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ORIGINAL ARTICLE

A case study of long-term field performance of check-dams in mitigation of soil erosion in Jiangjia stream, China

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Abstract This paper examines the long-term field performance of the check-dams in mitigation of soil erosion in the Duozhao catchment of Jiangjia stream, southwest China. Since their construction between 1979 and 1982, the check-dams have been functioning effectively. The examination is made via comparisons between the environmental conditions of the Duozhao catchment with its adjacent Menqian catchment in the stream, because no check dams were constructed in the Menqian catchment. The examination is based on recent field investigations and aerial photograph analyses, and covers four aspects: (a) bed gradients of catchment channels; (b) stability of bank slopes; (c) rates of land erosion; and (d) vegetations on bank slopes. The field data demonstrate that the check-dams have had the following good functions for mitigation of soil erosion: (1) restricting the channel depth and lateral erosions, (2) protecting the channel erosion base, (3) reducing the bed gradients of debris-flow channels, (4) fixing the channel bed, (5) stabilizing the bank slopes, as well as (6) facilitating the growth of vegetations.

Keywords Check-dam · Debris flow · Soil erosion · Environmental management · Jiangjia stream · Case studies

Introduction

Soil erosion is a common natural phenomenon in mountainous regions. It can change the ground geomorphology and induce debris flows and landslides. Debris flows and landslides can cause casualties to human beings and damages to civil infrastructures (Takahashi 1991; Armanini 1997). For many years, people have developed various mitigation or preventive measures to control soil erosions. Check-dam is one of the simple and effective engineering measures.

A check-dam can be defined as a dam constructed across a drainage channel to mitigate and reduce soil erosion (Hudson 1981; Morgan 1986; Chanson 2004). This structural measure is commonly used to reduce stream speed and to capture sediments. It can be made of various materials including woods, boulders, and concrete blocks. It can be close or open for preventing or allowing water flow through itself, respectively. It can be used to permanently store their sediments in the channel. Or it can be used to temporarily store their sediments. Once its above space is full of sediments, the sediments will be removed so that its above space can store new sediments again (VanDine 1996; Armanini 1997; Jaeggi and Pellandini 1997; Chanson 2004).

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Check-dam has a long history of development and utilization. Check-dams were built in the mountain of Alps in the fourteenth century and became popular there in the nineteenth century. They were constructed in the Loess Plateau, China in the sixteenth century. They were used in Japan in the early twentieth century. More details on the check-dam history can be found in Wu (1990), Jaeggi and Pellandini (1997), Shun et al. (1997), Mizuyama et al. (2000), Chanson (2004), and Xu et al. (2004).

This paper presents an investigation on the long-term field performance of masonry check-dams in mitigation of soil erosions in a stream where many debris flows had occurred. This stream is the Jiangjia stream near Kunming in southwest China (Fig. 1). The stream has two major catchments. One is named Duozhao and the other Menqian. The masonry check-dams were constructed between 1979 and 1982 for mitigating and reducing soil erosion in the Duozhao catchment only. Therefore, the investigation is carried out by comparing the current geomorphologic features of the Duozhao catchment with those of the Menqian catchment. The comparison covers four aspects: (a) the bed gradients of the catchment channels, (b) the bank slope stabilities of the two catchments, (c) the soil erosion rates of the two catchments and (d) the vegetation cover in the bank slopes of the two catchments. The examination has shown that the check-dams have effectively mitigated the severe soil erosions in Douzhao catchment. Consequently, the soil surfaces in Duozhao catchment are more stable and covered with much more vegetation and trees than those in Menqian catchment.

Jiangjia stream and its soil erosion

Jiangjia stream is located about 200 km north of Kunming city, Yunnan Province, Southwestern China (Fig. 1). It occupies a plane area of 48.6 km^2 and is a tributary watershed of the Xiaojiang River, a branch of Jinsha River of the Yangtze River. The stream is about 13.9 km long.

Jiangjia stream is known for its severe soil erosions and debris flows. During the wet season in each year, many rainstorm induced debris-flows occur in the stream (Li et al. 1983; Takahashi 1991; Zhang 1993; Corominas 1995; Lan et al. 2004). Since 1961, tremendous data on the debris flows and their characteristics have been collected and documented by researchers. The occurrence rate of debris flows in the stream is about 15 times per year. Solid materials of about 3 × 10^6 m^3 per year in the stream are transported into Xiaojiang River and then Yangtze River (Xu 2008). The recorded peak values for the discharge, velocity, head depth, and wet unit weight of the debris flows are 2,820 m^3/s, 15 m/s, 5.5 m and 23.7 kN/m^3, respectively (Wu 1990; Li et al. 2003).

The stream catchment soil is the core of a tectonic uplift. The original hillside slopes comprise mainly the Lower Proterozoic thin bedded slate with NE 60°–70° in strike and 40°–50° in dip, and slightly the Sinian medium-thick bedded dolomite. Due to strongly regional neotectonic activities and uplifts, the slate is strongly deformed and fractured. Table 1 presents the physical and mechanical properties of the slate and dolomite in the stream (Li 1993).

