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Research papers

The role of snowmelt discharge to runoff of an alpine watershed: Evidence from water stable isotopes

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ABSTRACT

Snow is an important form of water storage which profoundly affects the hydrological processes in alpine watersheds, especially the runoff during snowmelt period. As the strong impact of climate change, the concern about snowmelt water to runoff in alpine watersheds is dramatically growing. However, the studies are mainly focused on arid and semi-arid areas, the research on semi-humid regions sensitive to the climate change need to be strengthened. In this study, for evaluating the contribution of snowmelt water to runoff in snowmelt period, we calculated the stable isotope values (δD, $\delta^{18}O$ and *d*-excess) of different water bodies including river, snow, rain, groundwater, and snowmelt water in the Erdaobaihe River watershed of Changbai Mountains area. The results indicated that the $\delta^{18}O$ values of snowmelt water showed an increasing trend with increasing temperature, while the d-excess values of snowmelt water showed a decreasing trend. During the snowmelt period, the snow cover ratio varied from 20.31% to 0.02%. The contribution ratio of snowmelt water to runoff was from 14.4% to 59.8% with average of 42.60% and the total contribution discharge was about 36.56×10^6 m^3, which was higher than inland mountainous areas as different elevation and climate. As the stable water source of river, the groundwater contributed 19.2–61.6% with average of 43.88%. The snowmelt water plays an important role in regional water balance. Owing to climate change, the snowfall period in Changbai Mountains was gradually shortening and extreme snowfall events were increasing. The results will provide evidence for further hydrological studies and help to plan future water management strategies in the alpine watershed.

1. Introduction

Snow is significant for balance of Earth's hydrological cycle and its surface energy (Frei et al., 2012; Harsh et al., 2018). It shifts daily, seasonally, and annually according to meteorological conditions, from precipitation falling as snow to the period of sublimation and melting (Harsh et al., 2018). The dynamics of snow accumulation, storage and melting play a key role in hydrological, ecological, and geomorphological processes (Barnett et al., 1989; Chen et al., 2015). Additionally, snowmelt water serves as the major source for domestic, industrial, and agricultural water use, as well as for hydropower production especially in the alpine areas (Schaefli, 2015). In 2000, around one sixth of people around the world lived in alpine areas with snow-dominated water resources (Harsh et al., 2018). With global warming, the environmental systems in mountain areas has been disproportionately suffering from decreasing snow cover areas and glacial recession in past decades (Hill et al., 2020, Déry and Brown, 2007; Farinotti et al., 2015, Chen et al., 2016; Tang et al., 2017; Scherrer et al., 2013). Scientists have devoted enormous effort to estimating the contribution ratios of snowmelt water to runoff through stable isotope approach (Lutz et al., 2014; Bravo et al., 2017; Chen et al., 2019; Schmieder et al., 2016; Yang et al., 2021). For instance, Ohlanders et al. (2013) found the cryosphere meltwater

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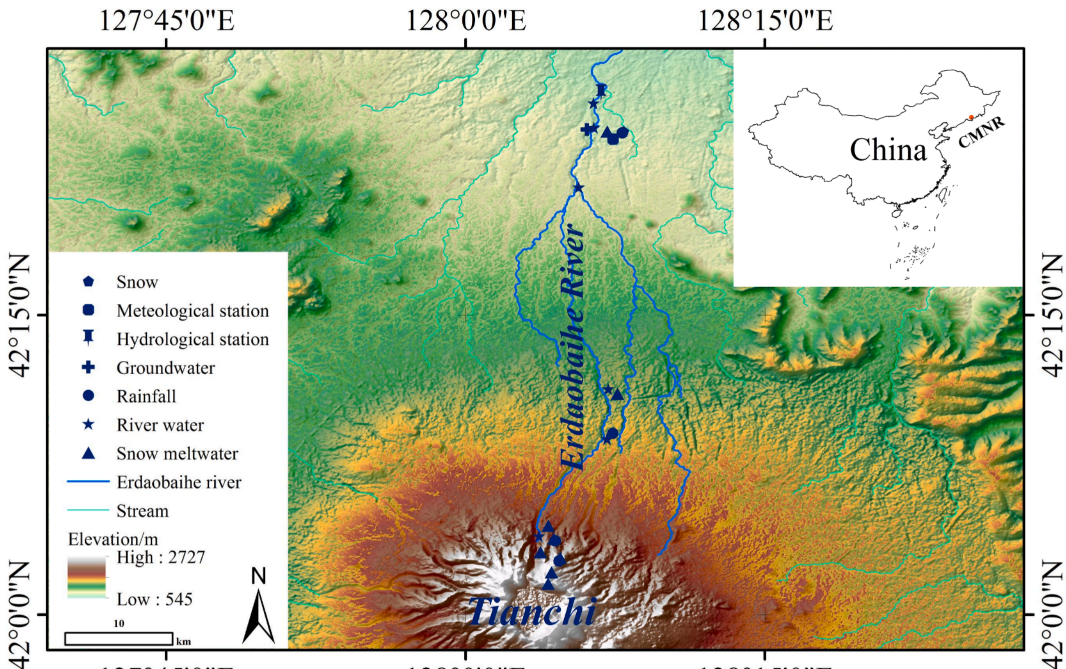

Fig. 1. Location map with the study region and sample collection sites in the Erdaobaohe River Basin.

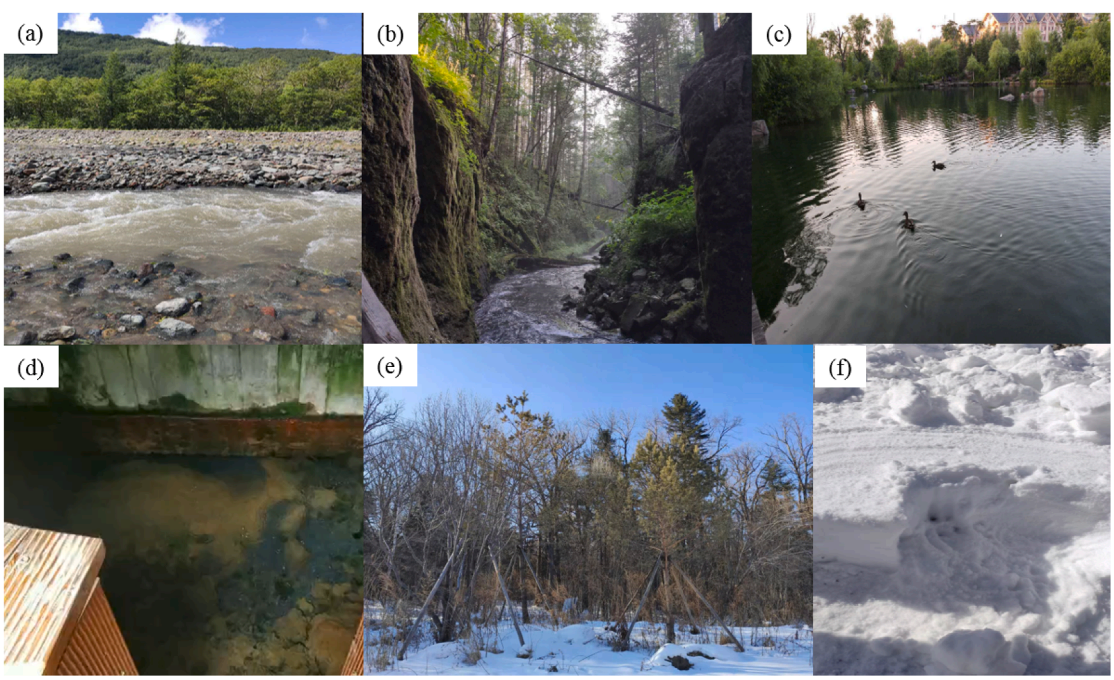

Fig. 2. The environment of sampling site. (a) denoted the river water samling site at 1700 m, (b) denoted the river water samling site at 1200 m, (c) denoted the river water samling site at 780 m, (d) denoted the groundwater sampling site, (e) and (f) denoted the snow cover at 780 m on Janurary.

accounted for 50% to 90% of runoff in the Central Chile. In the mountainous areas of western United Sates, snowmelt water accounted for 70% of the total runoff (Li et al., 2017). Li et al. (2019) found that the cryosphere belt accounted for 44% of mountainous area but contributed about 80% of water resources in inland regions of center Asia. However, there was an obvious deficiency that most of studies were focused on arid area, the contribution of snowmelt water to runoff in semi-humid areas only received little attention and it remaining unclear. Semi-humid areas are also sensitive to climate change, and their snow environment is important for regional hydrological management (Wang et al., 2020, 2013). In this scenario, it is particularly urgent to reveal the contribution of snowmelt to runoff in semi-humid areas by effective tools, especially in headwater of large rivers.

