Environ Geol (2005) 48: 771–777
DOI 10.1007/s00254-005-0017-z

ORIGINAL ARTICLE

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Debris flow erosion and deposition in Jiangjia Gully, Yunnan, China

Received: 25 January 2005
Accepted: 24 May 2005

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Abstract The erosion and deposition of debris flows at Jiangjia Gully in Dongchuan section of Yunnan province, southwestern China, was surveyed at 12 cross sections from 1999 to 2003. Deposition occurred in most sections because of the low debris-flow magnitude. The result was an increase in their elevations except for two sections at D17 and D19, where the channel was diverted in September 1999. As the annual sediment discharge of debris flow increased, the deposited volume decreased in the upper channel and increased in the lower channel. In each debris flow event, the erosion or deposition at the upper and the lower channel were different, but the eroded/deposited volume and the trend of erosion or deposition were similar between the neighboring sections. The average elevation change of all cross sections between consecutive surveys can reasonably represent the debris flow influence on the channel. Its relationship with the total sediment discharge between two surveys follows a three-stage pattern: when debris flow magnitude is small, deposition in the channel increases with the magnitude. When the magnitude reaches a certain level, the deposition begins to decrease and eventually erosion takes place. In three typical cross sections which had similar channel width, the debris flow showed a clear trend that the deposited volume decreased, while the eroded volume increased as the discharge of debris flow sediments increased.

Keywords Debris flow · Erosion and deposition · Jiangjia Gully · China

Introduction

Debris flow is a common phenomenon in mountain areas and is characterized by high capacity of sediment transport, catastrophic occurrence, high-concentrated sediment, wide range of grain size, high velocity, and short period of movement. A single debris flow can transport sediment of many thousand million tonnes into main river and make great influence on main river (Cui 1999). Debris flow also can dramatically change the channel morphology while transporting large quantities of sediments from an upper reach to a lower reach. In recent literature attention was mostly paid to the influence of debris flows on the channel (Hack and Goodlett 1960; Scott 1971; Williams and Guy 1973; Campbell 1975; Bogucki 1976; Pierson 1980, 1985; Benda 1990; Wohl and Pearthree 1991). Some researchers focused on quantifying erosion and sediment quantity feeding the debris flows (Caine 1976; Dietrich and Dunne 1978; Benda 1990), while others discussed the relationship between the erosion and debris flow magnitude (Rickenmann et al. 2003). Only a few researchers considered both erosion and deposition (Cenderelli and Kite 1998). However, most present research was based on some specific single debris flow events or laboratory experiments instead of systematical and continuous natural debris flows.

Based on 5 years of field observations and surveys in Jingjia Gully, variations of erosion and deposition in the middle and lower channel were analyzed. This area has high annual precipitation and frequent debris flows. Not only strong erosion, but also strong deposition occurred. In the lower reach erosion and deposition happened alternatively at irregular intervals and resulted in severe alteration of the channel bed. At a certain location, the channel can be eroded or deposited during a particular debris flow depending on local conditions. To quantify the influence of debris flows on the channel under natural conditions, it is first necessary to understand the mechanism of erosion and deposition along the channel and the influencing factors. Although research was done previously on the pattern of erosion and deposition of debris flow in Jiangjia Gully (Wu et al. 1990), duration of the research and density of the surveying stations in the channel were not considered sufficient.

