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Assessment of Water Provenances in Koxkar Glacier Region at the South Slope of Mt. Tianshan, China

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Abstract Various water samples were collected for electrical conductivity (EC) and $\delta^{18}O$ analysis, and the proportion and contribution of atmospheric precipitation, glacier ice and shallow groundwater to discharge in the Koxkar glacier basin at the south slope of the Tianshan Mountains were studied. The results show that glacial ice-water recharge was dominant, accounting for 72.11% of the annual runoff. It also had a significant positive correlation with temperature during the warm season (from May to September). However, glacier ice ablation replenishment still existed when the temperature in the cold season was below the critical temperature of 0 ℃. This could be that the heat generated by the friction between the ice body and the ice bed during the subglacial ice sliding process led ice to melt, what's more, the stored water in the geometric passages inside and below the glacier could slowly release. Groundwater recharge accounted for 16.38% of the total runoff. The supplement was small and its variation range was relatively small in the cold season. But in the warm season, the amount of groundwater recharge increased and changed drastically. It might be that the seasonal frozen soil in the basin was widely developed and was affected by temperature changes. Atmospheric precipitation replenishment only accounted for 11.51%. The daily precipitation recharge river water had a significant response to regional precipitation, but there was hysteresis in time, and there was still precipitation recharge runoff even in the absence of precipitation.

Key words Water provenance; Conductivity; $\delta^{18}O$; Three-component mixing models; Koxkar glacier
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One of the focuses of water chemistry research in glacial action areas supplemented by different water bodies such as ice and snow melt, atmospheric precipitation and groundwater is the use of information on soluble ions, electrical conductivity (EC) and isotopes in water to determine the various sources of water supply[1 –3]. During the hydrological cycle, the changes in solute concentration and conductivity and their differences in time and space may indirectly reflect the intrinsic information of the hydrological system, but there are many uncertain factors affecting the solute concentration, such as water – rock interaction and material exchange at gas – liquid – solid interface[2 –5]. Because stable isotopes are mainly affected by mixing in hydrological processes and isotope fractionation due to changes in physical conditions such as evaporation and condensation. Moreover, the influence of the former is large, and therefore, the error formed by the simple mixing of the solute can be avoided to some extent [3,5]. In the 1970s, Fritz (1976) applied stable isotope to determine the base flow component in the runoff of the basin. Accordingly, the use of natural stable isotopes to solve the hydrological problems such as runoff recharge sources and supplement has become more widespread[3,5 –9].

Previously, the research on water chemistry mainly focused on the chemical composition of water bodies and the inversion of paleoclimate information in ice cores in China[10 –11]. There are few studies on the sources of runoff recharge in glacial basins[12 –14]. From June 2004 to September 2005, water bodies such as river water, atmospheric precipitation, groundwater and glacier ice were sampled to illustrate the changes in pH, conductivity and $\delta^{18}O$ of the regional water bodies in the Koxkar Glacier, the south slope of the Tianshan Mountains. Based on the 3-terminal hydrological model, the contribution of different water sources to total runoff will be determined, which can provide some reference information for the future assessment of the impact of glacial changes on water resources.

1 Study area

The Koxkar Glacier (Glacier Catalog No.: 5Y674A5; 41°48.77′ N, 80°10.20′ E) is located at the south slope of the Tomur Peak in Tianshan, the source of the Kekeya River. The total length of the glacier is about 25.1 km, and its area and ice reserves are 82.89 km^2 and 15.79 km^3, respectively[15 –16]. The glacier ablation zone with a large number of debris and hailstones has a length of 19.0 km and an area of about 30.6 km^2. The hydrological section control area of the basin is 118.12 km^2, and the glaciers, grasslands and bare grounds (bedrock) account for 70.2%, 3.8% and 26.0% respectively (Fig.1).

Regional precipitation mainly relies on airflow from the Atlantic Ocean and the Arctic Ocean. The annual precipitation was about 630 mm, mainly concentrated during May – September, accounting for about 81%, and the precipitation in the cold season was less. Affected by regional topography, precipitation is mainly dominated by solid precipitation such as hail, alfalfa and rice snow. There are no obvious four seasons in the basin, and the cold season is cold and dry under the control of the

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North Atlantic circulation and the Arctic Ocean circulation[17]. The warm season is affected by the regional climate, and the climate is cool and humid. The annual average temperature is 0.4 ℃, and the average temperature in only 6 months is above 0 ℃.

