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Studies of ice-snow melt debris flows in the western Tian Shan Mountains, China

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Abstract The ice-snow melt debris flow in the west part of the Tian Shan Mountains is an important natural hazard. The sediment for the debris flows is derived from the thick Quaternary deposits which occur in the Tain Shan Mountains. Another cause of the debris flows is the ice-snow meltwater and the abundant precipitation in the western part of the Tian Shan Mountains. The mean annual precipitation is 500-840 mm, of which snowfall accounts for 40%. The seasonal snow cover is thick in the mountain areas. The maximum annual thickness of seasonal snow cover is 60-85 cm. The stream discharge during the period of seasonal snow melt is 3 times greater than the average. Therefore, stream discharge increases rapidly due to the rapid melting of seasonal snow cover. Thus, the loose Quaternary sediment readily loses its stability and a debris flow may occur when the sediment is saturated by ice-snow meltwater. Snowmelt, glacier melt and dam burst debris flows are the predominant types, and the rainstorm debris flow is subordinate in the western part of the Tian Shan Mountains. It is characterized by a small drainage area, widespread distribution and high burst frequency. There are 2 main burst periods in the year. Debris flows may block transport lines, destroy the ecological environment, and threaten the lives of human beings and animals, and the safety of factories, mines and other enterprises.

INTRODUCTION

Surrounded by large deserts, the Tian Shan Mountains stand out as a humid and cold island in the arid area and divide Xinjiang into two parts: dry and warm Southern Xinjiang and the relatively humid and cool Northern Xinjiang. A thick cover of unconsolidated Quaternary sediment has accumulated in the Tian Shan Mountains, originating from fluvial, frost weathering and glacier activity. It provides an abundant source of material for debris flows. In the arid environment, water is the main control of debris flow bursts. In terms of their origin, mechanics and distribution, the debris flows in the west part of the Tian Shan Mountains evidence spatial and temporal distributions characteristic of arid areas. The origin, classification and distribution of debris flows and associated protection measures are discussed in this paper.

SEDIMENT SUPPLY AND TOPOGRAPHY IN THE DEBRIS FLOW AREA

Since the Quaternary, abundant sedimentary deposits have accumulated under the joint action of palaeo glaciers, modern glaciers, frost weathering, nivation, snow avalanches, rockfalls, etc. in the Tian Shan Mountains. The palaeo cirques, glaciated troughs, moraine dams, nivation cirques, etc. are ideal locations for the accumulation of sediment. Fluvial action increased and intensified with the retreating of the glaciers and the uplifting of mountain blocks. Thus, a steep-gentle compound terrain was formed. It is particularly amenable to the development, initiation and downslope movement of debris flows. Most of the mountain slopes are steeper than 23°, and the longitudinal slopes are 8-25% in the area of the debris flows. Furthermore, the sediment supply is increasing. The sediment is mainly composed of gravel, sand and clay (Wang Shuji *et al.*, 1986). The gullies and piedmonts bordering the Ili River Valley in the western part of the Tian Shan Mountains (800-2200 m a.s.l.), are covered extensively by loess and loessial soil. This thick unconsolidated sediment is low in mechanical strength and unstable (Meng Heging, 1986), especially when saturated by water. Under such conditions a debris flow burst may occur.

In the Ili River Valley in the west part of the Tian Shan Mountains, the vegetation cover of the mountain slopes is good. The adret is covered by shrubs and steppe vegetation, and the ubac is covered by forest which is primarily picea (under 2800 m a.s.l.). The vegetation restricts the development and bursting of debris flows to some extent. Therefore, the distribution of debris flows in time and space is not extensive in the Tian Shan Mountains.

CLIMATE AND HYDROLOGY OF THE DEBRIS FLOW AREA

Situated in a continental climate zone of the middle latitudes, the Tian Shan Mountains provide a natural barrier. As a result it is relatively dry and warm with a sparse vegetation on the south slope. On the north slope, however, it is relatively humid and cool with more precipitation and obvious seasonal variations. This great disparity in climate between the south and north slopes of the Tian Shan Mountains gives rise to a distinctive feature of the physical geography of arid areas. The development of debris flows varies with the regional location.