Physical setting

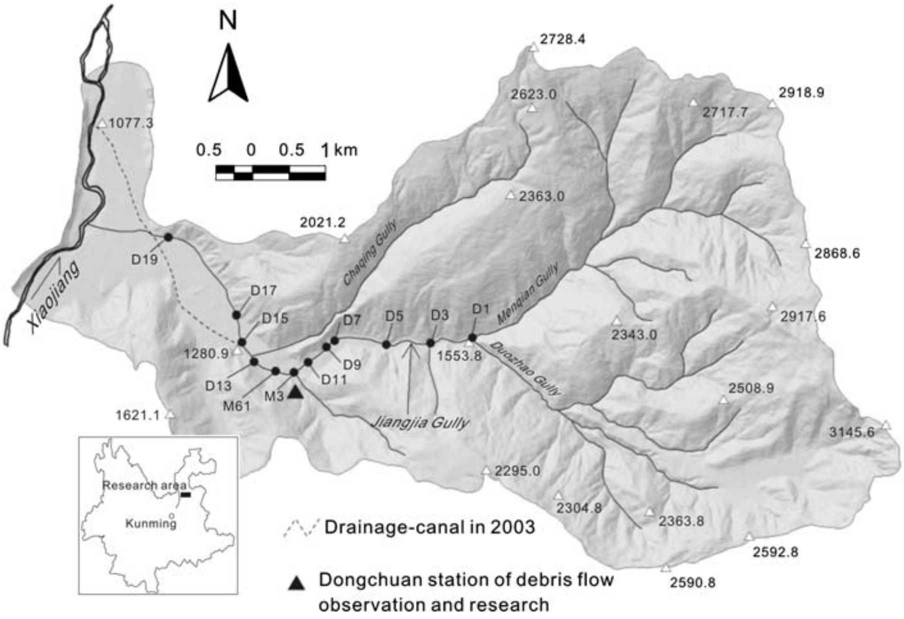
The Jiangjia Gully is at the right of the Xiaojiang River—a branch of Jinsha River northeast of Yunnan province—with the trunk channel length of 13.9 km covering a total area of 48.6 km^2 (Fig. 1). There is an estimated 1.23×10^{10} m^3 loose sediments stored in the valley. There are 12–20 debris flows in every rainy season (May–October). One debris flow may be composed of tens up to one hundred surges. Debris flow in this area is viscous in nature (Wu et al. 1990). Annual sediment yielded in Jiangjia Gully is 2.0 million m^3 on average while a maximum of 6.6 million m^3 occurred in 1991. The main channel can be divided into three sections with different morphologic characteristics: the erosion section, the debris flow transport section, and the deposition section (Cui et al. 2005).

Methods

Since 1999, the Dongchuan Debris Flow Observation and Research Station (DFORS) of Chinese Academy of Sciences (CAS) has arranged several cross sections along the 7.83 km channel of middle and lower reach according to the characters of the longitudinal profile (Fig. 1), in order to research erosion and deposition changes in detail. The longitudinal profile and the gradient are shown in Fig. 2 and Table 1. A fixed point on the left channel of each cross section was selected for the measuring instrument and another point on the right of the channel was marked for surveying reference. Sometimes debris flows happened within short intervals. A survey could not be done right after every debris flow event. There were a total of 48 debris flow events recorded during the period and 26 surveys were carried out in all the cross sections.

The erosion or deposition of a cross section is not uniform even in a single debris flow event. Erosion or deposition will generally change the elevation of the lowest point and the area of the cross section. That means the rise and fall of the lowest point is synchronous with the whole cross section (Fig. 3). The change of cross section area and the lowest height was used to reflect the change of the whole cross section. The rise and fall of the lowest point reflects the rise and fall of the whole cross section, and it also reflects the channel gradient adjustment under the influence of debris flow.

Fig. 1 Map of the study area and positions of cross sections (D11 is used from 2000 to 2003, M61 is used from 2001 to 2003, D17 and D19 are used from 1999 to 2002, and others are used from 1999 to 2003)



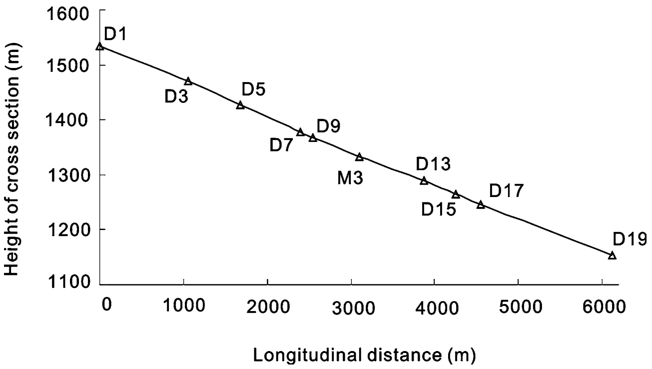


Fig. 2 Longitudinal profile from section D1 to D19 (Based on the elevation of the lowest points of cross sections from the first survey of 1999)

Here the erosion of a cross section is defined as the negative change, or decrease, of the cross section area and deposition is defined as the positive change.

