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SUDDEN FLOOD RELEASES FROM GLACIAL LAKES OF TARIM RIVER IN XINJIANG, CHINA

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ABSTRACT

Evidence is provided to indicate that widening tunnels beneath glaciers represent the most likely explanation for specific rapid flood releases from glacial lakes along the Tarim River. Such rapid flood releases are dangerous and happen frequently, being comparable to similar events in Alaska. During the past 5 decades, about twenty sudden flood releases linked to glaciers have taken place in the river. These floods are characterized by a rapid rise, high peak discharge and small total runoff compared with peak discharge. The duration is typically short with a single peak, occurring in high mountainous areas (4000-4700 m a.s.l.) during the later period of the flood season, being rather different from both rainstorm and snow-melt flood events. Field investigations have shown that flood releases are related to sudden drainage of glacier-lakes, such as that dammed by Keyajir Glacier. This drained as a result of rapidly expanding sub-glacial channels.

Key words: Sudden flood releases, sub-glacial tunnels, Tarim River

INTRODUCTION

The Tarim River is the largest continental river in China. Figure 1 shows that it is comprised of three principal tributaries, namely the Yarkand River, Hotan River and Aksu River, along with the mainstream. Glacial flood events in the Tarim River are very dangerous and happen frequently. Recent statistics for the past 5 decades show that about 20 and 35 glacial flood events occurred in Yarkand and Aksu Rivers, respectively. Such glacier-related floods have received widespread attention, causing disasters in Iceland, Peru, Switzerland, Canada, USSR, USA and Nepal.

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This paper discusses the cause of glacier floods in the Yarkand River, based on detailed analysis of aerial photography, together with field observations in the Yarkand River headwaters and related flood characteristics. It is suggested that such flood events are related to water releases from glacier-dammed lakes, based on changes of the glacier at the upper end of the Shaksgam Valley in the Yarkand River, on the northern slope of the Karakoram Mountain.

STUDY AREA AND SUDDEN FLOOD CHARACTERISTICS

The Tarim River basin with an area of 10,200,00 km^2 covers the entire south Xinjiang Province in China. Its area is 1.4 times that of the Yellow River basin, with a population of 8,257,000. Hydrologically, the Tarim River basin represents a closed catchment, where several tributaries drain into its interior, the Tarim depression. The mainstream catchment of the Tarim River basin is located below the confluence of the Hotan, Yarkand, and Aksu Rivers. It is a unique freshwater ecosystem found near one of the largest deserts in China, - the Taklamagan Desert.

Fig.1 The location of the Tarim River

The Tarim River is mainly fed by glacial-snow melt water and rainfall. Runoff composition is made up of glacial melt water, mixed rainfall and snow melt, and river base flow in the proportions 48.2%, 27.4% and 24.4%, respectively. Change of annual runoff volume is small, with a coefficient of variation (Cv) of around 0.15~0.25. Seasonal runoff is unevenly distributed, with runoff from June to August occupying 60~80% of annual runoff volume. This reflects the mountainous glacial-snow melt features of an arid area.

Yarkand River, one of the tributaries of the Tarim River, originates from the north slope of Karakoram Mountain. The watershed area is 50,248 km^2 and typical annual runoff amounts to 63.8 x 10^8 m^3. Since 1953 when the Kaqun hydrometric station (1420 m a.s.1.) was established, average annual discharge for the station is 202 $m^3 s^{-1}$, with an equivalent runoff depth of 132.6 mm for the basin. From that

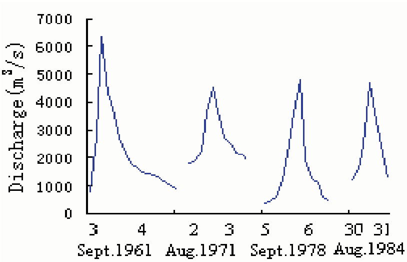

Fig. 2 Flood hydrograph in Kaqun hydrometric station

time until 2000, about 20 flood releases linked to glaciers have taken place in the Yarkand River. During the last 50 years, the distribution of sudden flood releases over time and space has varied considerably. Such floods might happen yearly or not recur over a period of seven years to occur again. Sudden flood releases might occur from June to November, being quite different from snow-melt or storm floods. Figure 2 shows that the flood hydrographs have comparable shapes and might be formed by the same mechanism.