Since June 2003, a hydrological monitoring point has been set up 800 m downstream of the ice outlet at the end of the glacier. The results showed that the average annual runoff of the basin was about 1.2×10^8 m^3, mainly concentrated in the warm season (5 – 10 months), accounting for about 94.5% of annual runoff[16]. In the warm season, the river water body was grayish white, and during the precipitation, the river water was reddish brown due to the erosion of the Tertiary red soil of the side ridge. The river water in the cold season was mainly caused by the release of stored water in groundwater and inglacial hydrological channels, and the water was clear.

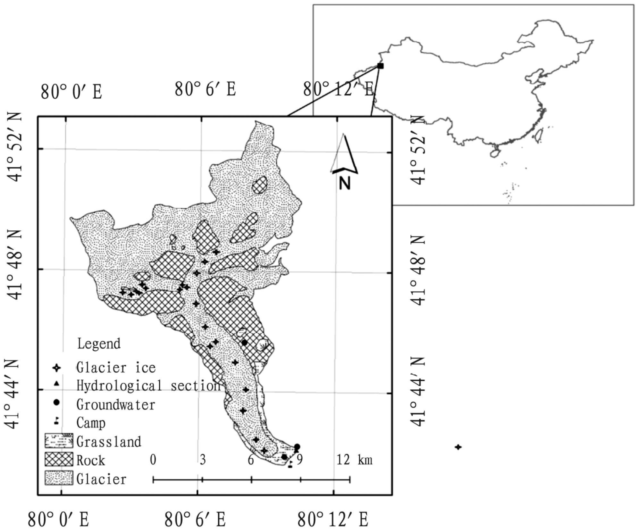

Fig. 1 Sketch map of sampling sites in Koxkar glacier region

2 Methodology

2.1 Sample collection From June 21, 2004 to September 10, 2005, the river sampling point was located downstream of the Koxkar glacier outlet. Sampling was chosen approximately 800 m downstream of the outlet to avoid sampling before the water of the different recharge sources was thoroughly mixed (Fig. 1). A sample of river water was collected at 14:00, for a total of 447. Secondly, groundwater was sampled on both sides of the glacier, and a total of 8 samples were collected. The atmospheric precipitation sampling point (41°42′02.4″ N, 80°10′14.2″ E, 2 996 m above sea level) was located in the camp meteorological observation field (observation items included temperature, precipitation, wind speed, wind direction, radiation, *etc.*). After the precipitation began, the porcelain-plated pots washed with ultrapure water were placed on a column (about 0.8 m high) to collect the precipitation. After the precipitation was over, the sample was collected into the water sample bottle in time (if it was snowfall, the above steps were repeated after it was naturally melted at room temperature), and a total of 63 precipitation samples were collected. In addition, along the direction of the main line of glacial development, 21 glacier ice samples were sampled in the ablation zone. The sampling bottle was a polyethylene bottle, which was presoaked in the laboratory with deionized water. During the sampling process, the polyethylene bottle was first washed with the corresponding river water, groundwater or precipitation for 3 times. Afterwords, the water sample was taken and then sealed at low temperature and protected from light. All samples were taken back to the State Key Laboratory of Cryosphere Science, Chinese Academy of Science for analysis.

2.2 Sample analysis After the samples were taken back to the laboratory, they were temporarily placed in a cold storage at –15 ℃, and allowed to naturally melt at room temperature before the test. The pH value was measured using pHs-3B produced by Shanghai Ray Magnetic with an error range of ±0.01; the conductivity was analyzed by DDS-308A conductivity meter with an error range of ±0.1 μs/cm. The oxygen isotope ratio was measured on a MAT-252 mass spectrometer and the measured $\delta^{18}O$ accuracy was ±0.2 ‰[18].

