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Response of Glacier Flash Flood to Climate Warming in the Tarim River Basin

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Abstract: In past 50 years, the air temperature fluctuation was raising trend in Tarim River Basin. The annual mean temperature has increased by 0.3℃ in the whole Tarim River Basin, and by 0.6℃ in the mountain areas. With global warming, the frequency of unstable and extreme climatic events increased, glaciers retreating accelerated and snow meltwater increased have resulted in the more frequency of snow-ice disasters such as glacier debrisflow and glacier flash flood etc. Since 1980s, in the process of intense climate warming, glaciers melting intensified, ice temperature rose and glaciers flows accelerated, and lead to more glacial lakes and extending water storage capacity and stronger glacial lake outburst floods occurrence. It is proposed that the monitoring and evaluating of the impact of climate change on water resources and floods should be enhanced.

Key words: climate warming; glacier flash flood; response; Tarim River Basin

Introduction

China is one of the countries which glacial flash floods and glacial lake outburst floods disasters take frequently place in the world. With the development of the national economy and global warming, the glacial flash floods seriously threaten to highways, bridges, hydroelectricity, reservoirs and the development of industry and agriculture. In some major projects and state development zones, the studying and monitoring of snow-ice disasters should especially be strengthened. For example, it is necessary to make clear the effect of the frequency and intensity of glacial lake outburst flood in the headwaters on the projects of the lower reaches for the development and governance of the Tarim River Basin.

Since 1958 China began to systematically study glaciers, the disasters of glacial lakes outburst flood have been paid much more attention. The disasters of moraine-dammed lake outburst flood of Pumqu (Arum) and Poiqu (Bhoto-Sun Kosi) River Basins in Himalayas Mountains, and the formation and outburst mechanism of the outburst floods induced by glacier-dammed lake of Yarkant River Basin in Karakorum Mountains have been successively studied [1−3]. On the basis of the field investigations and theoretical analysis, Zhang Xiangsong *et al.* [1] put forward that the frequency and the discharge of the glacier lake outburst floods will be decreasing in the upper reaches of Yarkant River due to the glaciers continuously retreating and the glacier lake water storage decreasing under the background of climate warming. However, as global warming since the 1980s, especially the sharply warming in the 1990s, glacier blocked the river valley again and formed glacial lakes because of glacier melting intensified and ice flow accelerated, large glacial lakes outburst floods occurred frequently [4]. Glacier flash flood and glacial lake outburst floods disasters in Tarim River Basin have closely correlation with the global warming. Thus it is important to study the relationship between climate change and the glacier flash flood under the global warming and abrupt climate change in order to provide the scientific basis for the early warning of disasters and the establishment of the decision system.

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1 Changes in climate and hydrology

The Tarim Basin is the biggest arid inland basin in China. The Tarim River Basin is located in the southern half of Xinjiang. There are numerous other rivers that disappear into the desert coming down from the mountains. A number of rivers fed by snowmelt and glacier melt begin in the mountains and drain into the basin with average annual virgin flow of about 35 billion m^3. Around the rivers oases of small villages and agriculture may be found.

In past 50 years, the air temperature of Tarim River Basin mainly takes on fluctuant rising trend [5]. The annual mean temperature has increased by 0.3℃ in the whole Tarim River Basin, and by 0.6℃ in the mountain areas. The temperature of summer, autumn, winter have a more obviously rising trend. The greatest temperature increasing is in autumn, the temperature rising in the 1990s is 1.1℃ higher than that in the 1960s. The temperature rising for both summer and winter are 0.7℃, the temperature in spring has no obvious change (Table1).

In mountain areas, precipitation increasing and moisture rising are obvious in the 1990s [6−7]. The decade mean precipitation in 1960s−1980s is 186.0−191.8 mm, the variation rate by 3.1%. In the 1990s, the decade mean precipitation is 220.3mm, which is 18.3% higher than that in the 1980s. The moisture increasing in spring or summer is more obvious than autumn or winter. More than 10 mm precipitation processes in summer have an obviously increasing trend since the 1990s.

