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Characteristics of water stable isotopes and runoff sources of a small permafrost basin in northeastern China

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Permafrost degradation may have significant impacts on regional water cycles, while little is known about the recharge sources of runoff in permafrost regions, hindering our capability to predict river discharges. Here, a small permafrost basin in Northeast China was selected as the study area. We analyzed isotopic tracers of 186 precipitation, river water, and supra-permafrost water samples collected from May to October 2021. We further calculated the contribution of supra-permafrost water and precipitation to river discharges. The $\delta^{18}O$ and δD of precipitation exhibited a significant correlation with air temperature ($p<0.05$). Similar values and trends were observed in the stable isotope changes of river water and supra-permafrost water, indicating a close hydraulic relationship between the two water sources. Hydrograph separation revealed that supra-permafrost water and precipitation are the first and second end-member of river water in the basin, with a contribution of 85% and 15%, respectively. Overall, our results suggest that supra-permafrost water is the main recharge source of runoff, highlighting the importance of permafrost in the regulation of runoff in small catchments.

KEYWORDS

stable isotopes, runoff, hydrograph separation, permafrost, greater Khingan mountains

1 Introduction

Over the past few years, permafrost degradation has become a common phenomenon in the permafrost regions due to the rapid global warming. Permafrost degradation caused by climate warming, including deepening of the active layer and melting of ground ice, can lead to changes in the surface thermal regime (Wu and Zhang, 2008; Wu and Zhang, 2010; Piao et al., 2019). Permafrost regions experience unique hydrological processes (Chai et al., 2023) because permafrost is a weak permeable layer that can prevent downward infiltration of water. In addition, melted ground ice can replenish surface water, and thus change in the form and amount of surface water recharge (Cheng and Jin, 2013). The groundwater systems in permafrost regions are composed of supra-permafrost, sub-permafrost and intra-permafrost water, which occur above the permafrost, below the permafrost, and within taliks, respectively (Kane et al., 2013). Supra-permafrost water in the active layer generally exhibits seasonality as the layer freezes and melts (Chang et al., 2018). Precipitation infiltrates the active layer and mixes with supra-permafrost water before flowing into rivers (Li Z. X. et al., 2020). The permafrost region of northern Greater Khingan Mountains is located near the southern limit of the Eurasian permafrost, where climate warming and permafrost degradation will inevitably have a significant impact on the hydrological processes in the region. However, due to the challenging field conditions and limited observations, the quantification of runoff sources of small permafrost basins in northern Greater Khingan Mountains is still absent and the understanding of local hydrological processes is still limited.

Environmental isotopes are important for studying the relationship among precipitation, groundwater, and surface water within the water cycle (Chen and Wang, 2009; Bolduc et al., 2018). $\delta^{18}O$ and δD are key isotopes of natural water. Evaporation and condensation in the water cycle process can lead to isotope fractionation. The water from different sources exhibits distinct stable isotopic composition characteristics of hydrogen and oxygen. As natural tracers, $\delta^{18}O$ and δD can provide valuable information on the water source, the processes controlling stream water dynamics, and its flow paths. Deuterium excess (D-excess) can provide valuable information about atmospheric humidity, surface temperature, and water evaporation (Gat et al., 2003; Vodila et al., 2011).

In recent decades, stable isotopes of precipitation (Yao et al., 2013; Ren et al., 2021), river water (Ala-aho et al., 2018), groundwater (Adomako et al., 2010), lake water (Pang et al., 2007) and snowmelt water (Jin et al., 2012; Miller et al., 2021) have been extensively studied. Hydrogen and oxygen stable isotope tracers have been widely employed to study the recharge sources of different water bodies in the water cycle of various regions (Sugimoto et al., 2003; Carey et al., 2013), as well as to explore the mutual transformation relationship between surface water and groundwater (Hren et al., 2009; Boucher and Carey, 2010; Turner et al., 2014). Sun et al. (2016) pointed out that precipitation serves as the primary source of runoff in inland river basins. Li Z. X. et al. (2019) utilized stable isotope tracing to reveal that the surface water and groundwater in the Qilian Mountains undergo distinct transformation patterns during different periods of the year, shedding light on their dynamic hydrological processes. Langman et al. (2022) found that winter meltwater (an early signal of depletion) may be a primary contributor to creeks and groundwater along the Palouse Mountains. Furthermore, stable isotope tracing has also made notable advancements in the study of biogeochemical cycles (Mul et al., 2008; Wu et al., 2009) and the determination of stream water residence times (Wang et al., 2022). In addition, numerous studies have demonstrated that permafrost degradation results in decreased or vanished soil impermeability, consequently intensifying the dynamic connectivity between surface water and groundwater under warming climatic conditions (Liu et al., 2003; Ye et al., 2003). These studies also confirmed the importance of supra-permafrost for surface river water in the permafrost regions (Li Z. X. et al., 2020; Gui et al., 2024). However, quantifying the contribution of supra-permafrost water to surface runoff in permafrost basins is largely unknown. Mountainous permafrost regions are more sensitive to climate change than other regions (Dedieu et al., 2014), and runoff changes in mountain areas can lead to floods or droughts in the downstream regions. Therefore, it is necessary to understand the relevant hydrological processes in order to provide references for the scientific use and effective prediction of water resources.

The permafrost region of the northern Greater Khingan Mountains is located in the southern margin of the Eurasian permafrost region. The permafrost in this region is sensitive to climate change. In this study, we explore the temporal variation of isotopes in various water sources, conduct hydrograph separation analysis of runoff, and identify their contributions to the river. The specific aims are to: (a) document the temporal characteristics of $\delta^{18}O$ and δD in various water bodies; (b) reveal the hydrological processes influenced by the stable isotopes; and (c) determine the contribution of each water source to runoff. The results can reveal the replenishment mechanism of runoff in cold regions and provide parameters for simulating and predicting runoff changes.

