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DEBRIS FLOW ANNUAL FREQUENCY AND SEDIMENT DELIVERY VARIATIONS COMPARED TO RAINFALL CHANGES OVER THE LAST 40 YEARS (JIANGJIA GULLY, CHINA)

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ABSTRACT

Natural hazards occur more frequently due to ongoing global climate change, which has increased the impact of precipitation. Debris flows and their relative activities have also changed over the past 39 years at Jiangjia Gully, a typical debris flow valley with high-frequency debris flows located in the Yunnan Province of China. This paper concentrates on the responses of sediment transportation induced by debris flows at Jiangjia Gully to rainfall change, using statistical analysis of the observation data of debris flows and rainfall. The results showed that: (1) the annual precipitation and rainy season precipitation both decreased in fluctuation over the past over 40 years and experienced two high rainfall stages and one low rainfall stage; (2) the days of the daily precipitation that exceeded 20mm, 30mm, and 50mm changed in dissimilarity, and the days with over 20mm of daily precipitation increased slowly and with over 30mm and 50mm both decreased slowly; (3) the sediment amount transported by debris flow generally increased with just a little fluctuation in the past 40 years, which was consistent with the change in annual precipitation and the days with over 20mm of daily precipitation; and (4) the sediment transported by debris flow had a good relativity to annual precipitation and the days with over 20mm of daily precipitation. The frequency of debris flow occurrence has a good relativity to the rainy season precipitation and the days with over 20mm of daily precipitation, and their correlation coefficients are 0.4454 and 0.4737, respectively. The work can provide a scientific basis for the long-term forecast and prevention of debris flows.

Key words: *debris flow transportation sediment; precipitation change; responded; Jiangjia Gully*

INTRODUCTION

Global climate change, which has caused a series changes, including precipitation, temperature increases, and more frequent natural disaster events, has become one of the world's most critical issues. Global warming makes precipitation increase in certain regions, which is then accompanied by an increase in floods in terms of their frequency and intensity. David Nolan of Miami University led a study group that concluded that global warming will lead to fewer tropical cyclones, but the intensity increased significantly through the model simulations. The MK trend test of the frequency and intensity of extreme precipitation events of the Yangtze River regions showed that the frequency of extreme precipitation events increased significantly (Wang *et alii*, 2005). At the same time, the past 50 years of land surface process observation shows that climate change has caused the frequency of block movement activities to increase (Evans & Clague, 1994; Eybergen & Imeson, 1989). Therefore, many researchers began to study the impact of climate change in terms of creating natural disasters. Since there are differences in the regional responses to global change, some scholars have studied the relation-