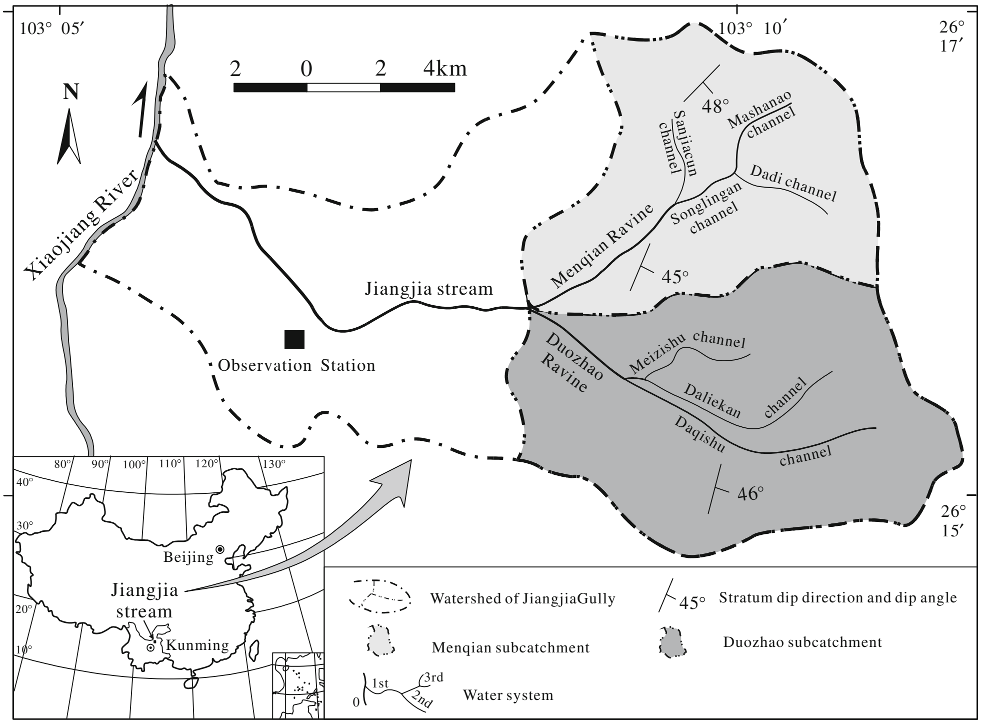


Fig. 1 Location plan of Jiangjia stream and its vicinities in China. The names of water system of different ranks are defined as follows: the primary as stream, like Jiangjia stream; the first as ravine, like Menqian and Duozhao ravine; the second and third and fourth as channel, like Daqishu channel

Table 1 Physical and mechanic properties of the slate and dolomite in Jiangjia stream area (after Li 1993)

Stratigraphy		Dry unit weight	Saturated unit weight	Specific gravity	Water absorption	Saturated water absorption	Dry compression strength (MPa)	Saturated compression strength (MPa)	Softening coefficient	Shear strength		Static elastic modulus	Poisson's ratio
Geologic time	Lithology	(g/cm^3)	(g/cm^3)	(g/cm^3)	(%)	(%)				c (MPa)	Φ (°)	(GPa)	
Proterozoic	Slate	2.71	2.72	2.77	0.66	0.99	49	36	0.7	6.5	30	4.4	0.02
Sinian	Dolomite	2.68	2.72	2.77	2.18	2.28	126	114	0.9	13.5	44	46.1	0.22

The fractured slate belongs to the type of loose and fractured structural rocks (Gu 1979). Besides the bedrocks, the stream has abundant and loose deposits of recent and old debris flows and landslides (Li et al. 2003).

As shown in Fig. 2, Duozhao and Menqian are the two major catchments of Jiangjia stream. They occupy the plane areas of 13.2 and 14.8 km^2, respectively (Wu 1990; Hu and Zhong 2002). They have eight and nine tributary debris-flow channels, respectively. Table 2 shows the features of these tributary debris-flow channels. The longitudinal profiles of the two catchments are shown in Fig. 3. In the paper, the stream system is ranked as follows: the primary stream is the Jiangjia stream; the first streams are the Menqian ravine and the Duozhao ravine; the second and third and fourth streams are named as channels.

Check-dams and performance in Jiangjia stream

General introduction

Due to the facts that the debris flows in Jiangjia stream had severe destruction to the civil infrastructure and farmland, some mitigation measures had been planed and implemented since 1960s.

