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Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge

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SUMMARY

The magnitude and variability of water system's response to climate change impacts have been assessed through a detailed analysis of discharge composition of two selected typical glacier rivers originated from Tianshan Mountains, Xinjiang Uygur Autonomous Region in West China, which is considered as the water tower of Central Asia. Here we demonstrate climate change in the last 60 years using meteorological data (1951–2009) in the region. Both of the temperature and precipitation show a remarkable rise before and after year 1990 and these changes are much more significant in North Xinjiang than it is in South Xinjiang. Response of water systems towards climate change is then assessed by comparing annual discharge change of Urumqi River (10.0%) in the North and Kumalak River (38.7%) in South Xinjiang. We found significant inconsistency of the climate change impact on water resources. Furthermore, we quantitatively determine the ratio of ice-melt water using isotope hydrograph separation as well as other conservative tracers. Results show that Urumqi River is recharged by less than 9% of ice-melt water, while Kumalak River contains more than 57% of ice-melt water in their discharges. The extent of glacier input to a water system governs its sensitivity towards climate change. The method has overwhelming potential for un-gauged watersheds and may offer ways of adaptation to climate change in terms of water resources management for flood control and sustainable agriculture.

1. Introduction

The earth has experienced a significant change of warming over the past 100 years. A temperature rise will lead to an increased volume of ice-melt water, and further result in the increase of discharge of headstream from mountainous areas, plus the increased volume of precipitation. Flood control and agriculture water are highly related to the discharge change affected by climate change. However, current studies show that there is not a clear assessment of the impact of climate change on water resources and agriculture in China (Piao et al., 2010).

Global warming will inevitably lead to increased volume of glacier/snow-melt water, and increased mountainous discharge, which is essentially the total water resources available in an arid region. To what extent this will occur highly depends on the sensitivity of a water system to such changes. Sensitivity of glacier rivers towards climate change has significant implications for water resources management and floods control. However, the magnitude and variability of water system response to climate change impacts have not been assessed.

Xinjiang Uygur Autonomous Region is the most far northwest region in China. The water shortage and low water use efficiency make the people and agriculture in the arid region very thirsty, while spring flood from ice-melt water occurs sometimes. In the last decades, mountain-front discharge has increased by about 10% (Chen et al., 2008; Shi and Zhang, 1995). In order to predict future changes in water resources, it is necessary to gain a good understanding of the impact of climate change on water resources in Xinjiang.

Isotope hydrograph separation has been traditionally used to quantitatively assess the proportion of precipitation (new water) and base flow (old water) in humid climates. But it should not be limited to this. Burns (2002) pointed out that isotope hydrograph separation could be used in catchments with different climatic and human disturbance regimes. Related studies have been carried out in different catchments (Buttle et al., 1995; Zhang et al., 2008). Recently, isotope hydrograph separation in alpine catchments flourished and emphasized the importance of ice-melt water (Liu et al., 2008; Zhang et al., 2008). Nevertheless, these studies did not involve the impact of climate change.

Kong and Pang (2011) pointed out that isotope hydrograph separation could be used to study the response of water resources to

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climate change, through determining the ratio of ice-melt water in watershed scale.

In this study, we first explore climate change in Xinjiang on the basis of the meteorological data from 1951 to 2009, and then use Urumqi River in North Xinjiang and Kumalak River in South Xinjiang as examples to: (1) calculate the ratio of precipitation, groundwater and ice-melt water in the two rivers; (2) evaluate the sensitivity of water systems to climate change. The results are expected to provide an insight into water resources and its management in arid regions.

2. Study area

This study was conducted in Urumqi River catchments in Eastern Tianshan, and Kumalak River in Western Tianshan, Xinjiang Uygur Autonomous Region of China (Fig. 1). Xinjiang region represents one sixth of China's land area. There are three major mountains that "border" the region, which are Altai Mts. in the north, Tianshan Mts. in the middle and Kunlun Mts. in the south. Inbetween these mountains, there are two large basins, namely Junggar Basin and Tarim Basin (Fig. 1). Xinjiang belongs to typical continental arid climate, where the average ambient temperature is 9–12 °C. There is sporadic precipitation and most of it pools in the mountainous areas.

The total volume of water resources in Xinjiang province is 83.2 billion m^3, in which the surface water resources are 78.9 billion m^3 and the groundwater recharge is 7.3 billion m^3 (Dong and Deng, 2005). The impact of climate change on water resources differ substantially among basins due to the high dependence on melt water. Choosing Urumqi River and Kumalak River as case studies, we can assess the different impact of Climate change on Xinjiang water resources.

Urumqi River originates from Glacier No. 1, which flanks Tianger Peak II, the highest peak in southeastern Tianshan with an elevation of 4484 m above sea level. The total length of Urumqi River is 214.3 km with a drainage area of 4684 km^2, and the length in the mountainous area above the outlet until Yingxiongqiao hydrologic station (UH18, Table 1) is 62.6 km with a drainage of 1070 km^2.

Kumalak River originates from Glacier No. 72, which flanks Tuomuer Peak, the highest peak in Tianshan with an elevation of 7435 m above sea level. The total length of the river until Xiehela hydrologic station (AH14, Table 2) is 208 km with a drainage area of 1.28×10^4 km^2.