2 Data and methodology

2.1 Study area

The permafrost region in the north of the Greater Khingan Mountains is situated on the southern margin of the Eurasian permafrost region (Ma et al., 2021). It is predominantly characterized by the presence of discontinuous permafrost, sporadic permafrost, and isolated permafrost. This region features a complex network of water systems and numerous small river basins. The Laoyeling basin, as a small permafrost basin within China, covers an area of 22.22 km^2. It is located in Mohe City, the highest latitude city in China and in the northern Greater Khingan Mountains (Figure 1). The main stream melts completely in late April to early May and freezes in late October to early November, while the tributaries appear intermittently. The water level of the main stream varies between 19.96 cm and 57.58 cm from May to October 2021, with the highest value appearing in June. Influenced by the continental monsoon climate of the cold temperate zone, winters are cold and prolonged, summers are cool and brief, and autumn arrives swiftly. The average annual temperature in the region ranges from −2.5°C–5.0°C, with 80–110 frost-free days per year (Zheng, 1980). Annual precipitation ranges from 350 to 500 mm, primarily concentrated between July and August. There is snowpack in the basin from November to April of the following year, with the deepest snowpack reaching about 40 cm in mid-March. The snowpack melting starts in mid-March and ends in mid-to-late April, lasting about 1 month. During melting periods, precipitation and supra-permafrost water provide the water sources. The active layer thickness in this region varies from 1.5 to 4.5 m (Duan et al., 2017). The soil is rich in gravels and exhibits high permeability. Larix gmelinii, Betula platyphylla, and Pinus sylvestris var. mongolica are the key forest species (Ma et al., 2021), while arbor and herbaceous vegetation in marshes line the river, along with a small area of meadow vegetation.

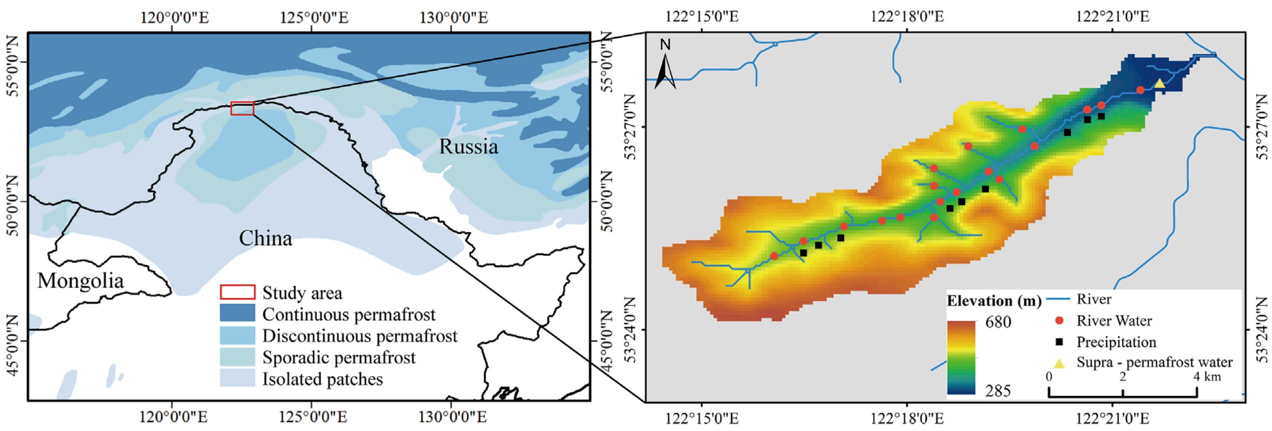

FIGURE 1
The location of the Laoyeling river basin in the northern Greater Khingan Mountains and the sampling sites.

TABLE 1 Sampling amounts and times of precipitation, river water and permafrost-water.

Sample	Sample amounts	Times
Precipitation	49	49
River water	83	6
Permafrost-water	54	6

2.2 Sampling and laboratory analysis

Precipitation samples were collected at the Laoyeling Hydrological Station (Figure 1) during precipitation events, resulting in a total of 49 samples from May to October 2021 (Table 1). Sample collectors were installed on the roof approximately 8 m above the ground, with an additional 1 m above the roof for protection against surface soil and other potential contaminants. Following each precipitation event, samples were carefully collected into pre-cleaned polyethylene bottles and sealed with Parafilm to prevent evaporation. Collection devices such as funnels, flecks, and polyethylene bottles were cleaned before each sampling event. All samples were stored in a refrigerator at 4°C. Meteorological data were obtained from the Mohe Forest Ecological Research Station, situated approximately 300 m above sea level and 200 m away from the study area (Figure 1).

A total of 83 water samples were collected along the Laoyeling River from May 2021 to October 2021 for the river water (Table 1). Monthly sampling was conducted at 12 sampling points in the mainstream, and six sampling sites in intermittently existing tributaries, which disappeared after July due to precipitation and snow meltwater effects (Figure 1).

Supra-permafrost water is widely distributed as a type of groundwater in the northern permafrost area of the Greater Khingan Mountains. It is mainly stored in the active layer above the permafrost. Affected by the melting of permafrost and the freezing-thawing cycles of seasonal frozen soil, the supra-permafrost water has complex and variable hydrological characteristics (Li Z. X. et al., 2020). The aquifer primarily consists of quaternary loose sediments and weathered fractures of bedrock in the study area. Permafrost water not only stores substantial solid water resources, but also plays an important role in maintaining the water levels of surface water and groundwater (Cheng and Jin, 2013). To investigate the characteristics of water on the permafrost, a total of 54 samples were collected monthly from May to October 2021. In order to have a more scientific and comprehensive understanding of the characteristics of supra-permafrost water in the basin, three sampling points were established in the upstream, midstream, and downstream respectively (Figure 1; Table 1). A 1.5-m deep profile of the permafrost active layer was excavated at each sampling site, and water samples were then collected after being filtered through a 0.45-μm Millipore filtration membrane at the bottom of the profile.