Last decade (1991−2000) is the warmest period for mountainous area and wettest period for the plain area in past 50 years, whereas began more wet in the plain area since the 1980s. A distinct increasing precipitation is in the 1990s for most parts of mountains region of Tarim River Basin including the south slopes of the Tianshan Mountains and Pamir Plateau, and a decreasing precipitation zone is in the west Kunlun Mountains in last 20 years.

By the influence of the warm-wet climate shift on the water resources since 1987, the streamflow sourced from the four source river systems that contribute flows to the Tarim River (Aksu, Hotan, Yarkant and Kaidu Rivers) have a increasing trend, and the total runoff of the Tarim River Basin during 1991−2000 increased by 7.6% of that during the past 40 years. The average annual runoff of 1994−2001 is 26.19 billion m^3, which is 2.0 billion m^3 increased in the 1990s, increased by 8.3% and more than average annual runoff up to 3.70 billion m^3 and increased by 16.5%.

2 Disaster characteristics of the glacier flash flood

Researches show that glaciers are melting more and more rapidly and consequently the lakes that are fed by glaciers are growing in size. Combined with this is an associated increase in air temperature. Glacial lake outburst floods (GLOFs) are not a new phenomenon; they have simply been happening more frequently over the last 20 years, but the damage they can cause is huge. Typical runoff hydrographs in the basin show two peaks, one formed from melting of snow on non glaciated surfaces and the other caused by melt on glaciated areas. The second hydrograph peak is usually significantly larger than the first one.

With global warming, the frequency of unstable and extreme weather increased, the glaciers retreating, and meltwater increasing in the Tarim Basin, and result in more frequency of avalanches, snowdrift, glacier and glacial lake debrisflow and ice-snow disasters such as floods [4,7−9]. When the climate shift from warm-dry to warm-wet since 1987 in Xinjiang region [7], the frequencies of floods have obviously increasing trend [9]. The frequency of flood disasters due to glaciers, debrisflows, landslides blocking has increased significantly. For instance, the frequency of glacier lake outburst floods has increased up to 1.0 times per year in the 1990s from 0.7 times per year in the 1980s (Table2),because of temperature rising and meltwater

Table 1 Decade mean temperature variation in source regions of the Tarim River (℃)

Period	Spring (Mar.−May)	Summer (Jun.−Aug.)	Autumn (Sept.−Nov.)	Winter (Dec.−Feb.)	Annual Mean
1961−1970	2.1	12.0	0.7	−14.0	0.2
1971−1980	2.3	12.6	1.3	−14.0	0.5
1981−1990	1.9	12.5	1.1	−14.1	0.3
1991−2000	2.1	12.7	1.8	−13.3	0.8

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Table 2 Annual frequency of glacier and snowmelt floods in Tarim River Basin during 1950–2000 (times per year)

Flood type	1950–1960	1961–1970	1971–1980	1981–1990	1991–2000
Snow-glacier melting flood	0.6	0.2	0.4	0.1	1.0
Rain and snow melting flood	0.2	0.3	0.2	1.8	0.9
Glacier flash flood	0.4	0.7	0.2	0.7	1.0
Total	1.2	1.2	0.8	2.6	2.9