The deposited or eroded volume (V_{si}) between cross section *i* and *i+1* can be calculated as follows

$$V_{si} = \frac{D_i\left(S_{i+1} + S_i + \sqrt{ABS(S_{i+1} + S_i)}\right)}{3}, \qquad (1)$$

$$V_{si} = \frac{D_i\left(S_{i+1} + S_i - \sqrt{ABS(S_{i+1} + S_i)}\right)}{3}, \qquad (2)$$

where S_i and S_{i+1} are the area changes of the cross sections *i* and *i+1*, and D_i is the corresponding channel length between the two cross sections. If the sum of S_i and S_{i+1} is above zero, Eq. 1 is used; otherwise Eq. 2 is used.

Water flow is not the dominant process in changing channel morphology. To consider the debris flow action only, the channel change is not compared overtime and the eroded/deposited volume by debris flow is calculated based on the first and the last surveys in a year.

Characteristics of the debris flows from 1999 to 2003

The average frequency of debris flow in this period is 9.6 times per year, with a total of 48 passing through the Dongchuan DFORS. This frequency is smaller than the average frequency of 11.7 times per year from 1965 to 2003. In comparison, the annual sediment discharge of debris flows in the 5-year period is somewhat smaller than that in the last 10 years (Fig. 4).

Wang et al. (2000) and Cui et al. (1999, 2004) indicated that a 6-year recurrence period for rain in this area resulted in a fluctuation of the landslide activity and the surface erosion. The debris flows discharge also has a 6-year recurrence period. If the period 1999–2003 is evaluated as a part of another debris flows recurrence after 1997 (the maximum discharge was in 2001), then flow activity in this period is a little bit low, or the debris flow can be considered to be at relative rest after intense activity.

In addition, part of the channel was influenced by the channel avulsion which happened in September 1999 downstream from D19 when debris flows destroyed one

Table 1 Channel gradient of each two-neighboring section in 1999

Section	D1-D3	D3-D5	D5-D7	D7-D9	D9-M3	M3-D13	D13-D15	D15-D17	D17-D19
Length(m)	1056.8	626.6	716.4	139.6	555.4	781.7	369.9	380.0	1487.0
Gradient	0.062	0.068	0.069	0.074	0.065	0.055	0.065	0.060	0.060

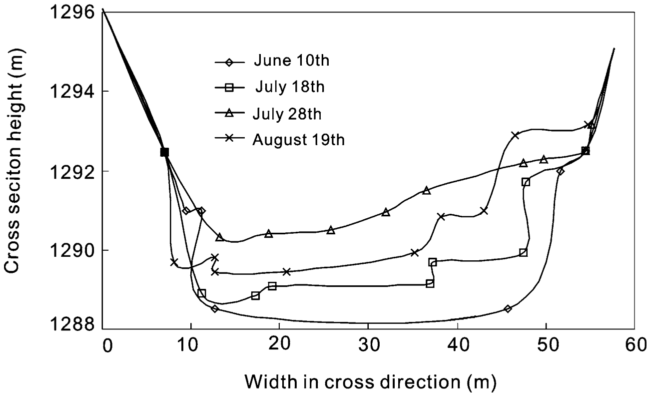


Fig. 3 Change of cross section D13 in 1999 (change: elevation of channel cross section)