Water stable isotopes have a long-standing tradition as tracers in hydrology researches with advantages of tracking, integration and indication (Bowen and Good, 2015; Klaus and McDonnell, 2013). At present, isotopic methods have been widely used to reveal hydrological process, separate different sources of streamflow and estimate the residence time of water at various catchment (Bravo et al., 2017; Chen et al., 2019; Schmieder et al., 2016). Winter precipitation falling as snow

Table 1
Water samples for isotopic measurements of different water types.

Sampling type	Altitude(m)	n	Sampling type	Altitude(m)	n
Snow meltwater	2600	20	River water	1700	68
	2400	13		1200	68
	2200	31		1000	27
	1900	13		800	27
	1800	31		750	202
	1500	31	Precipitation	2200	21
	1000	40		1900	21
	780	12		1200	21
Groundwater	750	135		780	65

generally has isotope composition differing from that of summer precipitation. The isotope measurement was particularly promising to trace the hydrological pathways and quantify contribution of snowmelt water in watersheds (Harsh et al., 2018). The differences in $\delta^{18}O$ and δD values among sources contributing to streamflow can be exploited to investigate the component of runoff. Precious studies have confirmed the importance of cryosphere meltwater to water resources under global warming in arid areas by water stable isotopes (Chen et al., 2016, Li et al., 2019; Yang et al., 2021), which was also helpful for revealing hydrological process in semi-humid. Compared with the arid and semi-arid regions, it was assumed that the contribution of snowmelt water to runoff was equally important in monsoon-influenced semi--humid watershed.

The Changbai Mountains areas is one of the three major stable snow areas in China, which is in the semi-humid area and significantly affected by climate change (Wang et al., 2020, 2013). It generates three major rivers in the northeast of China and provides important water source for the household and production of about 90 million people. So far, many scholars have studied the water resources in this region, among which, the research on the source of groundwater is more concentrated but controversial. Zhang et al., (2019) supposed that the groundwater in Changbai Mountain was originated from the Qiangtang region of the Qinghai-Tibet Plateau. But other scholars hold that it was from regional precipitation on a long-time scale (Fang et al., 2013). Obviously, the source of water and hydrological processes in Changbai Mountains was still remained uncertainty

For evaluating the contribution of snowmelt water in Changbai Mountains to regional water balance and testifying the importance of snow in semi-humid region, a typical and presentative watershed——Erdaobaihe river was selected. It was snow covered about half a year, originates from Tianchi, and flows into the Songhuajiang River. We sampled river water, snowmelt water, groundwater, and precipitation, estimated the contribution of snowmelt to runoff during the snowmelt period using a Bayesian isotope mixing model, and analyzed local water supply changes over the past decades basing on monitoring data and remote sensing data. The concrete objects of this study were: 1) quantifying the contribution of snowmelt water to runoff, 2) exploring the influences of climate change on snow storage and local water supplies, 3) evaluating the contribution of snowmelt water to regional water balance.

2. Study region

This research was conducted on Erdaobaihe watershed of Changbai Mountains. The Erdaobaihe River basin covers an area of 210 km^2, with a total length of 78.6 km, a total drop of 1,667 m and an average channel gradient of 2.54%. The annual average flow of Erdaobaihe River is 5.5 m^3/s, the mean annual runoff is 0.18 billion m^3(Fig. 1). The region's landscape is characterized by forests and rivers, the elevation of highest peak of the Changbai Mountains is about 2749 m. This area belongs to the northern temperate continental monsoon alpine climate, has a mean annual temperature between 2.1 °C and 4.9 °C. January is the coldest month, with an average temperature of −20 °C. Annual precipitation ranges from 1000 to 1100 mm at 2100 m and from 700 to 800 mm at

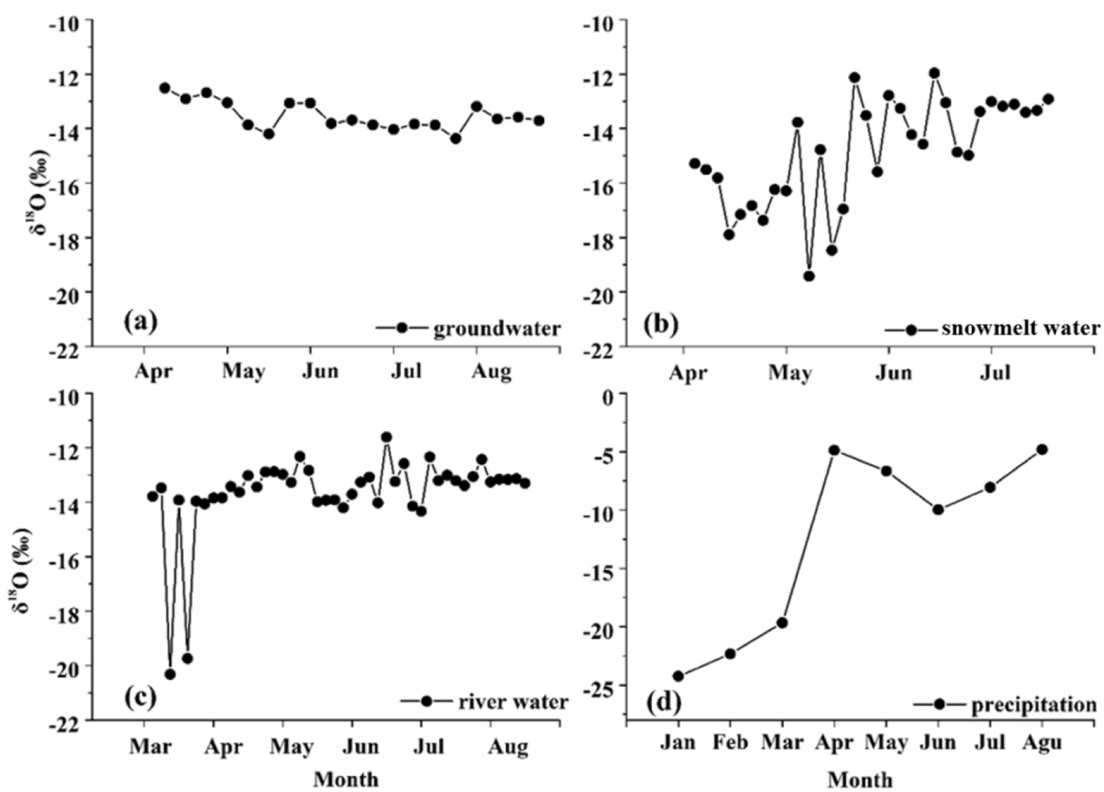

Fig. 3. The temporal variations of $\delta^{18}O$ value. (a) groundwater, (b) snowmelt water, (c) river water, (d) precipitation.

Table 2
Average $\delta^{18}O$, δ^2H and d-excess values for types of water.

