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Magnitude-frequency relationship of debris flows in the Jiangjia Gully, China

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Abstract: The magnitude-frequency (MF) relationship of debris flows is the basis for engineering designs and risk quantification. However, because of the lack of debris flow monitoring data, research progress in this area has been relatively slow. The MF relationship of debris flows in Jiangjia Gully, Yunnan Province was evaluated based on a regression analysis of 178 debris flow events that occurred from 1987-2004. The magnitude-cumulative frequency (MCF) relationship of the debris flows in the Jiangjia Gully is consistent with the linear logarithmic transformation function. Moreover, observed data for debris flows in Hunshui Gully of Yunnan Province and Huoshao Gully, Liuwan Gully, and Niwan Gully of Gansu Province were used to verify the function. The results showed that the MCF relationship of high-frequency debris flows is consistent with the power law equation, although the regression coefficients in the equation are considerably different. Further analysis showed a strong correlation between the differences in the constants and the drainage area and daily maximum precipitation.

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Introduction

Debris flow activity can be described by their magnitude and frequency, with frequency referring to the occurrence of the debris flow in units of time and magnitude referring to the total volume and peak discharge (Van Steijn 1996; Hungr et al. 2005).

The magnitude and frequency of debris flows are important for risk quantification and provide an important basis for disaster management, land use planning and research on geomorphology evolution (Rickenmann 1999; Hungr et al. 2008; Mao et al. 2009). Worldwide, debris flows cause serious disasters. For instance, in December 1999, more than 30,000 deaths were caused by a debris flow in Venezuela, which caused economic losses of up to 10 billion U.S. dollars (Wieczorek et al. 2001). In 2010, a debris flow in Zhouqu, Gansu Province, China, killed 1765 people (Yu et al. 2010). The frequent debris flow events in China, especially along the southeastern margin of the Qinghai-Tibet Plateau, have caused serious disasters and are the subject of widespread concern.

Scientific research on debris flows has been mainly focused on rheology and dynamics (Iverson 1997; Mcardell et al. 2007). A small amount of magnitude-frequency (MF) research has been based on hydrology and hydraulics for debris flow prevention (Bovis and Jakob 1999). In China, for example, engineering designs for debris flow control are calculated using the same regional rainfall frequencies (Zhou et al. 1991).The lack of debris flow studies is related to the debris flow event time intervals, which are long at tens or even hundreds of years, as well as the lack of accurate written records.

Although previous studies have focused on the MF relationship of debris flows (Hungr et al. 2008), most of these studies are based on indirect evidence, such as tree chronologies (Stoffel 2010), stratigraphic techniques (Blair and Mcpherson 1998; Blair 1999), lichen metrologies (Rapp and Nyberg 1981; Helsen et al. 2002), and remote sensing and LiDAR imagery (Jakob 2005; Stoffel et al. 2008). Studies have also focused on the total amount of source materials or source materials along the flow path (Eaton et al. 2003; Hungr et al. 2005), whereas other studies have attempted to determine the magnitude and frequency of debris flows based on experience or statistical equations (Marchi and D'agostino 2004).

Studies focused on these issues provide a better understanding of the MF relationships of debris flows. However, the number of samples obtained by these laws is too small or the samples are obtained in different areas and channels and cannot be tested. Moreover, the applicability of curve fitting is poor, and most curves are semi-quantitative and can only be applied to a certain gully.

In the case of abundant source material, debris flows are more frequent during active cycles, and outbursts may occur several or even dozens of times a year (Kang et al. 2004). In this paper, "abundant source" is more of a qualitative rather than quantitative concept. There are a lot of loose deposits in the five debris flow gullies studied in the paper. Compared with the total amount of solid materials in a single debris flow, the total amount of loose materials can reach tens or even hundreds of times. There will be no reduction in the magnitude and frequency of the debris flow due to the reduction of loose sources. Some experts and scholars call it the rain control type debris flow. Loose material sources include landslides and collapses after earthquakes, glacial melting and avalanches, and deposits of weathered metamorphic rocks.

