the river in the glacier permafrost area, there was a significant difference in the recharge proportion in the runoff area, in which there were several glaciers and permafrost in the basin, and other areas during the various ablation periods. The proportion of recharge from precipitation during the initial, total, and final ablations in 2016, the total ablation in 2017, and the total ablation in 2018 were 27.69%, 33.71%,

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32.38%, 33.21%, and 41.48%, respectively. However, the proportion of supra-permafrost water in the initial, total, and final ablations in 2016, the total ablation in 2017, and the total ablation in 2018 were 54.68%, 35.96%, 32.38%, 33.21%, and 41.48%, respectively. The proportions of glacier and snow meltwater in the initial, total, and final ablations in 2016, the total ablation in 2017, and the total ablation in 2018 were 17.63%, 30.33%, 21.24%, 29.39%, and 22.19%, respectively. These results show that supra-permafrost water was the important recharge source for runoff during the initial and final ablation periods. The proportion of supra-permafrost water was 50.53% during the initial and final ablation periods. It was also the next highest source of runoff recharge, next to precipitation, during the ablation from 2016 to 2018; the proportions were 36.13% and 36.66%, respectively. The recharge proportions for glacier and snow meltwater was higher during the total ablation period than in the initial and final ablation periods, at 19.44% and 27.30%, respectively.

For permafrost area river, the runoff area only with permafrost and no glacier in the basin, there was also an obvious difference for the recharge proportion in different ablation period. Compared with the glacier permafrost area river the recharge proportion of supra-permafrost water was higher for permafrost area river than that for the glacier permafrost area river (42.21%). The recharge proportion of supra-permafrost water was 69.54%. With the same as the glacier permafrost area river, the supra-permafrost water was the important recharge sources to runoff in the initial and final ablation, and the proportion was 80.97% in the initial and final

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ablation period. Meanwhile, the proportion of supra-permafrost water was 61.92% in the total ablation period. The proportion was higher than that for precipitation (24.13%) in the total ablation period. In general, the supra-permafrost water was the major recharge source for the permafrost area river in the different ablation periods in the study area. Meanwhile, the glacier and snow meltwater had little contribution to the permafrost area river in the initial and final ablation periods.

For the mainstream, the recharge proportions for precipitation during the initial, total, and final ablations in 2016, the total ablation in 2017, and the total ablation in 2018 were 28.67%, 48.35%, 43.18%, 46.97%, and 41.33%, respectively. The proportion was 35.93% in the initial and final ablation periods and 45.55% in the total ablation period. However, the proportions of supra-permafrost water during the initial, total, and final ablation in 2016, the total ablation in 2017, and the total ablation in 2018 were 52.37%, 33.52%, 42.61%, 39.68%, and 38.21%, respectively. The proportion was 47.49% during the initial and final ablation periods and 36.47% during the total ablation period. These results indicate that, for the study area, the supra-permafrost water was the major recharge source for the mainstream in the first two of these ablation periods while precipitation was the major recharge source for the mainstream in the total ablation period. The proportions of glacier and snow meltwater during the initial, total, and final ablation in 2016, the total ablation in 2017, and the total ablation in 2018 were 18.96%, 20.13%, 14.21%, 13.35%, and 20.46%, respectively. The proportion of glacier and snow meltwater for the mainstream (16.59%) was

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higher than that for the river in the permafrost area (3.25%) but lower than that for the river in the glacier permafrost area (19.44%) during the initial and final ablation periods. The former proportion was also higher than that for the river in the permafrost area (17.98% vs 13.95%) but lower than that for the river in the glacier permafrost area (27.30%) during the total ablation period.

The hydrological process in cold regions has one particularity. The low permeability in permafrost layer and the freeze-thaw depths of the soil reduces soil infiltration (Wu et al., 2015; Wang et al., 2019). Therefore, the rapid replenishment of meltwater by runoff results in a difference in the runoff generation mechanism in the permafrost and non-permafrost regions (Yang et al., 2010; Li et al., 2018). Moreover, because the freeze-thaw depths of the soil changes with annual fluctuations in temperature, there is an effect on soil water storage capacity that results in a difference in the runoff generation mechanism during different ablation periods (Wang et al., 2019). Wang et al. (2008) also found that the seasonal distributions and variations in rainfall runoff in the permafrost basin were controlled by the freeze-thaw process because of the impermeable nature of the freeze-thaw front and permafrost layer. During the initial ablation period, the supra-permafrost water—whether in the mainstream, the river in the glacier permafrost area, or the river in the permafrost area—was the major recharge source. During the total ablation period, precipitation was the main source of runoff recharge, followed by supra-permafrost water. Although there was little difference the proportion of precipitation and supra-permafrost water during the

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ablations from 2016 to 2018, precipitation was the major recharge source of runoff in this period. Supra-permafrost water was the main source of runoff recharge in the final ablation period, just as it was in the initial ablation period. In summary, runoff in the cold region during the different ablation periods was mainly composed of runoff from rainfall, meltwater, and supra-permafrost. Because of the inherent seasonal variation in precipitation, there were significant changes in precipitation during the different ablation periods and strong ablation periods in different years. Glacier and snow meltwater was also greatly affected by climatic factors during the different ablation periods, while the supra-permafrost water was relatively stable; the latter became the main source of runoff supply, except for precipitation, in the alpine region. Thus, with the changes that the low temperatures made in the physical properties of the underlying surface, the change in the permafrost had the most significant effect on the hydrological process in cold regions.