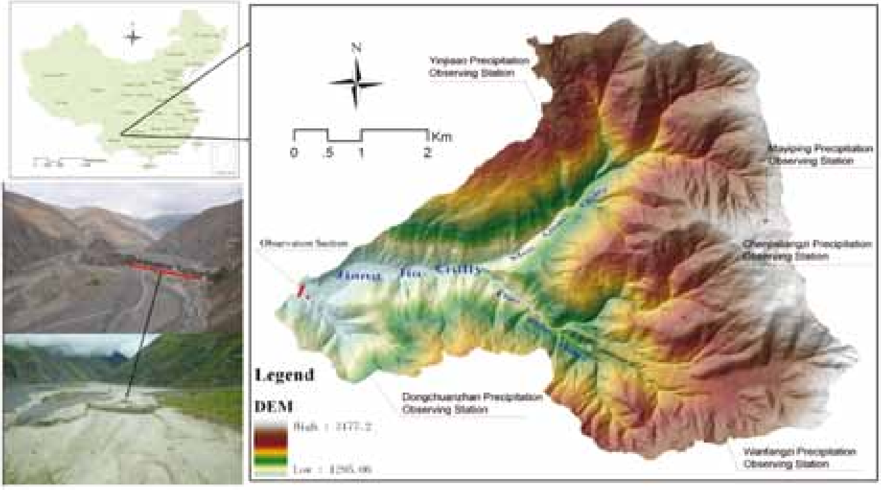

Fig. 1 - Location of study area

ships between the debris flow occurrence and precipitation changes in different regions and received different results. Van Steijn (1996) studied the relationships between the debris flows in northern Europe and found that the rainstorm debris flow occurrence increase was mainly caused by the intensity of the rainfall increase, but the impact degree of climate change to debris flow frequency and magnitude was still not conclusive. Jomelli *et alii* (2004) studied the relationship between gully debris flow and climate change and found that the relationship did not have a significant correlation. Rebetez *et alii* (1997) studied the relationship between debris flow and climate change and concluded that the occurrence frequency of the large-scale debris flow was increasing significantly, but the occurrence frequency of the small-scale debris flow has been decreasing significantly since the late 1980s. Global change in large-scale regional occurrences is a hot spot (Kumar & Parikh, 2001; Phillips *et alii*, 2009), but the responsiveness has been different within the large-scale region, so it is more reasonable to explore the response of small regions (watershed) to global change. For a single river basin, the rainfall changes are the main factor in the occurrence of the debris flow occurrence, and the periodic of debris flow frequency reflects its response to the periodic annual rainfall change. It is an important means of disaster prevention to be able to predict the occurrence probability of debris flow according to precipitation change over the last decade.

The sediment amount transported by debris flow and frequency of debris flow occurrence is a symbol of debris flow magnitude, and climate change affects the sediment amount transported by controlling the precipitation and temperature changes (Nearing, 2001; Zhang & Garbrecht, 2002). The dry-hot valley is the sensitive area of globe change and is the region of frequently occurring debris flow (Cui *et alii*, 2005). Documents about this relationship have showed a clear connection between precipitation and debris flow magnitude. This paper reveals the responses of sediment transportation induced by debris flows to rainfall change and provides a scientific basis for the prevention and mitigation of debris flow hazards.

STUDY REGION SETTING

The Jiangjia Gully (JJG) Ravine with a trunk channel length of 13.9km and covering a total area of 48.6 km^2 (Figure 1) is a tributary of the Xiaojiang River. It is located in the Xiaojiang fault zone in the northeast of the Yunnan Province of China (N23°13′-23°17′, E103°6′-103°13′). Complex geological structures, fragile rocks, numerous landslides, and abundant rainfall foster frequent debris flows. The highest annual record was 28 events in 1965. In 1961, the Dongchuan Debris Flow Observation and Research Station was set up, which is a facility of the Institute of Mountain Hazards and Environment at the Chinese Academy of Science. Since 1987, the station has performed regular observations and collected systematic data about debris flows. There is an estimated 1.23×1010 m^3 of loose sediments stored in the valley (Cui *et alii*, 2005). There are 12-20 debris flows in every rainy season (May-October). Annual sediment yield in JJG is 2.0 million m^3 on average while a maximum of 6.6 million m^3 occurred in 1991. In the watershed of JJG, the rainy season is the period from May to October and the average annual rainfall is 800 mm from the maximum of 1130 mm to the minimum of 514 mm. The precipitation in the rainy season amounts to more than 85% of the annual precipitation. Rainstorm and thundershowers occur frequently during the rainy season. The debris flows in JJG are rain-induced. Often, ten to twenty minutes of high intensity rainfall can initiate debris flow with and average density debris flow of 2.0t/m^3 (Kang *et alii*, 2007). The discharge of each debris flow is from hundreds to thousands of cubic meters per second (Kang *et alii*, 2007). The annual number of debris flow events from 1965 to 2004, which is regarded as the annual frequency for rare debris flow, occurs beyond the rainy season. The precipitation data from 1965 to 2004 was obtained from the Huili National Weather Station, which is 18km away from the JJG. The long-term record provides a good opportunity to analyze debris flow frequency because of the lack of such long-duration observation data in other areas and invalidation of post-event investigation methods, such as dendrochronology and lichenometry, in estimating annual frequency in high-frequency ravines like Jiangjia.

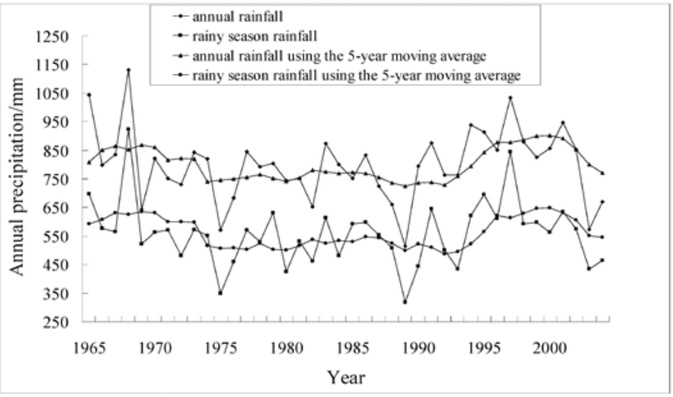

Fig. 2 - The Change in Annual Rainfall and Rainy Season Rainfall

DATA AND ANALYSIS APPROACH

Precipitation data: The precipitation data is from the Huili National Weather Station, which is 18km away from the JJG. The precipitation data is daily rainfall data from 1965 to 2004.