Sampling type		Altitude (m)	$\delta^{18}O$ (‰)	δ^2H (‰)	d-excess (‰)
Snow meltwater		2600	−16.43 ± 1.43	−120.13 ± 8.01	11.31 ± 5.49
		2400	−12.38 ± 0.36	−85.34 ± 1.24	13.67 ± 0.24
		2200	−13.65 ± 0.42	−99.26 ± 2.99	8.48 ± 1.33
		1900	−15.35 ± 0.43	−110.22 ± 2.02	12.60 ± 1.32
		1800	−18.83 ± 0.32	−134.50 ± 2.41	16.16 ± 0.45
		1500	−14.47 ± 0.20	−97.16 ± 4.34	20.54 ± 2.77
		1000	−16.39 ± 0.21	−117.40 ± 1.32	13.70 ± 0.23
		780	−15.54 ± 0.18	−108.73 ± 0.88	15.57 ± 0.44
River water		1700	−13.28 ± 0.3	−97.58 ± 0.78	7.42 ± 1.24
		1200	−13.93 ± 0.14	−101.75 ± 0.42	6.83 ± 0.67
		1000	−13.97 ± 0.12	−102.49 ± 0.41	9.26 ± 1.13
		800	−12.72 ± 0.13	−94.79 ± 0.32	9.786 ± 0.54
		750	−13.73 ± 0.16	−100.02 ± 1.25	7.00 ± 0.60
Precipitation	Rainfall	2200	−11.01 ± 0.12	−86.20 ± 0.11	0.52 ± 0.02
		1900	−10.75 ± 0.04	−81.68 ± 0.18	3.14 ± 0.13
		1200	−10.22 ± 0.07	−78.35 ± 0.05	2.46 ± 0.19
		780	−7.72 ± 0.14	−63.07 ± 0.14	−6.18 ± 0.11
	Snow	780	−22.09 ± 2.45	−163.38 ± 4.47	10.73 ± 1.24
Groundwater		750	−13.05 ± 0.12	−98.11 ± 0.32	6.32 ± 0.27

780 m (Wang et al., 2017). The average snowfall period generally last about 10 months, from August to June next year. The mean snow cover days is 257.5 in a year. However, in the leeward and shady areas, the snow can cover the whole year (Yang, 1981). The vegetation is vertically classified into four spectra: (1) broadleaf Korean pine forest (BKPF) ranging from 740 to 1100 m a.s.l., (2) Spruce-fir forest from 1100 to 1700 m a.s.l., (3) Erman's birch forest from 1700 to 2000 m a.s.l., and (4) a tundra belt above 2050 m a.s.l. (Yu et al., 2014). The environment of different sampling site was showed in Fig. 2.

In order to analyze accurately the change of snow cover ratio and snow depth by remote sensing, we chose the Changbai Mountains Nature Reserve that distribute in same area as the data boundary. The detail introduction of Changbai Mountains Nature Reserve could be found in Wang et al (2017).

3. Data and methods

3.1. Water samples

We collected a total of 846 samples of precipitation, river water, groundwater, and snowmelt water from 750 m a.s.l. to 2600 m a.s.l.in the Erdabaihe river watershed from January to August 2020 (Table 1, Fig. 1). Precipitation samples were collected using plastic funnel bottle sets immediately after each snowfall or rainfall event to decrease the influence of evaporation. Snow samples were collected in polyethylene bags, melted at room temperature, then transferred to 60 ml high-density polyethylene bottles, which were prewashed with ultra-pure water. Then, the samples were stored at 2 °C to 4 °C before analysis (Ma et al., 2018; Pu et al., 2020).River and groundwater samples were collected twice a week and kept in brown glass bottles to avoid illumination from sunlight, filled in screw-cap glass vials (5 ml or 10 ml), and sealed with Parafilm, then stored at about 2 °C to 4 °C.

Snowmelt water samples were collected from snowpack at eight sampling sites in the Erdaobaihe river watersheds from April to July (Table 1). A 1 m-long, 4.5 cm-diameter plastics tube was used to obtain a core representation of the total snowpack depth. The tube was gently pushed down through the snowpack until it reached the ground. The snow around the sampling tube was removed, then the sample was removed whilst covering the bottom of the tube with a gloved hand and placed in the plastic bags. Once transported back to the field station, the samples were packed tightly together with cold water samples and were not allowed to melt (Li et al., 2019). All snow samples were melted overnight at 4 °C at Changbai Mountains Forest Ecosystem Positioning Station. Then, they were filled in screw-cap glass vials (5 or 10 ml), sealed with Parafilm, then stored at about 2 °C to 4 °C.

All the water samples collected were analyzed with $\delta^{18}O$ and δD using a Thermo Fisher MAT253 isotope mass spectrometer coupled with Elemental Analyzer Flash 2000 HT (Pyrolysis through high temperature EA) in the Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. The results were expressed in the δ notation as differences in parts per thousand relative to the Vienna Standard Mean Ocean Water (VSMOW). The measurement precisions for δD and $\delta^{18}O$ were 0.5‰ and 0.2‰, respectively.

The meteorological and hydrology data including temperature, precipitation, the discharge of Erdaobaihe River was recorded at the Changbai Mountains Forest Ecosystem Positioning Station (Changbai Mountains Station and Tianchi Station) and Erdaobaihe River Hydrological Station, respectively.

3.2. Snow cover ratios and snow depth

The MOD10A1 V6 Snow Cover Daily Global 500 m dataset was used to calculate the snow cover area of the Changbai Mountains Nature Reserve (CBNR) based on the Google Earth Engine (https://earthengine.google.com/). The calculations for snow cover ratio were as followed:

$$SSC = \sum_{i=n} R_{gn} \times S_g (n = 1, 2, 3 \cdots n), \tag{1}$$

$$R_{SC} = S_{sc}/S_{CBNR}, \tag{2}$$

where S_{gn} was the area of grid (500 × 500 m), n was the grid number, R_{SC} was the ratios of snow cover in the CBNR, and S_{CBNR} was the area of CBNR (1965.31 km^2).

The remote-sensing-based snow depth data were obtained from Che (2015) (http://www.tpdc.ac.cn/zhhans/data/df40346a02024ed2bb07b65dfcda9368/). The database was developed specifically for China on the basis of different microwave remote sensing data sets (Che et al., 2008; Dai et al., 2012, 2015).

3.3. Contribution of snowmelt discharge to runoff

The contribution of different water sources to river was estimated using the MixSIAR package (Stock and Semmens, 2016) in R (R Core Development Team, 2012). MixSIAR is a Bayesian isotope mixing model to explore the source of mixture. It is used to reveal the food web originally, and it is currently applied to explore water sources in hydrological studies. Compared with the traditional end-member mixing model, MixSIAR contain uncertainty analysis in the estimate process and print results with higher accuracy. The formulation of this model as follows:

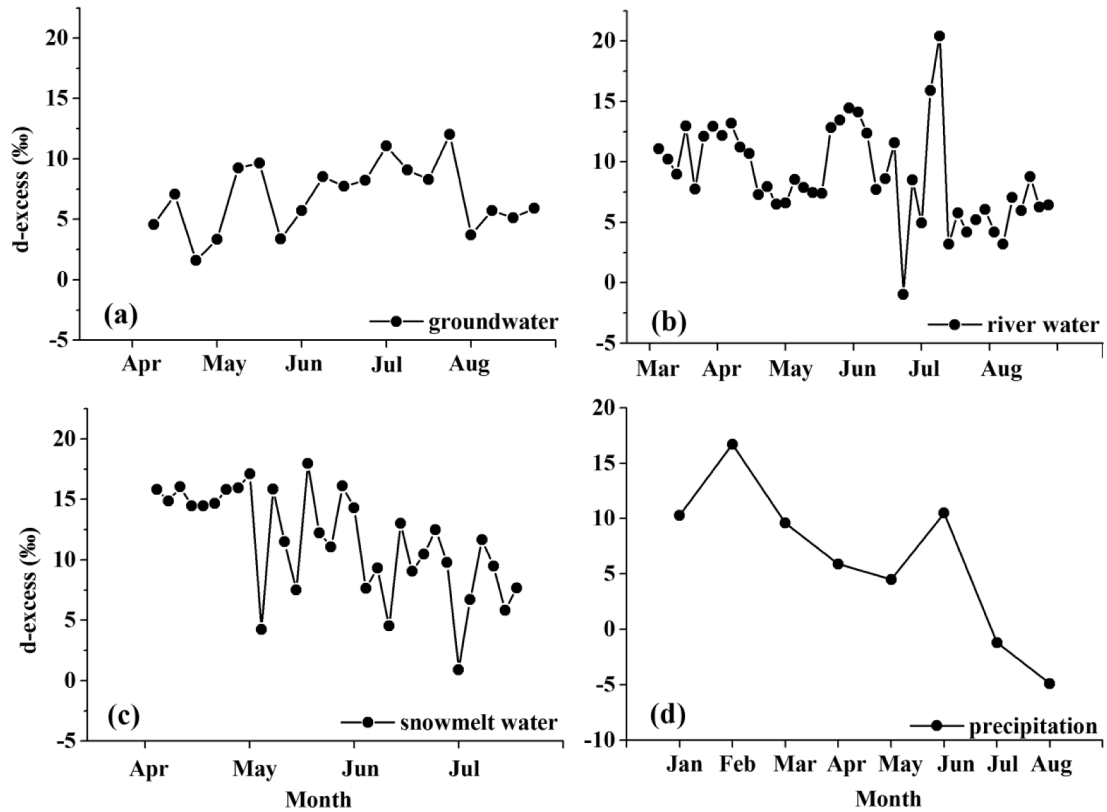

Fig. 4. The temporal variation of d-excess. (a) groundwater, (b) river water, (c) snowmelt water, (d) precipitation.