2.3 Determination of runoff sources The source composition of runoff in the basin was very complicated, especially in the glacirised ablation area where the hot karst hydrological channel was widely developed under ice. The information was all reflected in the flow process line of the outlet section of the basin. It was difficult to distinguish and determine the contribution of supplements of each water source[19]. At present, the commonly used method of hydrological separation was the more than 2 components hydrological mixing model proposed by Pinder and Jones (1969), which was mainly based on two aspects of material conservation, i. e., conservation of water and geochemical tracer. This method could divide the water supply ratio of different water sources or different watersheds. The simple 2 components hydrological mixing model was used to separate the runoff in order to distinguish between the snow-ice melt or new water (or fast runoff) and the soil-restored water or old water (slow runoff)[1]. The seasonal variation of the inglacial hydrological channel could affect the residence time of the water in the glacier, causing changes in the chemical composition of the meltwater. At the same time, chemical reactions occurred when water bodies of different sources were mixed, which also led to changes in ion concentration. Therefore, there were many uncertainties in the use of solute as a tracer to divide runoff recharging sources[7–9,12]. Conversely, stable isotopes were relatively stable, and their output was mainly derived from different water sources, avoiding errors caused by simple mixing of solute, and the tracer used as a mixing model was acceptable[3–9]. Jacob and Knudsen[6] suggested that the basin runoff might be divided into four components:

$$Q_{bulk}\delta_{bulk} = Q_{ice}\delta_{ice} + Q_{precipitation}\delta_{precipitation} + Q_{stored}\delta_{stored} \quad (1)$$

Here, Q is the discharge and δ is $\delta^{18}O$ value, and the subscripts indicate the total runoff, ice melt water, snow melt water, rainfall and inglacial storage water and release, respectively. In the field sampling process, the feasibility of distinguishing and sampling the glacier ice melt water and the ice storage water was little. At the same time, due to the large difference in the elevation of the glacier action zone, the higher elevation zone might be in the form of snow when the lower elevation in the precipitation process occurs with rainwater. Therefore, the equation is simplified to:

$$Q_{\text{bulk}}\delta_{\text{bulk}} = Q_{\text{glacier}}\delta_{\text{glacier}} + Q_{\text{pre}}\delta_{\text{pre}} \qquad (2)$$

Subscript glacier denotes glacial melt water, including glacial melt water and subglacial stored water; pre denotes precipitation, including snow melt water and rainwater.

During the field investigation, in the non-glacial areas on both sides of the Koxkar glacier, many springs flow out and replenish the river. Therefore, the basin runoff is divided into three parts:

$$Q_{\text{bulk}}\delta_{\text{bulk}} = Q_{\text{glacier}}\delta_{\text{glacier}} + Q_{\text{pre}}\delta_{\text{pre}} + Q_{\text{groundwater}}\delta_{\text{groundwater}} \qquad (3)$$

Subscript groundwater indicates the release of underground storage water.

3 Results

3.1 Meteorology and hydrology During the observation period (from June 21, 2004 to September 10, 2005), the average daily temperature was 2.5 ℃, and the extreme maximum temperature occurred on July 9, 2005, up to 17.0 ℃, while the extreme minimum temperature occurred on February 17, 2005, only −21.3 ℃ (Fig. 2). The total precipitation observed was 938.3 mm, and the maximum daily precipitation was 52.6 mm, which occurred on June 26, 2004. In a full year from June 21, 2004 to June 20, 2005, the average daily temperature was 0.5 ℃, and the total precipitation was 627.8 mm, of which precipitation in the summer glacial melting season (from May to September) accounted for 81%. On the contrary, the precipitation in the cold season was only 119 mm and less than 20% of the annual precipitation, and mainly concentrated in October and March, indicating that the precipitation distribution in the study area was very uneven during the year.

During the observation period, the daily runoff of the Koxkar glacier region was between 0.28 and 25.79 m^3/s, with an average of 4.81 m^3/s (Fig. 2). In a full year from June 21, 2004 to June 20, 2005, the average daily runoff of the section was 3.87 m^3/s, and was mainly concentrated in the warm season. From May to October, the runoff accounted for 94.5% of the whole year, of which the summer runoff accounted for 71.5% from June to August. In addition, the annual runoff coefficient was 0.19, which was higher than the adjacent Tailan glacier basin[17].