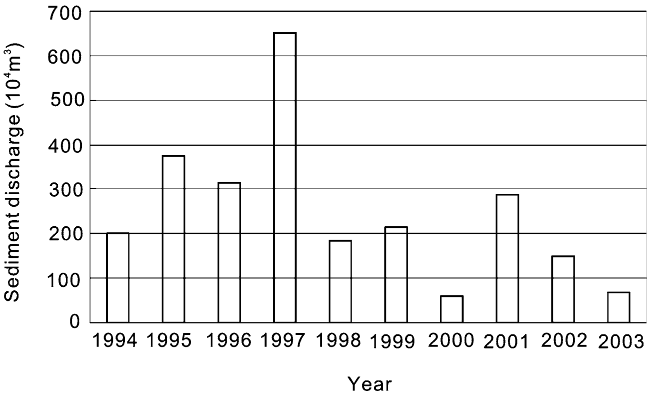


Fig. 4 Sediment discharge of Jiangjia Gully debris flows in the past 10 years

of the lower channel dikes after a long deposition (You et al. 2001). The channel avulsion also caused the 15-h block up of the Xiaojiang River in 2001 (Wei et al. 2002). To avoid future block up events, the local government constructed a diversion dike in 2003 (the dashed line in Fig. 1).

Characters of erosion and deposition in the middle and lower channel in 1999–2003

First, the total deposition volume was larger than the erosion volume in most of the cross sections (except for D17 and D19) in the 5 years. After the last survey of 2003, the lowest points of most cross sections were higher than those surveyed in 1999, and the rising speeds of the lowest height of most of the cross sections were more than 1 m/year (Table 2).

Secondly, annual changes of the cross sections during the 5 years were not uniform. In the upper channel, the annual deposited volume per unit length of the channel basically decreased with increasing of annual debris flow sediment discharge (erosion considered as negative deposition) (taking the section D5-D7 and D9-D11 as examples, Fig. 5a). In the lower channel, however, the annual deposited volume per unit length increased with increasing of the annual debris flow sediment discharge (taking section M3-D13 and D13-D15 as examples, Fig. 5b).

Thirdly, the neighboring cross sections were similar in change from the lowest point's height and the area of the cross section. For example, at sections M3 and D13, based on the lowest points of the first survey in 1999, the change in both height and pattern were similar (Fig. 6).

The relative changes of two cross section areas at M3-M61 and M61-D13 between two successive measurements followed a similar trend (Fig. 7). For cross sections far away from each other, there was no similar change, neither in the lowest point's height nor in the cross section area.

Fourthly, the D17 and D19 cross sections had distinctive change curves. As discussed, a channel avulsion in September 1999 at downstream D19 made the channel 1,070 m shorter and the local gradient sharply increased. The cross section was continuously eroded in 2000 and 2001 near the D19 cross section. In the last survey of 2001, the height of the lowest point at D19 was 21.28 m lower than that in the last survey of 1999. In