In the west part of the Tian Shan Mountains, the annual precipitation varies from 500 to 840 mm. Snowfall accounts for 40% of the annual precipitation and the maximum annual depth of seasonal snow cover is 60-85 cm. According to observations at the Tian Shan Snow and Avalanche Research Station of the Chinese Academy of Sciences, located in the upper reaches of the Ili River in the west part of the Tian Shan Mountains (84°24′, 43°16′, 1776 m a.s.l.), the mean annual air temperature is 1.3°C, the highest and lowest air temperatures are 32.7°C (23 July 1985) and −30.7°C (25 January 1981) respectively. The temperature here varies greatly between day and night (the diurnal range can be as high as 19°C), and shows the clear characteristics of a continental climate. Consequently, frost weathering is extremely strong. At the Station, the mean annual precipitation is 836.8 mm (1969 to 1990), and the maximum annual precipitation is 1112.9 mm (1987). The maximum thickness of seasonal snow cover is 124 cm. The periods of increased maximum precipitation and increased temperature are almost identical. There is also a rapid melt period for the seasonal snow cover in the mid-mountain zone. Therefore, snowmelt runoff increases rapidly on the mountain slopes and in the valleys. The maximum monthly precipitation occurs mostly in June and July (Fig. 1).

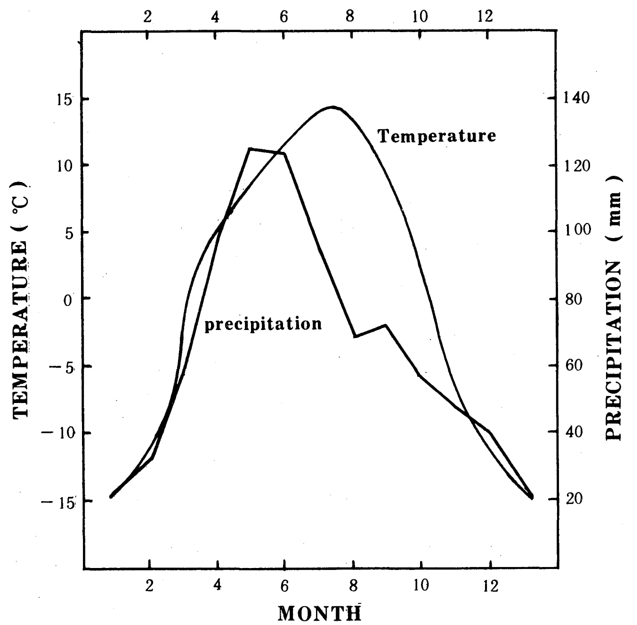

Fig. 1 Monthly mean precipitation and temperature from 1968 to 1990.

According to the observations at the Hydrologic Observation Station on the Kunes River near the Tian Shan Snow and Avalanche Research Station, the mean annual stream discharge is 12.7 $m^3\ s^{-1}$, mean monthly maximum is 36.3 $m^3\ s^{-1}$, and the mean monthly minimum is only 4.3 $m^3\ s^{-1}$ (Fig. 2). Figure 2 indicates that the stream discharge begins to increase with increasing temperature and melting of seasonal snow cover in the mid-mountain zone in April. But the increase in stream discharge is still limited because the seasonally frozen soil begins to thaw, and much snowmelt water infiltrates into the soil. The first flood period occurs in May in association with rapidly increasing temperature and snowmelt. However, the high mountain area is still

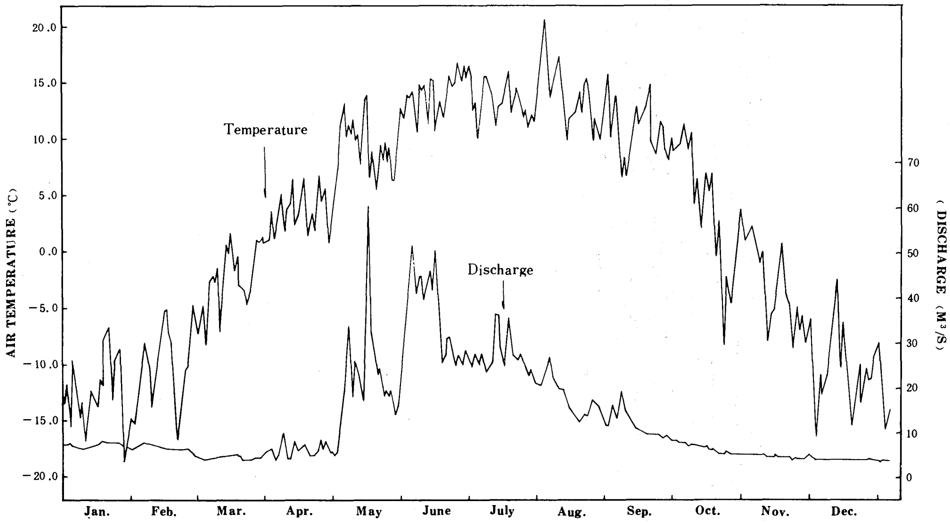

Fig. 2 Relationship between discharge and air temperature for the Kunes River at the Tian Shan Snow and Avalanche Research Station (1990).

covered by snow and ice, and its abundant sediment is still frozen. Hazardous debris flows are therefore rare in this period. The increase of precipitation and snow melt in the high mountain zone generates the second flood period in June. Large amounts of sediment thaw in this period, and hazardous debris flow bursts occur frequently (Table 1). The glacier melt debris flow bursts occur in the third flood period in July, during which the precipitation is relatively high and the glaciers melt rapidly.