4.3 Hydrological significance of permafrost

The Qinghai-Tibet Plateau (QTP) is the only mid-latitude region in the world that contains permafrost (Zhang et al., 2003). Its permafrost region is located at the source of two major rivers (the Yangtze River and the Yellow River) in China (Yu et al., 2013; 2014). Just like the rivers in the Arctic region of Eurasia, they play an important hydrological role in ensuring freshwater recharge and maintaining the ecological security of the basin (Yao et al., 2014; Li et al., 2017; Wang et al., 2019). Permafrost is an objective geological entity developed through the exchange of material and

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energy between the earth and the atmosphere under the influence of the regional geographic environment, geological structure, lithology, hydrology, and surface characteristics given geologic history and the impact of climate change (Chang et al., 2015). It has its own unique law of evolution and is extremely sensitive to environmental change. The active layer of permafrost is a near-surface soil and rock layer that thaws in the summer and freezes in winter (Wang et al., 2008; 2009; 2017; Chang et al., 2015; Li et al., 2018). Permafrost and active layers are the main factors controlling the hydrometeorological changes of the underlying surface, and the freeze-thaw process of the permafrost active layer is the most important factor affecting the process of runoff. The special water and heat exchange in the active layer of permafrost is the key factor to maintaining the stability of the alpine ecosystem. Permafrost, alpine marsh wetland, and alpine meadow ecosystems have remarkable water conservation functions. They are important factors in stabilizing the water cycle and river runoff in river source areas and have a very important impact on regional ecology and water resource security (Yang et al., 2010; Wu et al., 2015). Under global climate change conditions, permafrost degradation is mainly seen in terms of changes in the active layer. In recent decades, the thickness of permafrost active layers have changed significantly in the Qinghai-Tibet Plateau; since 1980, it has increased by 0.71 cm/a in the eastern part of this region (Zhao et al., 2004). Jin et al. (2006) believe that permafrost in the Qinghai-Tibet Plateau is deteriorating over a large area because of climate change. The observed permafrost data also show a significant increase in the thickness of the active layer in the Qinghai-Tibet Plateau over the past 10 years.

The permafrost active layer, particularly the hydrothermal environment of the active layer, is the most active and dominant influencing factor at the interface of the ecological environments in cold regions (Yang et al., 2010; Wu et al., 2015; Li et al., 2018). The change in the active layer not only changes the soil water retention capacity, directly affecting the living environment of vegetation, but also changes the soil freeze-thaw process in the active layer. At the same time, the energy-water exchanges accompanied by the freeze-thaw process directly affect the redistribution of soil water and the change in soil water capacity, the movement of water to surface of the frozen soil, and the exchange of latent heat of the water phase transformation. Permafrost reduces the hydraulic conductivity of soil, resulting in the reduction of snow meltwater or precipitation infiltration, changing runoff generation, confluence processes, and characteristics in cold regions (Boucher et al., 2010; Li et al., 2014a; 2016b; Mu et al., 2018; Shi et al., 2019).

Permafrost is the main component of ecosystem in the source area of the Yangtze River. The source of the Yangtze River is in one of the main permafrost districts in the Qinghai-Tibet Plateau. The permafrost area in the study area accounts for 70% of this area (Yao et al., 2014; Li et al., 2017).The change in and distribution of permafrost regions have a significant impact on vegetation and wetlands in this area, as the former is one of the most sensitive to global climate change. The increase in

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temperature leads to an increase in soil temperature, which deepens the active layer significantly, and causes the permafrost to begin to degenerate. This will certainly lead to significant changes in the ecology and water cycle of the region (McGuire et al., 2002; Walker et al., 2003; Yang et al., 2010).

In brief, the freeze-thaw of soil in the active layer plays an important role in controlling river runoff. The increase in melting depth leads to a decrease in the direct runoff rate and slow dewatering process. The two processes of runoff retreat are the result of soil freeze-thaw in the active layer. Permafrost has two hydrological functions: on the one hand, permafrost is an impervious layer, and it has the function of preventing surface water or liquid water from infiltrating into deep soil; on the other hand, it forms a soil temperature gradient, which makes the soil moisture close to the ice cover. Therefore, changes in the soil water capacity, soil water permeability, and soil water conductivity, as well as the redistribution of water in the soil profile, are caused by the freeze-thaw of the active layer. The seasonal freeze-thaw process of the active layer directly leads to seasonal flow changes in surface water and groundwater, which affects surface runoff. Climate warming is the main driving force in the degradation of cold ecosystems (Wang et al., 2009; Wu et al., 2015; Li et al., 2018; Wang et al., 2019).

5. Conclusions

Through systematically analysis of the characteristics of $\delta^{18}O$, δD, and d-excess of

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river water in the different ablation periods in 2016 and the total ablation periods from 2016 to 2018, the results were as follows.