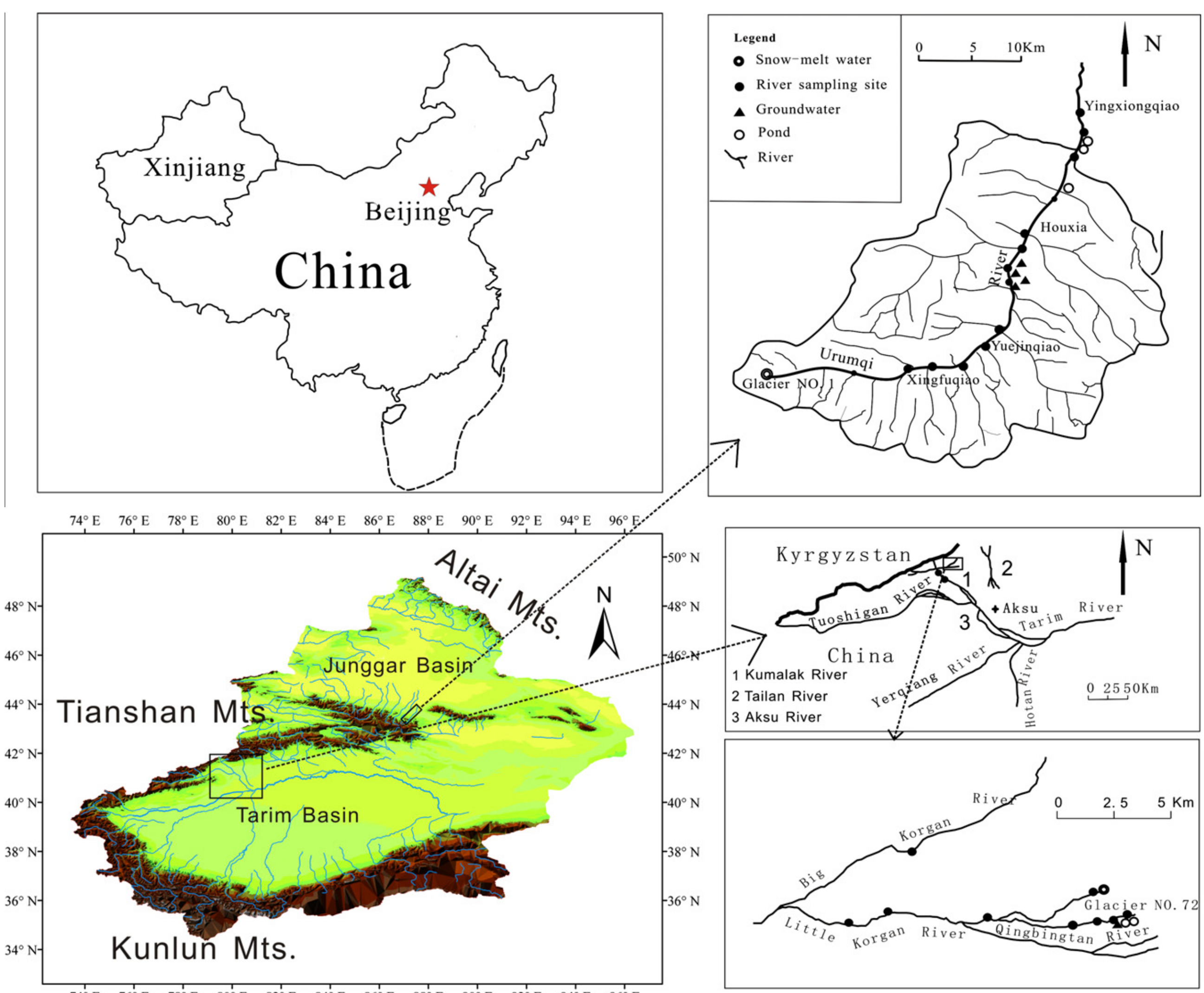

Fig. 1. Map showing the locations of sampling sites including geographical features in Xinjiang Autonomous Region. Urumqi River locates in North Xinjiang and Kumalak River locates in South Xinjiang, according to the tradition border of Tianshan Mountains.

Table 1
Measurements of surface water and groundwater along the Urumqi River.

Sample	Altitude (m.a.s.l.)	pH	T (°C)	K^+ (mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	F^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	NO_3^- (mg/L)	TDS (mg/L)	$\delta^{18}O$ (‰)	δ^2H (‰)	Water type
Ice-melt water																
UH01	3825	6.7	−0.1	0.2	0.2	4.3	0.7	0.5	0.0	4.8	8.5	0.7	15.6	−10.0	−65.8	Ca–Mg–SO_4–HCO_3
River																
UH02	2115	6.0	10.0	0.9	4.1	43.5	4.9	2.2	0.2	47.5	86.8	4.5	151.1	−8.7	−54.0	Ca–HCO_3–SO_4
UH03	2075	6.7	7.0	0.7	3.6	40.1	4.3	2.0	0.2	42.5	79.6	4.3	137.3	−8.6	−52.0	Ca–HCO_3–SO_4
UH04	3173	6.5	8.0	0.7	1.3	23.6	2.3	1.3	0.1	16.1	56.5	2.9	76.5	−8.7	−55.9	Ca–HCO_3–SO_4
UH05	2709	6.5	9.0	0.5	1.8	26.4	3.2	1.2	0.1	30.0	55.8	3.3	94.3	−8.2	−53.0	Ca–HCO_3–SO_4
UH06	2596	6.5	8.0	0.8	1.9	30.8	3.5	1.7	0.1	32.3	61.3	3.7	105.6	−8.5	−53.8	Ca–HCO_3–SO_4
UH07	2503	6.5	8.0	1.1	1.6	31.1	3.0	1.4	0.1	27.5	65.4	3.1	101.5	−8.8	−53.4	Ca–HCO_3–SO_4
UH08	2406	6.5	9.0	0.9	2.4	34.0	3.9	2.0	0.2	36.4	72.4	3.9	119.8	−8.9	−52.1	Ca–HCO_3–SO_4
UH09	2321	6.5	9.0	0.6	3.3	70.8	4.7	1.6	0.3	81.6	123.6	4.0	228.7	−8.9	−52.3	Ca–HCO_3–SO_4
UH10	2133	6.5	9.0	0.8	3.8	41.7	4.7	2.2	0.2	45.9	82.8	4.3	145.2	−9.2	−53.1	Ca–HCO_3–SO_4
UH11	2120	6.5	8.0	0.7	3.4	39.3	4.0	2.0	0.1	40.1	76.7	4.8	132.8	−8.6	−51.9	Ca–HCO_3–SO_4
UH12	1963	6.5	8.5	/	/	/	/	/	/	/	/	/	/	−8.8	−52.5	/
UH14	1926	7.0	9.5	1.1	4.5	41.3	5.0	2.5	0.2	44.5	116.0	4.7	161.8	−8.8	−53.8	Ca–HCO_3–SO_4
UH17	1919	7.0	10.0	1.0	5.3	43.0	5.3	2.8	0.2	45.6	93.5	5.0	154.9	−8.5	−52.6	Ca–HCO_3–SO_4
UH18	1919	7.0	9.8	1.0	5.2	43.2	5.4	2.7	0.2	44.8	98.3	5.0	156.6	−8.5	−52.5	Ca–HCO_3–SO_4
Pond																
UH13	1961	7.0	8.0	0.8	4.1	41.6	4.5	2.3	0.2	43.9	83.2	4.6	143.5	−8.6	−53.4	Ca–HCO_3–SO_4
UH15	1922	7.5	12.0	/	/	/	/	/	/	/	/	/	/	−8.6	−54.6	/
UH16	1922	7.5	14.0	/	/	/	/	/	/	/	/	/	/	−8.7	−54.1	/
Groundwater																
U1	2121	6.0	10.0	0.9	3.7	36.4	4.2	1.9	0.3	35.4	84.4	4.3	129.3	−8.8	−53.5	Ca–HCO_3–SO_4
U2	2115	6.5	10.0	0.9	3.3	38.8	4.3	2.0	0.2	38.9	78.8	4.2	132.0	−9.0	−53.5	Ca–HCO_3–SO_4
U3	2113	6.5	8.0	0.9	3.5	36.8	4.2	1.9	0.3	36.1	81.3	4.2	128.5	−8.9	−53.8	Ca–HCO_3–SO_4
U4	2081	6.5	10.0	1.2	6.0	43.6	4.9	3.0	0.3	38.9	99.7	6.0	153.6	−9.0	−55.8	Ca–HCO_3–SO_4