The analysis work was conducted at the Heilongjiang Provincial Key Laboratory of Geographical Environment Monitoring and Spatial Information Services in Cold Regions, Harbin Normal University. Prior to testing, all water samples were treated with a disposable membrane filter of 0.22 μm. Stable isotopes of hydrogen and oxygen were analyzed using a stable isotope ratio mass spectrometer (MAT253, United States). The results are reported in standard δ-notation (‰) relative to the Vienna Standard Mean Ocean Water, with precisions of ±2‰ for δD and ±0.1‰ for $\delta^{18}O$.

2.3 Hydrograph separation

End-member mixing analysis (EMMA) is commonly employed to analyze potential recharge sources of river water (Hooper et al., 1990; Gibson et al., 2015). It quantifies the contribution of different water sources to runoff based on the mass balance principle (Genereux, 1998; Uhlenbrook and Hoeg, 2003). The approach assumes that the chemical properties of stable isotopic tracers ($\delta^{18}O$, δD, etc.) and geochemical tracers (TDS, EC, Cl-, etc.) are constant, and any changes observed in the tracers are mainly caused by water transformation and mixing processes. In this study, $\delta^{18}O$ was used as a tracer to separate water sources. The two-component method of isotopic hydrograph separation (IHS) described using Equations 1, 2 as follows:

$$Q_r = Q_p + Q_s \tag{1}$$

$$\delta_r Q_r = \delta_p Q_p + \delta_s Q_s \tag{2}$$

where Q_r, Q_p, and Q_s denote river water, precipitation water and supra-permafrost water volume, respectively; and δ_r, δ_p and δ_s are the corresponding isotope values. The contributions of precipitation water and event water to stream water can be determined by combining Equations 1, 2 to obtain Equations 3, 4:

$$F_p = \frac{\delta_r - \delta_s}{\delta_p - \delta_s} \tag{3}$$

$$F_g = \frac{\delta_p - \delta_r}{\delta_p - \delta_s} \tag{4}$$

where F_p and F_s denote the relative contribution ratio of precipitation water and ground water to river water, respectively. In this study, we adopt the precipitation-weighted average of precipitation isotopes to assess river water components on a monthly scale.

3 Results

3.1 Stable isotopes composition

The δ^{18}O value of precipitation ranged from −24.32‰ to −5.20‰, with an average of −11.63‰. The corresponding δD value ranged from −152.47‰ to −40.53‰, with an average of −92.37‰. The stable isotopes of precipitation in the Laoyeling basin exhibited clear time variation, initially increasing and subsequently decreasing with time (Figure 2). Stable isotopic composition of summer precipitation (June to August) ranged from −16.70‰ to −5.20‰ for δ^{18}O and from −119.65‰ to −40.53‰ for δD, with mean values of −10.82‰ and −82.29‰ for δ^{18}O and δD, which were greater than those obtained for the entire sampling period. The δ^{18}O and δD values of precipitation in May, September, and October ranged from −24.32‰ to −9.28‰ and −188.01‰ to −78.07‰, with average values of −16.20‰ and −124.49‰, respectively. These values were lower than those obtained for the entire sampling period.

The δ^{18}O of river ranged from −19.01‰ to −15.59‰, with a mean value of −17.08‰. The δD ranged from −128.75‰ to −109.39‰, with a mean value of −118.00‰. The mean value of d-excess was 19.86‰, ranging from 6.64‰ to 29.43‰. Despite the large seasonal variation in precipitation isotopes, the stable isotopes of river water showed slight fluctuations during the study period, with more positive values in summer (June–August) and more negative values in May, September, and October. For the summer months, the stable isotopic values of river water ranged from −19.96‰ to −17.15‰ for δ^{18}O and from −131.00‰ to −116.01‰ for δD, with mean values of −18.43 and −125.54‰, respectively. The depleted isotopic values were attributed to increased supra-permafrost water recharge to rivers. In May, September, and October, the δ^{18}O and δD values ranged from −20.04‰ to −16.71‰ and from −139.19‰ to −113.71‰, with average values of −17.76‰ and −125.07‰, respectively. Although the average flow of river water is large in precipitation months, the change in stable isotopes is not obvious (Figure 2).

The δ^{18}O of supra-permafrost water ranged from −20.64‰ to −16.96‰, with an average value of −18.53‰. The δD ranged from −146.66‰ to −114.43‰, with an average value of −21.44‰. The d-excess ranged from 8.76‰ to 29.16‰, with an average value of 21.44‰. The δ^{18}O, δD, and d-excess values of supra-permafrost water exhibited slight temporal variation during the observation period, while greater fluctuations were observed for the corresponding values of precipitation and river water (Figure 2).

The deuterium excess (d-excess) is an important parameter for precipitation because it contains key information related to water vapor sources. The d-excess range of precipitation were determined as −12.62‰ to 16.15‰, with an average of 3.70‰. The temporal variation of the d-excess showed an inverse trend compared to that of δ^{18}O, with low values in June to August and high values in May, September, and October (Figure 2). The d-excess values of precipitation varied widely in summer (June–August), ranging from −12.62‰ to 16.15‰, with an average value of 4.24‰. A narrow range was observed for the d-excess values of precipitation in May, September, and October, ranging from −5.39‰ to 15.92‰, with an average of 5.09‰. The d-excess values of both river water and supra-permafrost water showed slight fluctuations, similar to the patterns of their δ^{18}O and δD values.

3.2 Meteorological effects

From May to October, a significant positive correlation was observed between the isotopic composition of precipitation and temperature in the study area (Figure 3A). When the temperature increased by 1°C, the isotope value of precipitation δ^{18}O increased by 0.66‰ and δD by 4.96‰, indicating a significant temperature effect. This shows that sub-cloud evaporation significantly affects precipitation during the fall of raindrops. An increase in precipitation was accompanied by a significant rise in temperature and noticeable secondary evaporation occurring below cloud. As a result, the amount effect was not significant (Figure 3B). In addition, this may also be due to the mixing of raindrops with a certain amount of locally recirculated water vapor during their descent. Further analysis of the relationship between isotopic composition and precipitation in summer (June–August) showed that the relationship between δ^{18}O and precipitation remained non-significant. These findings indicated that precipitation alone is not the key factor affecting its isotopic composition in this region.