The debris flow data: The debris flow data contains the annual number of debris flow events, and the sediment amount transported by debris flow is from the Dongchuan Debris Flow Observation and Research Station, which is a facility of the Institute of Mountain Hazards and Environment at the Chinese Academy of Science. The debris flow data is annual data from 1965 to 2004.

Analysis approach: The changing tendency of the precipitation and the annual number of debris flow events and sediment amount transported by debris flow was studied, utilizing five-year smoothed trend analysis for climate change. This tends to be a tedious process. Additionally, the relationship between the annual number of debris flow events and sediment amount transported by debris flow and precipitation data was studied, using spearman correlation analysis to reveal the response law of debris flow to climate change.

PRECIPITATION AND DEBRIS FLOW ANNUAL TIME SERIES ANALYSIS

The JJG debris flow was mainly triggered by rain, especially by rainstorms that occurred between June and September every year. The sediment amount transported and the annual numbers of debris flow events, which are the key parameters of the debris flow, are the most factor response to precipitation change. Analyzing the trend of the sediment amount transported, the annual number of debris flow events, and the precipitation data are the first steps toward revealing the relationship between debris flow and precipitation. This can assist with obtaining the change characteristics of the debris flow and precipitation, especially the change characters of rainstorms during the past forty years.

PRECIPITATION ANNUAL TIME SERIES

Figure 2 shows the change characteristics of annual rainfall and rainy season rainfall over the past 40 years. The trend of annual rainfall and rainy season rainfall showed a slight decrease in the fluctuation with large variations. The variation coefficients were 0.157 and 0.203, respectively; the maximum annual rainfall and rainy season rainfall are 1130.8 mm and 922.4 mm, respectively, in 1968, and the minimum annual rainfall and rainy season rainfall are 514.5 mm and 318.4 mm, respectively, in 1989. The precipitation can be divided into three stages, using the five-year moving average curve (Fig. 2). The first stage is rainy year with higher

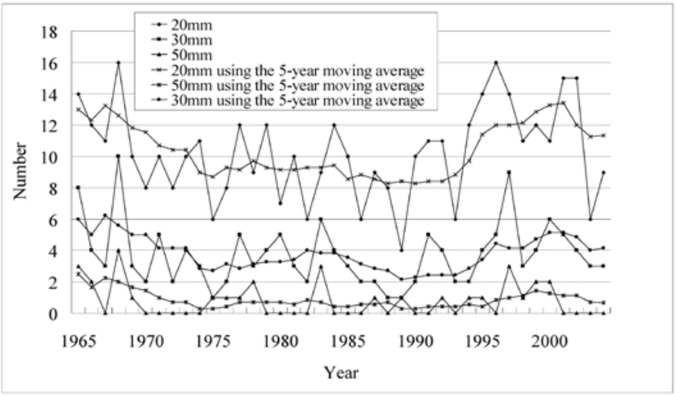

Fig. 3 - The Change in Daily Rainfall Greater than 20mm, 30mm, and 50mm

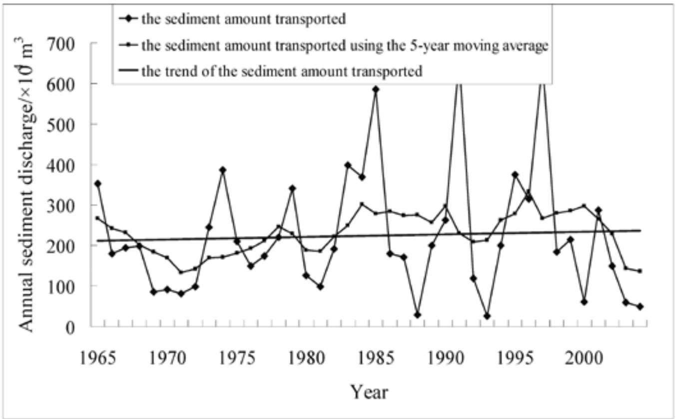

Fig. 4 - The Change Characteristics of Sediment Amount Transported

rainfall from 1965 to 1974; the second stage is dry year with lower rainfall from 1975 to 1994; the third stage is rainy year with higher rainfall from 1995 to 2002; and the decrease in the precipitation from 2003.