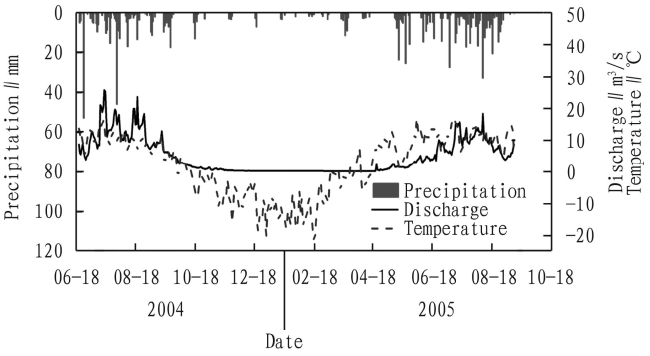

Fig. 2 Mean daily discharges, mean daily temperature and mean daily precipitation in Koxkar glacier region

3.2 Variations of pH and electrical conductivity (EC) of regional water The pH value of the river was between 7.07 and 9.38, with an average of 8.34 in the Koxkar glacier basin. The precipitation pH ranged from 5.61 to 9.30, with an average of 7.88. The pH value of the glacial ice ranged from 7.46 to 8.38, with an average of 8.04. The pH value of exposed groundwater ranged from 7.94 to 8.24, with an average of 8.11 (Table 1). The pH value of river water was significantly higher than that of arid and semi-arid areas[12,20], and was larger than other water bodies in the region, which might be due to the distribution of a large amount of alkaline debris and marine sediments in the study area, in the process of runoff formation, flushing the surface soluble matter, causing water-rock action, and resulting in the consumption of H^+. The pH value of atmospheric precipitation was much lower than that of river water, indicating that H^+ loss occurred during the surface hydrological processes, reflecting the influence of alkaline dust and water – rock interaction on the chemical composition of surface runoff formed by precipitation[20]. The pH value of glacier ice was between river water and atmospheric precipitation, which meant that the process of glacial formation and ablation was affected by atmospheric aerosol deposition or water-rock interaction. In general, the pH value of regional water bodies was: river water > groundwater > glacier ice > atmospheric precipitation.

Table 1 The pH and electrical conductivity of different water in the Koxkar glacier basin from June 2004 to September 2005

Water body	pH			EC // μs/cm		
	Average	Maximum	Minimum	Average	Maximum	Minimum
River water (N=447)[a]	8.34	9.38	7.07	168.09	447.00	54.70
Precipitation (N=63)	7.88	9.30	5.61	58.07	263.00	14.45
Glacier ice (N=20)[b]	8.04	8.38	7.46	25.35	37.55	18.12
Groundwater (N=8)	8.11	8.24	7.94	422.38	433.00	411.00

Note: a. N is the number of samples; b. There is no sample at 3 340 m in the statistical process, which may be contaminated.

Electrical conductivity (EC) is a comprehensive indicator of the ions contained in a water body. The EC of river water in the study area varied from 54.70 to 447.00 μs/cm, with an average of 168.09 μs/cm. The EC of precipitation samples ranged from 14.45 to 263.00 μs/cm, with an average of 58.07 μs/cm. The EC of glacier ice was between 18.12 and 37.55 μs/cm, with an average of 25.35 μs/cm. The EC of exposed shallow groundwater was between 411.00 and 433.00 μs/cm, with an average of 422.38 μs/cm (Table 1), suggested that the regional water conductivity followed: groundwater > river water > atmospheric precipitation > glacier ice, which was significantly different from the pH order. The EC of the river water in the Koxkar glacier basin was also significantly higher than that of other glaciers in the arid and semi-arid areas[12-14,18], which might be related to a lot of debris on supraglacier and the strong water - rock interaction. In general, the ionic concentration of atmospheric precipitation is less than that of glacier ice, that is, the precipitation conductivity is less than that of glacier ice, because precipitation (snow) reaches the glacier surface and forms glacier ice through freezing and ice formation. In the process of ice formation, soluble matter exchange at the solid (including glacial ice and snow) - liquid - gas interface causes the EC of glacier ice to be greater than precipitation However, the EC of atmospheric precipitation in the study area was higher than that of glacier ice, probably because the glacier ice samples in the Koxkar glacier ablation zone were formed by historical precipitation, and its background value could differ from 2004 to 2005. Although there were only 8 exposed groundwater samples, the difference between the maximum and minimum conductivity was only 5.1%, indicating that the chemical composition of groundwater in the study area was relatively stable.