3. Sampling and analyses

Water samples including groundwater and surface water were collected along Urumqi River and Kumalak River during August, 2009. The sampling locations are illustrated in Fig. 1. Sampling details are as follows:

Groundwater: In the mountainous watersheds, it is difficult to find suitable wells for sample collection. Along Urumqi River, groundwater sample was collected from four different wells. Along Kumalak River, a spring sample was collected.
River: A total of 25 samples of river water were collected at sites of interest, among which 14 samples are along Urumqi River, and the 11 samples are along Kumalak River.
Pond: Samples from three ponds in Urumqi River and two ponds in Kumalak River were collected.
Ice-melt water: At the tongue of Glacier Nos. 1 and 72, a sample of ice-melt water was collected underneath the snow pack, respectively.

Field parameters, including pH, dissolved oxygen (DO), Eh, electrical conductivity (EC) and temperature were recorded at the time of sample collection. Samples were later analyzed in the Water Isotopes and Water–Rock Interaction Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences. δ^2H and $\delta^{18}O$ were measured on a laser absorption water isotope spectrometer analyzer (DEL-100, Los Gatos Research). All δ^2H and $\delta^{18}O$ values are expressed related to Vienna Standard Mean Ocean Water (V SMOW) in ‰, and the measurement precision was 0.5‰ and 0.2‰ for δ^2H and $\delta^{18}O$, respectively. The analysis of water chemistry was completed using ion chromatography in Analytical Laboratory of Beijing Research Institute of Uranium Geology. The methods for cation measurements are taken from the National Analysis Standard DZ/T0064.28-93 while for anions are from DZ/T0064.51-93. Alkalinity was measured on automatic titrator (785 DMP™). Analytical precision was 3% of concentration based on reproducibility of samples and standards and detection limit was 0.1 mg/L. The results are shown in Tables 1 and 2.

4. Methods

4.1. Climate change mapping

The meteorological data including amount of the precipitation and air temperature of 15 meteorological stations in Xinjiang province from 1951 to 2009 are downloaded from China Meteorological Data Sharing Service System. Then the contours are mapped to characterize the climate change using the method of Kring interpolation.

4.2. Hydrograph separation

Two and three-component isotope hydrograph separation (Clark and Fritz, 1997; Fritz et al., 1976; Rodhe, 1984) have been adopted to calculate the ratio of various recharging sources in Urumqi and Kumalak River. Both the two and three-component method can be described as a uniform equation:

$$Q_t = \sum_{m=1}^{n} Q_m, \quad Q_t C_t^j = \sum_{m=1}^{n} Q_m C_m^j, \quad j = l, \ldots, k \tag{1}$$

where Q_t is total runoff discharge, Q_m is the discharge of component m, and C_m^j is the tracer j incorporated in the component m. As refer to isotope hydrograph separation, one of the tracers should be a kind of isotope.

The model requires several assumptions as follows (Sklash and Farvolden, 1979; Turner et al., 1992):

(1) C_m^j should be constant during the calculation period, such as a rainfall–runoff process.
(2) C_m^j should be different between each component.
(3) A steady-state model adequately represents watershed conditions.

Table 2
Measurements of surface water and groundwater along the Kumalak River.