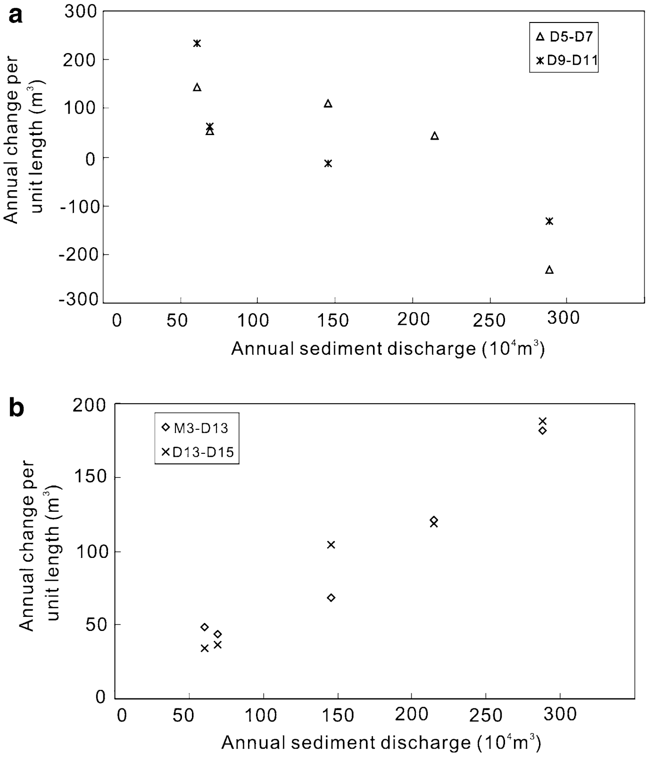


Fig. 5 Relationship between annual deposited/eroded volume per unit channel-length and annual sediment discharge, **a** upper channel section D5-D7 and D9-D11; **b** lower channel section M3-D13 and D13-D15

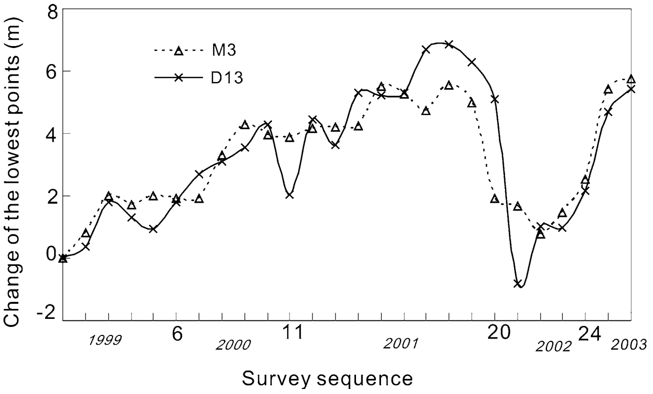


Fig. 6 Elevation change of the lowest points of M3 and D13 since the first survey in 1999

Table 2 Deposited/eroded volumes in the channel sections and rise/fall of cross sections

Section	D1-D3	D3-D5	D5-D7	D7-D9	D9-M3	M3-D13	D13-D15	D15-D17	D17-D19
Length(m)	1056.8	626.6	716.4	139.6	555.4	781.7	369.9	380.0	1487.0
Gradient	0.062	0.068	0.069	0.074	0.065	0.055	0.065	0.060	0.060

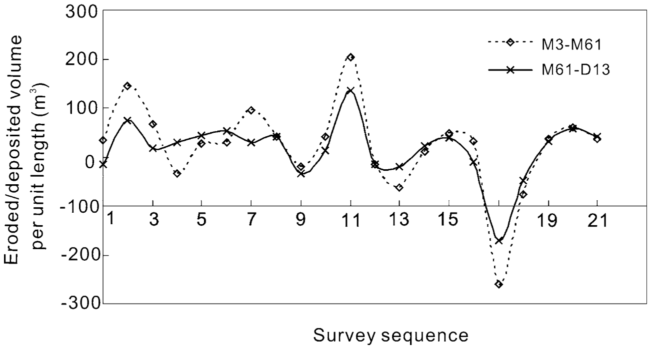


Fig. 7 Eroded/deposited volumes per unit channel-length at M3-M61 and M61-D13 sections

2002, as debris flow intensity reduced, deposition occurred again in this section, raising the channel bed (Fig. 8). Unlike its neighbor section D15, the channel bed at cross section D17 in the last survey of 2002 was 3.84 m lower than in the first survey of 1999, which indicated that D17 was possibly influenced by the drop of D19, especially in 2002 (Fig. 8). Station D17 and D19 were not used since 2003.

Analysis of the influencing factors of erosion and deposition

The research considered the middle and lower reach, called transportation/deposition zone, which has smaller gradient (Table 1). Effect of debris flow in this area is mainly deposition. There are other factors that affect erosion or deposition, such as debris flow characters (density, viscosity, composition, flow depth, and speed), channel characters (composition of banks, mobility of components, and shape), erosive base of the channel, debris flow in tributary channels, and slope failure along the valley (Wu et al. 1993).