The stable isotopes exhibited a gradual decrease during continuous precipitation. For example, during a sustained precipitation event from June 14 to June 15, δ^{18}O and δD decreased from −7.66‰ and −60.07‰ to −8.72‰ and −64.74‰, respectively. Similarly, during a sustained precipitation event from July 22 to 23, δ^{18}O and δD decreased from −6.11‰ and −48.28‰ to −7.97‰ and −62.14‰, respectively (Table 2). The results reveal that the amount effect was more significant during the continuous precipitation period. During the early stage of continuous precipitation, water vapor, enriched in the heavier isotopes δ^{18}O and δD, preferentially condenses into raindrops, resulting in a gradual depletion of heavy isotopes in subsequent precipitation. Therefore, δ^{18}O and δD in

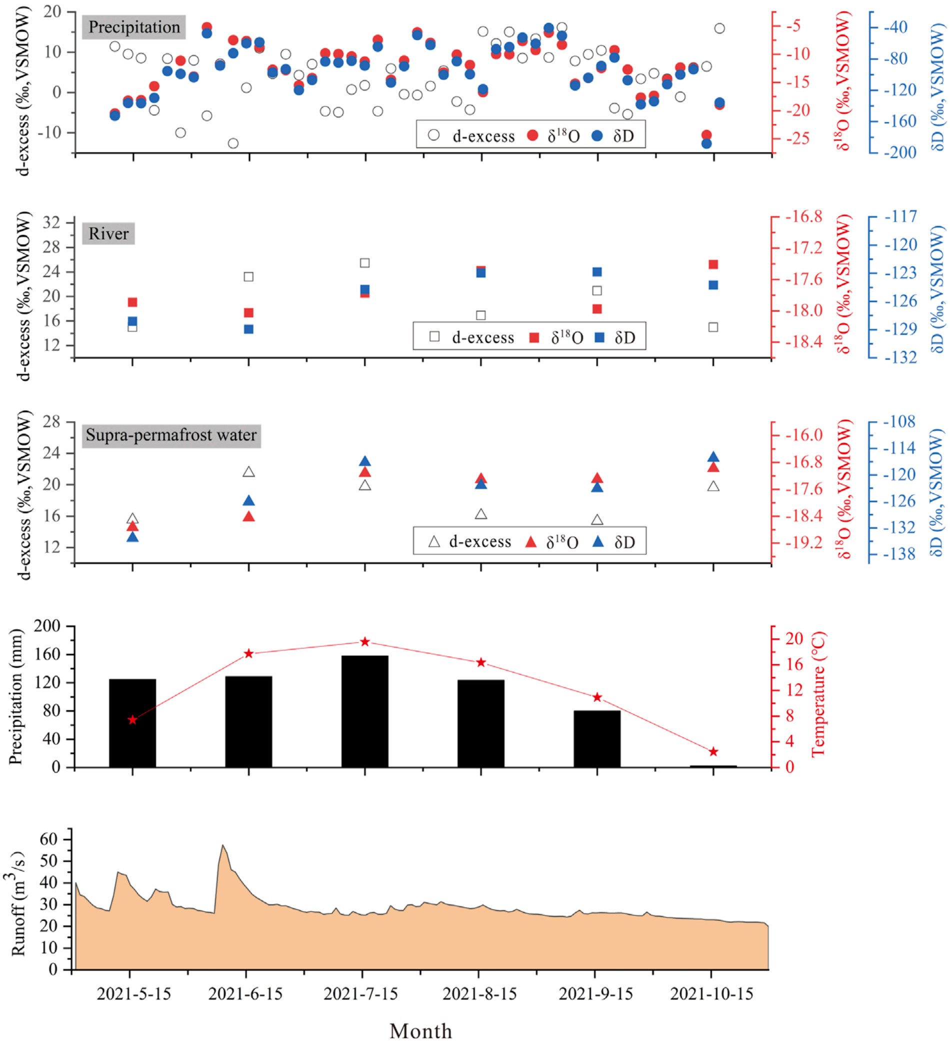

FIGURE 2
Stable isotopic composition of precipitation, river water, supra-permafrost water, air temperature, precipitation amount, and runoff depth in the Laoyeling basin.

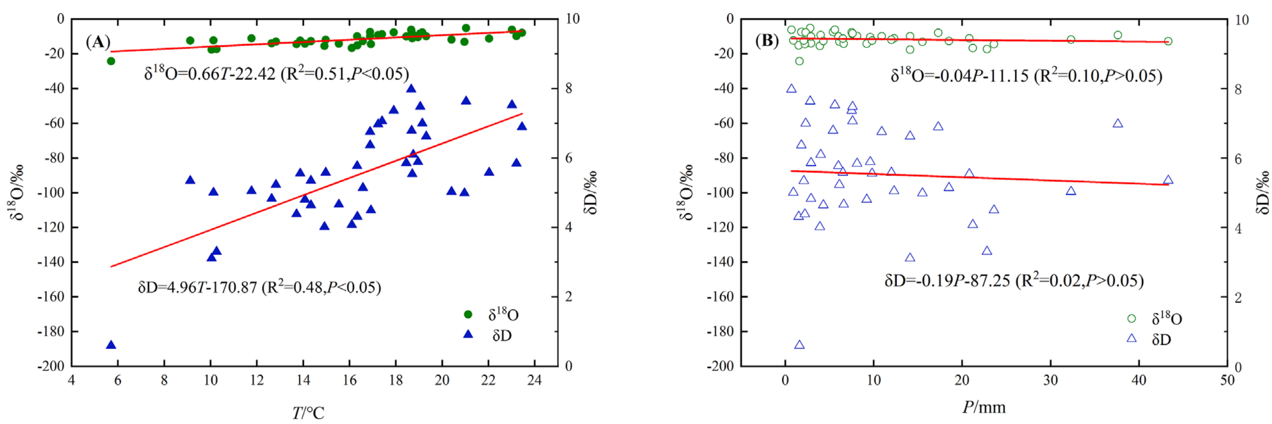

FIGURE 3
Relationship between the stable isotopes of precipitation and temperature **(A)**, amount **(B)** in the Laoyeling basin.