THE INFLUENCE OF HUMAN ACTIVITY

Human activities produce a very important effect on debris flow development and initiation. The main anthropogenic effects in the western part of the Tian

Table 1 Debris flows between km 86 and km 94 of the D-K Highway in the Tian Shan Mountains, China.

Place	Time	Date	Month	Year	Burst cause	Character of debris flow
km 93	1900-2100	1	June	1984	Rainstorm	Viscous
km 86	1800-0400	25	June	1984	High temperature	Viscous
km 88	1900-2300	13	June	1985	High temperature	Micro-viscous and viscous
km 86	2000-2400	1	July	1985	High temperature	Viscous
km 93	2200-2300	13	July	1986	High temperature	Viscous
km 86	1800-2400	11	July	1987	High temperature	Viscous
km 86	2100-2300	19	July	1989	High temperature	Viscous
km 88	1900-2100	25	June	1989	Rainstorm	Micro-viscous
km 86	2000-2300	22	June	1991	Rainstorm	Micro-viscous and viscous

Shan Mountains are summarized as follows:

(a) The stability of sediment is reduced and much new debris is produced by road construction, quarrying, mining, etc. The resulting rockfalls, landslides and soil erosion promote the initiation of debris flows. For instance, 138 debris flows were associated with the construction of the D-K Highway and I-R Highway in the Tian Shan Mountains.

(b) Soil erosion is intensifying and the mechanical strength of the soils is declining because of the destruction of vegetation on the mountain slopes by indiscriminate felling of forests, the digging of medicinal herbs, and the construction of temporary dwelling places for herdsmen. These are all conducive to the formation and initiation of debris flows. For example, the micro-viscous debris flow burst which occurred between km 287 and km 295 of the D-K Highway was caused by felling the forest completely over a whole mountain slope and constructing temporary dwelling places for the forest clearers.

CLASSIFICATION AND NATURE OF DEBRIS FLOWS

Snowmelt, glacier melt and dam burst debris flows are the predominant types. Rainstorm debris flows are subordinate in the west part of the Tian Shan Mountains. The debris flows are located along the mountain highways and in the areas adversely affected by the activities of the residents of Xinyuan County, Gongliu County, Takes County, Nilka County, etc. The debris flows in the western part of the Tian Shan Mountains are characterized by extensive distribution, clear regional features and great disparity in discharge. The debris flows with different features (viscous debris flow or micro-viscous debris flow) occur in different seasons and situations of sediment supply and topography.

Seasonal snowmelt debris flows

Generally speaking, snowmelt debris flows do not occur in the accumulation period of seasonal snow cover. The highways often cut down through the large amounts of piedmont sediment, resulting in many unstable slopes without proper protection. Earthquakes, snow avalanches and the destruction of the ecological environment due to human activities often cause landslides and displacement of slopes. Active stream erosion and infiltration of snow meltwater begins with the thawing of seasonally frozen soil during the period of snowmelt in spring. After saturation by snow meltwater, the mechanical strength of the sediment is reduced (Lanchou Institute of Glaciology and Cryopedology, 1982). Under the condition of abundant loose sediment and conducive terrain, debris flows may burst if the temperature increases and the snow melts rapidly or heavy precipitation occurs. Snowmelt debris flows are in general micro-viscous flows with a small drainage area (about 1000 m^2) and limited hazard (disrupts transportation and frequently damages the highway surface). Their distribution is extensive, with a large frequency of bursts along the Tian Shan highways, especially in the western part of the Tian Shan Mountains. Bursts generally occur during the period 1900 to 2300 in April and the beginning of May. For example, debris flow bursts occur in 38 places which have not yet been protected along the D-K Highway and I-R Highway during the last 10 days of April almost every year.