3.3 Variations of water isotope The δ^{18}O in the river water of the Koxkar glacier basin fluctuated from -14.45‰ to -9.23‰, with an arithmetic mean of -10.95‰ and a weighted average of -10.86‰; the minimum occurred on May 15, 2005 during the seasonal snow melting period, and the maximum occurs on June 11, 2005 at the end of the seasonal snow melting and at the beginning of the glacier ice-melting (Fig.3). In a complete year from June 21, 2004 to June 20, 2005, the arithmetic mean of δ^{18}O in river water was -10.99‰, and the weighted average was -10.89‰, similar to the δ^{18}O of the river water in the Urumqi River headwater (it was -10.0‰ in June and -9.56‰ in July)[21]. However, it was significantly smaller than the δ^{18}O (-7.71‰) of the Molin River recharged by non-glacial meltwater in the inland Ordos Basin[22].

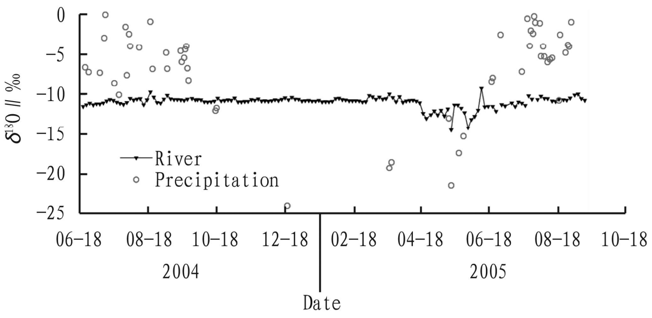

Fig.3 Variations of δ^{18}O of river water and precipitation in the Koxkar glacier basin from June 2004 to September 2005

The variation of δ^{18}O in river water from September to March in the second year was small, and fluctuated around -10.7‰ on the whole. The variance of each month was less than 0.07. With the temperature rising, seasonal snow melting and soil water released in seasonal frozen soil, the ratio of precipitation, groundwater and glacier ice melt water in the river water changed, resulting in a large fluctuation range of δ^{18}O, especially from April 20 to June 17, 2005. The maximum value of δ^{18}O in river water was -9.23‰, and the minimum value was -14.45‰, so the difference was 5.23‰, and the monthly variance was even 1.09 in May.

The variation of δ^{18}O in precipitation ranged from -21.7‰ to -0.1‰, with a weighted average of -7.45‰ (Fig.3). During the glacial melting season from June 21 to September 10, 2004, the precipitation δ^{18}O ranged from -10.9‰ to -0.1‰, with a weighted average of -4.94‰, similar to the observational values of No. 1 glacier station (-5.43‰) in the Urumqi River headwater, Yuejin hydrology station (-6.43‰) in the north[23] and Muztag glacier area[24] in the south, and higher than that of the Lhasa[25] and Delingha[26] in Qinghai - Tibet Plateau. The precipitation δ^{18}O in the warm season was significantly higher than that in the cold season (-11.92 ‰), which could be affected by the " seasonal effect" caused by the different sources of water vapor in the basin. In the warm season, because regional microclimates led to enhanced evapotranspiration, precipitation was mainly due to evapotranspiration of glacirised areas. The lower temperature in the cold season caused the evapotranspiration to weaken or even disappear. The Koxkar basin was mainly controlled by the polar high-pressure gas mass, which was dry and less rainy, and the water vapor sources mainly relied on the recharge of the North Atlantic and the Arctic Ocean[17].