Since the 1960s, Chinese scientists have performed long-term scientific observations of the debris flow of Jiangjia Gully in Yunnan Province, which has an ample source and is highly frequent. The array flow, runoff, sediment transport rate, over-current time and other data have been recorded. A number of scientific studies have described its characteristics, including debris flow magnitude-frequency relation (Li et al. 1983; Li et al. 2003, 2004; Davies 1986, 1990; Liu et al. 2008). For instance, Liu et al. (2008) used 40 years (1965-2007) of debris flow data to derive magnitude-frequency relation for debris flows. In this paper, we obtained data on the Jiangjia Gully debris flow events over 18 years from 1987 to 2004 and analyzed the MCF relationship in detail. In addition, we compared the data with the debris flows of Huoshao Gully, Liuwan Gully, and Niwan Gully in Gansu Province and Hunshui Gully of the Daying River in Yunnan Province to discuss general rules regarding the scale and frequency of debris flows. After obtaining the mathematical model of the MCF relationship of the high-frequency debris flow, this paper further establishes the mathematical relationship between the model and the physical characteristics of the debris flow channel (drainage area, daily maximum precipitation). This model can be applied in similar areas. This progress from mathematical models to physical models helps to establish the MCF relationship of high-frequency debris flow in other different regions.

1 Background of Debris Flows in Jiangjia Gully

1.1 Study area

Jiangjia Gully is a debris flow monitoring site well known for its high frequency of debris flows (Chen et al. 2017; Li et al. 2015). According to many years of observations, debris flows have been reported every year and up to 28 times in 1965 (Cui et al. 2005).

Jiangjia Gully, a tributary of Xiaojiang River in the upper reaches of the Yangtze River, is located near the city of Dongchuan, Yunnan Province, in south-western China. The drainage area of Jiangjia Gully is 48.6 km² with a main channel of 13.9 km long (Figure 1). The main channel of the Jiangjia Gully extends from the drainage divide at 3269-m altitude west of the junction with Xiaojiang River at 1042 m. The bed slope is 20% on average. The watershed has a total of 178 channels (with a groove length greater than 500 m). The vegetation coverage is less than 5%. The annual precipitation of this region is between 700 mm to 1200 mm, and more than 90% of the rainfalls occur from May to October, which is also the high incidence of debris flows (Table 1). The annual evaporation varies between 1700 to 3700 mm (Cui et al. 2005; Chen et al. 2011).

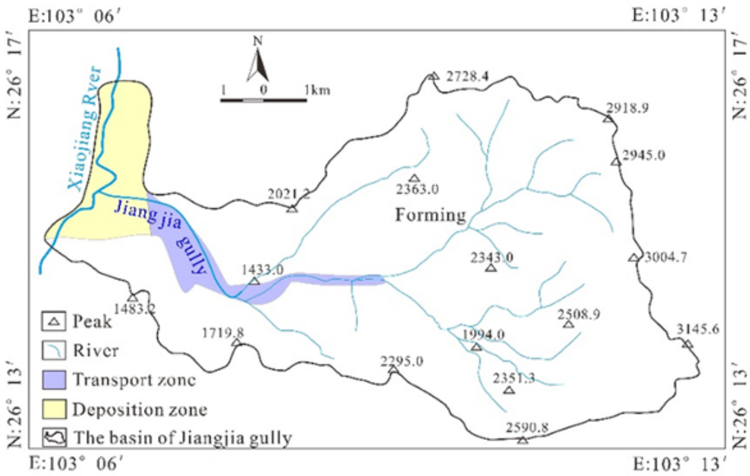

Figure 1 Drainage map of Jiangjia Gully (JJG) in Yunnan, China.

The Jiangjia Gully watershed is situated in the Xiaojiang fault (north-south direction) and the earthquake belt. The folds and fractures in the area are well developed, and the Neo-tectonic movement is intense. The Lower Proterozoic slate within the basin accounts for 80% of the total basin area and represents the main source of debris flow solid material. Debris flow sources include residual layers, slope deposits and old debris flow deposits in the basin. Under the long-term influence of the Xiaojiang fault and Neo-tectonic movement, the slate folds are intense with clear plates, joints, and structural crushed rock formations (mostly 3-5 cm or 7-10 cm fragments). The anti-weathering ability is poor. In addition, Quaternary loose sediments are distributed in the basin. The particle size ranges from 2 to 20 cm, the dry density is about 1.4 g/cm³, and the clay content is between 5%-10%. The total amount of solid material in Jiangjia Gully is 1.23×10^{10} m³ (Chen et al. 2005).

In order to compare with the MCF relationship of Jiangjia Gully debris flow and further study the physical laws represented by the MCF formula, this paper also collected observation data of other four high frequency debris flows. The debris flows of Huoshao Gully, Liuwan Gully, and Niwan Gully in Gansu Province and Hunshui Gully of the Daying River in Yunnan Province were equally rich in material and exhibited high frequency debris flow characteristics.