TABLE 2 Variation of isotopic composition and meteorological factors of continuous precipitation events.

Date	$\delta^{18}O$ /(‰)	δD /(‰)	d-excess /(°C)	Temperature /(°C)	Precipitation /(mm)
2021-06-14	−7.66	−60.07	1.19	19.14	2.3
2021-06-15	−8.72	−64.74	2.02	17.4	7.6
2021-07-22	−6.11	−48.28	0.60	23.01	5.6
2021-07-23	−7.97	−62.14	1.63	23.45	17.3

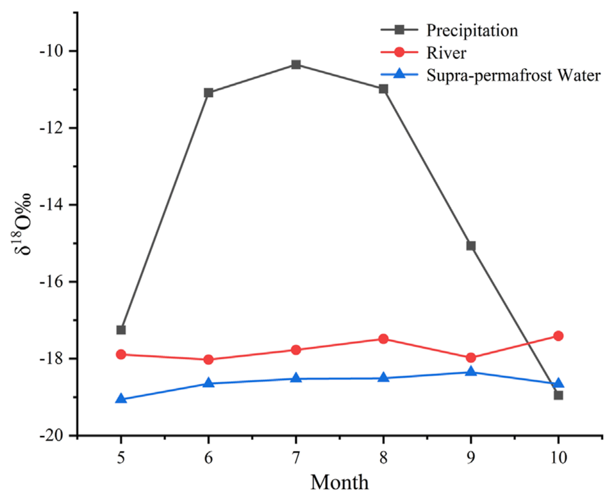

FIGURE 4
Temporal variation of $\delta^{18}O$ in precipitation, river water, and supra-permafrost water.

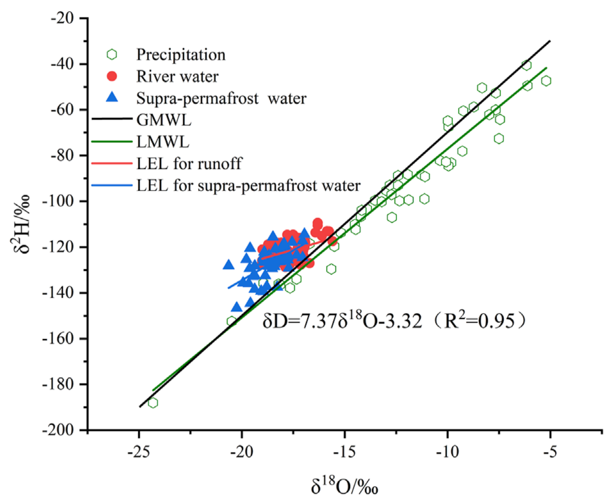

FIGURE 5
Scatter plot of $\delta^{18}O$ and δD for different water types.

water vapor gradually deplete with the duration of precipitation events, leading to a decline in stable isotope concentration over time.

3.3 Recharge sources of river water in the laoyeling basin

The distribution of river water and supra-permafrost water was observed to closely follow a similar distribution pattern, with river water falling between supra-permafrost water and precipitation (Figure 4). The isotopic composition of both river water and supra-permafrost water in the basin coincided with the local meteoric water line (LMWL), and the clustering of isotopic data from river water, precipitation, and supra-permafrost water demonstrated a close hydraulic connection in terms of recharge and discharge (Figure 5). A local evaporation line (LEL) for river water was established as $\delta D = 3.12\delta^{18}O - 68.93$ ($R^2 = 0.63$). The slope of the LEL (3.12) was notably lower than that of the LMWL (7.37), indicating a stronger evaporation effect.

The stable isotope composition of precipitation in the Laoyeling basin exhibited noticeable temporal variation, characterized by an initial increase followed by a decrease. In contrast, the stable isotope composition of river water showed only slight temporal variation, suggesting that the direct influence of precipitation on river water was not pronounced during the study period. Correlation analysis indicated a positive but not significant correlation between precipitation and runoff depth during the sampling period (Table 3). From April to June and from August to October, a significant positive correlation was observed, indicating that precipitation was an important water source of runoff (Table 3). Notably, the correlation between precipitation and runoff depth from June to August was not significant (Table 3). This may be attributed to that vegetation intercepted and utilized a significant portion of precipitation, which then infiltrated underground to contribute to other water sources. Moreover, the maximum monthly mean value of runoff depth occurred from April to June, while the maximum monthly mean value of precipitation appeared from June to August. All the above indicated that precipitation was not the sole source of the runoff. The same seasonal patterns and the similar range of monthly mean $\delta^{18}O$ values were observed between river water and supra-permafrost water (Figure 2). Moreover, most of the δD versus $\delta^{18}O$ points of river water lay between the points of precipitation and supra-permafrost water (Figure 5). These indicated that the river water was mainly dominated and replenished by supra-permafrost water.

TABLE 3 Variation trend of monthly average runoff depth, precipitation, and temperature (°C or mm), the correlation coefficient between runoff depth and corresponding values of precipitation(R&P) and temperature (R&T).

Month	4–10	4–6	6–8	8–10
Runoff depth	28.28	31.12	29.32	24.49
Precipitation	2.95	2.89	4.47	2.28
Temperature	10.93	9.07	17.89	9.91
R&P	0.22	**0.99**	−0.04	**0.99**
R&T	0.06	0.59	0.01	**1.00**

[a]Trends significance at the 5% level are in bold.