The surface glacial ice samples were mainly distributed in the glacial ablation zone, and the δ^{18}O was between -9.77‰ and -13.99‰, with an arithmetic mean of -11.18‰. In the region with an elevation of 3 738 - 4 200 m, the δ^{18}O of the glacier ice showed a decreasing trend with the decrease of altitude. In the area with an elevation of below 3 738 m, the variation trend of δ^{18}O with altitude was opposite to that of the former (Fig.4). Perhaps due to: (1) Glacier ice samples formed in different historical periods. The use of δ^{18}O in the ice core to invert paleoclimate information suggests that there is a significant difference in the δ^{18}O information stored in different ice layers[10-11]. Glacier ice samples in the ablation zone were the supraglacial ice, which belonged to different exposed historical ice layers, resulting in a large difference in δ^{18}O values of glacier ice samples. (2) The effect of precipitation on δ^{18}O in glacier ice samples. When atmospheric precipitation reaches the surface to form runoff, it may exchange with glacier melt water and then re-freeze, resulting in isotope interference and redistribution. The difference in runoff lag time also affects the oxygen isotope exchange, resulting in changes in δ^{18}O of supraglacial ice samples; (3) Glacier ice melting-refreezing. The sampling points were located in the glacier ablation zone, and there was no effective runoff temporarily after the surface ice was ablated. After mixing with ice-melt water of other layers, re-freezing occurred, resulting in redistribution of supraglacial ice δ^{18}O at the sampling points[4-7]. (4) The role of the debris. There was a large amount of gravel, debris and sand on the ice surface of the ablation zone, and soluble substances exchange with the soluble matter in the melt and then freeze, which may affect the distribution of δ^{18}O in the ice body of the ice surface, and so on.

The average value of δ^{18}O of the eight groundwater samples was -7.94‰, and the variation range was small, fluctuating between -8.08 and -7.73‰; the variance was 0.01, which also indicated that the source of groundwater recharge in the basin was relatively stable.

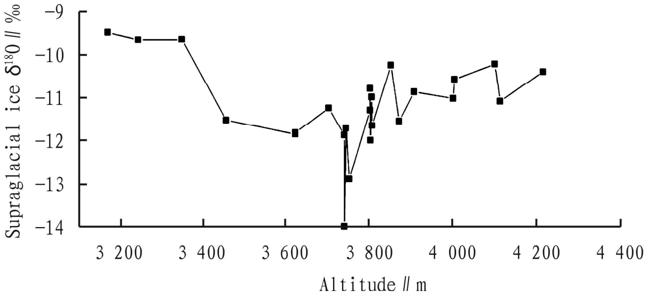

Fig.4 Variation of $\delta^{18}O$ of supraglacial ice in the melting area of the Koxkar glacier region

3.4 Recharge of different water sources In a complete runoff year from June 21, 2004 to June 20, 2005, the results of the runoff source hydrological separation in the Koxkar glacial basin indicated that the glacial ice-melt water supply was dominant, accounting for 72.11% of the annual runoff flux, followed by groundwater recharge, accounting for 16.38%, while atmospheric precipitation (snow) replenishing was the least (11.51%) (Fig. 5). During the glacial melting period (from June 21 to September 20 in 2004), glacial ice melt water accounted for 77.63% of the total runoff, and groundwater recharge accounted for 14.93%, while atmospheric precipitation accounted for 7.44%. This result was close to the results of glacial ice melt water accounting for 84%, and atmospheric precipitation recharge accounted for 8%, which were simulated with the degree-day factor method in the Koxkar glacier basin from July to September in 2003. This suggested that it was feasible to use the $\delta^{18}O$ value and EC as indicators of the hydrological mixing model to separate the different water sources in the glacier basin.

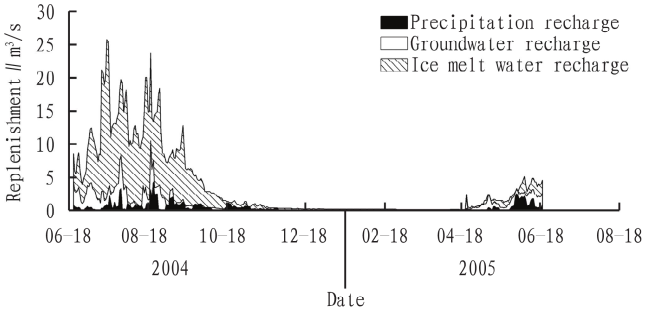

Fig.5 Hydrological separation into ice melt water, precipitation and groundwater using conductivity and $\delta^{18}O$ as tracers in the Koxkar glacier region