Dry packed random rubble check-dams

Between 1965 and 1967, 117 check-dams were made with dry packed random rubbles and constructed. The dams were 1.0–2.5 m high, about 1 m wide at the top surface, and less than 1:0.5 for the gradient of the dam downstream slope. Dolomite boulders were directly built on the channel beds without disposal of dam foundation and abutment. Spillway and apron were not used. Consequently, all 117 check-dams were destroyed by stream water and debris flows in 1974. No any relicts of the check-dams could be found during present investigations in 2004.

Pointed random rubble check-dams

From 1979 to 1982, 44 random rubble check-dams pointed with cement mortar were built in the tertiary channels along the Duozhao middle upstream. They are located mainly in the Meizishu and Daqishu sub-catchments (Fig. 2). However, there were no check-dams or other mitigation measures constructed in the Menqian catchment in between 1974 and 2000.

Figure 2 shows the distribution of the check-dams in the middle region of the Duozhao ravine. In Fig. 2, a Cartesian coordinate system is set up for the local eastern and

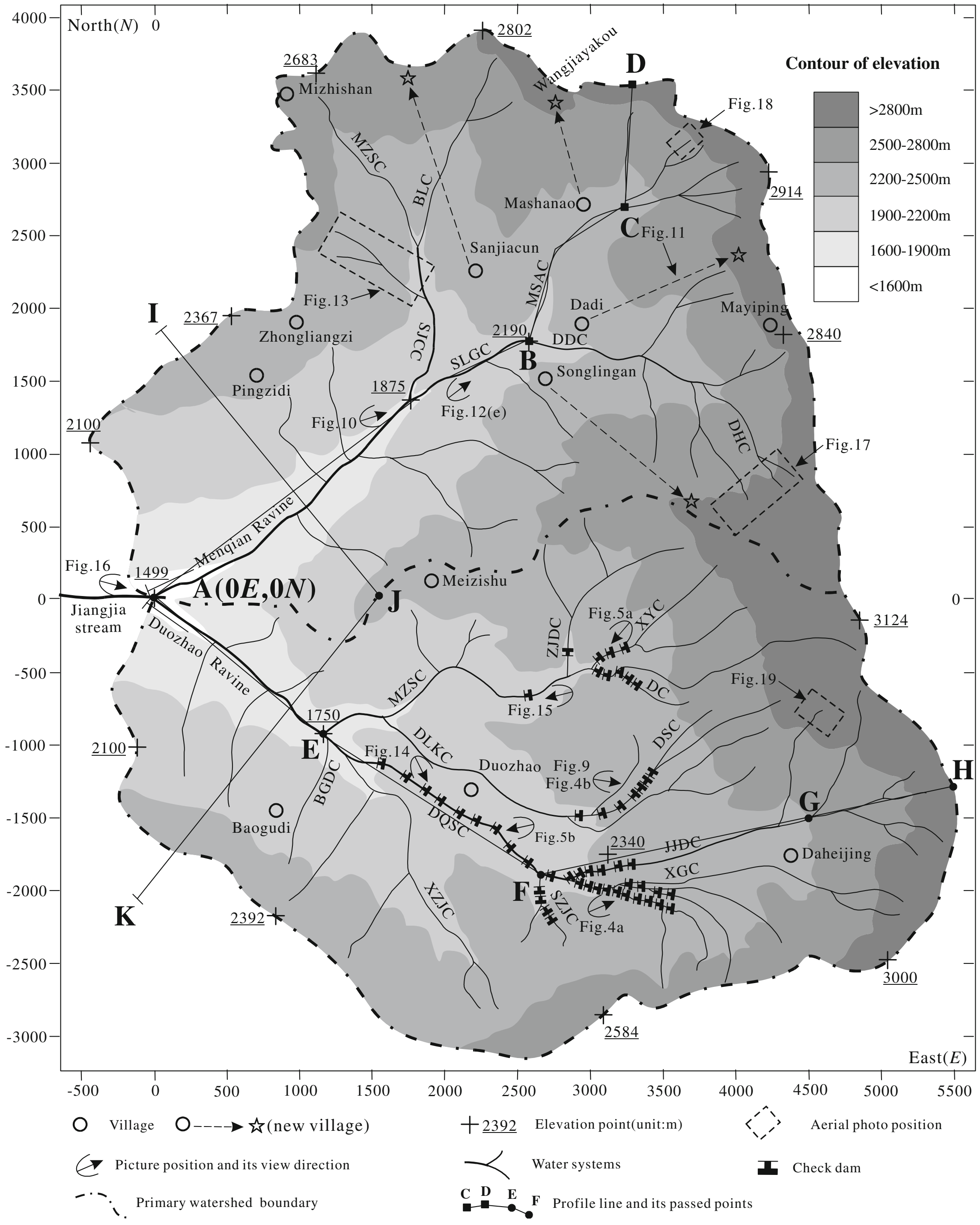


Fig. 2 Comprehensive plan of Menqian and Duozhao ravines above Jiangjia stream including (**a**) distribution of check-dams, (**b**) elevation information, (**c**) profile locations, (**c**) positions and view directions of photos, and (**d**) position index of other figures

northern coordinates of the important positions. The origin of the local eastern and northern coordinate system (0E, 0N) is at the junction of the Duozhao ravine and the Menqian ravine, where the two ravines combine into the main Jiangjia stream.