Hunshui Gully is located at latitude 24°25'N and longitude 98°12'E, and it is the most active and damaging high-frequency viscous debris flow gully in the Daying River Basin. The main channel of the gully is 3.75 km in length, the average width is 1.3 km, the average longitudinal gradient is 13.6%, and the basin area is 4.5 km². Landslides are the main source of the debris flow. The maximum daily precipitation in the drainage area is more than 140

Table 1 Characteristics and data sources of Debris flows

Gully	Number of samples	Drainage area (km²)	MDP (mm/d)	Annual rainfall (mm)	Total source (10^4 m³)	Observation period (a)	Peak discharge (m³/s)
Jiangjia	178	48.6	153.3	700	27,600	1987-2004	2913
Hunshui	72	4.5	146	1464	5170.6	1976-1978	400
Huoshao	11	1.98	78.8	470	775	1969-1975	354.06
Liuwan	17	1.97	78.8	470	/	1963-1964	60.7
Niwan	15	10.3	78.8	470	/	1965-1967	123

Note: MDP=Maximum daily precipitation; Total source=the total amount of loose source materials such as deposits and landslide in the gully.

(a) (b)

Figure 2 Observation equipment for the velocity measurements in Jiangjia Gully. (a) Measuring section; (b) Observation equipment.

mm, the maximum rainfall over 10 minutes is 14.2 mm, and the annual rainfall is approximately 1464 mm. The Bailong River Basin in Wudu County, Gansu Province is a high-incidence area of debris flows. The average annual rainfall in this area is only 470 mm, and the maximum daily precipitation is 78.8 mm. The main sources of these gullies are weathered and loose Quaternary sediments in arid, semi-arid and earthquake-prone areas with abundant loose earth and a high frequency of debris flows.

1.2 Data

The data used in this paper were measured by the Dongchuan Debris Flow Field Observation Station from 1987 to 2004. Since 1987, Dongchuan Station has used radar and other advanced monitoring equipment, so the data accuracy is high. Data for the period 1987-2004 have been published and made available to researchers (Zhang and Xiong 1997; Kang et al. 2006,2007).

An ultrasonic sludge level meter, speed radar, video camera and other equipment can accurately detect debris flow velocity, section width, mud depth, over-flow time and other indicators, and then the flow array and total flow are calculated. Then, according to the sampling, the measured bulk density index is converted to the sediment load value. The observation channel in the field is selected in the straight and stable channel of the debris flow in Jiangjia Gully, which presents two sections up and down with a spacing of 200 m (Figure 2a). The speed of the debris flow was determined by the speed radar running through a 200 m section in the faucet. The width, depth and cross-sectional area of the channel were measured before and after each debris flow. Over the course of the debris flows, a UL-2 ultrasonic mud gauge was used to automatically record the mud position (Figure 2b). Because of the continuous difference in the distance between the surface height of the furrow flow head and the mud head, the debris flow approaches the maximum mud depth. The peak flow of the debris flow is determined based on the maximum mud depth, the section width and the average flow rate. Based on the triangle distribution in the array section of the debris flow, the flow rate of the debris flow in each array was calculated using the triangle formula.

During the 18 years from 1987 to 2004, a total of 178 debris flow events were observed in Jiangjia Gully. The average number was approximately 10 events per year. The total volume and peak discharge of the 178 debris flows are shown chronologically in Figure 3. The classification criteria of debris flows in China are divided into Class S (<10^4 m^3), Class M (10^4 m^3-10^5 m^3), Class L (10^5 m^3-10^6 m^3) and Class XL (>10^6 m^3) according to the total volume of a single debris flow (Kang et al. 2004). Class S debris flows occurred twice,

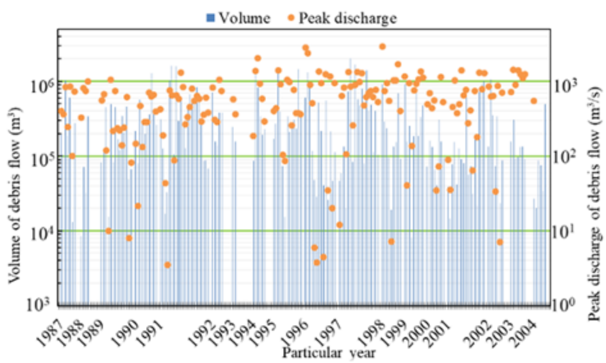

Figure 3 The magnitudes of 178 debris flows in Jiangjia Gully (1987-2004).

accounting for 1.12% of all events, Class M debris flows occurred 55 times, accounting for 30.89% of all events, Class L debris flows occurred 107 times, accounting for 60.11% of all events, and Class XL debris flows occurred 14 times, accounting for 7.86% of all events. Most of the Jiangjia Gully debris flows are Class M and Class L.