Glacier melt and dam burst debris flows

Glacier melt debris flows are a special kind of debris flow in the Tian Shan Mountains. Near the glacier margin, large amounts of till and debris accumulate due to glacial activity and frost weathering. During the period of glacier and firn melting, if the temperature remains high for several days or heavy precipitation occurs after high air temperature, glacier melt debris flows may burst in some of the valleys with a steep-gentle compound terrain, high longitudinal slope and abundant loose sediment (Table 1). For example, a total of 17 debris flows burst between km 86 and km 95 of the D-K Highway during a nine-year period (Hu Ruji *et al.*, 1991). Of these, 12 were glacier melt debris flows caused by continued high air temperature. Investigations and observations show that the glacier melt debris flows burst at 1400 or later during the period June to July. The frequency and intensity of the burst depend upon the continued high air temperature and occurrence of heavy precipitation.

The stream of glacier and snow melt water near the glacier margin may sometimes be dammed up by snow avalanches, rockfalls, landslides, etc. and form a temporary lake. The dam of the temporary lake may burst suddenly with an increase of glacier and snowmelt water or heavy precipitation. Thus, a dam burst debris flow occurs. The return period of dam burst debris flows is two years or more. They are characterized by a high discharge, increased deposition, and highly damaging forces, as, for example, the dam burst debris flow that was caused by a rainstorm at km 88 of the D-K Highway on 25 June 1988.

Rainstorm debris flows

Abundant Quaternary sediments have accumulated in most areas of the Tian Shan Mountains. Under certain terrain conditions, so long as the loose sediment is supplied with excess water to cause saturation, a debris flow may occur. Therefore, whether in the eastern or western part of the Tian Shan Mountains, when precipitation exceeds a certain amount, rainstorm debris flows may occur (Table 2). In the valleys with glaciers and snow meltwater in the western part of the Tian Shan Mountains, the mountain slopes experience erosion by the melting water, and the sediment on the slopes contains much more water. When a regional rainstorm occurs, the glacier and snow meltwater and the rainwater act together and both landslides and debris flows may occur. Rainstorm debris flows burst rapidly with a high discharge and produce a serious hazard. However, in the absence of clear temporal and spatial patterns it is difficult to forecast and apply protection. The two rainstorm debris flow bursts that occurred on 23 August 1985 and 7 June 1991 respectively caused heavy losses of property, animals, and even human lives.

Table 2 Typical rainstorm debris flows in the Tian Shan Mountains, China.

Place	Burst time	Precipitation (mm)	Character of debris flow	Hazard degree
Mountainous region of north Kuqa County	13/8/58	56	Viscous	A
Mountainous region of north Tuypan	25/6/69	30	Viscous	B
Upper reaches of Santun River near Changji City	23/5/84	38	Micro-viscous	C
New Dragon Mouth of Kuytun River	5/7/87	47	Micro-viscous	D
Alagou Channel of the South Mountain of Urumqi	24/6/88	29	Viscous	E
86 km of D-K Highway	22/6/91	48	Micro-viscous	F
Botugou Channel in Gongliu County	6/6/91	50	Viscous	G

A. A dyke of the reservoir was burst by the debris flow. The Kuqa County Town suffered a serious disaster.
B. A section of the railway was covered and transportation was severed by the debris flow.
C. The structures along the channel and the irrigation works on the farmland of the lower reaches were damaged.
D. Some of the irrigation works along the Kuytun River were damaged.
E. Buildings, factories, etc. were destroyed for 40 km along the path of the debris flow.
F. In total more than 60 km of highway was damaged seriously. 36 km of highway were destroyed and 41 sections of highway were cut.
G. The local population and farm animals suffered a serious disaster. It was the most serious dam burst debris flow caused by a rainstorm in Xinjiang.

PROTECTION FROM DEBRIS FLOW HAZARDS

Debris flows in the western part of the Tian Shan Mountains obstruct transportation, threaten the safety of human life, animals, factories, mines and other enterprises and destroy the ecological environment. In order to reduce and protect from debris flow hazards, different protection measures should be selected according to the different types of debris flow and the degree of hazard. In the area around factories, and other installations, the slopes should not be disturbed and the ecological environment should be protected as far as possible. On the unstable slopes with abundant sediment, reinforced concrete protection banks and stabilizing terraces should be constructed on the slopes. In areas prone to landslides or on steep cut slopes, parapets, rock dykes and reinforced concrete protection banks should be built. In total, 104 places have been protected with rock dykes, parapets and reinforced concrete protection banks. The engineering quantities involved exceed 7000 m^3, the effective rate of protection is up to 91%.

It is worth emphasizing that all engineering measures should be combined with vegetation measures, such as the planting of grasses and trees. These integrated measures of protection are the only effective ways to remove the potential danger of debris flows, and they are also advantageous for the ecological environment.

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