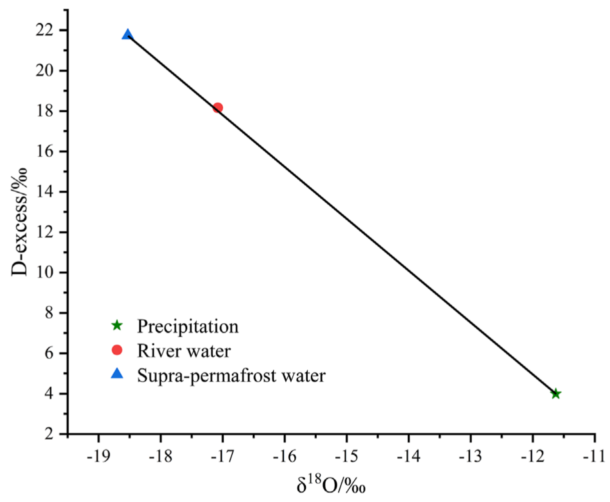

FIGURE 6
End-member mixing analysis for the Laoyeling basin.

These characteristics indicated that river water in the basin was recharged by two sources, namely supra-permafrost water and precipitation. The $\delta^{18}O$ concentrations in river water, precipitation, and supra-permafrost water exhibited significant value variations within the basin. Thus, the $\delta^{18}O$ concentration was selected for further analysis and to optimize the separation of water sources. The isotopic composition of river water lay along the line between supra-permafrost water and precipitation, indicating that both supra-permafrost water and precipitation served as recharge sources for river water. Supra-permafrost water was considered the first end-member, while precipitation served as the second end-member (Figure 6). The average $\delta^{18}O$ values were determined as −11.63‰, −17.76‰, and −18.53‰ for precipitation, river water, and supra-permafrost water, respectively. The distinct $\delta^{18}O$ values of each potential recharge source served as tracers for end-member mixing analysis (EMMA). According to the EMMA model, supra-permafrost water and precipitation accounted for 85% and 15% of the river water in the Laoyeling basin, respectively. This indicates that the primary source of runoff is supra-permafrost water.

4 Discussion

4.1 Assumptions and uncertainties of the EMMA model

The model uncertainty of EMMA is usually ignored in the hydrograph separation using stable isotope tracers (Genereux, 1998). It is necessary to make assumptions and explanations about the model before constructing it. In this study, the Laoyeling basin is regarded as a closed area. Precipitation is the input to the water cycle in the basin. Since there is no snowpack in the catchment during the sampling period, it is assumed that there is no snow recharge to runoff in the model. However, snowmelt water is one of the sources of supra-permafrost water in permafrost regions (Li et al., 2020a; Gui et al., 2024). Therefore, snowmelt water before the sampling period may have indirectly and delayed effect on surface runoff by recharging the supra-permafrost water in this study area. Permafrost degradation can significantly affect hydrological processes in winter (Niu et al., 2011). However, the Laoyeling river in this study is seasonal and does not exist in winter. Therefore, it is assumed that permafrost degradation does not recharge the river in the model. The groundwater in northeast China mainly contains three types: supra-permafrost water, sub-permafrost water, and river and lake talik water (Cheng and Jin, 2013). The river is not replenished by sub-permafrost water because it does not disappear in the winter if it is recharged by sub-permafrost water. Taliks usually exist under large rivers and lakes. However, the river in the study area is small, with a maximum runoff depth of only 57.58 cm. Therefore, it is assumed that the river is not recharged by river and lake talik water in the model. Moreover, the river's existence coincides with the thawing period of the active layer above permafrost. Therefore, it is assumed that the river is recharged by supra-permafrost water in the model. Although there are some uncertainties for EMMA, it is still a valuable tool for quantitatively evaluating the contribution of different water bodies to runoff and improving our understanding of hydrological processes in permafrost regions.

4.2 Stable isotopes and their meteorological effects

Precipitation is an input to the terrestrial hydrological cycle, and understanding the isotopic characteristics of precipitation is very important for ecohydrological studies of wetlands (dos Santos et al., 2019; Tao et al., 2021). The stable isotopes of precipitation in the study area initially increased and subsequently decreased with time. This trend is attributed to evaporation. From June to August, the high temperatures significantly influenced precipitation, leading to secondary evaporation beneath clouds as raindrops fall. This contributed to the elevated $\delta^{18}O$ values of precipitation. The d-excess values were closely related to the relative humidity of water vapor sources and the dynamic fractionation during evaporation (Dansgaard, 1964). The $\delta^{18}O$ values of precipitation in the northeast China monsoon region were closely related to the advance and retreat of East Asian monsoon and the rainfall belt transfer (Liu et al., 2010). From June to August, the wet air mass not only brought a large amount of precipitation, but also led to a low d-excess. In May, September and October, air masses with low humidity, along with local water vapor recycling processes, resulted in higher d-excess values. Moreover, d-excess values were affected by the evaporation of water vapor (Aron et al., 2021). The higher temperatures from June to August led to strong evaporation, contributing to lower d-excess values. In contrast, the colder temperatures in May, September, and October, along with weaker evaporation, resulted in higher d-excess values. The meteoric water line contains a wealth of information, including the evaporation, transport, condensation, and precipitation of water vapor during the water cycle (Breitenbach et al., 2010). It not only reflects the changes in natural factors in the region but also holds significant importance for studying the variations of stable isotopes in atmospheric precipitation. The first local meteoric water line (LMWL) established for the Laoyeling basin was determined as $\delta D = 7.37\delta^{18}O - 3.32$, $R^2 = 0.95$ (Figure 5). Compared with the meteoric water line in China, $\delta D = 7.9\delta^{18}O + 8.2$ (Zheng et al., 1983) and the global meteoric water line (GMWL), $\delta D = 8\delta^{18}O + 10$ (Craig, 1961), the local meteoric water line (LMWL) at Laoyeling exhibited a lower slope and intercept. The relatively low slope indicates the presence of significant secondary evaporation during the precipitation process in the basin.