The scale data of the other four channels were measured between the 60s and 70s of the last century. The methods were section measurements with tape measuring, and the accuracy was lower than that of Jiangjia Gully. Some smaller debris flows have not been recorded, but this data is still important for building MCF models. According to the observed data, debris flows occur in the Hunshui Gully every year, with an annual average of more than 50 events, although most are small debris flows (less than 2-3 m^3/s) and thus have not been documented (Zhang and Liu 1989). In the 1960s and 1970s, several debris flow gullies were observed on the left bank of Bailong River(Kang et al. 2004). Huoshao Gully, with a drainage area of 1.98 km^2, a main trench length of 1.35 km, and an average longitudinal slope of 48%, experienced 30 total debris flows from 1969 to 1977. The maximum peak discharge was 313.5 m^3/s, which occurred on June 13, 1973. The Liuwan Gully has a drainage area of 1.97 km^2, a main channel length of 1.23 km, and an average longitudinal slope of 29%. Between 1963 and 1964, the gully experienced 17 debris flows, and its maximum peak discharge was 60.7 m^3/s, which occurred on September 1, 1963. The Niwan Gully's drainage area is 10.30 km^2, its main channel length is 5.34 km, and the average longitudinal slope is 23%. From 1965 to 1967, the channel experienced 15 debris flows, and its maximum peak discharge was 123 m^3/s, which occurred on September 8, 1967. The characteristics of these gullies are shown in Table 1.

2 Method

The records are ranked in the order of decreasing magnitude (Hungr et al. 2008). The incremental frequency of an event of rank i is determined as follows:

$$f_i = \frac{1}{T_i} \quad (1)$$

where T_i is the length in years of the e sampling interval. The MCF relationship is constructed by accumulating the incremental frequencies from the largest magnitude downward:

$$F_i = \sum_{i=1}^{n} f_i \quad (2)$$

where F_i is the annual frequency of debris flow events of magnitude M_i or larger. The MCF curve is obtained by plotting F_i against M_i on a logarithmic scale (Hungr et al. 2008). For a single debris flow, the scale includes two indicators, peak discharge Q_p and total volume W_c, from the instantaneous scale and overall debris flow statement scale, respectively, and the analysis fits the two indicators separately. The MCF relationship of the debris flow is well approximated by a power law; thus, the parameters are fitted using the three-parameter logarithm function. The formula is as follows:

$$y = a - b \times \ln(x + c) \quad (3)$$

where y is the cumulative frequency of debris flow CF; x is the magnitude of the debris flow, including the Q_p and W_c; and a, b, and c are constants for the MCF function (Table 2).

The MCF relationships of debris flows in Jiangjia Gully can be well approximated by a power law equation. To verify whether this law holds in other gullies, we used the same method to analyze other four gullies. Observation records of these debris flows included only peak discharges.

The magnitude of debris flow mainly depends on the flood flow and the abundance of sources. The MCF equation for each debris flow channel is a power law equation, and the constants a, b, and c determine its curve. With sufficient sources, the debris flow is mainly affected by rainfall conditions, and the magnitude is related to the drainage area A and rainfall intensity P. Therefore, this paper modifies the formula by using the drainage area A

Table 2 The regression coefficients in the Magnitude-cumulative frequency function of the gullies

Peak discharge	*a*	Standard Error	*b*	Standard Error	*c*	Standard Error	R-Square
Jiangjia Gully	49.913	3.212	6.500	0.408	462.802	56.733	0.962
Hunshui Gully	32.931	0.519	5.830	0.113	-0.446	0.405	0.995
Huoshao Gully	3.247	0.513	0.520	0.095	-18.790	9.833	0.964
Liuwan Gully	3.128	0.234	0.655	0.071	0.1518	0.566	0.940
Niwan Gully	1.903	0.156	0.454	0.055	0.343	0.340	0.928

Notes: The regression coefficients *a*, *b* and *c* of each gully are constants.

and precipitation P as indices. Thus the constants a, b, c become a function of variables A and P. There are five channel constants a, b, c in the paper, each gully has different variables A, P. Using the least squares method and regression analysis with "Origin" software, we can get the functional equations of a, b, and c and variables A and P, respectively.