4 Control factors of runoff flux variation in the Koxkar glacier basin

4.1 Reasons for changes in the proportion of runoff source recharge The ratio of groundwater, glacial ice melt water and atmospheric precipitation to the total flow flux of river water indicated that the recharge of each water source was very unstable in the Koxkar glacier basin (Fig.6). During the ablation season, glacial ice-melting water was absolutely dominant, mainly because of the high temperature and strong radiation, which led to an increase in ice-melting water supplement (Fig.7). However, when the average temperature was only −8.0 ℃, glacial meltwater also occupied a dominant position, which was essentially different from the former, because supragalcial ice rarely melted or even disappeared from December 20, 2004 to April 19, 2005. In the cold season, atmospheric precipitation was less and mainly occurred in the form of snow. Low temperature not only inhibited the melting of ice and snow, but also promoted the formation of seasonal frozen soil, which could reduce the replenishment of various water sources. However, the release of stored water inside the glacier and the melting water of the basic ice due to frictional heat and sensible heat on the ice bed might still exist[3-8], which could be the main reason for the relatively large ice melt water in the cold season.

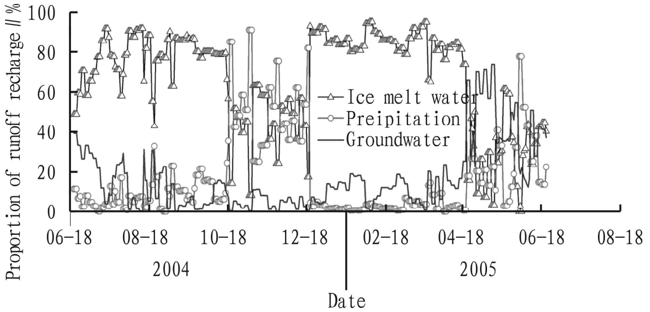

Fig. 6 Proportions of ice melt water, precipitation and groundwater to total flow flux

Secondly, in the transitional period of cold and warm season, the proportion of water sources was very disordered (Fig.6). From October 17, 2004 to December 19, 2004, the melting of glacial ice gradually decreased with the decrease of temperature. The accumulation of seasonal snow and the formation of seasonal frozen soil were the main reasons for the change in the proportion of supply sources. The reason for the phenomenon from April 20, 2005 to June 13, 2005 was opposite to the former. As the temperature raised, seasonal snow, seasonal frozen soil and glacier ice gradually began to melt, causing changes in the composition of river water.

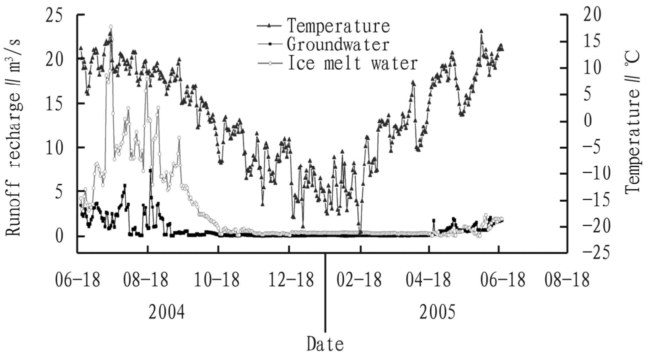

Fig.7 Response of fluxes of ice melt water and groundwater in the Koxkar glacier region to air temperature from June 21, 2004 to June 20, 2005

4.2 Precipitation supply even between precipitation recharge and precipitation There is a close positive correlation between runoff flux and precipitation in non-glaciation basin.