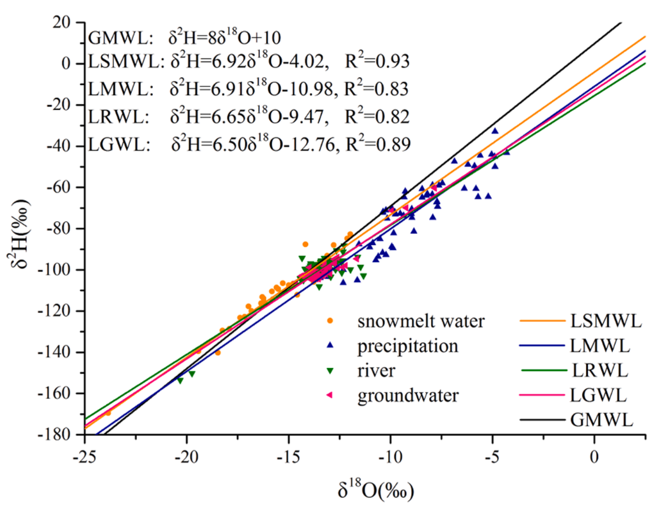

Fig. 5. Local Snowmelt water Line (LSMWL), Local Groundwater Line (LGWL), Local Meteoric Water Line (LMWL), Local River Water line (LRWL) and Global Meteoric Water Line.

$$\phi_i = i|\gamma(P_i) = v^T \log\left[\frac{p_{i1}}{g(p_i)}, \cdots, \frac{p_{iK}}{g(p_i)}\right] \text{with} g(p_i) = \left(\prod_{i=1}^{K} p_{iK}\right)^{1/K} \quad (3)$$

In this formula, P was the proportion of each source. The inverse transformation $P_i = i|\gamma^{-1}(\phi_i)$ simply involved exponentiating and re-normalising the values. p_{iK} was the contribution of source k for consumer i . p_i was the K-vector of source proportions for consumer i (Parnell et al., 2013).

3.4. Moisture source

The moisture source of precipitation in study area was analyzed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, which was available online at www.arl.noaa.gov/ready/hysplit4.html (Rolph et al., 2017). HYSPLIT permits air parcels to be tracked backward in time and space from a given location (Stein et al., 2015). We used output from the Global Data Assimilation System (GDAS) and calculated 48-hour back trajectories for precipitation events from January to August 2020.

4. Results

4.1. Variations of stable isotopes and linear isotopic relationship

4.1.1. $\delta^{18}O$

During the observation period, the distribution patterns of $\delta^{18}O$ and δ^2H values were similar. In this study, the $\delta^{18}O$ value could represented the change of stable isotopes. From Fig. 3, it showed that the $\delta^{18}O$ value of groundwater was relatively stable, from −14.37‰ to −12.52‰ with an average of −13.05‰ (Fig. 3a). But there was an upward trend in snowmelt water, increased from −19.41‰ to −11.96‰ with an average of −15.51‰ (Fig. 3b). The $\delta^{18}O$ value of river water also showed relatively stable with an average of −13.73‰, except two days (-20.31‰ and −19.74‰) which affected by snowfall (3 mm and 2.5 mm) in March (Fig. 3c). In total period of precipitation, the average $\delta^{18}O$ value of snowfall and rainfall was −22.08‰, −9.97‰ respectively (Fig. 3d). It showed that the precipitation in Changbai Mountains was affected by different moisture source in different time.

In spatial variation, there was no significant variation in the $\delta^{18}O$ value of river water (Table 2). On the contrary, the $\delta^{18}O$ value of snowmelt water showed a trend of first decreasing and then increasing with the elevation, with the maximum value of −12.38‰ at 2400 m and the minimum value of −18.83‰ at 1800 m. The $\delta^{18}O$ value of

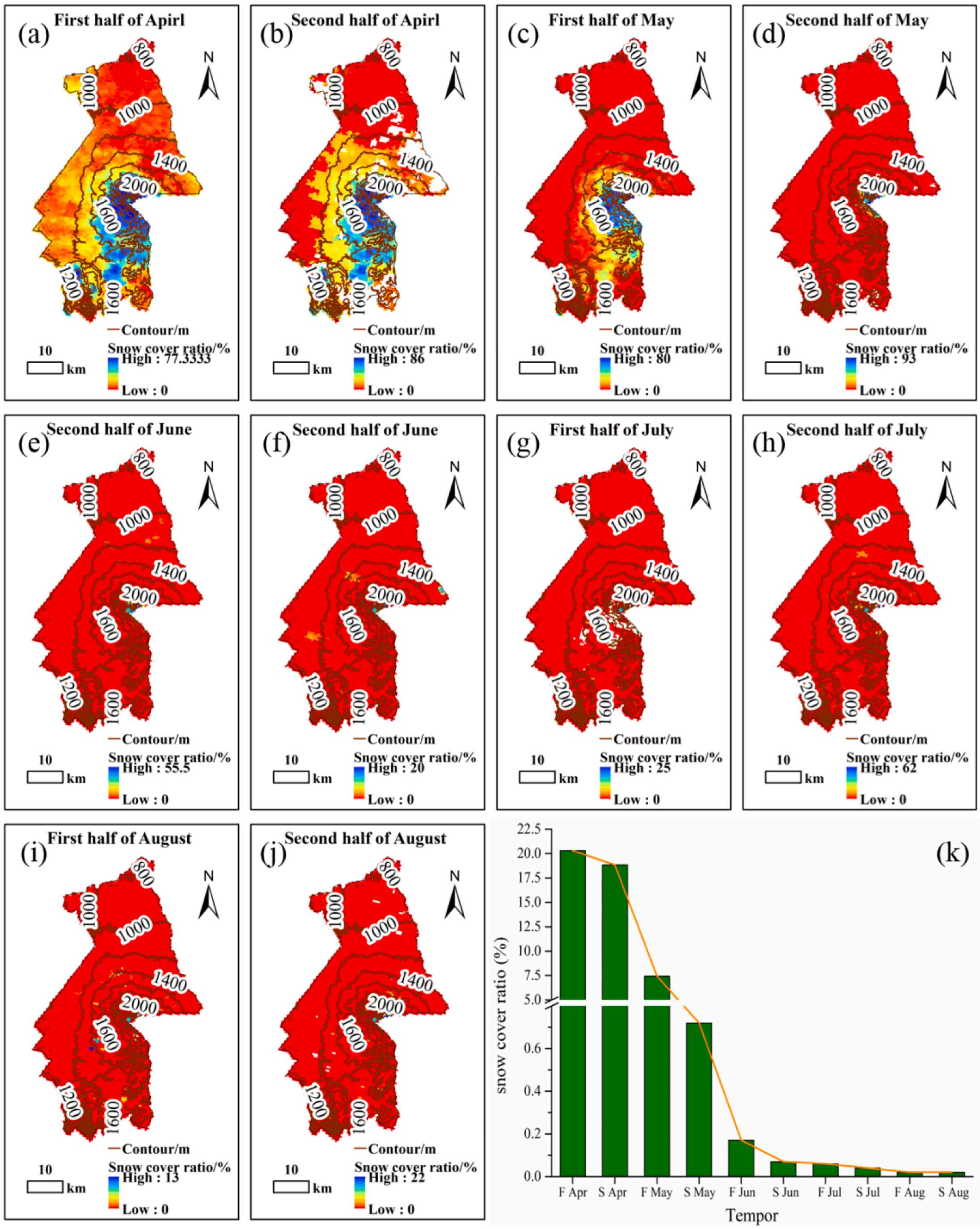

Fig. 6. The snow cover ratios during snowmelt period. "F month" is the first half of month, "S month" is the second half of month. (a) to (j) are the spatial distribution change of snow cover area, (k) is the temporal change of snow cover ratios.

precipitation decreased with the elevation from −7.72‰ at 780 m to −11.01‰ at 2200 m.