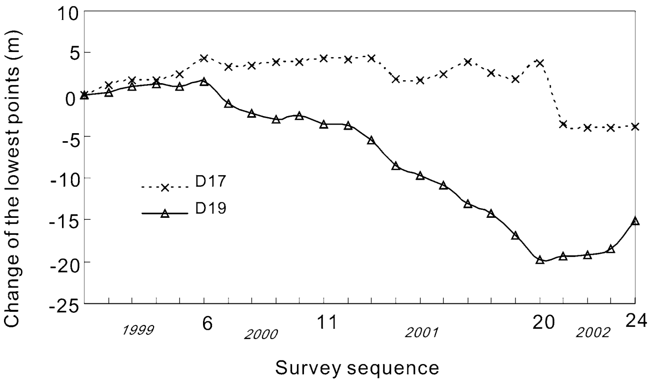


Fig. 8 Elevation changes of the lowest points at D17 and D19 since the first survey in 1999

The effect of erosive base of the channel is demonstrated by the change of D17 and D19 (Fig. 8). Other factors that are harder to quantify were not considered, such as composition of channel bank, influence of tributary channel, and channel bank failure. The main factors considered were debris flow magnitude and channel character. The debris flow magnitude is related to debris flow sediment discharge and debris flow duration.

From field observations, there was a paving process in the channel during the early stage of debris flow. A residual layer remained afterwards which contributed to protection of the channel bed (Wang et al. 2001). When debris flow at a later stage was small, the channel would not be eroded because of the protection of the residual layer and the disturbance to the channel would be weak. On the other hand, due to the small flow velocity and shallow flow depth, debris flows were prone to deposition. Within a certain range, deposition quantity in the channel increased with the sediment discharge. When the debris flow discharge and the flow speed increased to a level sufficient to break the protection of the residual layer, erosion happened. If debris flows discharge is high enough, the channel will be eroded layer by layer.

Small scale debris flows usually have shorter duration, while larger debris flows have longer duration. In a particular debris flow event, its early stage is mostly a paving and deposition process, and its later stage is mostly an erosion process. The main result of small debris flows in the channel is deposition. As debris flows sediment discharge increases, erosion in the later stage also increases.

The relationship between the eroded/deposited volume and the debris flow discharge was analyzed. We did not find an equation suitable for forecasting the deposited/eroded volume of the whole channel.

The effects of a debris flow on the upper channel and the lower channel may not be the same, therefore eroded/deposited volume may differ. Some cross sections were eroded while the others were deposited. At the same time, erosion and deposition will adjust the overall channel gradient. The lowest point's cross section determines the gradient of the channel. So the change of the lowest point's cross sections reflects debris flows influence on the whole channel gradient. To find the inherent correlation between debris flow discharge and change of the channel, the average change in elevation of the lowest point and debris flow discharge were determined.

Debris flow discharge and elevation change of cross section's lowest point

The general change Q_j of the whole channel between survey *j-1* and survey *j* can be expressed as:

$$Q_j = \frac{\sum_{i=1}^{n} s_i}{n}, \tag{3}$$

where s_i is the change of the lowest point height of cross section i between survey j-1 and survey j, and n is the number of cross sections.

Figure 9 shows that there are three stages of average change at the lowest points. At the beginning, change of the lowest point increased with the total sediment discharge of debris flows. When the total sediment discharge increased to a certain value (about 26.5×10^4 m^3), the rise of the lowest point started decreasing, and eventually erosion of the section happened. The decrease slowed when the total discharge increased further (Fig. 9). The change of the three stages can be described by a linear polynomial function and a quadratic polynomial function. To the first stage, $y = 0.0258x + 0.1873$, $R^2 = 0.851$; and to the second and the third stage, $y = 0.0002x^2 - 0.0496x + 2.1382$, $R^2 = 0.7908$ (Fig. 9).