The equations obtained above are in the form of constant (a, b or c) = f (A, P). In order to verify the accuracy of the equations, the maximum daily precipitation P and the drainage area A of the five channels are respectively brought into the equations to obtain the constants a', b', c'. The curve fitting values a, b, c of each gully are compared with the calculated values a', b' and c', and the residuals indicate the applicability of equation.

3 Results and Discussion

3.1 Results

Figure 4 shows an MCF curve generated from manually collected records of the debris flow events in Jiangjia Gully. The annual frequency of debris flows belonging to a certain magnitude category can be determined from the curve. For example, Line 1 shows that debris flows smaller than 10 × 10^4 m^3 may occur seven times per year, and line 2 shows that debris flows smaller than 20 × 10^4 m^3 may occur five times per year. The number of annual debris flows between magnitudes 10 × 10^4 m^3 and 20 × 10^4 m^3 is two.

The relationship between the Q_p and CF of Jiangjia Gully is as Eq. (4):

$$y_{Qp} = 49.91 - 6.50 \times ln(x_{Qp} + 462.8) \quad (4)$$

The relationship between the W_c and CF of Jiangjia Gully is as Eq. (5):

$$y_{Wc} = 40.20 - 2.86 \times ln\ (x_{Wc} + 2836.41) \quad (5)$$

The Q_p and W_c curve shapes are not consistent because different debris flows have different durations. When the debris flow is small, its MCF curve is not linear because the debris flow observation section is located downstream of the channel, and certain small-scale debris flows have stopped silting in the channel and cannot flow to the observation section. Therefore, the number of observed small-scale debris flows is less than the actual number of such events.

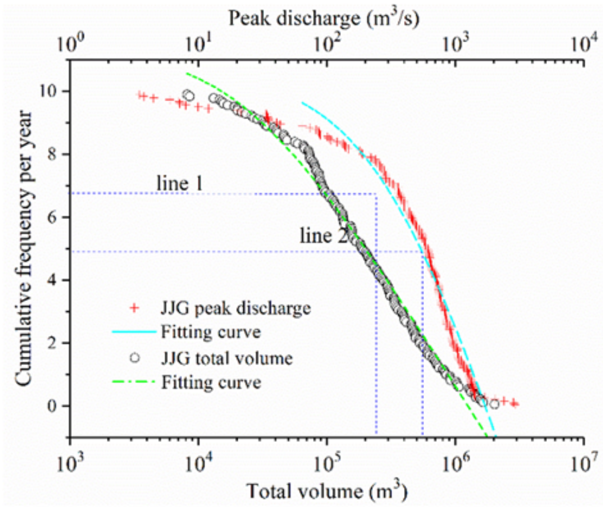

Figure 4 Magnitude–cumulative frequency (MCF) curve for the debris flows of Jiangjia Gully (JJG).

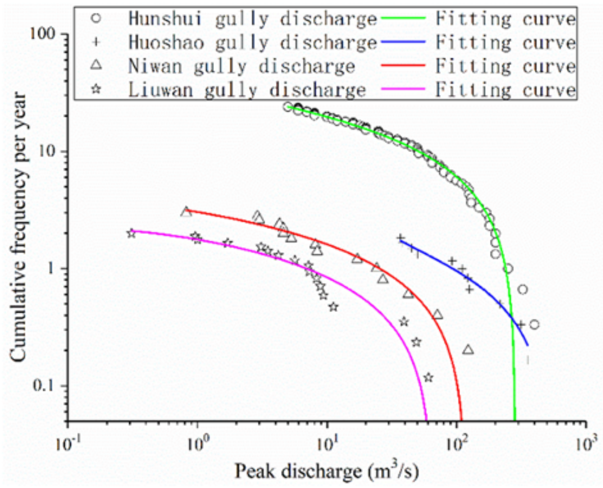

Figure 5 Magnitude-cumulative frequency (MCF) curves for the other four debris flows.

The results of the other four gullies indicate that the generated MCF curve is consistent with the power law equation (Figure 5). However, the curve shape of each gully varies greatly. Constants a, b, and c in the equations and the standard errors are shown in Table 2.