Figure 3 shows the longitudinal profile of the Duozhao ravine following the locations A, E, F, G and H, and the check-dams in Fig. 2 and the longitudinal profile of the Menqian ravine following the locations A, B, C and D in Fig. 2. Figure 4a and b shows some of the check-dams in

Table 2 Characteristic indexes of Duozhao and Menqian ravines and their tributaries (modified after Hu and Zhong 2002)

Duozhao catchment and its tributaries					Menqian catchment and its tributaries				
Tributaries	Rank	Area (km^2)	Length (km)	Mean grad. (%)	Tributaries	Rank	Area (km^2)	Length (km)	Mean grad. (%)
DZR	1st	14.8	7.2	22.3	MQR	1st	13.2	6.3	23.5
XZJC	2nd	2	2.9	25.9	SLGC	2nd	0.8	1.8	37.8
SZJC	2nd	2.5	3.2	26.3	SJSC	2nd	2.5	3.1	26.3
DLKC	2nd	1.8	3.4	40	BLC	3rd	0.6	1.7	38.2
PYC	2nd	0.7	1.4	44.3	DDC	3rd	2.1	2.4	31.1
MZSC	2nd	4.3	3.4	33.8	MZSC	3rd	0.9	1.8	32.7
DC	3rd	0.7	1	38	MSAC	3rd	2.2	2.7	29.7
SJYC	3rd	0.9	1.9	36.8	MZC	3rd	0.7	1.5	48.7
XYC	3rd	0.7	1.8	41.1	DHC	3rd	2.7	3.4	27.7
CJLC	3rd	0.2	0.7	34.3					

The mean bed gradient of a ditch refers to the percentage of the height difference visa horizontal distance between two points. The locations of the tributaries are shown in Fig. 2

Fig. 3 Longitudinal profiles of Menqian and Duozhao ravines. The position (3,243E−2,048N) refers to the local east and north coordinate system in the Fig. 2

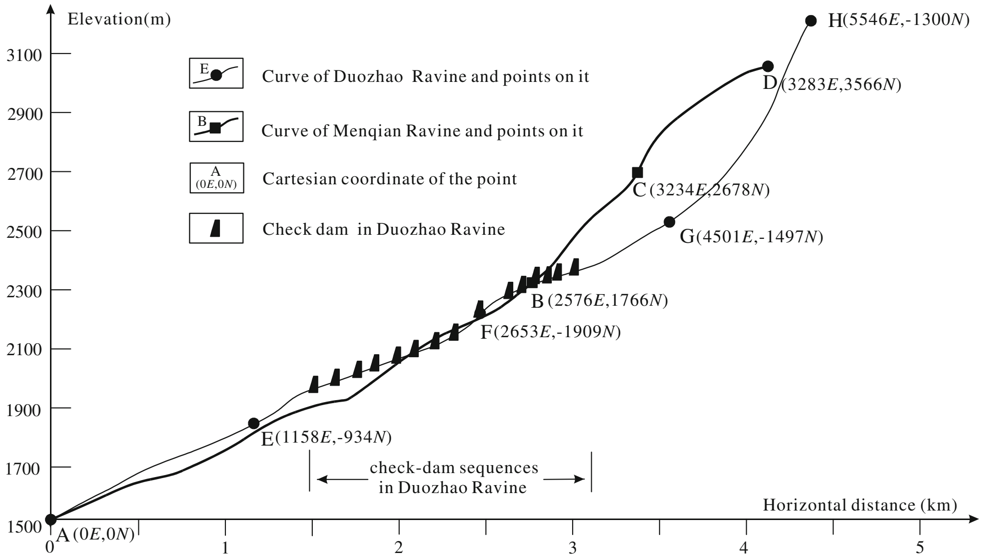


Fig. 4 Site photographs showing sequence of pointed random rubble check-dams in good condition in the debris-flow channels in Duozhao. **a** Check-dams in Daqishu channel, position (3,240E−2,050N); **b** check-dams in Dasha channel, position (3,340E−1,310N)

Fig. 5 Site photographs showing two broken check-dams in upstream of Duozhao ravine. **a** Broken check-dam in Xiaoya channel, position (3,140E−380N), by the impact of dolomite blocks from upstreams; (**b**) broken check-dam in Daqishu channel, position (2,350E−580N), by the abrasion of debris flow

sequence at good conditions. The locations where the photographs in Fig. 4a and b were taken are marked in Fig. 2. Furthermore, local farmers constructed seven mortared masonry check-dams in the Dasha channel in 1985, as shown in Figs. 2 and 4b.