It can be concluded that the lowest point's cross section and the channel gradient have a more direct correlation with debris flow discharge. Because different debris flow magnitudes need different channel gradients, the lowest points always rise and fall due to adjustment of each debris flow. Since the width of the upper and lower channel is different even from similar changes in the elevation of the lowest points, both the area change of cross sections and the deposited/eroded volumes per unit channel-length may be different at the upper and lower channel. Therefore, a close correlation between the deposited/eroded volume and the debris flow magnitude is not demonstrated.

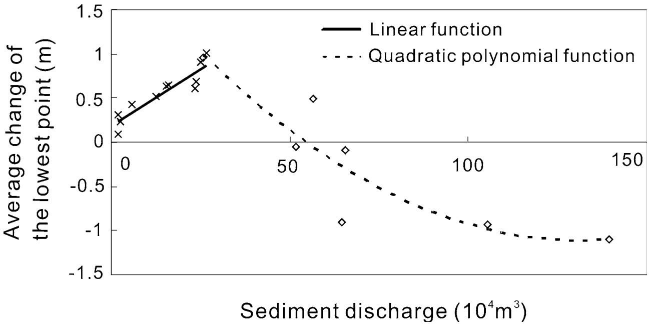


Fig. 9 Relationship between average elevation change of all the lowest points and total sediment discharge in two successive surveys

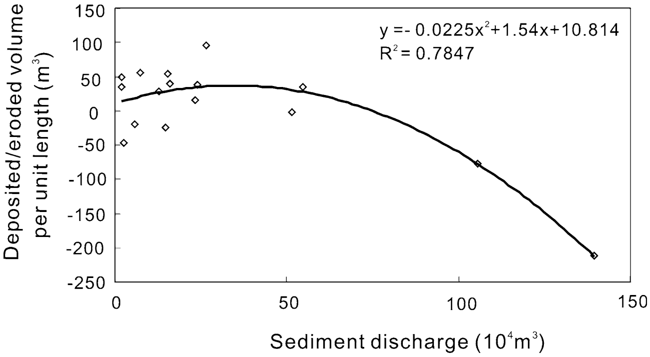


Fig. 10 Relationship between deposited/eroded volumes per unit channel-length and debris flow discharge in the section D11-M61

Deposited/eroded volumes between the typical cross sections

To further analyze the relationship between the eroded/deposited volume and the debris flow magnitude, three typical neighboring cross sections with similar width were selected. The distance of D11-M3 and M3-M61 are 227 and 236 m respectively. Widths of the three cross sections are almost the same, about 70 m.

Figure 10 shows that the deposited volume per unit channel-length can be reasonably expressed as a quadratic polynomial function of the debris flow sediment discharge.

Conclusions and discussions

Due to the weak activity of debris flows in 1999–2003, most of the cross sections received deposition during debris flows. Actually, during most of the years, the debris flows were at their sub-active stage. Therefore the overall trend in the middle and lower channel is deposition.

If erosion is considered as negative deposition, the relationship between the annual deposition volume and the total sediment discharge in the upper channel can be described by a negative linear expression and in the lower channel by a positive linear expression. The neighboring cross sections have similar trend in change of elevation of the lowest points.

Taking the average change value of all the lowest points between two successive surveys as the total influence of debris flow on the channel gradient, there is an increase of influence at the beginning, and then a decrease as the total sediment discharge increases. A linear polynomial function and a quadratic polynomial function can be used to express the relationships in the different stages. At three typical neighboring cross sections which have similar width, the deposited/eroded volume can be reasonably expressed by a quadratic polynomial function of the debris flow sediment discharge.

Acknowledgements The authors would like to thank the whole staff of Dongchuan Station of Debris Flow Observation and Research who provided great help and data to this research, and Sun Enzhi for his field work. Many thanks to Professor Li Yong and Dr. Zhu Yingyan for providing very good ideas for this article and also for translation help. Our special thanks go to Professor Steve Zou in Dalhousie University, Canada, for revisions and correction of language errors in this paper. This study was directed by Professor Cui Peng and supported by Ministry of Science and Technology 973 plan project (2003CB415202), NSFC key project (49831010), and National Outstanding Youth Scientific Foundation of China (40025103).

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