The results of the least squares analysis are shown in Eqs. (6), (7) and (8). A comparison indicated that the maximum daily precipitation is more strongly correlated with magnitude rather than annual rainfall. We found that a, b, and c can be obtained from the drainage area and daily maximum rainfall, and their correlation is good (Table 3). A maximum rainfall intensity of 1 hour may represent a better parameter; however, relevant data were lacking in the mountain area.

$$a = -34.71 + 0.287A + 0.458P \quad (6)$$

$$b = -5.688 + 0.01\,A + 0.079\,P \quad (7)$$

$$c = -76.018 + 10.015\,A + 0.279\,P \quad (8)$$

where A is the drainage area of each gully and P is the regional maximum daily precipitation.

These equations are preliminary results because the number of samples is too small and other important influencing factors must be addressed, such as the ratio and pre-rainfall.

Table 3 F test of the regression coefficients in the Magnitude-cumulative frequency (MCF) function

Constant	*F*	*p*
a	203.350	0.005
b	1611.550	0.001
c	42.823	0.023

In Eqs. (6), (7) and (8), the three constants a, b and c that determine the shape of the MCF curve are all positively correlated with the drainage area and daily maximum precipitation. The value of constant a in the formula has the largest share of the weight, and the value of constant b has the second largest share. After the natural logarithm operation, the value of constant c has the smallest weight. Taking Jiangjia Gully as an example, when c is 452, its natural logarithm is only 6.11.

The range of A values is usually between 0-50 km², while the range of P values is usually between 50-300 mm/d. In Eq. (6), the coefficient of P is 1.6-times the coefficient of A, showing that the daily maximum precipitation P has a greater influence on the MCF relationships of debris flows than the drainage area A. The value of constant b shows the same pattern. In Eq.(8), when the drainage area is larger, A's weight is greater than that of P. After taking the natural logarithm, the value of constant c decreases.

For constant a, when the peak discharge (x) of debris flow takes a fixed value, a larger drainage area and greater rainfall correspond to a greater CF of debris flows that are smaller than this magnitude. Constants b and c and the cumulative frequency are negatively correlated, but because their weights are less than that of constant a, overall, the CF of debris flow is positively correlated with drainage area and maximum daily precipitation.

3.2 The boundary conditions and scope of application for the formula

Debris flow is mainly controlled by loose sources and hydrodynamic conditions. In the case of abundant sources, the magnitude and frequency of debris flow are mainly controlled by rainfall characteristics and the drainage area. The bed channel ratio is generally negatively correlated with the drainage area. The drainage areas of the five debris flow gullies analyzed in this paper are between 1 and 50 km². In China, most debris flow drainage areas are within this range. When the area is smaller than 1 km², the magnitude of debris flow is too small to be a threat. When the watershed area is larger than 50 km², forming debris flows is difficult (Liu et al. 2008). The statistics of 1437 debris flow gullies in Panxi region, Sichuan Province show that gullies with a drainage area of 0.4-50 km² account for 90.2% of all gullies, gullies with a drainage area of less than 0.4 km² account for 5.1% of all gullies, and gullies with a drainage area of more than 50 km² account for 4.7% of all gullies (Tan et al. 1994). Therefore, the drainage areas of the debris flow gullies in this paper are typical.

In terms of climatic conditions, the Wudu region in Gansu Province belongs to a semi-arid area, while the Jiangjia Gully region in Yunnan Province belongs to a semi-humid area. The Hunshui Gully region in Yunnan Province belongs to a humid area. In these conductions, the annual precipitation has less impact on debris flow. Some regions with greater rainfall do not necessarily experience a high incidence of debris flows. Areas with heavy rainfall tend to have greater vegetation coverage, which has a certain inhibitory effect on debris flow hazards. Maximum hourly precipitation is a more sensitive indicator, but in mountainous China, this parameter is often difficult to obtain.