The temporal and spatial characteristics of stable isotopes of river water were significant in the study area. The mean of $\delta^{18}O$ in TTH was −10.59‰, and the mean of d-excess was 9.24‰, while the mean of $\delta^{18}O$ and d-excess in ZMD was −11.99‰ and 9.66‰, respectively. The oxygen isotope in ZMD was more negative than TTH, while the d-excess in ZMD was more positive than TTH. The $\delta^{18}O$ in mainstream was more negative than that in the glacier permafrost area river and permafrost area river. The influence of evaporation on isotope and d-excess is only prevalent in some places, such as the central and northern parts of the study area in the initial ablation and total ablation periods. However, the influence of evaporation on isotope and d-excess is prevalent in most places except the southeastern part of the study area. Meanwhile, this results also indicated that there may be a hysteresis for the influence of meteorological factors on isotopes and d-excess. The altitude effect is only present during the total ablation periods in 2016 and 2018, and the altitude effect was −0.16‰/100 m ($p < 0.05$) and −0.14‰/100 m ($p < 0.05$). The altitude effects were higher for the glacier permafrost area river than those for the mainstream and permafrost in the total ablation period in 2016. Meanwhile, the anti-altitude effect of the glacier permafrost area river was higher than that of the mainstream and permafrost area river. The $\delta^{18}O$ in the initial and final ablation periods in 2016 showed a significant anti-altitude effect for the mainstream and the glacier permafrost area river, while a significant altitude effect appeared in the initial ablation period for

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the permafrost area river. The slope of LEL for river water showed an increasing trend from initial ablation to final ablation in 2016. Meanwhile, the intercept of LEL for river water also increased from the initial ablation to the final ablation period.

Moreover, the average of precipitation was 371.9 mm during the sampling period, and the precipitation in the total ablation period accounted for 78.87%. The average of the temperature, relative humidity, and evaporation during the sampling period were −1.42 °C, 52.20%, and 4.14 mm, respectively. However, the average of the temperature, relative humidity, and evaporation in the ablation period were 8.04 °C, 66.47%, and 5.57 mm, respectively. Through correlation analysis, it is concluded that: there was a significant negative correlation between the precipitation and $\delta^{18}O$ at the 0.01 level (2-tailed), while a significant positive correlation between precipitation and d-excess. More interestingly, just as with precipitation, significant negative correlations were prevalent between $\delta^{18}O$ and temperature, relative humidity, and evaporation, with coefficients of −0.671, −0.555, and −0.636, respectively.

Finally, the mixed segmentation model of the end-member is used to determine the contribution proportion of different water sources to the target water. The results showed that the recharge proportion of precipitation decreased with an increase in altitude in the initial ablation, while the proportions of supra-permafrost water and glacier and snow meltwater showed increasing trends with an increase in altitude. However, the recharge proportion of precipitation was higher than those of the

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supra-permafrost water and glacier and snow meltwater, and also showed a decreasing trend from low to high altitude in the final ablation period in 2016. The proportion of glacier and snow meltwater increased with an increase in altitude, but the recharge proportion of supra-permafrost water was stable with the change in altitude in the final ablation period in 2016. The proportion of supra-permafrost water was 50.53% in the initial and final ablation periods. Meanwhile, supra-permafrost water was the main recharge source of runoff, followed by precipitation in the total ablation period from 2016 to 2018, and the proportions of precipitation and supra-permafrost water were 36.13% and 36.66%, respectively. The recharge proportion of glacier and snow meltwater was higher in the total ablation period than those in the initial and final ablation periods, with a proportion of 19.44% in the initial and final ablation periods and 27.30% in the total ablation period. Compared with the glacier permafrost area river, the recharge proportion of supra-permafrost water was higher for the permafrost area river than that for the glacier permafrost area river (42.21%). The recharge proportion of supra-permafrost water was 69.54%. Just as with the glacier permafrost area river, the supra-permafrost water was the important recharge source to the runoff in the initial and final ablation periods, and the proportion was 80.97% in the initial and final ablation periods. Meanwhile, the proportion of the supra-permafrost water was 61.92% in the total ablation period. The proportion was higher than that for precipitation (24.13%) in the same period. In general, the supra-permafrost water was the major recharge source for the permafrost area river in the study area. Meanwhile, the glacier and snow meltwater contributed little to the permafrost area river in the

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initial and final ablation periods. For the mainstream, the proportion was 35.93% in initial and final ablation periods, and 45.55% in the total ablation period. However, the proportion was 47.49% in the initial and final ablation periods, and 36.47% in the total ablation period. The proportion of glacier and snow meltwater for the mainstream (16.59%) was higher than that for the permafrost area river (3.25%) but was lower than that for the glacier permafrost area river (19.44%) in the initial and final ablation periods. Meanwhile, the proportion of glacier and snow meltwater for the mainstream (17.98%) was higher than that for the permafrost area river (13.95%) but was lower than that for the glacier permafrost area river (27.30%) in the total ablation period.

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Tables:

Table 1 The correlation analysis of $\delta^{18}O$ and d-excess and meteorological factors in the fixed point (TTH and ZMD) from March,16 to July, 18.