increase, the occurrence of the glacier lake outburst flood increasing [4,7]. Snow-ice melting floods are greatly affected by temperature in the mountain areas, especially consistent with the high altitude temperatures [10]. The peak discharge and the volume of floods are not only greatly related to the alpine temperature, but also to the glacier area, the snow reserves, and the summer snowfalls [10]; glacier meltwater in mountain areas has a obvious diurnal variation with same as the seasonal snow meltwater [10]. Most glacier and snow melting floods originated in the Karakorum Mountains, and the northern slope of the Kunlun Mountain occurred in July and August, this is an extremely flood period with high temperature on the northern slope of the Kunlun Mountains. In generally, glaciers floods have features of both rising and falling slowly, with flood lasting long, flood volume large and not high peaks. Large rivers originated in the Tianshan Mountain with a short-term high temperature period, flood usually lasted only 4–10 days, and flooding increasing and falling processes with steep slopes, and has a high flood peak relative to peaks of glacier-snow melting flood in Kunlun Mountain. Flood peak from rivers of the Tianshan Mountains reflects a short-term high temperature climate characteristic [10] and a large number of snowmelt in high temperatures periods, and therefore flood rising rapidly, but in the rainy period, temperature sharply dropped, melt water decreased, and flooding fell quickly. Rivers originate in the northern slope of the Kunlun Mountains, have longer-term high temperature period, floods usually lasted more than 10 days, even for one month; peak lasted several days, or more than 10 days, with a great flood volume, but both flooding rising and falling processes are very slow. And the flood falling phase is faster than the rising phase.

Glaciers temporarily store and release water at time scales from days to seasons. Whether this is due to evolving internal hydraulic systems or to stable structures within the system is unclear. However, subglacial water flow is coupled to glacier movement such that one can not understand subglacial water flow without understanding glacier movement. In some circumstances, storage and release processes result in catastrophic floods like those in Lake Merzbacher, which inundate flood plains without warning. Water can be impounded along the ice margin, as ice dammed lakes, or within the body of the ice. Moraine-dammed lakes formed by a glacier retreating from its terminal moraine, also present a hazard. These lakes are present in many regions of the Tianshan, Karakorum, Kunlun and Pamir, but are particularly catastrophic in the Tianshan, Karakorum , Himalayas, where rapid glacier retreat and large moraines impound large volumes of water and present significant hazards to villages in the valleys below. Engineering strategies to mitigate the flood hazard are currently underway.

3 Response of glacier flash flood to climate warming

Tarim River system is mainly fed by glaciers and snow melt water. The Khan Tengry glacier massif in the Central Tianshan, West Kunlun glaciers, and K2 glacier massif in Karakorum are the major source of the Tarim River Basin, where 45%–50% of total runoff is contributed by these glaciers. There are a total of 14285 glaciers, with an area of 23628.98 km^2, ice reserves 2669.435 km^3 in Tarim River system. As one of the most important water resources in the basin runoff from glacier meltwater reaches up 15 billion m^3, occupying 40% of total surface runoff of the basin [8]. In past 50 years, the winter and spring are main seasons for climate warming, and summer is cooling. The warming in winter would lose a lot of cold storage of glaciers, and make ice temperature rising, and result in a large number of glaciers melt caused if a very short summer warming. The glacier mass balance in this region takes mainly on negative balance in recent 40 years. The glacier mass balance are −150 mm/a in the Pamir and Karakoram Mountain and −350 mm/a, in the southern slope of Tianshan Mountain, but the Kunlun Mountain is basically stable [8].

The surface melting observation on the glaciers in Muztag areas of the East Pamir Plateau was carried out in 1960. In the 1987 and 2001, the observation was carried out again ,and the results [11] show the ice melting increased from 16 mm/d in 1960 to 20 mm/d in 1987, and 37 mm/d in 2001. The results show an obvious intensified glacier melting and the response of glacier melting to climate warming. The discharge in the river fed by glaciers meltwater in Tarim basin is extremely sensitive to the climatic change, especially to the air temperature. The 1℃ changes in air temperature will make 127 mm fluctuation of the discharge of the rivers in Tianshan [8]. Therefore, the temperature rising will easily cause the glacier floods, and damage to the social and economic development. The effect of the precipitation to discharge is less than the temperature. The100 mm precipitation change will lead to 66 mm discharge change of the Tailanhe River. In the situation of the global warming, the discharge of the glacier meltwater will obviously increase. The average annual mass balance in Tailanhe river basin located in the south slope of Tianshan is −287 mm/a [12] during 1957−2000, and the accumulated glacier mass balance is up to−12.6 m, equals to 5.45 billion m^3. The net ablation from glacier by the temperature increasing is equal to the runoff volume of 5.45 billion m^3 in past 44 years, which accounted for 15% annual runoff of the rivers. The mass balance in the Tailanhe basin takes almost on negative value after 1982, the average one is −168 mm/a in 1957−1981, and −445 mm/a in 1982−2000. According to the results in reference [8], the temperature changes by 1℃ , the glacier mass balance will change by 300mm, the runoff in Tailanhe river basin will change to a range of 16%. This means that, with the climate shift from warm-dry to warm-wet in Xinjiang region, the glaciers are more sensitive to temperature, the glacier melting accelerated, and the meltwater continuously to increasing [12].