The previous studies have revealed that extreme rainfall is important for the occurrence of debris flows and that the debris flows are mainly caused by extreme rainfall events. The statistics were for the number of days of daily rainfall greater than 20 mm, 30mm, and 50mm. The trend in the number of days of daily rainfall greater than 20 mm showed a slight increasing trend, but the trend in the number of days of daily rainfall greater than 30 mm and 50 mm showed a slight decrease (Fig. 3). Figure 3 shows the five-year moving average trend in which, before 1975, the number of days of daily rainfall greater than 20mm, 30mm, and 50mm showed a rapid decrease and fluctuation with lower rates between 1975 and 1995. Here, the number of days of daily rainfall greater than 20mm, 30mm, and 50mm showed a quick increase since 1995. This trend is consistent with the precipitation calculations.

THE SEDIMENT AMOUNT TRANSPORTED AND ANNUAL NUMBER OF DEBRIS FLOW EVENTS ANNUAL TIME SERIES

Figure 4 shows the change characteristics of the sediment amount transported over the past 40 years. The trend of the sediment amount transported showed a slight increase in fluctuation with large variations with a variation coefficient of 0.693. The maximum sediment amount transported was 659×10^4 m^3 in 1991, and the minimum sediment amount transported was only 26×10^4 m^3 in 1993. Figure 4 shows the five-year moving average trend. Before 1971, the sediment amount transported showed a decrease and fluctuation increase between 1972 and 1995, and the sediment amount transported showed a quick decrease since 1995. The change characteristics are consistent with the precipitation change. The sediment amount transported is three years earlier than the precipitation in the first change year and consistent with the precipitation in the second change year.

The trend in the annual number of debris flow

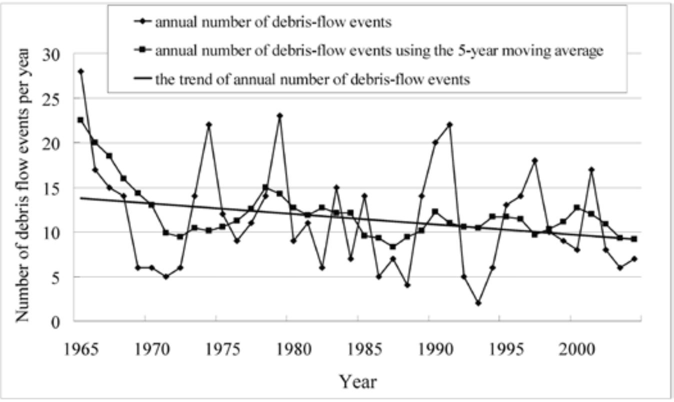

Fig. 5 - The Change in the Annual Number of Debris Flow Events

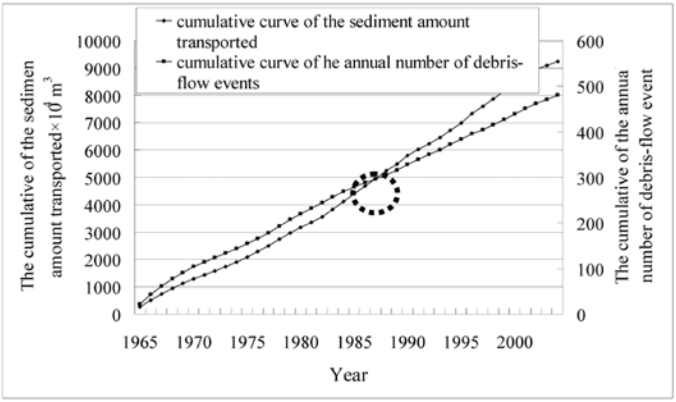

Fig. 6 - The Cumulative Curve of the Sediment Amount Transported and the Annual Number of Debris Flow events

events showed a slight decrease in fluctuation with large variations (Fig. 5), and the variation coefficient was 0.527; the maximum annual number of debris flow events was 28 in 1965; and the minimum annual number of debris flow events was two in 1993 with two stages. Before 1971, the annual number of debris flow events showed a rapid decrease and a fluctuation decrease after 1972 (Figure 5). The change trend was different between the annual number of debris flow events and the sediment amount transported and precipitation change. The annual number of debris flow events was controlled by precipitation, which then affected the sediment amount transported.

The "abnormal" phenomenon was rationality plotted, using the cumulative curve of the sediment amount transported and the annual number of debris flow events (Fig. 6). The annual number of debris flow events decreased, but the sediment amount transported increased. The result was that the magnitude of debris flow increased and its damage intensity also increased.