4.1.2. *d-excess*

During the snowmelt period, the *d*-excess value of groundwater was relatively stable, varied from 1.58‰ to 12.02‰ with an average of 6.84‰ (Fig. 4a). However, the river water was in an unstable fluctuation state, varied from −0.95‰ to 20.43‰ with an average of 8.84‰ (Fig. 4b). The *d*-excess of snowmelt water and precipitation showed a decreasing trend from 17.97‰ to 0.90‰, 16.70‰ to −7.78‰ (Fig. 4d), it resulted from moisture source, wind speed and temperature.

In spatial variation, there was no significant variation in *d-excess* values of runoff. But snowmelt water presented a trend of rise and then down with evaluation rising, the maximum value was 20.54‰ at 1500 m, the minimum was 8.48‰ at 2200 m (Table 2). *d-excess* value of rainfall first increased and then decreased, reached the maximum of 3.14‰ at 1900 m. These phenomena were influenced by topography and microenvironment.

4.1.3. *Linear isotopic relationship*

The Global Meteoric Water Line (GMWL, $\delta D = 8\delta^{18}O + 10$) and the Local Meteoric Water Line (LMWL) are important references for hydrological process research and are also benchmarks for stable isotope applications. In the Changbai Mountains area, the LMWL, Local

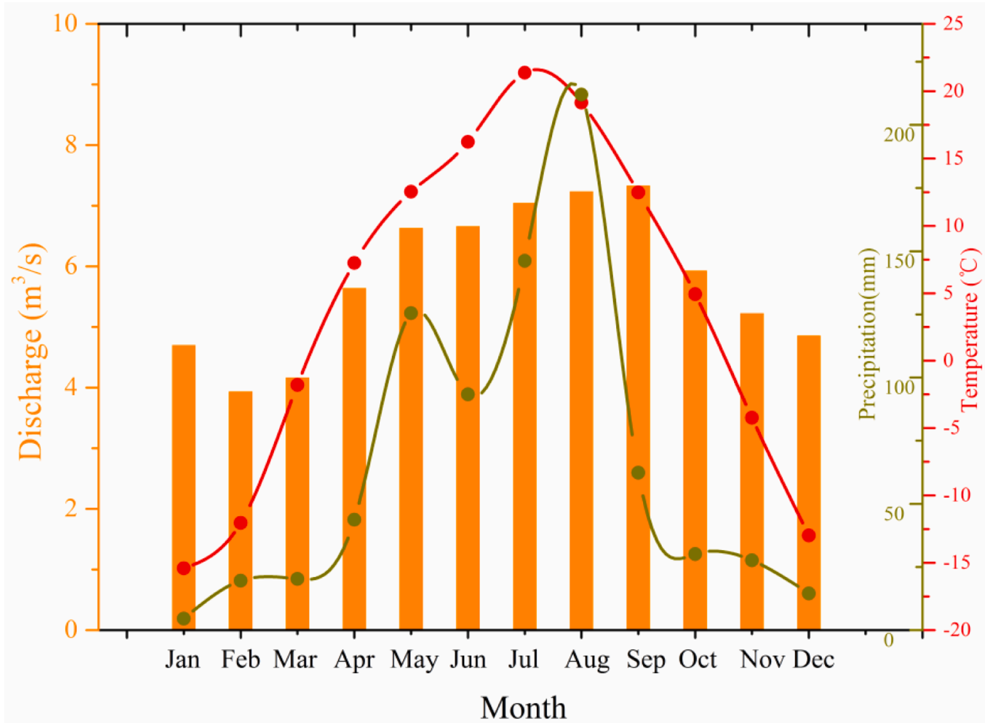

Fig. 7. Mean monthly precipitation, temperature and discharge of Changbai Mountain area.

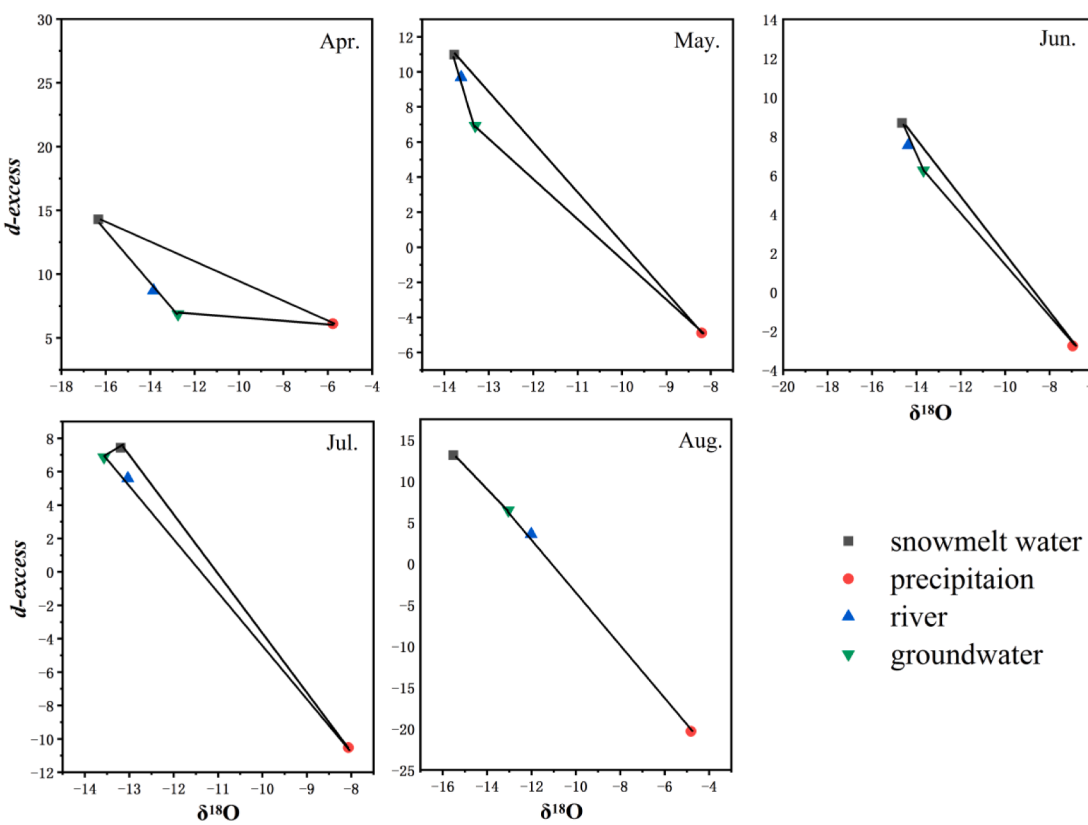

Fig. 8. Mixing diagram using the mean $\delta^{18}O$ and d-excess values for runoff.

Snowmelt Water Line (LSMWL), Local Groundwater Line (LGWL), and Local River Water Line (LRWL) deviated from the GMWL (Fig. 5) due to the moisture source and local hydrological conditions. The slope of LSMWL was almost the same as LMWL, indicating that the evaporation of snow cover was scarce during the snowmelt period owing to the low temperature in spring. The slope of the LGWL (6.50) was closest to that of the LRWL (6.65). The result was same with previous studies that 65% of the Tianchi Waterfall in Changbai Mountains, the source of the

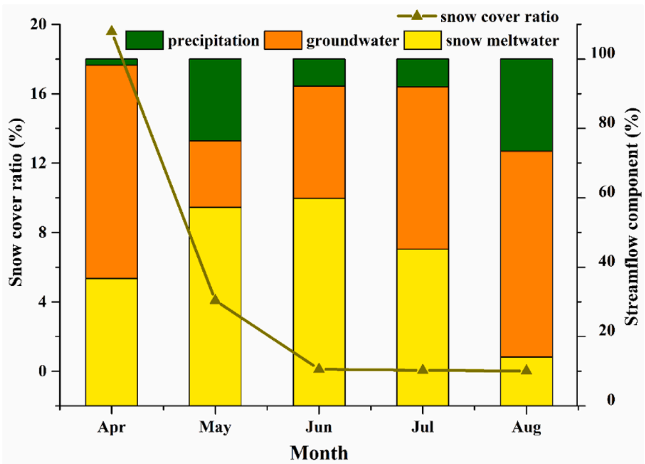

Fig. 9. Monthly streamflow component and the relationship between contribution and snowmelt water ratio.