Sample	pH	Altitude (m.a.s.l.)	T (°C)	K^+ (mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	F^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	NO_3^- (mg/L)	TDS (mg/L)	$\delta^{18}O$ (‰)	δ^2H (‰)	Water type
Ice-melt water																
AH03	6.2	3746	0.4	3.6	2.2	21.9	6.4	1.6	0.1	10.9	89.6	1.6	93.1	−9.4	−53.7	Ca–Mg–HCO_3
River																
AH04[a]	6.2	3751	0.2	/	/	/	/	/	/	/	/	/	/	−9.8	−55.3	/
AH05	6.2	3604	4.4	3.2	2.1	21.9	6.4	1.6	0.1	12.1	81.5	1.5	89.6	−9.4	−53.1	Ca–Mg–HCO_3
AH06	6.7	3597	7	4.2	1.5	18.6	6.2	0.7	0.1	4.4	82.9	0.6	77.7	−10.2	−63.6	Ca–Mg–HCO_3
AH07	6.9	3470	7.6	3.5	1.3	18.1	5.3	0.6	0.0	4.3	87.4	0.5	77.3	−10.3	−60.6	Ca–Mg–HCO_3
AH08	6.8	3314	8.2	2.9	1.1	17.8	4.4	0.6	0.0	4.0	76.3	0.5	69.4	−10.3	−61.0	Ca–Mg–HCO_3
AH09	6.5	2859	9.1	4.6	12.2	44.4	25.7	11.2	0.3	59.3	179.8	4.2	251.8	−8.2	−44.4	Ca–Mg–HCO_3–SO_4
AH10	7.3	2474	9.0	2.8	6.0	33.8	13.5	6.3	0.1	34.4	96.4	2.7	147.7	−8.5	−45.9	Ca–Mg–HCO_3–SO_4
AH11	7.5	2401	10.3	3.0	6.3	34.1	13.8	6.4	0.1	34.6	119.2	2.7	160.6	−8.6	−46.4	Ca–Mg–HCO_3–SO_4
AH12	6.3	2334	5.9	4.9	4.7	30.6	6.9	2.5	0.7	28.6	93.7	1.4	127.1	−11.1	−68.8	Ca–Mg–HCO_3–SO_4
AH13	6.5	1466	12.8	2.4	3.7	42.6	13.0	2.3	0.3	62.1	106.7	1.5	181.2	−11.1	−71.8	Ca–Mg–HCO_3–SO_4
AH14	6.5	1427	14	2.2	3.5	42.8	12.8	2.4	0.3	62.3	105.7	1.6	180.7	−11.2	−71.9	Ca–Mg–HCO_3–SO_4
Pond																
AH01	6.3	3670	8.1	/	/	/	/	/	/	/	/	/	/	−8.0	−41.6	/
AH02	/	3670	/	/	/	/	/	/	/	/	/	/	/	−7.9	−42.6	/
Spring																
A1	6.0	3672	9.9	8.6	9.6	48.8	26.8	7.0	0.4	107.0	142.5	1.4	280.7	−7.7	−42.3	Ca–Mg–HCO_3–SO_4
Precipitation																
AP1	/	3751	/	/	/	/	/	/	/	/	/	/	/	−4.0	−5.3	/

[a] Most of AH04's ions are below detection limit.

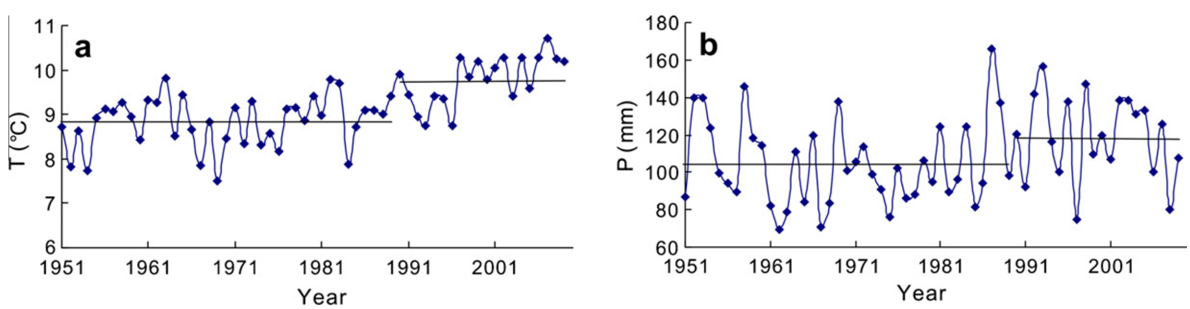

Fig. 2. Annual temperature (a) and precipitation (b) change based on the data of 15 meteorological stations across Xinjiang province from 1951 to 2009. Multi-year mean annual temperature and precipitation change significantly before and after 1990: T, 8.8 increases to 9.8 °C; P, 104–119 mm.

To meet these assumptions, tracers have been used in various kinds including environmental tracers such as ^{18}O, ^2H, d excess and geochemical data such as TDS, EC, Cl^-, Si, SiO_2 and even DOC and temperature (Gibson et al., 2005; Kong and Pang, 2011; Laudon and Slaymaker, 1997; Trcek et al., 2006; Turner et al., 1992). In this study, we choose $\delta^{18}O$ and TDS as tracers for their significant differences in recharging sources.

5. Results

5.1. Climate change

The rate of global warming has accelerated significantly since 1990. Meanwhile, both a step change of temperature and precipitation appeared around 1986 in the Tarim River basin (Chen et al., 2007; IPCC, 2007). Thus, we choose 1990 as the cut-off year to discuss the variation of precipitation and temperature. Fig. 2 illustrates that annual temperature across Xinjiang province increased from 8.8 to 9.8 °C, and precipitation increased from 104 to 119 mm.

Fig. 3 illustrates that both temperature and precipitation increased in the past 50 years across nearly all the Xinjiang province. In most regions, temperature increased by 0.6–1 °C, and precipitation increased by 0–20 mm. Both temperature and precipitation increased the most in the northern part of Xinjiang province, which is close to the Altai Mountains. Apparently, temperature and precipitation change in North Xinjiang was much more significant than that in South Xinjiang, according to the traditional border of Tianshan Mountains.