THE RESPONSE OF DEBRIS FLOW TO PRECIPITATION

Precipitation affects the debris flow characteristics by influencing the watershed hydrology process, material weathering, and soil evolution (Nearing, 2001; Zhang & Garbrecht, 2002).

THE RESPONSE OF THE SEDIMENT AMOUNT TRANSPORTED TO PRECIPITATION

The sediment amount transported is the symbol of debris flow magnitude and an important factor of debris flow prevention and assessment. The response degree and characteristics of the sediment amount transported by debris flow to precipitation can be obtained by studying the relationship between rainfall and the sediment amount transported. The response of sediment amount transported to precipitation is obvious with the same inter-annual oscillation trend. The correlation coefficient between the sediment amount transported and rainy season precipitation is 0.5341 ($p<0.01$) higher than the correlation coefficient, which is 0.5032 ($p<0.01$), between the sediment amount transported and annual precipitation, using S-related analysis. This is because the debris flow mainly occurs during the rainy season. The correlation degree is different between the sediment amount transported and the days of daily rainfall that are greater than 20mm, 30mm, and 50mm. In this case, the correlation coefficients were 0.4408 ($p<0.05$), 0.3387 ($p<0.05$), and 0.1860 (this did not pass the test reliability), respectively. The response degree of sediment amount transported to days of daily rainfall greater than 2 mm is higher than the daily rainfall that was greater than 30 mm and 50 mm.

The region in the southwest monsoon climate is where rainfall events are concentrated in summer (the rainy season). The extreme rainfall events (daily rainfall that is greater than 20mm) is a key factor of debris flow occurrence, which affects soil erosion and landslides number and size and then influences the sediment amount transported (Zhuang *et alii*, 2009). In short, the debris flow occurrence and magnitude are controlled by rainfall; the change of the precipitation will lead to changes in the sediment amount transported by debris flow.

THE RESPONSE OF THE ANNUAL NUMBER OF DEBRIS FLOW EVENTS TO PRECIPITATION

The accumulation of material and the hydrological process within the catchment are affected by the inter-annual variability of rainfall and then influence the debris flow occurrence (Cui *et alii*, 2008). The response relationship between the annual number of debris flow events and the annual and rainy season precipitation resulted in correlation coefficients of 0.444 ($p<0.05$) and 0.4454 ($p<0.05$), respectively. The relationship between the annual number of debris flow events and the days of daily rainfall greater than 20mm, 30mm, and 50mm were studied because the debris flows are mainly caused by extreme rainfall events. In this case, the correlation coefficients were 0.4408 ($p<0.05$), 0.3387 ($p<0.05$), and 0.1860 (this did not pass the test reliability), respectively. The response degree of the annual number of debris flow events to the days of daily rainfall greater than 20 mm is higher than that of daily rainfall greater than 30mm and 50mm. Hence, it can be concluded that the debris flow is mainly caused by daily rainfall greater than 20mm, and the critical rainfall daily rainfall is small mainly due to the geological factors that make the loose material in the catchment move easily (Cui *et alii*, 2005).

CONCLUSIONS

Global climate change affects the evolution and occurrence of natural disasters, which makes it important to determine a means of predicting how these global changes in order to provide relief and assistance. The following conclusions have been determined from this research study:

1. The annual precipitation and rainy season precipitation both decreased in fluctuation over the past 40 years and experienced two high rainfall stages and one low rainfall stage. The two high rainfall stages appeared from 1965 to 1974 and from 1995 to2002, respectively, and the low rainfall stage occurred from 1974 to 1995. The abrupt change of rainfall occurred in 1974, 1995, and 2002, respectively. The days of daily precipitation that exceeded 20mm, 30mm, and 50mm changed in dissimilarity, and the days with over 20mm of daily precipitation increased slowly while those with over 30mm and 50mm both decreased slowly.
2. The sediment amount transported by debris flow generally increased with little fluctuation during the past 39 years, which was consistent with the change in annual precipitation and the days with over 20mm of daily precipitation. The frequency of debris flow occurrence generally decreased during the past 39 years and reduced quickly before 1971 and in fluctuation after 1971. The annual number of debris flow events decreased, but the sediment amount transported increased. The result is that the magnitude of debris flow increased and its damage intensity also increased.
3. The sediment transported by debris flow had a good relativity to annual precipitation and the days with over 20mm of daily precipitation with correlation coefficients of 0.4408 and 0.5341, respectively. The frequency of debris flow occurrence has a good relativity to rainy season precipitation and the days with over 20mm of daily precipitation had correlation coefficient of 0.4454 and 0.4737, respectively.

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