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Table 1 The correlation analysis of $\delta^{18}O$ and d-excess and meteorological factors in the fixed point (TTH and ZMD) from March,16 to July, 18.

	Precipitation (mm)	Temperature (℃)	Ralative humidity (%)	Evaporation (mm)	$\delta^{18}O$(‰)	D-excess (‰)
Precipitation(mm)	1					
Temperature(℃)	0.853**	1				
Ralative humidity(%)	0.760**	0.836**	1			
Evaporation(mm)	0.658**	0.865**	0.586**	1		
$\delta^{18}O$(‰)	-0.518**	-0.671**	-0.555**	-0.636**	1	
D-excess(‰)	0.500**	0.602**	0.524**	0.533**	-0.568**	1

Note: **, Correlation is significant at the 0.01 level (2-tailed).

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Figures:

Fig.1 The map of the study area and the sampling point of river water in different ablation period

(Fig.1a was the detail location of the study area in China and Asian and the distribution of fixed point for precipitation, river water and glacier and snow meltwater; Fig.1b was the distribution of sampling point in initial ablation in 2016; Fig.1c was the distribution of sampling point in ablation in 2016; Fig.1d was the distribution of sampling point in end ablation in 2016; Fig.1e was the distribution of sampling point in ablation in 2017; Fig.1f was the distribution of sampling point in ablation in 2018)

Fig.2 Variation of meteorological factors during sampling period

(Shadow represents the ablation period)

Fig.3 Temporal variation of $\delta^{18}O$ and d-excess during the sampling period in study area

(This figure mainly showed the temporal variation of $\delta^{18}O$ and d-excess for different type runoff based on different ablation in 2016 and strong ablation from 2016 to 2018; Fig.2a, b, c showed the change of $\delta^{18}O$ and d-excess in different ablation period for mainstream, glacier and snow runoff and river in permafrost area; Fig.2d, e, f showed the change of $\delta^{18}O$ and d-excess in ablation period from 2016 to 2018 for mainstream, glacier and snow runoff and river in permafrost area)

Fig.4 Spatial variation of $\delta^{18}O$ based on different ablation in 2016 and ablation from 2016 to 2018

Fig.5 Spatial variation of d-excess based on different ablation in 2016 and ablation from 2016 to 2018

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Fig.6 The variation of $\delta^{18}O$ and d-excess with the altitude change in study area

(Fig.6a was the variation of $\delta^{18}O$ and d-excess with the altitude change for mainstream; Fig.6b was the variation of $\delta^{18}O$ and d-excess with the altitude change for river in glacier permafrost area;Fig.6c was the variation of $\delta^{18}O$ and d-excess with the altitude change for river in permafrost area; IA in 2016 represents Initial ablation in 2016; A in 2016 represents Ablation in 2016; EA in 2016 represents End ablation in 2016; A in 2017 represents Ablation in 2017; A in 2018 represents Ablation in 2018)

Fig.7 The distribution of δD and $\delta^{18}O$ for river water among other water bodies in study area

(Fig.7a was the plot of $\delta^{18}O$ for river water in different type, supra-permafrost water, glacier snow meltwater and precipitation; Fig.7b was the plot of δD for river water in different type, supra-permafrost water, glacier snow meltwater and precipitation; Fig.7c was the plot of δD versus $\delta^{18}O$ for river water, supra-permafrost water, glacier snow meltwater and precipitation)

Fig.8 Three end element diagram using the mean values of $\delta^{18}O$ and d-excess for river water in different ablation in 2016 and ablation from 2016 to 2018

Fig.9 Recharge proportion from possible sources to river water in different altitude during different ablation in 2016 and ablation from 2016 to 2018

Fig.10 The variation of location evaporation line (LEL) of river water based on different ablation in 2016 and ablation from 2016 to 2018

Fig.11 Conceptual model map of the recharge form and proportion of the river water in different ablation period

(Dark green represents the basin of river in permafrost area; Gray and light green represents the

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basin of the river in glacier permafrost area)