These floods are characterized by a rapid rise, high peak discharge, small volume compared to peak discharge, being of short duration with a single peak hydrograph. Discharge also falls suddenly. Peak flood discharges in excess of 4500 m^3/s have occurred four times, with a further four events in the range 2000 - 4500 m^3/s. Other events include flows of 800 – 2000 m^3/s. Peak flood discharges are usually six times the base flow, with a maximum of over ten times. Most flood durations are about 20 hours, the shortest being 12 hours. Some of these floods only take half an hour to reach the flood peak. The 1961 sudden flood release took only half an hour to rise to a flow of 6270 m^3/s from a base flow of 806 m^3/s. The 1984 sudden flood release is another example, taking only 18 minutes from initiation to reaching the flood peak. Rate of increase of flood flow was 203 m^3/minute.

Flood peak discharges exceeding 4,500 m^3/s have appeared between August and early September, while discharges of 3-800 m^3/s are typical during fall and at the beginning of winter. Whilst sudden floods arising in different seasons have peak discharges varying by a factor of eight, nevertheless they have a similar pattern. Discharges are quite large, but volumes are relatively small. Flood discharges are 10-25 times larger than mean annual flow rate. However, flood volumes are only 0.2-l.7% of mean cumulative flow. The 1961 outburst discharge was 6,270 m^3/s, being 25 times the annual average flow. But the related runoff volume was $1.5\times10^8\, m^3$, being less than 2% annual cumulative flow. Nearly all the flood volumes were below $1.0\times10^8\, m^3$, except for the 1961, 1978 and 1984 floods.

ORIGIN OF SUDDEN FLOOD RELEASES

Reasons for the sudden floods on the Yarkand River have been debated for many years and remain un-answered. Two hypotheses have been considered. One is that this kind of flood is caused by precipitation while the other links them to glaciation processes. Now a three-year field investigation suggests that sudden floods on the Yarkand River were not caused by precipitation.

Basic reasons for discarding the rainfall hypothesis include consideration of the Yarkand River's location at the southwest edge of the Taklamagan Desert, far from any ocean. In addition, southern basins of the Himalaya Mountains and Karakoram Mountain divert air currents containing moisture from the Indian Ocean away from the area. The annual precipitation there is only 350~400 mm. A further reason is that the air temperature falls about 2-4°C during precipitation in mountain regions above 4000 m a.s.l. Forms of precipitation change with change of altitude. New snow falling at different altitudes cannot melt simultaneously to form such a large discharge. Finally, air temperatures fall in the high mountain regions after the end of August and precipitation is almost always in the solid form. So precipitation cannot explain the sudden floods occurring after that time.

Detailed analysis of meteorological data and satellite cloud pictures prior to sudden floods also cannot substantiate the precipitation hypothesis for the event on August 30th, 1984. The air temperature at 600 hPa in the K2 region shows that when this is at the maximum value of 10.3°C, then the height of the zero layer is around 5500 m a.s.l., and the last ten day period in August is mainly pyro-temperature weather without any precipitation and cloud activity. Investigations of sudden floods on the upper Yarkand River also suggest that such floods originate from the upper end of the Shaksgam Valley, a big tributary of the Yarkand River, and are related to glaciers.

It appears possible that some sudden floods are caused by releases from two lakes formed by the damming action of the KyaGar and Tram Kanri Glaciers, located on the northern slope of the Karakoram Mountain. Both glaciers are aligned nearly N-S damming the Shaksgam Valley to form the two lakes which extend in an E-W direction. One of them, Kyagar Thso Lake, currently one of the largest active glacier-dammed lakes in the Yarkand River, is the original site of flooding in the basin.