Table 3
The monthly contribution of snowmelt, precipitation and groundwater to the total discharge of the river during the snow melt period (1×10^6 m^3).

	Apr.	May.	Jun.	Jul.	Aug.
snow meltwater	5.41	9.97	10.35	8.21	2.62
rainfall	0.25	4.06	1.35	1.46	4.97
groundwater	9.00	3.30	5.60	8.54	11.13

Erdaobaihe River, came from groundwater (Jiang and Chen, 2015; Zhang et al., 2019). In addition, the slope of LGWL was lower than that of LMWL and GMWL, which indicated that the groundwater underwent evaporation. In Changbai Mountains area, the groundwater types were complete, and basaltic pore fracture water was widely distributed (Zhang et al., 2019). We suggested that there were three evaporation processes: 1) groundwater formation, where surface water infiltration through the soil and unsaturated zone into the saturated zone or aquifer with evaporation, 2) groundwater storage, where complex hydrochemical reactions between groundwater and surrounding rocks with evaporation and isotope enrichment (Fang et al., 2013), and 3) spring upwelling, as an important form of groundwater, spring upwelled from the saturated zone to the surface with evaporation.

4.2. The change of snow cover ratio during the snowmelt period

Snowmelt speed in the Changbai Mountains area was significantly affected by the temperature, altitude and topographic factors. During the snowmelt period, the half-monthly mean snow cover shrinks significantly (Fig. 6). As shown in Fig. 7, the average temperature was above 0 °C and the snow cover ratio was 20.31% in April, when the snow began to melt in areas below 1000 m asl. The melting of snow accelerated and reached the fastest rate in May and the snow cover ratio was about 7.44% with the disappear of snow below 1600 m. Subsequently, although temperatures were still rising, the snow areas below 2200 m melted with a relatively steady rate and the snow cover ratio reached about 0.17% in the first half of June. In July, there was almost no snow cover on the sunny slopes above 2200 m. Snow cover was close to zero in August.

The rough has led to uneven snow thickness in the Changbai mountains areas, resulting in both debris cover and clean snow. The effect of debris cover on melt rates is well known, and several studies have quantified the relationship between debris thickness and melt rate (Scherler et al., 2011; Khan et al., 2015). When the thickness of debris cover is less than clean snow, the albedo effect dominates and snow melting accelerates, whereas the thickness of a debris is more than clean snow, the insulation effect dominates and melt rates are lower compared to clean ice. In the study area, the top and ridge of mountain was covered less thickness snow with higher melt rates, meanwhile, the valley was covered more thickness snow resulting in the slower melting accelerates, even remaining to summer.

4.3. The contribution of snowmelt water to runoff

To determine the source of river water, incorporated $\delta^{18}O$ verses d-excess plot of the three-end member was showed in Fig. 8. There were significant temporal variations in the concentrations of d-excess and $\delta^{18}O$ for snow meltwater, precipitation, and river water during the sampling period (Fig. 8). Accordingly, the concentrations of $\delta^{18}O$ and d-excess were selected for analysis because this combination provides the best separation of water sources (Li et al., 2019). There were large temporal variations in the concentrations of these water source, and the river water was located within the triangle spanning the three end-members, suggesting that runoff was a mixture of them (Fig. 8). Therefore, groundwater water can be treated as the first end-member, and snowmelt water and precipitation as the second and third end-members, respectively.

Through MixSIAR analysis, the study found that the contribution of snowmelt water to runoff increased firstly and then increased, the ratios varied from 14.1% to 59.8% (Fig. 9), with an average of 42.6% (Table 3). According to the mean monthly discharge of the Erdaobaihe River (Table 3, Fig. 7), the maximum contribution discharge of snowmelt water to runoff was 10.35×10^6 m^3 in June. The minimum and maximum contribution of groundwater, the main source of streamflow, were 19.2% in May and 61.6% in April, respectively. Precipitation was the scarce component of the runoff, with the smallest contribution being 1.7% in April and the largest being 26.5% in August, an average of 13.52%.

From April to June, the contribution of snowmelt water was negatively correlated with snow cover (Fig. 9). During the snowmelt period, the contribution of snowmelt to runoff increased sharply and the contribution of groundwater decreased gradually as the temperature increased and snowmelt surged (Fig. 9, Table 3). The fastest snowmelt rate was in the first half of May, and the largest contribution was in June (Fig. 9). It could be concluded that there was a lag about one month between snowmelt and runoff.

5. Discussion

5.1. Isotopic compositions

The isotopic compositions of precipitation were characterized by pronounced seasonal variation with higher $\delta^{18}O$ value in summer and lower in winter, with opposite pattern *of d*-excess (Fig. 3d, Fig. 4d). The value of $\delta^{18}O$ and *d*-excess of precipitation is mainly controlled by the wind speed at the source area of atmospheric moisture, the relative humidity and temperature of the evaporating surface (Merlivat and Jouzel, 1979; Rozanski et al., 2003; Kreutz et al., 2003). From January to March, the high *d*-excess and low $\delta^{18}O$ of precipitation in the Changbai Mountains resulted from the moisture mainly from the Mongolian Plateau and Siberia with low humidity and low precipitation (Fig. 10) (Froehlich et al., 2008; Pang et al., 2006). The relatively lower d-excess and higher $\delta^{18}O$ of rainfall in summer and spring were mainly contributed by moisture from ocean source and subcloud evaporation (Pu et al., 2017). From April to August, wet and warm moisture from the western Pacific Ocean was transported to this region, contributing to relatively high humidity and more precipitation. The $\delta^{18}O$ of rainfall was higher than them of snow with lower *d-excess*. It indicated that temperature rising lead to higher values of $\delta^{18}O$ in precipitation with a positive correlation between $\delta^{18}O$ value and temperature (Li et al., 2019). Snowmelt water showed the same feature, the $\delta^{18}O$ value of snowmelt water was richer more and more caused by the increase of