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Fig.1

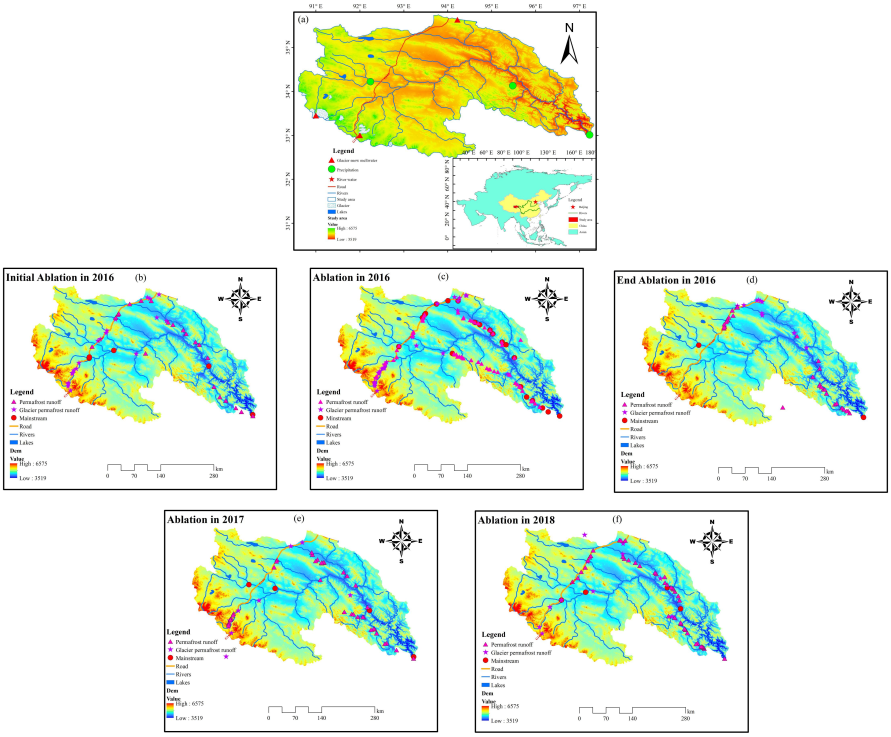

Fig.1 The map of the study area and the sampling point of river water in different ablation period (Fig.1a was the detail location of the study area in China and Asian and the distribution of fixed point for precipitation, river water and glacier and snow meltwater; Fig.1b was the distribution of sampling point in initial ablation in 2016; Fig.1c was the distribution of sampling point in ablation in 2016; Fig.1d was the distribution of sampling point in end ablation in 2016; Fig.1e was the distribution of sampling point in ablation in 2017; Fig.1f was the distribution of sampling point in ablation in 2018)

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Fig.2

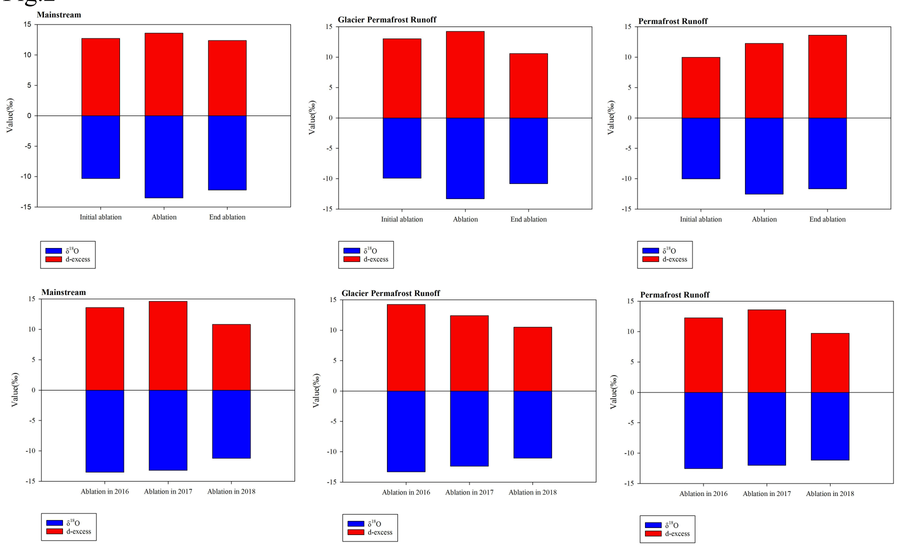

Fig.2 Variation of meteorological factors during sampling period (Shadow represents the ablation period)

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Fig.3

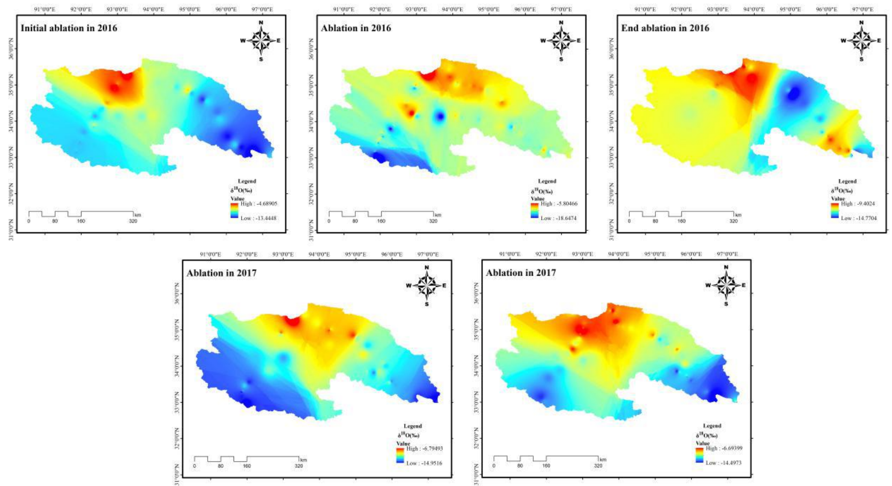

Fig.3 Temporal variation of $\delta^{18}O$ and d-excess during the sampling period in study area (This figure mainly showed the temporal variation of $\delta^{18}O$ and d-excess for different type runoff based on different ablation in 2016 and strong ablation from 2016 to 2018; Fig.2a, b, c showed the change of $\delta^{18}O$ and d-excess in different ablation period for mainstream, glacier and snow runoff and river in permafrost area; Fig.2d, e, f showed the change of $\delta^{18}O$ and d-excess in ablation period from 2016 to 2018 for mainstream, glacier and snow runoff and river in permafrost area)