River runoff responds positively to the change of precipitation[2,23]. In fact, it was difficult to find a statistical relationship between total runoff flux and precipitation in the Koxkar basin, and even after precipitation, the total runoff was reduced on June 26 and July 30, 2004 (Fig. 2). There was also no statistical relationship between precipitation recharge and precipitation. It might be due to the large range of catchment area and the inglacial complex hydrological geometry system. For precipitation, the runoff had significant hysteresis, and even there was still precipitation supply during the day without precipitation (Fig. 8), which may be caused by the following factors. Firstly, after the atmospheric precipitation reached the surface of the glacier, in addition to evapotranspiration and re-freezing to supply the glacier ice, part of the precipitation (snow-melting water) entered the inner or bottom of the ice along the glacier fissures, glacial pots, and ice-faced rivers, and was supplied to the river through the under-gray geometric passages or temporarily stored the glacial inside to form stored water. The storage water from the precipitation was released quickly or slowly, or the precipitation formed a glacier ice ablation, which showed that the precipitation had a certain hysteresis effect on the river recharge. The second one is seasonal snow cover. Various water bodies in the Koxkar glacier basin were developed at an altitude of over 2 990 m, which might lead to precipitation in the solid form such as snow and hail in June and August. There was a certain hysteresis in the process of ablation and replenishment to the river, especially the ablation supply of snow in the early warm season. Thirdly, the non-glacial area accounted for about 30% of the total area of the Koxkar glacier basin, while the thickness of the debris and gravel of the glacier ablation area was more than 2 m. After precipitation, the water that infiltrated into the soil did not fractionate to form groundwater, and formed underground runoff to replenish the river water, causing the hysteresis of precipitation to the river.

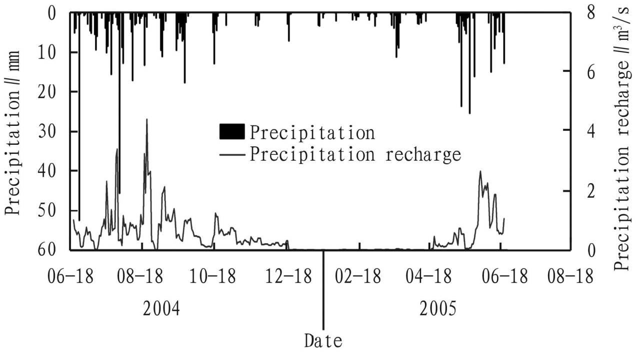

Fig. 8 **Variations of precipitation and its supply in the Koxkar glacier basin**

5 Conclusions

(1) The runoff flux fluctuated drastically, of which 72.11% originated from the supply of glacial ice melt water, while the precipitation supplement only accounted for 11.51% in the Koxkar glacier basin.

(2) Glacial ice ablation during the warm season (from May to September) was significantly affected by temperature. However, when the temperature in the cold season was lower than the critical temperature of 0 ℃, the glacial ice melting replenishment still existed. This could be that the heat generated by the friction between the ice body and the ice bed during the subglacial ice sliding process led ice to melt, what's more, the stored water in the geometric passages inside and below the glacier could slowly release.

(3) The groundwater recharge runoff was affected by seasonal frozen soil and fluctuated greatly in the early and late warm seasons. Precipitation recharge had a certain hysteresis on the time scale, and there was still a phenomenon of precipitation replenishment to runoff even in the absence of precipitation.

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tourism development, plan and coordinate the tourism development of the city, and coordinate the spatial layout of tourism, development of tourism projects, and the differential development of tourism in counties and districts to promote the differential positioning and spatial cooperation of tourist attractions based on the regional tourism development of Binzhou City and enhance the attraction of Binzhou tourism.

4 Conclusions

(1) The nearest distance index R of tourist attractions graded AAA and above in Binzhou City is 1.35, greater than 1, showing that these tourist attractions are evenly distributed. However, there is a big difference between different counties and districts in the distribution of tourist attractions graded AAA and above in Binzhou City. The nearest distance index R of the tourist attractions in High-tech Industrial Development Zone, Yangxin County, Huimin County and Zouping City is less than 1, that is, the spatial aggregation of the tourist attractions is strong.

(2) The β index and γ index of tourist attractions graded AAA and above in Binzhou City are 1.36 and 0.47 respectively, revealing that the tourism traffic connectivity of Binzhou City has not yet reached the ideal state and needs to be improved further.

(3) The average accessibility A_i of tourist attractions graded AAA and above in Binzhou City is 45.26 km, and the accessibility index of 13 tourist attractions graded AAA and above in Binzhou City is higher than the city's average, and they are mainly concentrated in the north of Binzhou City.

(4) The compactness index C of tourist attractions graded AAA and above in Binzhou City is 0.74, showing that the compactness degree of tourist attractions graded AAA and above in Binzhou City is high, which provides a certain foundation for the setting of regional tourism traffic network and the layout of the spatial structure in Binzhou City.

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