5.2. Discharge change

Climate shift before and after 1990 should result in the corresponding shift of discharge in glacier rivers. However, discharge does not always response consistently to climate change. Some rivers like Shuimo River in North Xinjiang diminished even annual precipitation has an increasing trend (Gong et al., 2003), while discharge of some rivers in south slopes of Tianshan Mountains increased 14% from 1951 to 2000 (Ye et al., 2006). Xu et al. (2010) analyzed eight representative rivers in Xinjiang including Burjin River, Tex River and Manas River in North Xinjiang, Kaidu River, Kumalak River, Yarkant River and Karakax River in Sourthern Xinjiang, and Erdaogou River in Eastern Tianshan, and then concluded discharge of most rivers has increased significantly since 1990s, but in a different magnitude.

In this study, we choose Urumqi and Kumalak River as case studies to identify the mechanism of the response of water systems

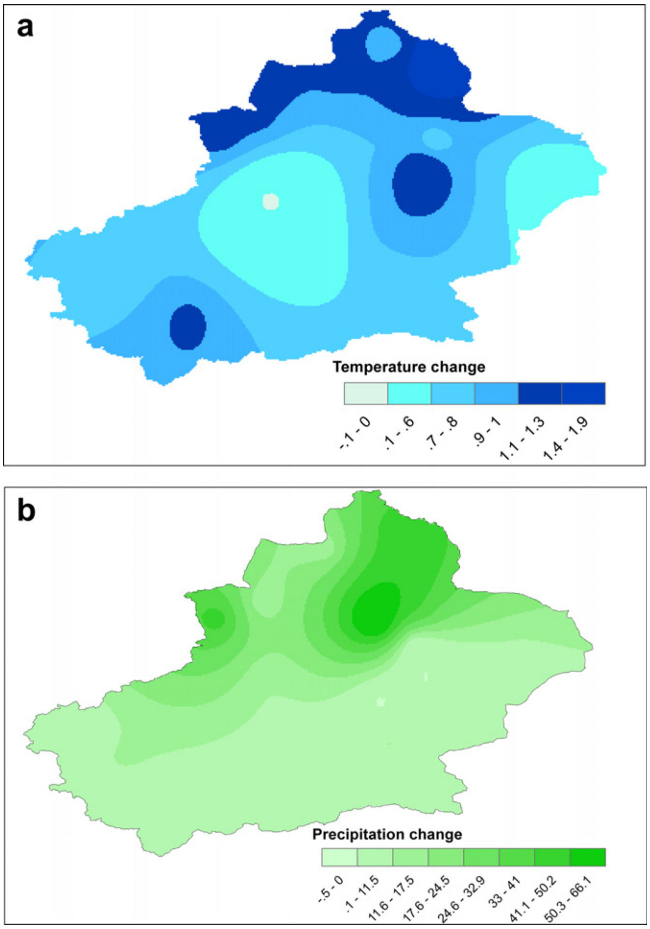

Fig. 3. Contours of temperature and precipitation change before (1960–1989) and after 1990 (1990–2009) across Xinjiang province, based on the data of 15 meteorological stations from 1960 to 2009. As the data in some stations from 1951 to 1959 are absent, only data from 1960 to 2009 are chosen.

to climate change. Discharge in Urumqi River and Kumalak River has both increased about 10.0% and 38.7% with 1990 as the cut-off year (Fig. 4). Nevertheless, discharge in Urumqi River rose less than it in Kumalak River, even though climate change in North Xinjiang was much more significant than it in South Xinjiang. Why it happens? In the following, we will use isotope hydrograph separation to check the reasons after an analysis of groundwater and surface water interaction of the two rivers.

5.3. Hydrograph separation in Urumqi River

5.3.1. Characteristics of water chemistry and isotopes in Urumqi River

Fig. 5 illustrates that samples of Urumqi River just locate between samples of ice-melt water and groundwater, and most of the groundwater samples have been covered by river samples. Meanwhile, from the glacier front to the mountain-pass, all the samples are distributed in a quite concentrated way, which shows the close relationship between groundwater and surface water bodies (Fig. 5).

Changes of TDS along Urumqi River further prove the interaction between surface water and groundwater (Fig. 6). TDS of Urumqi River lies between that of ice-melt water and groundwater, with the water type of $Ca–HCO_3–SO_4$ (Table 1). Fig. 6 illustrates that TDS of river evolves from the low TDS of ice-melt water to the conservative TDS of groundwater, and tends to a constant value from Houxia station (UH10). The sample (UH09) is an exception which belongs to the tributary but not the main stream. Thus, the river should be composed of ice-melt water and groundwater, and mainly groundwater.

Isotopic characteristics of all the water samples present a similar style with that of hydrochemical data. Samples of river, ponds and groundwater lie above Local Meteoric Water Line (LMWL, (Pang et al., 2011)), and all distribute in a concentrated way relative to LMWL (Table 1 and Fig. 7). As groundwater comes from infiltrated precipitation and ice-melt water, its isotopes are just between these two sources. The ponds should not have experienced the process of evaporation because of their similar isotopes and TDS to the vicinal river. Though isotopes of the river vary only a little, most of them are enriched than groundwater and ice-melt water, showing that Urumqi River could not be constituted of only groundwater and ice-melt water.

Pang et al. (2011) indicated that weighted isotopes of precipitation in Eastern Tianshan were $-6.3‰$ for $\delta^{18}O$, $-43.5‰$ for δ^2H in August. Then isotopes of precipitation are the most enriched, while the isotopes of ice-melt water are most depleted, and isotopes of river just lie among that of precipitation, ice-melt water and groundwater. Therefore, combining the isotopic data with the hydrochemical evidence stated above, we can conclude that Urumqi River is composed of precipitation, ice-melt water and groundwater, and the recharging ratio of groundwater rises gradually towards the downstream.

5.3.2. Contribution of different water sources in Urumqi River

As stated above, TDS of ice-melt water, river and groundwater varies significantly above Houxia station, showing that groundwater has experienced the process of dissolution, and then discharges to the river gradually. Because significant differences of TDS and isotopes only exist in the upper reach of Urumqi River above Houxia station, we just carry out hydrograph separation above the section of Houxia station, and deem that the river below Houxia section is mainly composed of groundwater owing to their similar composition of chemistry and isotopes (Table 1, Figs. 6 and 7).