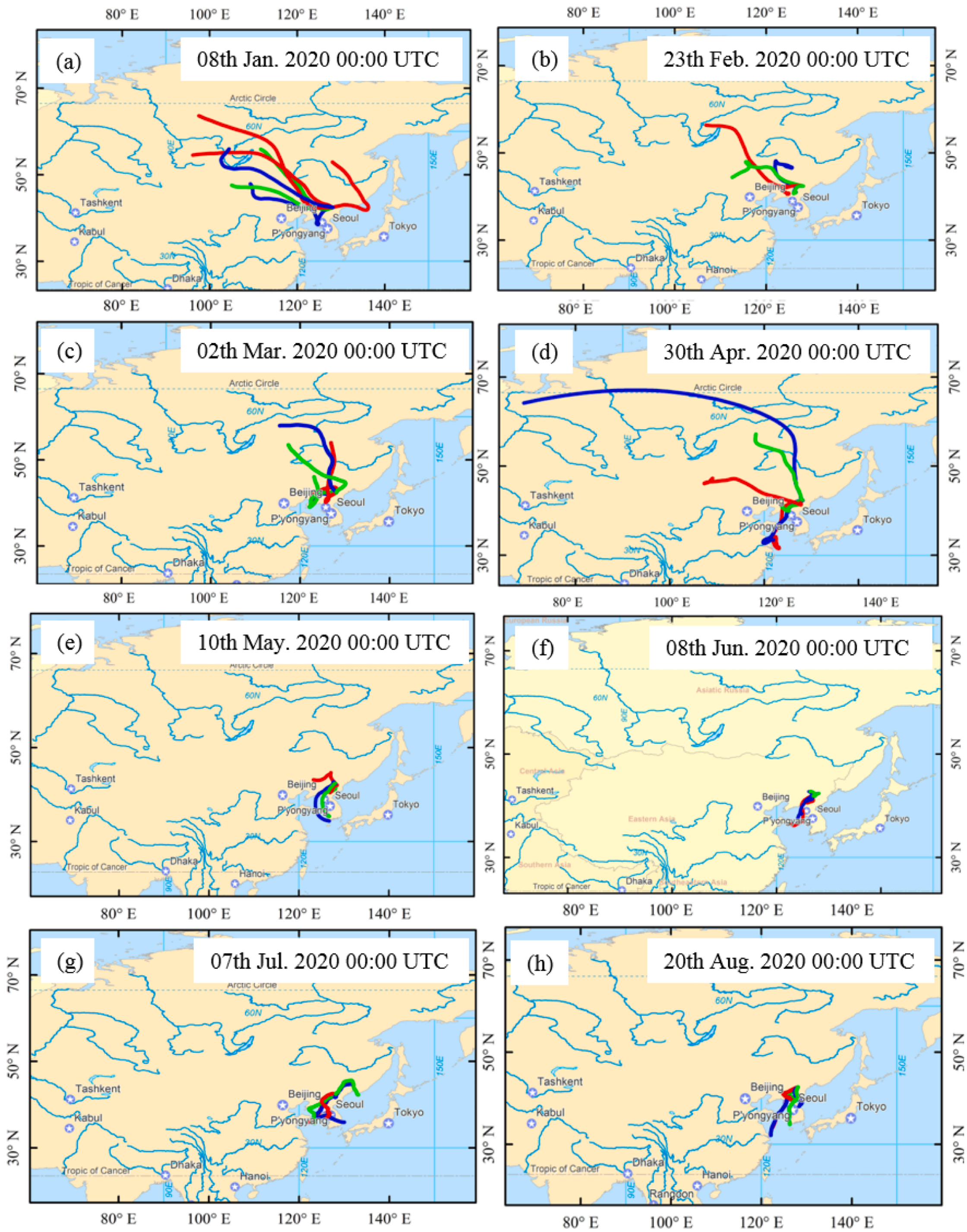

Fig. 10. The HYSPLIT reverse-calculated 48 h trajectories ending at the Changbai Mountains Station. The red, green, and blue lines in the maps represented the paths of air parcels terminating at 500, 1000 and 1500 m above ground level for the 48 h period prior to the date given in the top right-hand corner. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
The elevation, temperature and precipitation among the three alpine watersheds.

Mountain	Elevation (m)	Average temperature of melting season (°C)	Annual precipitation(mm)	Alpine watershed
Tianshan Mountain	7443 m	18.0	290	Main six catchments
Yulong Snow Mountain	5596 m	15.4	930	Baishui catchment, Yanggong catchment
Changbai Mountain	2749 m	15.0	790	Erdaobaihe river catchment

The data of average temperature of melting season and annual precipitation were from each hydrological station at middle altitude areas of watershed.

Table 5
Changes in snow cover ratio from 2000 to 2020.

Month	2000–2001	2005–2006	2010–2011	2015–2016	2019–2020
9	11.67	0.09	1.19	0.20	0.07
10	12.77	0.30	3.86	5.14	2.20
11	13.67	5.50	3.86	26.14	14.67
12	28.98	30.18	26.32	30.50	29.81
1	29.99	25.96	27.12	29.63	24.04
2	23.32	25.97	21.66	25.10	23.33
3	23.66	25.96	21.89	22.65	22.23
4	13.94	21.07	17.00	16.15	19.58
5	2.06	3.36	5.56	2.87	4.08
6	0.15	0.67	0.19	0.22	0.12
7	0.09	0.14	0.27	0.09	0.05
8	0.07	0.51	0.41	0.08	0.02
Mean	13.36	11.96	10.78	13.23	11.68

evaporation during the snow melting period, though the evaporation was not tremendous as described previously. The groundwater in Changbai Mountains is mainly mineral water, with an age of about 50 years. The extensive basaltic rocks were developed with polypore and columnar joints influenced by volcanic karst action. Constrained by hydrogeological conditions, the vast majority of groundwater is basaltic pore fissure water. So, it was less disturbed by temperature and surface environment (Zhang et al., 2019), which resulting in the relatively stable isotopic compositions of groundwater during the snowmelt period.

In spatial variation, the $\delta^{18}O$ value of snowmelt water showed a trend of first decreasing and then increasing with the elevation, while the *d-excess* value with the opposite pattern. This phenomenon mainly resulted from that the relative higher altitudes with lower temperature and weaker evaporation than lower altitudes. In addition, the snow maybe reacted with the soil elements during snowmelt period, which resulted to snowmelt water with different value of $\delta^{18}O$ and *d-excess* in different altitudes (Schmieder et al., 2016). The $\delta^{18}O$ values of rainfall decreased with elevation, it showed significantly altitude effect and rainfall amount effect with altitude gradient about 0.24‰/100 m ($p < 0.05$). The altitude effect was mainly resulted from the lower temperature, more precipitation and weaker evaporation (Li et al., 2016). The $\delta^{18}O$ value of river showed stable trend as highly speed flow and lower temperature.

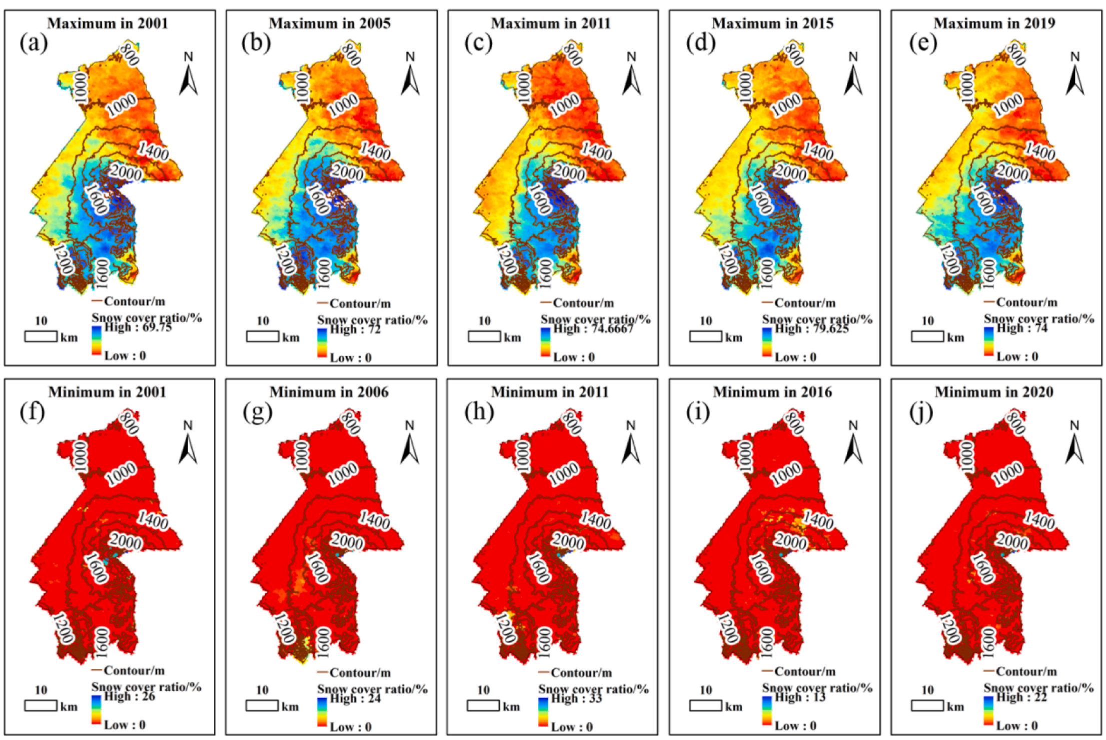

Fig. 11. Changes in maximum and minimum snow cover ratios in 2000, 2005, 2010, 2015 and 2020. (a) to (e) are the months with maximum snow cover ratio and (f) to (j) are the months with minimum snow cover.