The check-dams are 3–6 m high, 2 m deep in foundation, 0.8–1.2 m wide on the top surface, 1:0.2 for the gradient of the dam downstream slope, and steeper in the dam upstream slope. Some check-dams have wings and weirs while others do not have.

When a field investigation was carried out in 1984, it was found that six check-dams were destroyed and seven check-dams were seriously damaged (Wu 1990). An example of the destroyed check-dam is shown in Fig. 5a. During the present field investigation in 2004, it was found that other two check-dams on the Daqishu channel were broken. One of the two broken check-dams is shown in Fig. 5b. Figure 2 shows the locations of the two broken check-dams in Fig. 5a and b.

Key question and methodology

Key question

Many debris flows had occurred in Jiangjia stream each year over the last 25 years. Therefore, the following key question can be asked:

- What is the performance of the check-dams constructed 25 years ago in the Duozhao catchment in terms of soil erosion mitigation and debris flow prevention although some of the check-dams were destroyed or damaged?

This question can be answered because of the Menqian catchment where no check-dams were constructed. Logically, a methodology is developed to answer the question by comparing the geomorphologic features of the two catchments.

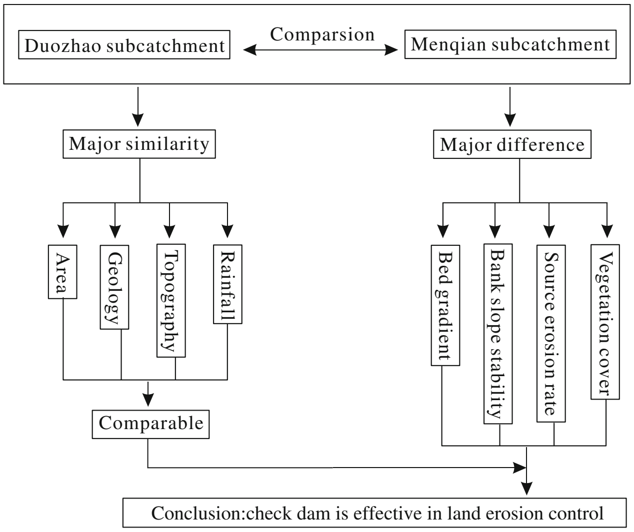


Fig. 6 Approach for present investigation of the long-term performances of the check-dams in Jiangjia stream

Methodology

Figure 6 shows a flow chart of the methodology for the investigation of the long-term performance of the check-dams in erosion mitigation in the Duozhao catchment. Table 2 shows a summary of the streambed gradients, channel lengths and plane areas for the Duozhao ravine, the Menqian ravines, and their tributaries. Figure 3 shows a comparison between the longitudinal profiles of the Duozhao and Menqian ravines. Figure 1 of ESM shows a comparison between the cross-sectional profiles of the Duozhao and Menqian ravines passing through the three points I, J and K. The exact locations of the points I, J and K are shown in Fig. 2. A detailed summary of the comparisons between the two catchments is further given in Table 3.

As shown in Table 3 and Fig. 6, the two adjacent catchments are very similar in size, geological condition, topography and rainfall. On the other hand, the two adjacent

Table 3 Summary of comparisons between Menqian and Duozhao ravines

		Comparative objects				
Comparative items		Menqian catchment	Duozhao catchment	Results of comparison		Remarks
Area (km^2)		13.2	14.8	1.2 km^2 Difference		The two adjacent catchments, Menqian and Duozhao catchments, are very similar in area, geology, topography and rainfall
Geology	Stratum component	Slate (97%) + Dolomite (3%)	Slate (80%) + Dolomite (15%) + Pleistocene debris (5%)	80% Similar in slate	80% Similar in loose and fractured slate	
	Structure of rock mass	Slate: loose and fractured; dolomite: fractured	Slate: loose and fractured; dolomite: fractured; debris: loose	Fractured and loose		
Topography	Tributary debris ditch number	8	9	1 Ditch difference	Little difference	
	Channel length Difference	15.3 km	18.4 km	3.1 km		
Mean bed gradient	22.3%	23.5%	Almost the same			
Rainfall	Annual rainfall (elevations between 1,500 and 2,200 m)	700–850 mm		The rainfall data are the averages for years in Jiangjia Stream by the Station (Wu 1990). It is assumed that the rainfalls in the two catchments are the same for they are adjacent		
	Annual rainfall (elevations between 2,200 and 3,200 m)	850–1,200 mm				
	Rainfall intensity (elevations between 1,500 and 2,200 m)	(54–58 mm/day)				
	Rainfall intensity (elevations between 2,200 and 3,200 m)	(58–65 mm/day)				
Tributary bed gradient		Severe downward cutting and becoming higher	Becoming lower	Steeper in Menqian catchment than in Duozhao catchment		There are remarkable differences between these two adjacent catchments in tributary bed gradient, bank slope stability, erosion rate and vegetation covering in bank slopes
Bank slope stability		Unstable, landslide and collapse and rock fall occur frequently	Basically stable and landslide stopping movement	More unstable in Menqian catchment than in Duozhao catchment		
Erosion rate		Fast, 2.2 m/year in average	Slow, 0.3 m/year in average	Faster in Menqian catchment than in Duozhao catchment		
Vegetation cover in bank slopes		Decreasing	Increasing	Fast destructed in Menqian catchment while slowly growing in Duozhao catchment		
Conclusion: check-dam is an effective structure against soil erosion due to debris flow						

catchments have major differences in the following aspects: bed gradient of channel, bank slope stability, soil erosion rate and vegetation covering on bank slope. Consequently, the following two assumptions may be made:

(a) The two catchments had the similar conditions before the construction of the check-dams in the Duozhao catchment about 25 years ago;
(b) The major differences in the bed gradient, banks slope stability, soil erosion rate and vegetation coverage on bank slopes are mainly due to the differences that there were 51 check-dams in the Duozhao catchment but no check-dams in the Menqian catchment for the last 25 years.

The above two assumptions can be justified due to the facts that:

- the two adjacent catchments were very similar in geological, topographic, and environment conditions;
- the major differences are geomorphologic features and caused mainly due to the differences in surface erosion; and
- the main function of the check-dams was to reduce surface erosions.

Therefore, the long-term field performance of the check-dams can be examined and identified through a detailed comparison between the geomorphologic features of the two catchments. Special field investigations were carried out in April and May 2004 in the two catchments to examine their similarities and differences. Previous investigation records reported in the literature in Chinese are also examined. In addition, an interpretation of aerial photographs taken over the two catchments at different time periods was conducted for the comparison. Details of the examinations are given below.

Long-term performances of check-dams

Bed gradient

The bed gradient of stream or channel is an important index of the topography of a debris flow catchment. It affects the energy level and the hazard potential of debris flows. The bed gradient of a channel is calculated using the percentage ratio of the elevation difference between two locations along the channel over the horizontal distance between the selected two locations.

Reduction of bed gradients above check-dams

Based on the data in Wu (1990) and the present field investigation, it has been found that remarkable changes had taken place in the bed gradients of the channels before and after construction of the check-dams in Duozhao catchment.

Figure 7 shows the percentage bed gradients of seven channels in the Duozhao catchment in 1970s and 1984 before and after the construction of the check-dams, respectively (Wu 1990). The channel bed gradient above each check-dam became gentle and was about 27.3% reduction of the original bed gradient. It is noted that the captured sediments above the catch dams were about 146,000 m^3 in total and were about 17.5% of the annual debris supply from the Duozhao catchment into the Jiangjia stream.

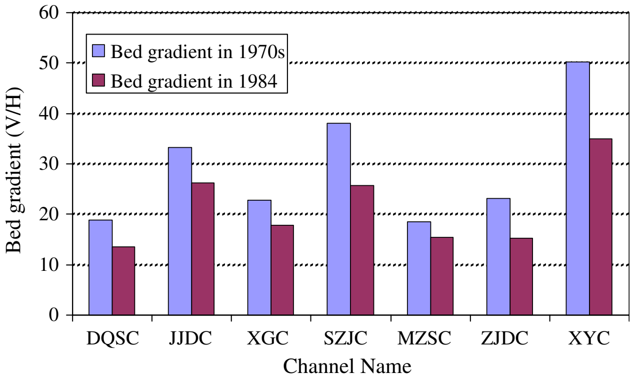


Fig. 7 Comparison of bed gradients in 1970s before and in 1984 after the construction of the pointed check-dams in middle stream of Duozhao ravine (after Wu 1990). The channel names are given in Table 2 and Fig. 2

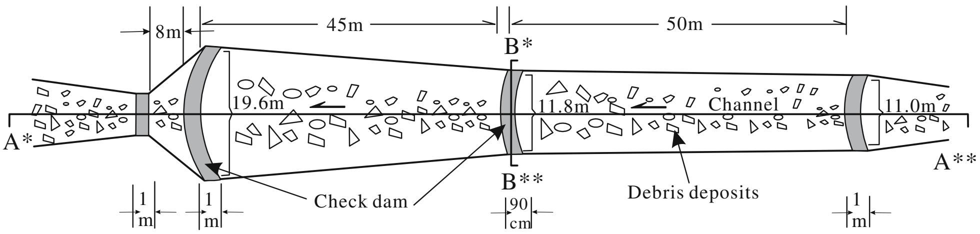
Backfilling of check-dams in series

Figure 8 illustrates the plan, lateral and front profiles of three typical check-dams in series along Dasha channel in Duozhao catchment measured during the present field investigation. From Fig. 8, it can be observed that the sediments were captured above each of the three check-dams in series. Consequently, the bed gradients were reduced. Moreover, the three check-dams could reduce the flow velocity and increase the channel roughness. The concavity at the top centre of each check-dam could restrict the flow direction of the small-scale debris and water, which accordingly could limit the widening and downward cutting of the channel below the check-dam.