ANALYSIS OF THE AUGUST 1984 SUDDEN FLOOD EVENT

Site Geomorphology

The Gasherbrum, Urdok and Stagar Glaciers are examples of isolated rocks covered by moraine gravels along the Shakegam River (Figure 3). Gravels beyond the fronts of these glaciers, testify that these glaciers had at sometime barred the valley. But it seems that these glaciers could not have formed dammed-lakes, for there are no lacustrine traces, neither terraces nor deposits. However, dammed rivers and lakes are distributed at the upper end of the Shaksgam Valley, at the Kyagar and Tram Kanri Glaciers. This is more pronounced at the Kyagar Glacier some 19 km upstream from Tram Kanri Glacier. It suggests that whether a lake is formed or a river becomes blocked depends on the location of a glacier in the river.

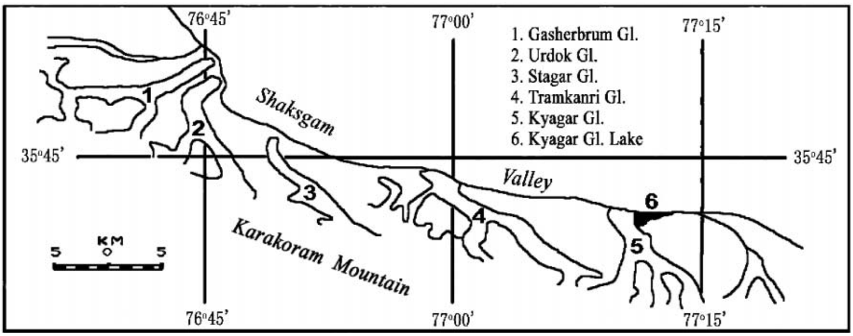

Fig. 3 The glaciers distributed in Shaksgam Valley, northern slope of the Karakrum Mts.

Distribution of lakes in the Shakegam River shows that lakes are more readily formed in the upper reaches, barred by glaciers. At present, the Tram Kanri Glacier may not fully dam the lake for the glacier terminus has partly separated from the right-bank of the river, so melting water can drain away.

Detailed analysis of the two lake dimensions and sudden flood volumes suggest that the four peak discharges exceeding 4500 m^3/s may have been caused by the two lakes. There is the possibility of the two lakes emptying simultaneously. In the case of the Kyagar glacier, a sudden release into the dammed lake of the Tram Kanri glacier could have triggered the maximum instantaneous discharge. The combined volume of the two water bodies matches the runoff volumes associated with the four 4500 m^3/s events.

It appears that the Kyagar Lake was formed at about the beginning of this century, (Mason, 1927; Desio, 1930). During the period of its existence, the glacier-dammed lake has emptied and refilled many times. There are 134 sedimentary markings along both sides of the lake, indicating previous water levels of the Kyagar Thso Lake. Some remains of lacustrine terraces and sand beds are distributed at the upper level of those markings and most lacustrine deposits marks which are in the shape of lines, less than 50 cm wide at the middle and lower level of the lake banks.

The distributions of lacustrine marks suggests that the Kyagar Lake was more stable in the early stages, and then the frequency of emptying and refilling of the lake speeded up with recession of the Kyagar glacier. The largest recorded volume of the Kyagar Lake is 3.6×10^8 m^3, based on the highest marking that is now some 72 m above the height of the Kyagar Glacier Dam. While changes affecting the front of the Kyagar glacier were not very remarkable over the past half-century, a reducing thickness of the Kyagar Glacier is quite conspicuous. Kyagar Lake is reducing in volume as the Kyagar Glacier retreats and now only stores 0.6×10^8 m^3.

Specific Flood Event Details

Peak discharge for the 1984 flood release was 10,480 m^3/s, based its flood profile marks near the leading edge of the TramKanri Glacier in the upper Shakegam Valley. This became 8,300 m^3/s at Stargar Gorger, 18.5 km downstream, then further declined to 4,940 m^3/s at the Lan Gan Hydrometric Station, some 324 km from the last measuring section. Finally it was only 4,570 m^3/s at the Kaqiun Hydrometric station, a further 112 km downstream. While there were some branch rivers flowing into the main channel during this flooding routing process, it was evident that the flood discharge was simply declining (Figure 4). In addition, propagation velocities of flood discharges were nearly equal. Along the reach, average propagation