The samples of river just distribute in the triangle formed by that of precipitation, ice-melt water and groundwater (Fig. 8). Using the average TDS and $\delta^{18}O$ of groundwater, ice-melt water and precipitation as parameters, we can get the ratios of each component contributing to Urumqi River based on Eq. (1) (Table 3).

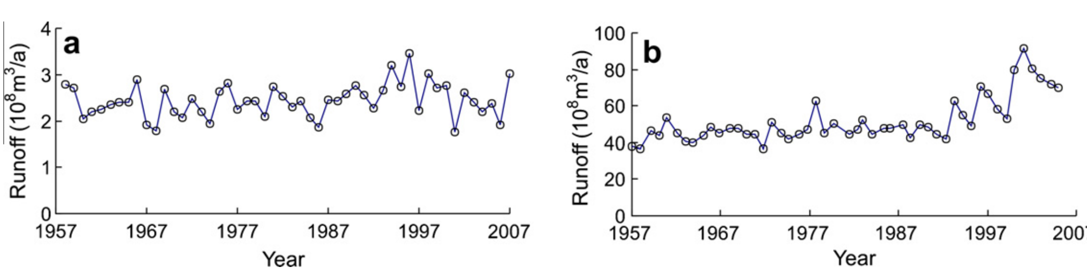

Fig. 4. Discharge of Urumqi River at Yingxiongqiao station and Kumalak River at Xiehela station. Discharge of Urumqi River is calculated based on the data from Li et al. (2010); and discharge of Kumalak River is cited from Xu et al. (2010).

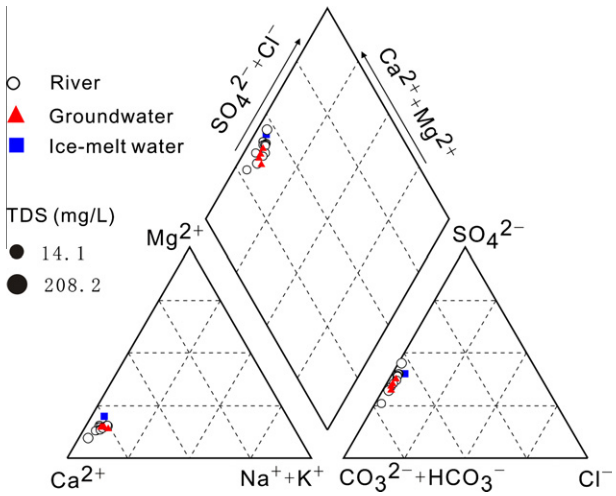

Fig. 5. The piper map of surface water and groundwater water along Urumqi River.

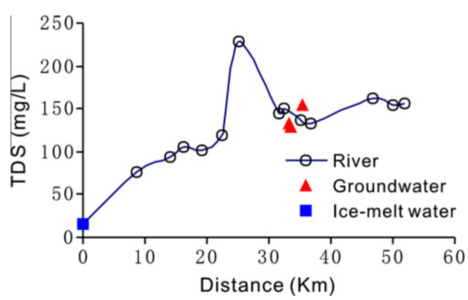

Fig. 6. Changes of TDS in surface water and groundwater along Urumqi River.

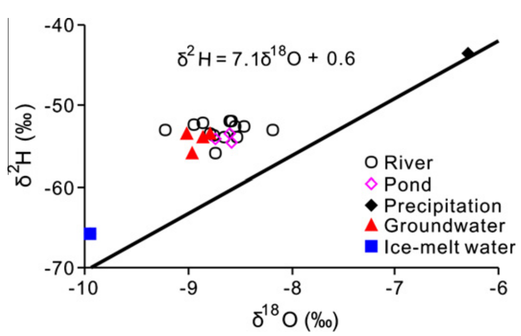

Fig. 7. Distribution of isotopes incorporated in the surface water and groundwater relative to Local Meteoric Water Line (LMWL). LMWL is cited from Pang et al. (2011).

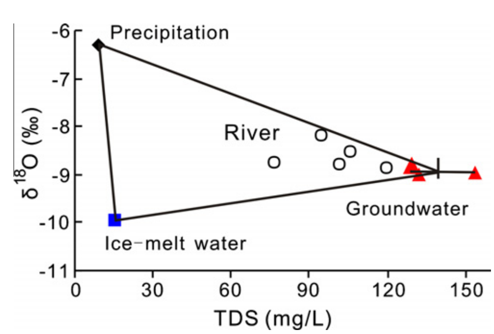

Fig. 8. Relations of TDS–$\delta^{18}O$ of surface water and groundwater along Urumqi River. Chemical data of precipitation are calculated based on the data from Zhao et al. (2008). The cross around groundwater represents the maximum and minimum TDS and $\delta^{18}O$, and the intersection of the cross is the average.

Table 3 shows that groundwater accounts for a larger and larger part of the river with the rising of the distance from glacier front. At the distance of 9 km, the ratio of groundwater has exceeded 50%. The ratio of precipitation diminished gradually, while the ratio of ice-melt water has decreased to 29% at the distance of 9 km, and then further decreased to 9% at 22 km. Therefore, groundwater is the main source recharging Urumqi River and the ice-melt accounts for less than 9% in total at Yingxiongqiao station (UH18).