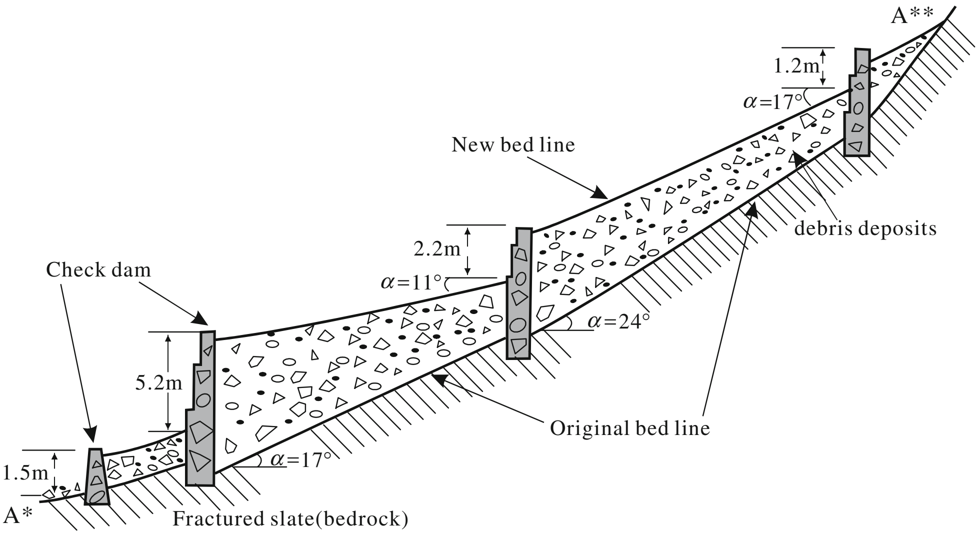
Bed gradient reduction along the Duozhao ravine

As shown in Tables 2 and 3, the overall bed gradients of the channels in the Duozhao catchments are similar to those in the Menqian catchment. However, the local regions, where the check-dams were constructed and

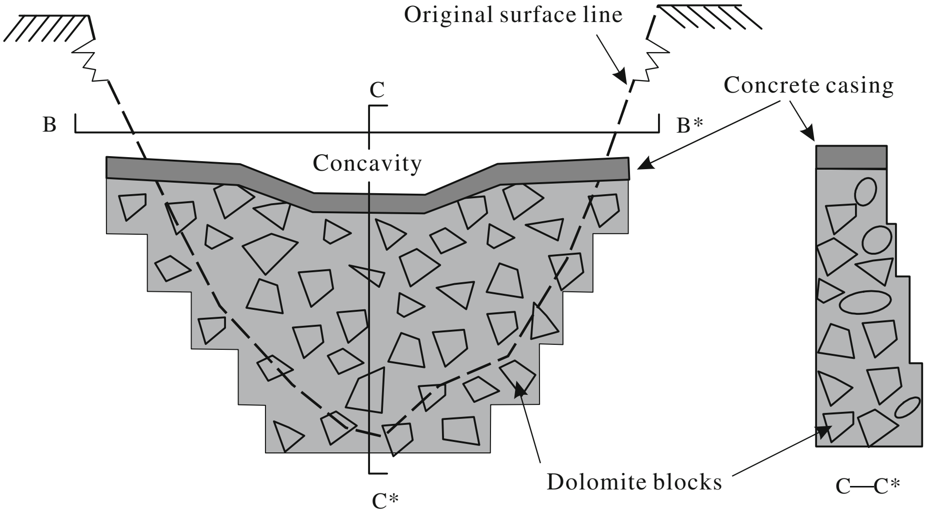
Fig. 8 Typical design of check-dams in sequences in Dasha ravine, position (3,340E−1,310N)



a Plane view of the four check-dams in sequence



b Longitudinal profile of the four check-dams in sequence



c Cross and longitudinal profiles of a check-dam

functioned, have their bed gradients generally smaller than other regions where no check-dams were constructed.

Specifically, as shown in Fig. 3, the Duozhao ravine is slightly longer and higher than the Menqian ravine. The overall bed gradients of the two ravines are almost the same. The bed gradients of the two ravines from the original point A to 4 km upstream are similar and gentle although the Menqian ravine has local bed zones with higher gradients. The Menqian ravine has its bed gradient sharply increase after the point B. The Duozhao ravine has its bed gradient sharply increase after the point G. The steep bed slope in the upper regions of the Duozhao and Menqian ravines are mainly due to the presence of dolomites which have strong resistance to erosion. The middle region of the Duozhao ravine where the check-dams were constructed has the gentler bed gradients.