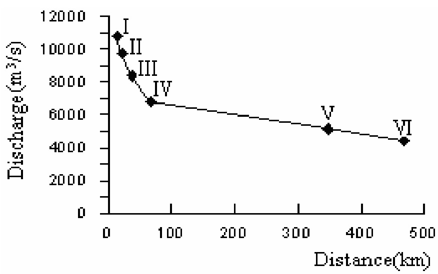

Fig. 4 The declining of flood discharge in 1984

velocities were about 12.9 km/h from Lan Gan Station to Kaqiun Station. Propagation velocities of some large sudden floods occurring in summer were even higher, at about 14 to 16 km/h. For example, in the 1971 sudden flood occurring on August 2nd, discharge was 4,570 m^3/s with a velocity of up to 16 km/h.

Suggested Flood Mechanism

It is difficult to positively identify the mechanism of dammed water release. Usually there are three main ways in which glacier-dammed water bodies might drain. The dam might be overtopped, there might be flow underneath the glacier dam or the dam might collapse. Complete and well-documented observations of the sudden floods don't exist. Fortunately, a survey team met twice at the Kyagar glacier-dammed lake area during 1995-1997. Some direct evidence and facts about the mode of emptying of the Kyagqr glacier-dammed lake were obtained by detailed field observations of the glacier dam and lake area both before and after flooding.

Evidence to Support Flood Release Hypothesis

Our team visited the Kyagar Lake area and glacier of the end of July 1996, when the Kyagar lake water level was rising at the rate of 1.3 m per day and had a volume of approximately 1.6×10^7 m^3. Detailed surveys were made of both the Kyagar Lake and glacier dam, and photographs were taken prior to the August 14 flood event. There were some ice bodies, as large as 4.5×6×7.5 m, scattered on the river bed in the lower reaches of the Kyagar glacier dam. These were lying on the banks of the emptied lake within a distance of one km of the dam. Hence the water escape velocities were so quick that ice bodies crumbling from the Kyagar Glacier could not be gathered together at the bottom of the lake as the water drained. Such observations correspond with the sharp, single peaked flood hydrographs. The Kyagar Glacier dam had no marks or indications of cracking, and no gullied erosion of the glacier surface. What had been floating material was spread across glacier surface. Comparing the Kyagar Glacier dam before and after the flood event, we observed that the Kyagar Glacier dam had partially collapsed. The lower edge of the glacier remained in contact with the bedrock of the right-bank of the river.

Evidence showed that the mode of lake emptying is neither by collapse of the glacier dam, nor overtopping of the glacier dam. The lake suddenly empties when sub glacial drainage tunnels in the Kyagar Glacier dam rapidly increase in diameter as their walls are further melted by friction associated with the increasing water flow. Proof of this drainage mechanism was obtained from observations on August 9, 1987 when a flood event occurred at the leading edge of the Tram-Kanri glacier. This was in the lower reaches at a distance of 15 km from Kyagar glacier dammed lake. After the event, we returned to Kyagar Lake and noticed an opening beneath the glacier dam, along with a similar opening at the leading edge of the Tram Kanri Glacier.

Lake releases from the Kyagar Glacier Dam are closely related to the physical characteristics of the glacier. The forward edge of some huge mountain valley glaciers is characterized by ocean warming type of glacier. That is, the temperature of the glacier's leading edge developed there is warmer than that of other regions. Melting water drains from this kind of glacier both within and beneath. Tunnels for passing melting water evolve over time. Such tunnels provide suitable conditions for the lake releases.

Several factors probably contribute to the sudden releases. Pyr-temperature may accelerate ice-snow melting and fill in the lakes, then water levels rise as inflows exceed outflows. Moreover, temperature of the lake water may be raised by pyr-temperature weather, especially when there is surface runoff across surrounding rocks and into the lake. Thus, more heat will be available for melting the glacier dam. These will also be more frictional heat per unit area of tunnel wall as sub-glacier tunnels change their dimensions, with rates of melting and tunnel enlargement becoming even faster. So the glacier-dammed lake water bodies empty rapidly.

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