The temporal variation of $\delta^{18}O$ in river water and permafrost is not obvious. This is consistent with the temporal variation of river water and permafrost water in other areas where supra-permafrost water participates in river recharge (Gui et al., 2019; Li Z. X. et al., 2020). Previous study determined that river water with high d-excess values represents the isotopic signature of spring or summer precipitation, while a medium d-excess value indicates the recharge signal of supra-permafrost water or active layer water to river (Yang et al., 2019). The precipitation amount in July is the largest, and the d-excess of river also shows a high value (Figure 2), indicating that precipitation may play a more important role in the process of replenishing river water at this time. With the decrease of precipitation from August to October, the d-excess value of river water decreased compared with that from May to July, indicating that supra-permafrost water as a recharge source may have a greater impact on the composition of river water. The LEL of river water and supra-permafrost water were $\delta D = 3.12\delta^{18}O - 68.93$ ($R^2 = 0.63$) and $\delta D = 6.39\delta^{18}O - 10.40$ ($R^2 = 0.771$),respectively. The low slopes indicated that both of them were subject to strong evaporation, especially as the river is more sensitive to evaporation due to its narrow channel and small discharge. Theoretically, increased temperature would enhance evaporation, resulting in higher $\delta^{18}O$ values in the water (Li Y. et al., 2023). However, we found that the highest $\delta^{18}O$ value of the river water did not occur in July, the hottest month, but in August(Figure 2). The reason was that the highest precipitation occurred in July, counteracting the effect of evaporation on $\delta^{18}O$ in the river water.

Temperature is a crucial factor influencing the isotopic composition of precipitation (Matthews et al., 2016). Near-surface temperature is linked to the condensation temperature of the corresponding air mass, impacting the stable isotope values in atmospheric precipitation. Rayleigh fractionation, driven by temperature, results in lower stable isotope concentrations in precipitation as temperature decreases. Under the influence of temperature, sub-cloud evaporation and water vapor cycles are vital factors affecting isotope evolution during precipitation (Li et al., 2015; Sun et al., 2015; Li Z. J. et al., 2019). The temperature effect on the stable isotopes of precipitation in the Laolaoling basin was found to be smaller than in inland areas of China (Wu and Zhang, 2010; Li et al., 2012; Zhu et al., 2015). This difference may be attributed to the wetter climate in the study area compared to inland areas. In addition, the sampling period in the study area took place from May to October, characterized by high temperatures and abundant precipitation. Stable isotope enrichment caused by intense sub-cloud evaporation was counteracted by depletion caused by water vapor recirculation. This result aligns with previous studies indicating that temperature is the primary factor controlling changes in the stable isotope composition of precipitation in middle and high latitudes, with the temperature effect becoming more pronounced further inland (Li et al., 2011).

The significant negative correlation between stable isotope concentration and precipitation, known as the amount effect, is observed in coastal areas of middle and low latitudes and regions influenced by monsoons. This effect is likely associated with intense convective weather (Dansgaard, 1964; Yapp and Epstein, 1982). The formation mechanism of the amount effect is complex and depends on three precipitation formation processes: evaporation conditions in the water vapor source area, the water vapor transport process, and the degree of condensation during precipitation. The study area has a temperate continental monsoon climate, characterized by the influence of the East Asian monsoon, westerlies, and local evaporation. The alternation of air masses from different sources, combined with temperature effects, leads to seasonal variations in stable isotopes of atmospheric precipitation.

4.3 Importance of supra-permafrost water

The supra-permafrost water plays a crucial role as a source of runoff in the cryosphere, which holds significant importance for local hydrological processes and ecosystems. In the three-river headwater region, known as "Chinese Water Tower," supra-permafrost water accounts for 39% of river water (Li Z. X. et al., 2023). In the source regions of the Yangtze River, the river water contains 42.21% and 69.54% of supra-permafrost water in the glacier permafrost area and the permafrost area, respectively (Li et al., 2020b). Supra-permafrost water is the main water source of Tuotuo River on the Qinghai-Tibet Plateau, accounting for 51% (Li Z. X. et al., 2020).

Our results also showed that supra-permafrost water is the main source of river water in the mountains small river basin, but it is different from high mountainous arid inland river basins, where precipitation is the main source of rivers (Li et al., 2015; Li et al., 2016b; Gui et al., 2019). Water vapor can be lifted by the blocking effect of mountains to a high altitude where temperatures are low, forming local precipitation that replenishing rivers. However, the elevation of the mountains in the study area is relatively low, and thus the effect on the local water vapor lifting is not significant. In addition, precipitation may experience more soil infiltration and interception by vegetation roots during its downward flow along mountains and recharge the rivers due to the higher vegetation coverage and looser soil of the mountains in the study area. Besides supra-permafrost water, snowmelt water and glacier melt water are also important components of surface water supply in cold regions (Penna et al., 2014; Rai et al., 2019; Kong and Pang, 2012;

Wang et al., 2015). However, our results are not consistent with those of the previous studies. This is due to the lack of perennial glaciers and snow cover in the permafrost area of the northern Greater Khingan Mountains during the sampling period of this study. Previous research identified subsurface water as the main source of rivers in Northeast China (Kendall, 1993). This agrees with the current study, which we identified supra-permafrost water as the main source of seasonal runoff in the permafrost region of the northern Greater Khingan Mountains. Dense vegetation and loose soil provide favorable conditions for the conversion of precipitation into subsurface water.