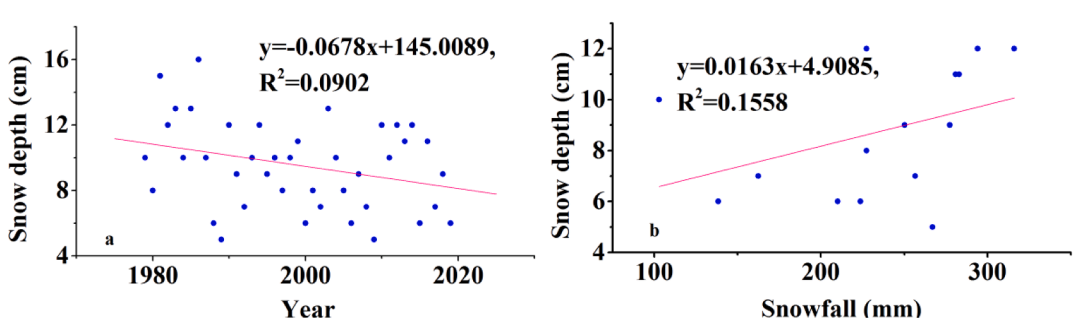

Fig. 12. The changes in snow depth in January (a) and the relationship between snow depth in January and snowfall (b) during 1979–2019.

5.2. The importance of snowmelt water in the alpine watershed

Snowmelt water is generally an important recharge source for alpine catchments. In the Tianshan Mountains, the snowmelt water contributed 43%, 28%, 49%, 33%, 22% and 23% to the river runoff of the six main benchmark catchments during the typical snowmelt period (Chen et al., 2019). In the Baishui River Basin and Yanggong River Basin (Yulong Snow Mountains), prior to monsoon season, snowmelt water contributed 38.3% and 47.9% to river runoff, respectively (Pu et al., 2017). In general, the contribution of snowmelt water to river runoff does correlate positively with the maximum snow cover in mountainous areas, the different contribution of snowmelt water within different watersheds was caused by the local climate and topography (Saydi and Ding, 2020; López-Moreno et al., 2013, 2014). In Changbai Mountains, for the dramatically influence of monsoon, elevation and topography, the snowfall is about half of precipitation with more depth and cover than Tianshan Mountains (Hantel et al., 2000; Wang et al., 2009; Chen et al., 2019). This suggested that more snowmelt water flows into runoff in the Changbai Mountains region during the snowmelt period (Berghuijs et al., 2014), especially in the dry spring and early summer. In addition, primarily affected by elevation, the temperature of peak in Changbai Mountains was about 6 °C while in Yulong Snow Mountain was about −6°C in summer (Wang et al., 2017; Pu et al., 2017), which caused the dramatically difference of snow cover areas between Changbai Mountains and Yulong Snow Mountains. Therefore, the contribution of snowmelt water to runoff in Changbai Mountains was higher than Yulong Snow Mountains (Table 4).

In the Erdaobaihe River basin, there was about a month time lag between snowmelt and contribution to runoff, it suggested that snowmelt water did not immediately contributed to runoff but firstly infiltrated into the alpine soil maintaining soil moisture before eventually flowing into the river. In fact, snowmelt contributes to the watershed not only by recharging runoff, but also by contributing to atmospheric precipitation, soil, plants, and even the entire alpine watershed ecosystem (Pu et al., 2017; Yu et al., 2010). Snow replenishes the moisture in the atmosphere during both the accumulation and the ablation periods, and replenishes the moisture in the soil and the plants during the ablation period (Li et al., 2013, 2020). In the Tibetan Plateau, the contributions from glacier and snowmelt water to permafrost were 7.15% and 5.07% in initial and end ablation periods, respectively (Li et al., 2020). In the Gurbantunggut Desert of Northwest China, Yin et al. (2020) found that snowmelt water was an important water resource for plant roots, and changes in snow cover altered the herbaceous root biomass and root morphology in growing season. In the alpine regions of Northeast China, snow prevents evaporation of surface soil moisture, the surface soil moisture generally increases by 20%, and snowmelt water provides a vital water supply to agricultural production and decreases the requirement of irrigation (Qi et al., 2020; Yu et al., 2010). The precipitation season in the Changbai Mountains was mostly from July to August, while the germination season for the main vegetation is from late May to late June. (Xu et al., 2004; Wang and Liu, 2010), which coincides with the snowmelt period. This suggested that snowmelt water played a key role in vegetation growth in the Changbai Mountains region, especially in the early stages of plant growth.

6. The effect of climate change on water supplies

The global mean temperature increased by 0.89 °C in the past 100 years, according to the fifth climate change assessment report of the Intergovernmental Panel on Climate Change (IPCC). And over the last 50 years, the temperature has increased by up to 0.1 °C per decade. (Shen and Wang, 2013). From 1951 to 2017, China's surface temperature increased by 0.24 °C per decade, higher than the global average temperature increase (Zhang et al., 2020). Since 1958, the annual average in the Changbai Mountains area has been increasing at a trend of 0.39 °C per decade, which is higher than national average (Liu et al., 2019). In addition, the average and minimum winter temperatures in the Changbai Mountains area have increased significantly. Annual precipitation has shown a slight downward trend of 5.7 mm per decade over the past 50 years, but has increased significantly over the past decade (Wang et al., 2020). The greater concentration of precipitation resulted in a 34% increase in the frequency of extreme precipitation and a 52.8% increase in the total amount of extreme precipitation. (Wang et al., 2013). Snow has a profound impact on the thermal conditions of the surface and atmosphere and is extremely sensitive to climate change due to its high reflectivity, low thermal conductivity and hydrological effects through snowmelt (Barnett et al., 1989; Groisman et al., 1994; Ke et al., 2016). Under the conditions of global change, the number of snow-covered days in Changbai Mountains from 1951 to 2010 showed a distinctly downward trend (Ke et al., 2016). As shown in Table 5 and Fig. 11, although there was no distinct variation in the average snow cover rate, there were significant monthly changes in snow cover rate from 2000 to 2020. The decrease in snowfall rates in September indicated a delay in the onset of the snowfall period, which was in accordance with previous studies (Ke et al., 2016; Li et al., 2009). The month with the highest snow cover shifted from January to December, indicating a concentration of snowfall events in November and December, especially in December. Over the past 20 years, an increasing number of extreme climate events have occurred, which has led to more extreme snowfall events in the winter and lower snow cover in the summer. (Table 5). There was no obvious trend in snow cover rate in Changbai Mountains area in past 20 years. However, as shown in Fig. 12a, the snow depth in January from 1979 to 2019 showed a decreasing trend of 0.68 cm per decade, and positively correlated with snowfall (Fig. 12b). This indicated that climate change with increasing temperature and fluctuating precipitation reduced the snow and eventually affected the hydrological processes in the watershed.

7. Conclusion

In this study, the contribution of snowmelt water to runoff in an alpine watershed of semi-humid areas was investigated based on stable isotopes, and three salient features were illustrated as follows. Firstly, the stable isotopes of snowmelt water exhibited significant spatial and temporal variability. Secondly, snowmelt water played a considerable role to runoff in the snowmelt period in the semi-humid region, with the contribution of snowmelt water to runoff ranging from 14.4% (April) to 59.8% (June), which was higher than that of the arid areas. With the climate has become warmer and drier, snowfall period was shortened with increasing extreme snowfall events. Finally, the snowmelt water was one of important water sources for Changbai Mountains. Under the scenarios of global warming, snowmelt water will affect the balance of local water resources and sustainable development. This study will be promoted for the exploration of global hydro-climatic process mechanisms, enhance the importance of alpine snowmelt in semi-humid areas under global change, support flood risk management in alpine watersheds, and improve the hydrological management system of watersheds under global warming conditions.

CRediT authorship contribution statement

Mingming Feng: Methodology, Formal analysis. **Wenguang Zhang:** Conceptualization, Methodology, Writing – review & editing. **Shaoqing Zhang:** Investigation. **Zeyu Sun:** Investigation. **Yang Li:** Investigation. **Yiqiang Huang:** Investigation. **Wenjuan Wang:** Supervision. **Peng Qi:** Resources. **Yuanchun Zou:** Project administration, Funding acquisition. **Ming Jiang:** Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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