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Fig.4

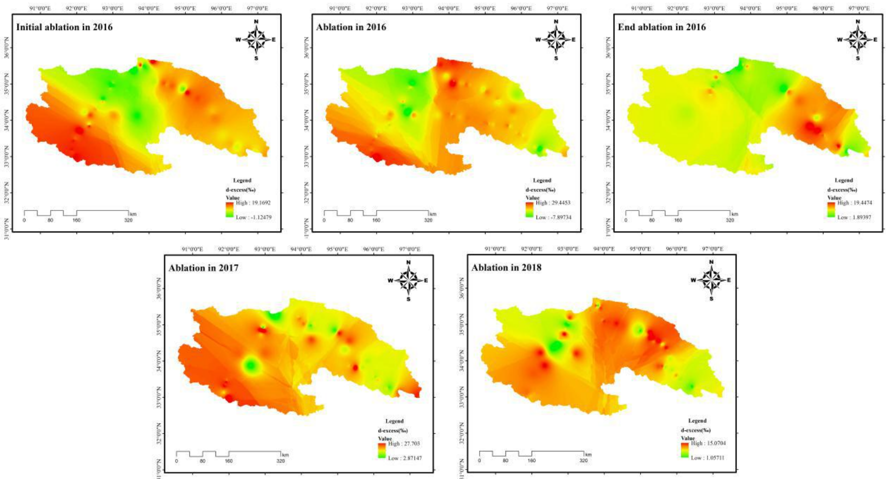

Fig.4 Spatial variation of $\delta^{18}O$ based on different ablation in 2016 and ablation from 2016 to 2018

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Fig.5

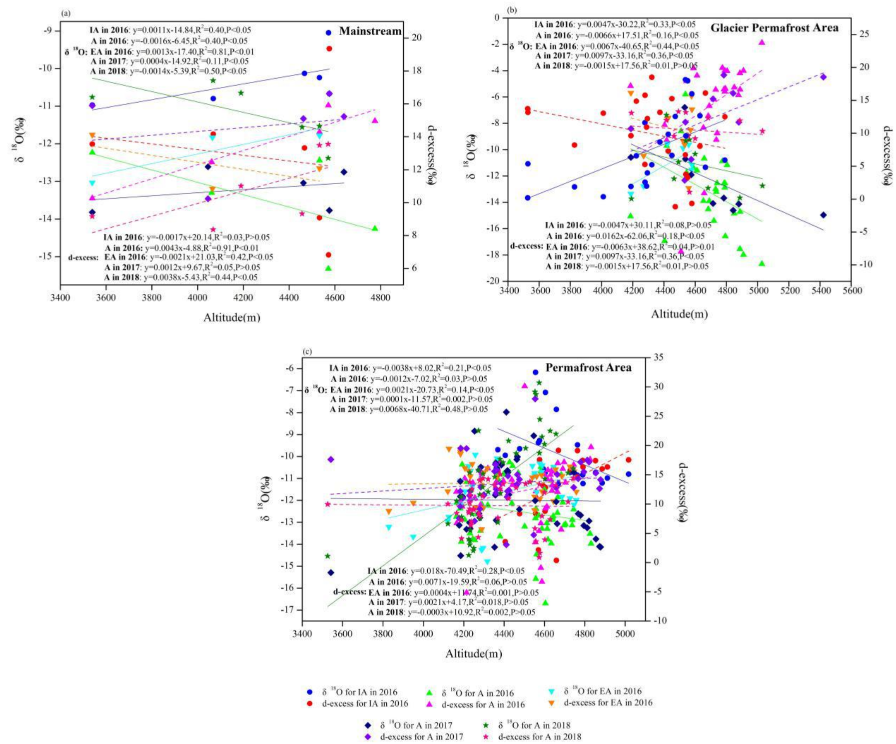

Fig.5 Spatial variation of d-excess based on different ablation in 2016 and ablation from 2016 to 2018

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Fig.6

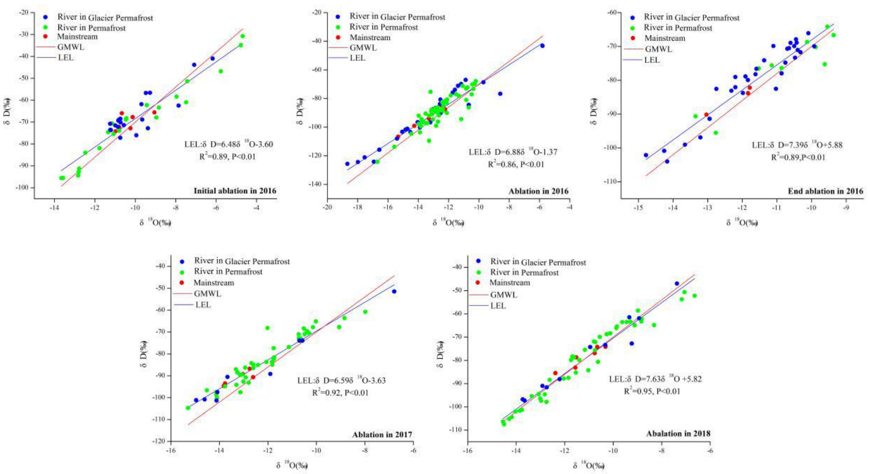

Fig.6 The variation of $\delta^{18}O$ and d-excess with the altitude change in study area