Negative impacts of climate warming on the Tarim River Basin are mainly increased glacier runoff and more frequency of glacier flood disasters. Glacial floods will cause huge economic losses in areas of the lower reaches, for example the direct economic losses amounted to 7.6 billion RMB Yuan by the floods in 1996 and 1999, and damage to the local economy and development.

Kumarik River is the biggest branch of the Aksu River; it is also the main source of the Tarim River. Its source area and the main runoff forming area located within the boundaries of the Kyrgyzstan Republic. Kumarik River sources from the glaciated center of Central Asia in the Mount Khan Tengry of Tianshan, drainage area of 12816 km^2 (of which 2306 km^2 in Kyrgyzstan) in which glacier area is 3195 km^2. Inylchek glacier is the largest one with 61 km length 567.20 km^2 area. The glacial runoff is 54% of average annual runoff at Shehela Gauge Station. In the source region of Kumarik River, sandwiched between the South and the North Inylchek Glaciers, is the mysterious Merzbacher Lake. Every year, and sometimes twice a year, the lake suddenly empties, only to refill again with the melted glaciers that surround. When the Merzbacher Lake level is high, the length of the lake surface is 4.5 km, the width is 1.5km, the biggest water storage capacity can be up to 0.33 billion m^3, the altitude is 3600 m, and the biggest lake volume is 0.5 billion cubic meters, and the lake depth can reach to 140 m. With the climate warming, the glacier retreating, the glacier lake storage capacity is increasing, and the flood risk increasing year by year.

Over the past some years, the Tianshan have started melting down with the increase in temperature leading to formation of increasing number of glacier-fed lakes. According to a study conducted from 1932 to 2005, 58 GLOFs have recorded at the Kumarik river hydrological record, and more than 90% frequency. Based on Shehela recording data, annual runoff have increased 10×10^8 m^3 from1960s to1990s, and 25% of total annual mean runoff. Peak discharge has increased 32% from1950s to1990s [5, 7−8] (Fig. 1, Table 3). Flooding discharge is increasing to 3.5×10^8 m^3 in 1990s from 1.5×10^8 m^3 in 1960s. Before1990s , flood period lasted 5−10 days with flood increasing last in 5−8 days , and flood falling last 1−2 days, and flood discharge was in $1 \times 10^8 - 4 \times 10^8$ m^3, of which 2/3−4/5 occurred in increasing days. But the hydrograph processes has greatly change since 1998 as global warming and ice velocity speed up , flood period lasted is 10−13 days, flood increasing last only 2−3 days, and flood falling last 7−10 days, flooding discharge is $1.5 \times 10^8 - 2.0 \times 10^8$ m^3,of which 3/4 from falling days, 1/4 from increasing days.

Glacier floods from the headwater of the Yarkant River originated in the Shaksgam Valley of the north slope of the Karakorum, there are 4−5 glaciers, including Keyakier Glacier, Teram Kangri Glacier, and Gasherbrum Glacier, extend down to main valley and blocked the valley and stream, and formation glacier lakes in mainstream valley. When the glacier ice dam was floated or drainage channels open, it will triggered glacial lake outburst floods. After the event of 1986 glacier lake outburst flood, it did not occurred outburst flood again until 1996, because of the glacier discharge tunnel opened. According to history of

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Table 3 Peak discharge (Q_p) of glacier lake outburst floods of Kumarik and Yarkant Rivers in 1987–2002