5.4. Hydrograph separation in Kumalak River

5.4.1. Characteristics of water chemistry and isotopes in Kumalak River

From the glacier front to mountain pass, water type of the river evolves from Ca–Mg–HCO_3 to Ca–Mg–HCO_3–SO_4 (Figs. 1 and 9 and Table 2). Figs. 9 and 10 illustrate that the river samples around the ice-melt water are samples AH04–AH08, TDS of which are less that 90 mg/L (TDS of ice-melt water). The five samples all locate near the glacier front, and characterize with depleted isotopes (Table 2, Figs. 1 and 11). What's more, temperature of AH04 and AH05 is 0.2 and 4.4 °C, which is close to the glacier water. Therefore, we treat all the samples AH04–AH08 as ice-melt water in the hydrograph separation section, which means that in the first 5 km of Kumalak River, ice-melt water is the major one, accounting for almost 100% of the recharging sources.

Fig. 10 illustrates that the river ranks just between the ice-melt water and groundwater with an exception at 5.4 km. TDS of the

Table 3
Estimated fractions of water sources as a result of hydrograph separation above Houxia section along the Urumqi River.

Sampling sites (distance from glacier front (km))	Estimated fractions (%)		
	Precipitation (%)	Groundwater (%)	Ice-melt water (%)
UH04 (9)	19	52	29
UH05 (14)	29	67	4
UH06 (16)	18	76	6
UH07 (19)	11	71	17
UH08 (22)	4	87	9

Input parameters: Precipitation: TDS = 9.3 (Zhao et al., 2008), $\delta^{18}O = -6.3$ (Pang et al., 2011); groundwater: TDS = 135.9, $\delta^{18}O = -8.9$; ice-melt water: TDS = 15.6, $\delta^{18}O = -10.0$; river: TDS and $\delta^{18}O$ of UH04–UH08 see Table 1.

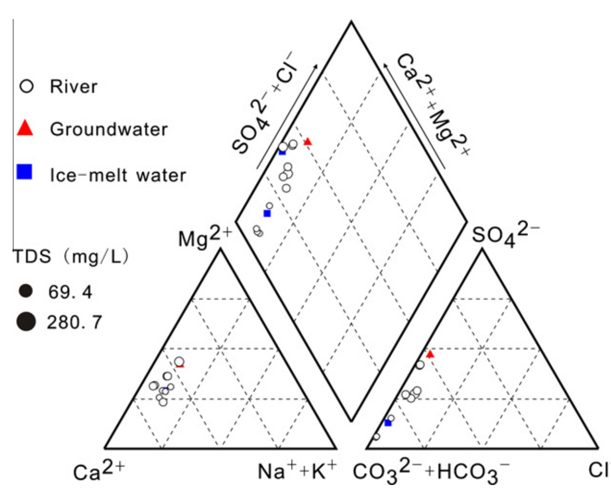

Fig. 9. The piper map of surface water and groundwater water along Kumalak River.

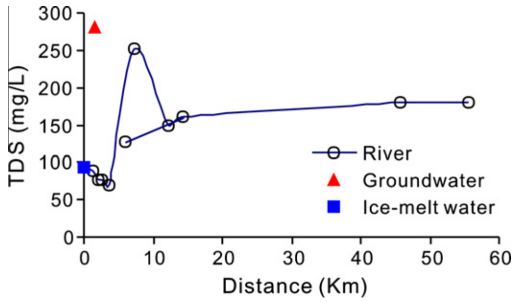

Fig. 10. Changes of TDS in surface water and groundwater along Kumalak River. The short line is another tributary of Kumalak River named Big Kuergan River with a sample of AH12.

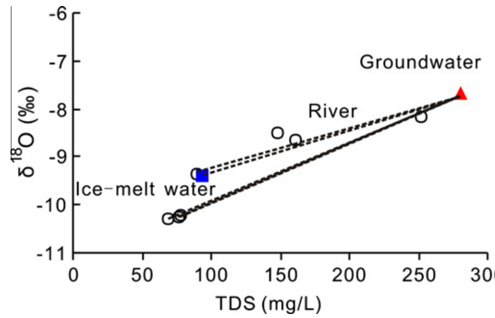

Fig. 12. Relations of TDS–δ^{18}O of surface water and groundwater along Kumalak River. Five dashed lines are different mixing lines using different ice-melt water as an end member.

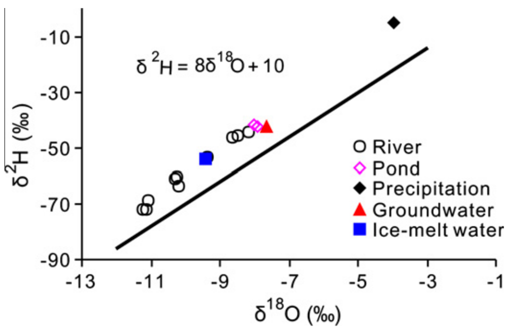

Fig. 11. Distribution of isotopes incorporated in Kumalak water, precipitation, ponds and vicinal spring relative to Global Meteoric Water Line (GMWL). Because in Western Tianshan there is not enough isotopic data of precipitation to form LMWL, the GMWL was adopted.

Table 4
Estimated fractions of water sources as a result of hydrograph separation along the Kumalak River.

Sampling sites (distance from glacier front (km))	Estimated fractions (%)	
	Groundwater (%)	Ice-melt water (%)
AH09 (7)	85–86	14–15
AH10 (12)	29–37	63–71
AH11 (14)	36–43	57–64

Input parameters: Groundwater: TDS of A01; ice-melt water: TDS of AH03 and AH05–AH08, respectively; river: TDS of AH09–AH11 respectively; see Table 2.

river evolves towards to a constant value gradually after mixing with Big Kuergan River.

Isotopes of various water bodies provide a further insight of ground water and surface water interaction. All the samples just lie above the GMWL, similar to the style in Urumqi River (Fig. 11). Apparently, the two ponds have not experienced evaporation. And their isotopes distribute very closely to the spring A1. Considering the samples' site measurements (T: 8.1 °C and EC: 175.7 µs/cm), the ponds should be recharged from groundwater. So before mixing with Big Kuergan River, the isotopes of river samples (AH09, AH10 and AH11) lie between that of ice-melt water and groundwater (Fig. 11).