(Fig.6a was the variation of $\delta^{18}O$ and d-excess with the altitude change for mainstream; Fig.6b was the variation of $\delta^{18}O$ and d-excess with the altitude change for river in glacier permafrost area;Fig.6c was the variation of $\delta^{18}O$ and d-excess with the altitude change for river in permafrost area; IA in 2016 represents Initial ablation in 2016; A in 2016 represents Ablation in 2016; EA in 2016 represents End ablation in 2016; A in 2017 represents Ablation in 2017; A in 2018 represents Ablation in 2018)

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Fig.7

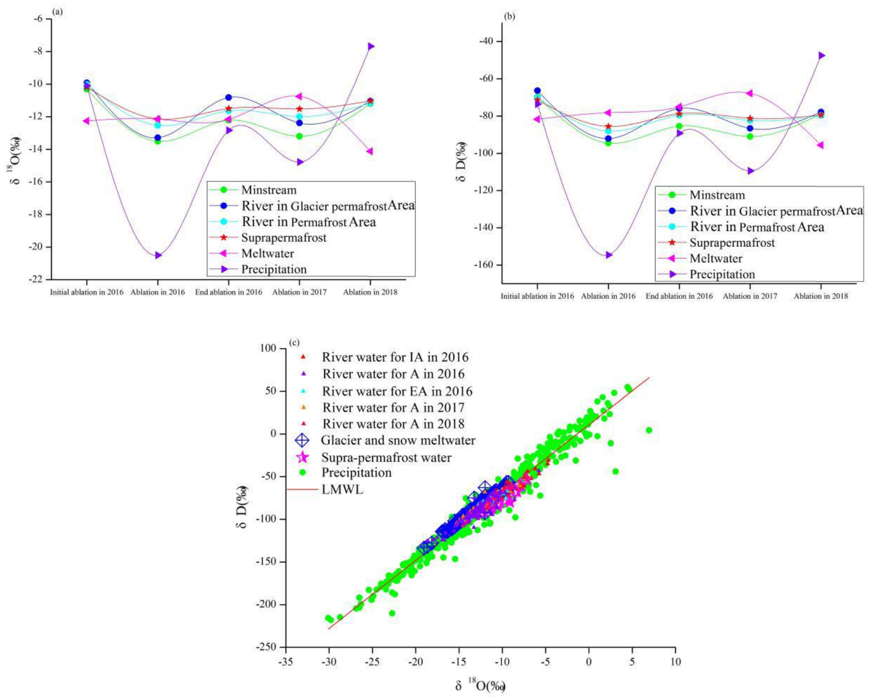

Fig.7 The distribution of δD and δ18O for river water among other water bodies in study area (Fig.7a was the plot of δ18O for river water in different type, supra-permafrost water, glacier snow meltwater and precipitation; Fig.7b was the plot of δD for river water in different type, supra-permafrost water, glacier snow meltwater and precipitation; Fig.7c was the plot of δD versus δ18O for river water, supra-permafrost water, glacier snow meltwater and precipitation)

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Fig.8

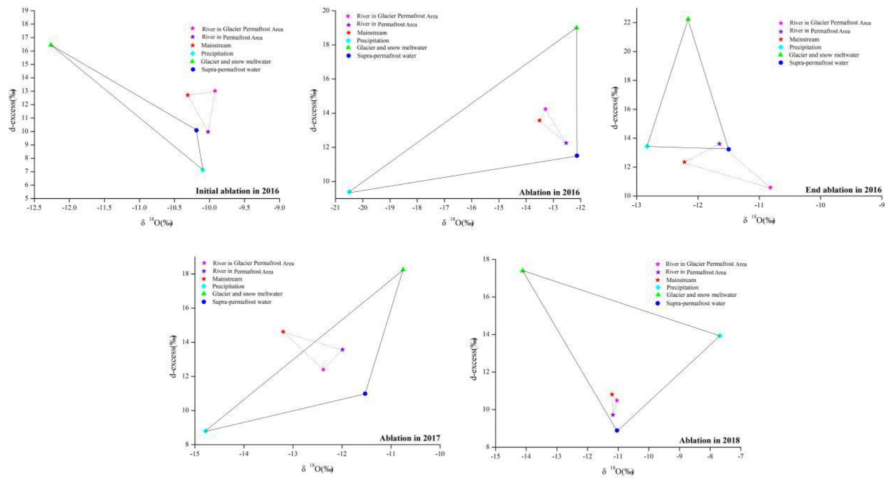

Fig.8 Three end element diagram using the mean values of $\delta^{18}O$ and d-excess for river water in different ablation in 2016 and ablation from 2016 to 2018