Compared the constants a', b' and c' with constants a, b and c (Table 4), the difference between Jiangjia Gully and Hunshui Gully is small, while the values for Liuwan Gully, Huoshao Gully and Niwan Gully are quite different for two main reasons. First, the number of samples in these three gullies is too small, and the peak discharges and frequency do not represent the long-term characteristics of debris flow. Taking Huoshao Gully and Liuwan Gully as examples, the loose

Table 4 The differences between constants the regression coefficients and the calculated coefficients

Gully	*a*	*a'*	*b*	*b'*	*c*	*c'*
Jiangjia	49.912	49.450	6.500	6.909	462.802	453.482
Hunshui	32.931	33.450	5.830	5.891	-0.446	9.784
Huoshao	3.247	1.949	0.520	0.557	-18.790	-34.203
Liuwan	3.128	1.946	0.655	0.557	0.152	-34.303
Niwan	1.903	4.337	0.454	0.640	0.343	49.122

Note: Constants *a*', *b*', and *c*' are calculated by bringing drainage area *A* and rainfall intensity *P* of the five gullies into the curve coefficients equations.

sources of both gullies are abundant, with equal drainage areas and the same rainfall characteristics in the same region. From 1969 to 1975, the 11 debris flow events' peak discharges in Huoshao Gully were between 37-354.09 m^3/s. From 1963 to 1964, the peak discharges of 17 debris flow events in Liuwan Gully ranged from 0.31 to 60.7 m^3/s. The reason for this difference is that the observation times of the two gullies are different. Second, the average longitudinal slope is also an important factor affecting the magnitude of debris flow. The drainage areas of Liuwan Gully and Huoshao Gully are same, but the difference between the average longitudinal slopes is larger. More samples and longer field observation periods are required to fix this error.

Since the sample of the formula has more constraints, the scope of application of the formula has certain limitations. The samples obtained from the formula are all high-frequency debris flows, so this formula is suitable for calculating the magnitude frequency relationship of high-frequency debris flows. This requires sufficient loose sources in the channel to cause multiple debris flow events within one year. The current formula does not apply to channels where the watershed area is small and the maximum daily precipitation is low, which causes the value of a in Eq. (6) to be negative. When a is a negative number, it may be concluded that the larger the magnitude of the debris flow and the higher the frequency, the opposite of the actual situation. At this point, it is beyond the scope of the formula. The observation time span of the Jiangjia Gully debris flow in Yunnan is 28 years, and the observation time of the other 4 gullies is only 2-3 years. Therefore, this formula is only applicable to the calculation of debris flows within 20 years of the regression period. We tested the formula and found that when the designed frequency of debris flow is low (e.g. 50 years return to 100 years return), the corresponding peak discharge only increase by 1m^3/s, therefore it is severely distorted.

Because some of the observations were conducted more than fifty years ago, the observations were primarily carried out via rope measurements and tape measures. The calculated flow velocity of the debris flow is also an estimate, which produces low observation accuracy for the debris flows. In addition, some of the smaller debris flows were not recorded or counted because the observational purpose at that time was focused on debris flow disaster management. The actual occurrences were higher than the statistics, and real debris flows were more frequent. However, the larger debris flow events were not lost.

3.3 Comparison with other research results

The Jiangjia Gully debris flow has been attracting the attention of scientists all over the world for decades. The researchers have studied it from different disciplines, and the scale-frequency relationship is one of the important research topics.

Li et al. (1983) studied the main features of the debris flow in Jiangjia Gully. The laboratory moving-bed flume was used to study the development, behavior and characteristics of high-concentration grain-in-fluid waves (Davies 1986,1990). Li et al. (2003, 2004) found that there was a statistical commonality in velocity, flow depth, and deposition thickness of debris flow surges. Liu et al. (2008) used 40 years of debris flow data to derive magnitude-frequency relation for debris flow. Their study shows that in the regional scales, the MF relationship of debris flows obeys the power law equation and is closely related to the gully drainage area. This correlation is significantly different in different regions. In the channel scales, the MF relationship of debris flow is also subject to the power law equation and is closely related to Q_m of surge in the debris flow process.

This paper shows that the MCF relationship of high-frequency debris flow accords with the power law equation. The difference of the debris flow equation curves of different regions and channels is obvious. The curve is controlled by the drainage area and rainfall intensity of the debris flow. This finding help guide the debris flow prevention and mitigation in areas with loose abundant sources, and also applies to the debris flow disasters after strong earthquakes or large landslides.

The MF relationship is central to debris flow hazard management and risk assessment. For low-frequency debris flows, scientists have used various methods for qualitative or semi-quantitative research, whereas the number of annual events is far below the research goal of this article. It also shows that the scale-frequency relationship of debris flows is consistent with power-law equations or logarithmic equations and is related to watershed area and rainfall intensity.