The groundwater in northeast China mainly contains three types: supra-permafrost water, sub-permafrost water, and river and lake talik water (Cheng and Jin, 2013). Interestingly, a previous study showed that Huma river in the permafrost region of northeast China was mainly recharged by sub-permafrost water, rather than supra-permafrost water (Ma et al., 2021). The river will not disappear in the winter if it is recharged by sub-permafrost water. Huma river is a perennial river, and runoff remains in the winter when the active layer freezes. This indicates that the river is recharged by sub-permafrost water. However, the Laoyeling river in the study area is seasonal, and its presence and disappearance coincide with the thawing and freezing of the active layer on the permafrost. Therefore, the river in the study area is not recharged by sub-permafrost water. River and lake talik water vary with the areal extent of surface-water bodies. It is more likely to be found under large rivers and lakes (Cheng and Jin, 2013). Since there is no lake and the river is very small in our study area, we speculate that river and lake talik water may not exist. Due to the significant difficulty of sampling, the isotope data on river and lake talik water is still unclear. We will continue to explore in the future.

4.4 Implications of supra-permafrost water on runoff

There has been a notable upward trend in global temperatures over the past 100 years (Pu et al., 2017). In the context of global warming, there has been a continuous acceleration in the degradation of permafrost, resulting in a gradual increase in permafrost thawing water. This situation has led to changes in the spatial and temporal distribution of water resources and water cycle, ultimately exerting a profound impact on the ecological environment. Permafrost acts as a hydrological barrier, impeding the lateral and vertical movement and recharge of groundwater. Previous studies have also confirmed the effect of permafrost degradation on runoff, with its degradation reducing soil impermeability and enhancing the connection between surface water and groundwater (Li et al., 2016a; Li et al., 2016b; Li et al., 2016c).

The Laoyeling basin is a typical permafrost area at middle and high latitudes, belonging to the Xing'an-Baikal permafrost in northeast China. Xing'an-Baikal permafrost is located at the southeast edge of the Eurasian permafrost zone, and its total permafrost area is about 2.57 × 105 km^2 with the stable permafrost area (mean annual ground temperature ≤1.0°C) of 1.07 × 105 km^2 (Wei et al., 2011). The supra-permafrost water accounts for 85% of runoff, indicating that supra-permafrost water is a vital resource in the Laoyeing basin. The majority of precipitation freezes underground or is used to convert into soil water, rather than contributing to surface runoff directly in permafrost regions (Li et al., 2009). The direct contribution of precipitation to runoff in the Laoyeling basin is relatively small, and it has an insignificant impact on the total annual runoff in the study area. Furthermore, the temperature in the northeastern permafrost region shows an increasing trend, and this trend is expected to continue in the future, which is consistent with the global trend of rising temperatures (Shan et al., 2023). The river water is influenced by both precipitation and temperature, with the latter showing a positive correlation to the amount of water released by the melting of ice above the permafrost in the northeastern permafrost region (Shan et al., 2023). Therefore, the freezing and thawing of the active layer play a crucial role in the hydrological processes within the study area.

In the context of global warming, there is increasing focus on permafrost degradation. In the past 20 years, climate change has caused the area of permafrost in northeastern China to shrink from 3.31 × 105 km^2 to 2.70 × 105 km^2, a degradation rate of 18.43%, and the ice stored in the permafrost is showing an increasingly rapid rate of release. The total ice volume in the permafrost of northeast China is 3.178×10^{11} m^3, and it is projected to decrease to 6.641×10^{10} m^3 after 100 years, representing a reduction of 2.514×10^{11} m^3. The released water volume from permafrost degradation accounts for 79.11% of the current total ice volume, with a release rate of 2.51×10^9 m^3/a (Shan et al., 2023). The distribution and recharge-discharge processes of groundwater in cold regions are significantly influenced by permafrost. Permafrost degradation alters soil connectivity, thereby influencing the interaction between surface water and groundwater (Li Z. X. et al., 2020). Therefore, the degradation of permafrost is expected to significantly impact the regional water cycle in the future. As the thickness of the active layer increases and the area of permafrost decreases, the contribution of water from the frozen soil layer to runoff is expected to initially increase and subsequently decrease as permafrost diminishes. Changes in hydrological processes will have complex impacts on the environment. Therefore, future research should pay more attention to the environmental response to permafrost degradation, which will provide more insights for environmental protection and economic development in the permafrost region of northeastern China.

5 Conclusion

In this study, we examined the different isotopes of precipitation, supra-permafrost water and river water in a small catchment during 2021. The results showed that the isotopes displayed distinct seasonal variations. The d-excess followed the opposite trend compared to that of $\delta^{18}O$. The relatively low slope of the local meteoric water line (LMWL) indicated pronounced evaporation during the descent of precipitation. A significant positive correlation was determined between precipitation isotopes and temperature. The relationship between precipitation isotopes and precipitation amount was not significant, possibly due to either the mixing of evaporated local water vapor with falling raindrops or strong secondary evaporation affecting raindrops. The isotopes suggested a close hydraulic connection among river water, precipitation, and supra-permafrost water. Compared to precipitation, isotopes in river water and supra-permafrost water exhibited smaller changes, with similar variation ranges and patterns. This implies that direct precipitation recharge to river water was not substantial. Instead, supra-permafrost water served as the primary recharge source. End-member mixture analysis identified supra-permafrost water and precipitation as the first and second end-members, contributing 85% and 15% to river water composition, respectively. In the context of global warming, permafrost is expected to continue to degrade, and this will have significant impacts on the water resource balance and ecological environment in northeastern China. Therefore, future research will focus on investigating the impact of permafrost melting due to climate warming on the water cycle mechanisms and the environmental impact of permafrost degradation, particularly over extended periods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BZ: Conceptualization, Data curation, Formal Analysis, Investigation, Writing–original draft, Writing–review and editing. SZ: Funding acquisition, Project administration, Resources, Supervision, Writing–review and editing. LZ: Conceptualization, Supervision, Writing–review and editing. XW: Supervision, Validation, Writing–review and editing. RL: Investigation, Writing–review and editing. XD: Investigation, Writing–review and editing. DY: Software, Writing–review and editing. XC: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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