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Fig.9

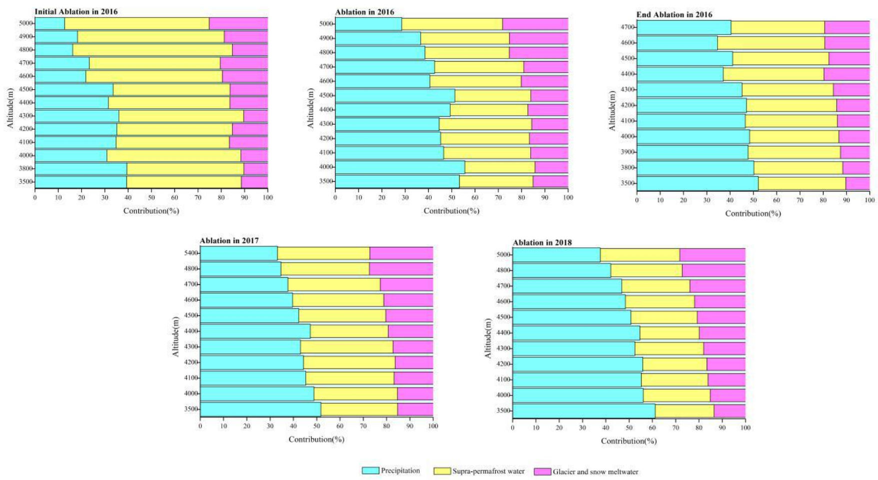

Fig.9 Recharge proportion from possible sources to river water in different altitude during different ablation in 2016 and ablation from 2016 to 2018

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Fig.10

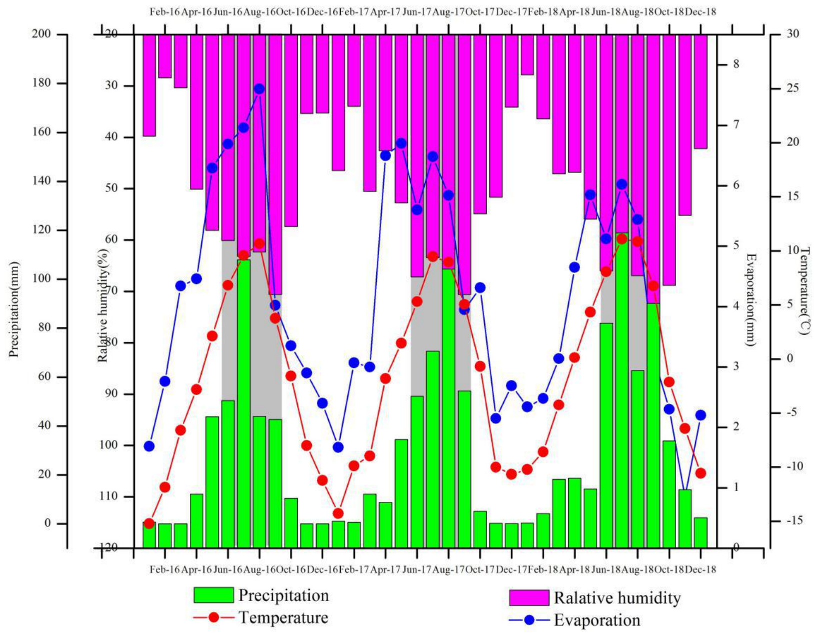

Fig.10 The variation of location evaporation line (LEL) of river water based on different ablation in 2016 and ablation from 2016 to 2018

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Fig.11

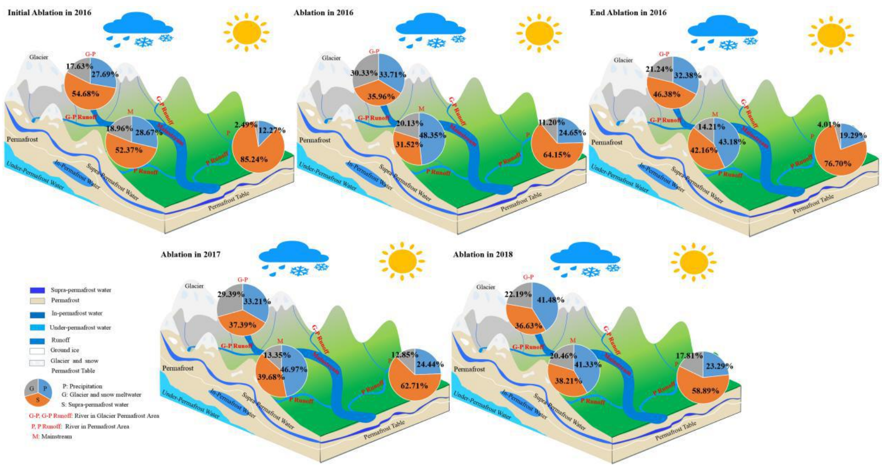

Fig.11 Conceptual model map of the recharge form and proportion of the river water in different ablation period (Dark green represents the basin of river in permafrost area; Gray and light green represents the basin of the river in glacier permafrost area)