Van Steijn (1996) conducted a study of mountainous areas in central and northern Europe with a time scale of 1000 years. The results show that the magnitude and frequency of debris flows in different regions are all distributed in a straight line under the double logarithmic curve, but no formula can be calculated. The magnitude and frequency of debris flows in different regions vary substantially. The frequency of events of a given magnitude was higher in central Europe than in northern Scandinavia. The researcher believes that this finding is due to the richer source of debris in the mountains of central Europe, which can be converted to mudslides in the event of heavy rainfall. Rainfall is an important predisposing factor for both regions. In northwest Europe, shallow landslides and subsequent transformation into debris flows were typical events, whereas in the Alps, integration of landslides with passing debris flows in important in larger torrent systems was reported. In this case, very large flows develop.

The study of debris flow in the Cheekye Basin in British Columbia, Canada, has a time scale of more than 10,000 years (Jakob and Friele 2010). Based on a tree chronology analysis of the trees in the Cheekye Fan and dating of the drilling samples of sediments, the authors constructed rough graphs of the total volumes and peak discharges of the debris flows to determine the 10,000-year event magnitude. The graph shows that the MF relationship of the debris flows is linear in double logarithmic coordinates, but important data are missing on the millennium time scales from 200 to 3000 years ago.

Research in Los Angeles, California, USA, shows that the MF relationship of debris flow is a function of the relief ratio, hypsometric index and occurrence interval (Johnson et al. 1991). The researchers developed an MF equation in this area and obtained a formula for debris flows in return periods of 2, 5, 10, 25, 50 and 100 years. The influence of rainfall is included in the formula for the return periods. A 2-year debris flow is used as an index flow. The magnitude of a 25-year debris flow is calculated to be 25-times larger than that of the 2-year flow, and the magnitude of a 100-year debris flow is 80-times larger than that of the 2-year flow.

Gao et al. (2018) analyzed the scale frequency relationship of the 197,633 landslides and debris flows in Hong Kong as of 2013. Their research results show that in Hong Kong, the MCF curve of landslide accords with the logarithmic equation. The mathematical formula is $\mathrm{Log}N=\mathrm{A}+\mathrm{B}M$, where N is the number of landslides with a certain scale, which can be converted into cumulative frequency values, M For the scale of the landslide. The form of the formula is closer to the formula obtained in this paper. For the rainfall intensity factor, they also believe that landslide hazards are more sensitive to the 4-24 hour maximum precipitation intensity than the 1 hour maximum precipitation intensity.

By comparison with other research results, we find that the influencing factors considered by researchers are similar, and the conclusions drawn are comparable. The accuracy of the sample is high, but the time scale of the study is short; more debris flow data must be collected for long time intervals.

4 Conclusions

In this paper, long-term monitoring data on the debris flow in Jiangjia Gully, Dongchuan County, Yunnan Province are used to analyze the MCF relationship of a high-frequency debris flows area.

Based on a nonlinear regression analysis of the

MCF relationship of 178 debris flow events in Jiangjia Gully between 1987 and 2004, we find that these debris flows generally obey the power law of $y = a-b\times ln(x+c)$. To verify this rule, the same analysis was performed for Hunshui Gully in Yingjiang County, Yunnan Province and Huoshao Gully, Liuwan Gully, and Niwan Gully in Wudu County, Gansu Province. The MCF relationships of these gullies were also consistent with the power law relation, although constants a, b, and c have large differences.

Since debris flow characteristics are generally controlled by watershed characteristics and rainfall characteristics, we use the least squares method to perform a linear regression of the above three constants with the drainage area and the maximum daily rainfall. According to the five gullies, the correlation between the MCF curve and the drainage area and daily maximum precipitation is strong. As the number of samples increases, other important factors, such as the ratio of the channel, can be considered, and the MF relationship of debris flows will be more accurate.

The relationships derived in this paper can guide the study of the magnitude and frequency of debris flows in adjacent areas. The relationship is particularly applicable for areas with abundant weathered soft rock and metamorphic rock and other rich sources. For a disturbed area after a strong earthquake, debris flow activity may start to intensify due to extensive accumulation of sources in the channel within a short time, and high-frequency characteristics, which are applicable to this power law relationship, may also be observed (Tang et al. 2009; Yu et al. 2010; Ni et al. 2011). When the source of a channel decreases, the relationship between the magnitude and the frequency of the debris flow changes towards a lower frequency.

However, a greater number of low-frequency debris flows occur in nature, and the accumulation rate of loose sources in ravines becomes an important factor for debris flows. With a greater number of samples, the MCF curve can be more effectively analyzed to determine whether it complies with another power law relationship multiplied by a reduction factor.

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