Year	Kumarik River Q_p/(m^3/s)	Yarkant River Q_p/(m^3/s)	Year	Kumarik River Q_p/(m^3/s)	Yarkant River Q_p/(m^3/s)
1987	1720	/	1996	1840; 825	/
1988	583	/	1997	1900	4040
1990	1540	/	1998	/	1850
1992	1610	/	1999	2100	6070
1994	2200	/	2000	1380	/
1995	1420	/	2002	1610	4550

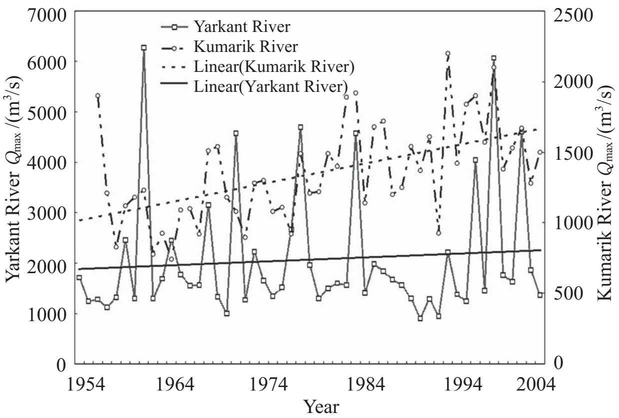

Fig. 1 Annual peak discharge changes at Shehela hydrological station of Kumarik River and Kaqun hydrological station of Yarkant River (Q_{max})

the glacier advancing and retreating change [1] in the Karokoram at that time, it is considered that 10-year-scale glacier advancing pulsations in the 20th century have already passed in Yarkant River; the glaciers would be in the relative stable, retreating and shrinking stage. It is projected that the continuous climate warming will be at the beginning of the 21st century, and most glaciers will be retreating and thinning. The possibility of the glacier lake outburst floods is very small, and the possibility of the outburst floods with several thousand cubic meters per second is also very rare, the glacier flood disaster in the Yarkant River Basin will reduce after 1986 [1]. However, as the glacier melting intensified since the 1990s, the glacier meltwater increased, ice temperature rising, the glacier flow speeded up, and result in the glacier blocked the river course and formed the new glacier lakes, and then the large glacier lake outburst floods frequently occurred [4] (Table 3). According to studies [7, 9], under global warming, the flood peak discharge and the flood total discharge of the glacier lake outburst flood are more and more large (Fig. 1), the scale of glacial lake expands correspondingly, and the outburst flood risk increases.

The main performances of the response of glacier changes to global warming are: a) softened ice, ice deformation increased, ice bottom sliding fast, speed up ice flow and the melting of glaciers; b) glacier velocity increased, blocked glacier valley, and forming glacier lakes; c) Ice temperature rising, glaciers softened, and more easy open ice-water drainage channels; d) warming, glaciers melting intensified, increased runoff, and flood frequency; e) retreating of glaciers, glacial lake storage capacity increasing, glacial lake area expanding; peak discharge and the volume of the floods increasing.

4 Concluding remarks

Glacier water resources in Tarim River Basin is not only important freshwater resources, keeping stable rivers' hydrological changes, and Also, the drastic increase of glacial meltwater resulting from global warming is the main reason of glacial flood disaster, further more much disaster will be produced due to glacial lake outburst floods. The climate changes have an important impact on water resource and occurrence of glacial flood. It is necessary and urgently to control Tarim River and ensure water supply in virtue of studying the water resource changes and glacial flood under global warming. With the developing of economy, intensifying of human activities, and global warming, the peak discharge and total flooding volume of glacial lake outburst floods are becoming more and larger. Corresponding the scale of glacial lake are expanding, the criticality and risk of glacial lake outburst floods are increasing, the endangerment of glacial flash floods are worse and worse. Strengthening impact assessment of

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climate change on water resources and flood disaster, should pay enough attention for national and local governments.

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