In fact, great difference of landscape exists above and below the sampling site AH08 which is 455 m higher than site AH09. Above AH08, bare mountains behave precipitous, and meadow begins to occur until AH08. At the site AH09, the terrain has become relative flat. Such a topographic difference creates the conditions for interaction between groundwater and surface water. Thus, Kumalak River is composed of the ice-melt water and groundwater.

5.4.2. Contribution of different water sources in Kumalak River

Above the site AH08, Kumalak River is mainly composed of ice-melt water. Below the site AH11, Kumalak River has mixed with Big Kuergan River. As Big Kuergan River is more depleted than the ice-melt water during the sampling period, the samples below AH12 become much depleted. We deduce there should be more depleted ice-melt water at the source of Big Kuergan River, though we have no details of that. Then hydrograph separation was only carried out at the site AH09–AH11, as a representative of upper reach of Kumalak River.

During the sampling period, only a little precipitation occurs, and its isotopes are quite enriched, which may be attributed to the amount effect of convective precipitation (Clark and Fritz, 1997). Furthermore, the river samples of AH09, AH10, and AH11 just lie on the line connected by ice-melt water and groundwater (Fig. 12). So precipitation was assumed to be not incorporated in the river.

Here we choose TDS other than δ^{18}O as the parameter to carry out two-component hydrograph separation. This is because isotopes of ice-melt water varied considerably over time (Hooper and Shoemaker, 1986), and δ^{18}O in Kumalak River does not have significance to differentiate ice-melt water and groundwater, while TDS of groundwater is about three times than that of ice-melt water (Table 2).

As most of AH04's cations are below detection limit, we excluded the sample when carrying out hydrograph separation. Using the TDS of AH3 and AH05–AH08 as that of ice-melt water, respectively, TDS of A1 as that of groundwater, and TDS of AH09–AH11 as that of the river, we could get that the ratio of ice-melt water and groundwater at AH09–AH11 using Eq. (1).

At AH09 site, groundwater accounts for about 85%, which is different to other sites above or below it (Table 4). As its d excess ($d = \delta^2H - 8\delta^{18}O$, (Dansgaard, 1964)) is close to but not less than other river samples, it should not have experienced the process of evaporation. Its location on the mixing line further bolster it a result of mixing with groundwater around. Then at other sampling sites ice-melt water accounts for more than 57%. Due to the more depleted isotopes of AH12 from Big Kuergan River and AH13–AH14, the contribution of ice-melt water to Kumalak River at Xiehela hydrological station (AH14) should not be less than 57%.

6. Discussion

In Urumqi River, groundwater is the major recharging source. Average discharge of Glacier No. 1 from 1985 to 2006 has increased by 66% owing to global warming, but the absolute value only increased 165.1 × 10^4 m^3 from 1956 to 2006 (Li et al., 2010). Surely, the increase of discharge in Urumqi River is not mainly due to the glacier melting but the increased recharge of precipitation and groundwater. In fact, analysis of intra-annual discharge in Urumqi River shows that discharge increases mainly in autumn and winter (Wu et al., 2006), which further bolster that the rise of recharging from precipitation and groundwater is the main reason.

In Kumalak River, above the sampling site AH11, the ice-melt water contributes the most. As the isotopes at Xiehela hydrological station (AH14, Table 2) become more depleted, there must be more ice-melt water recharging Kumalak River. Glacier No. 72 retreated from 7.27 km^2 to 5.52 km^2 during the period 1964–2008 (Li and Dong, 2009). Meanwhile, precipitation has increased by about 30 mm (Fig. 3). Melted glaciers and increased precipitation jointly caused the shift in the discharge of Kumalak River.

Flood is one of the attributes that climate affects hydrology. A flood event can cause a great deal of loss in life and property. Flood frequency and prediction studies have flourished in the last decades, but difficulties are still there for its uncertainties (Nezhad et al., 2010; Schmocker-Fackel and Naef, 2010; Xu et al., 2010). Agriculture is another focus due to the impact of climate change on water resources. However, the effects of climate change on water availability and food security cannot be generalized, which is attributed to the complex replenishment of rivers (Immerzeel et al., 2010; Piao et al., 2010). Isotope Hydrograph separation provides a quantitative method to differentiate the replenishment of rivers for water resources management, especially in the ungauged basins. In this study, Kumalak River is a glacier river that should be paid more attention to as flood events and agricultural water supply are concerned, while Urumqi River is not as sensitive to climate change.

7. Conclusions

On the basis of the meteorological data from 1951 to 2009 in Xinjiang, China, we found that annual precipitation has increased by 15 mm and annual air temperature has risen by 1 °C, with 1990 as the cut-off year. Although both temperature and precipitation rose in the total Xinjiang region, climate change in North Xinjiang was more significant than it in South Xinjiang.

However, the larger rise of climate change in North Xinjiang has not led to a more significant response of Urumqi River. On the contrary, Kumalak River in South Xinjiang is more sensitive to climate change than Urumqi River: discharge in Urumqi and Kumalak River rose by 10.0% and 38.7%, respectively.

Using hydrograph separation, we find that Urumqi River is a groundwater-dependent river while Kumalak River is a glacier-dependent river. In Urumqi River, from the glacier front to Yingxiongqiao station, groundwater recharges the river increasing with distance down stream. At 9 km groundwater accounts for 52%, and it becomes more than 87% and ice-melt water for less than 9% at Yingxiongqiao station, where groundwater accounts for nearly 100%. In Kumalak River, ice-melt water accounts for 57–64% at 14 km from the glacier front, and more than 57% at the Xiehela hydrological station.

Therefore, the nature of glacier rivers determines the climate sensitivity of watersheds fed by them. Glacier rivers like Kumalak River are more relevant to flood control and agriculture water division than Urumqi River. In water resources management, both differences of climate change and the replenishment of rivers should be given sufficient emphasis.

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