Figure 9 shows an example of the seriously periodic downward cutting in the channel of the Menqian ravine. The position where the photograph in Fig. 9 was taken in 2004 is marked on Fig. 2. From Fig. 9, it is evident that there were at least three erosion levels. The channel was cut into the old debris flow deposits forming the channel bed. The total cutting depth was about 5–8 m. Figure 2 of ESM shows a typical example of the details of the steep bank slope profiles.

Bank slope stability

Over the last 25 years, the check-dams have performed well in protecting and stabilizing the bank slopes on both sides of the debris flow streams above the check-dams.

Bank slopes of streams without check-dams

The present investigation has found that the bank slopes on the debris flow streams where no check-dams were constructed have their slope angles about 35° to 60° and are comprised of fractured rocks or old debris flow deposits. The two bank slopes normally form a V-shape valley. Normally no mature trees could be found living on these bank slopes. These phenomena may have indicated that the channel beds have been experiencing downward cutting and their bank slopes have been experiencing retrogressive instabilities and landslides. Figure 3 of ESM illustrates the evolution process of a typical channel where the bed cutting and retrogressive bank slope instability continued happening along a section of the upstream channel of the Menqian ravine.

Fig. 9 Site photograph showing fast cutting and severe erosion in Menqian ravine, position (1,660E, 1,280N)

As shown in Fig. 3a of ESM, the channel was in V-shape and its bed comprised of fractured slates. The bank slopes were at a state of equilibrium (say, the FOS is equal or slightly greater than 1.0). Vegetations and small trees could grow on the bank slopes. Subsequently, the channel bed was further cut by water and debris flows. A new channel bed was formed as shown in Fig. 3b of ESM. As a result, the bank slopes became unstable with FOS is less or equal to 1.0 and slope failures occurred, as shown in Fig. 3c of ESM. The soils and rocks together with the vegetations and trees on the slope also slipped down and deposited on the channel bed temporally. The bank slopes became marginally stable after the failures. New stream water or debris flows would wash and carry away the debris deposits on the channel bed. Consequently, a new clear channel bed comprising the fractured slate would be exposed and experience further cutting by water and debris flows (Fig. 3d of ESM). Such retrogressive failure process of the bank slopes can continued and cause non-stopped soil erosion. A typical example of the actual bank slopes experiencing retrogressive slope failures is shown in Fig. 3e of ESM.

Figure 10 shows the two aerial photographs taken in 1967 and 1991 respectively on the upstream area of the Sanjiacun channel in the Menqian catchment. The aerial photograph interpretation indicates that the soil erosion degree of the upstream area can be identified into three zones: strong erosion zone (SEZ), high erosion zone (HEZ) and weak erosion zone (WEZ). Comparing the two aerial photographs, it can be observed that the bank slopes of the Sanjiacun channel had experienced significant enlargements due to strong erosions over the 24 years.

Bank slopes of streams with check-dams

As discussed above, debris flow activities have been extremely active in the valleys and streams. It was reported that the reservoir spaces above the check-dams were completely filled with debris flow deposits two years after the construction of the check-dams, except those destroyed check-dams (Wu 1990). An example of the occupation of filling and keeping of debris flow deposits into the check-dam reservoir spaces is shown in Fig. 8. Consequently, the original channel beds were covered and protected by the deposits above the check-dams, which made it impossible for water or debris flows to further downward cutting into the original bed. Moreover, the toes of the bank slopes were also covered and protected by the deposits, which in turn has shortened the bank slope heights, had reduced the bank slope angle, and increased substantially the bank slope stabilities. The present field investigation has found many mature trees, grass and brushes living in the bank slopes above the channels protected by check-dams and the deposits. Figure 4 of ESM shows the evolution process of a channel bed and its bank slopes before and after the construction of a check-dam.

It was reported that the Meizishu and Daqishu streams were the main source areas for debris flows in the Duozhao catchment (Wu 1990). A check-dam was constructed in the Meizishu channel, as shown in Fig. 11. It is 6 m high and 22 m long. The present investigation has found that the height of the debris flow deposits restored above the check-dam was about 6.5 m. The length of the deposits was about 523 m along the channel bed above the check-dam. The channel bed gradient decreased from the original 18.6% to the present 15.5% over the 523 m long section. The restored deposits were estimated to be 61,000 m^3. Moreover, the restored deposits blocked and stabilized the further movement of an old landslide. The entire bank slopes have been covered with dense forests as shown in Fig. 11b.

Twenty mortar masonry check-dams in series were constructed in the Daqishu stream. The check-dams have successfully eliminated the undermining and widening of the channel bed and resulted in the stable bank slopes composing of old debris-flow deposits. As shown in Fig. 4a, vegetations, brushes and trees are growing well in the channel bed and the bank slopes. It seems that debris flows had not occurred in the stream for many years.

Soil erosion rate

According to the statistic data of field survey by Yang (1997), 60% of total solid materials of debris-flow in Jiangjia stream are from Menqian watershed, while only 30% from Duozhao watershed.

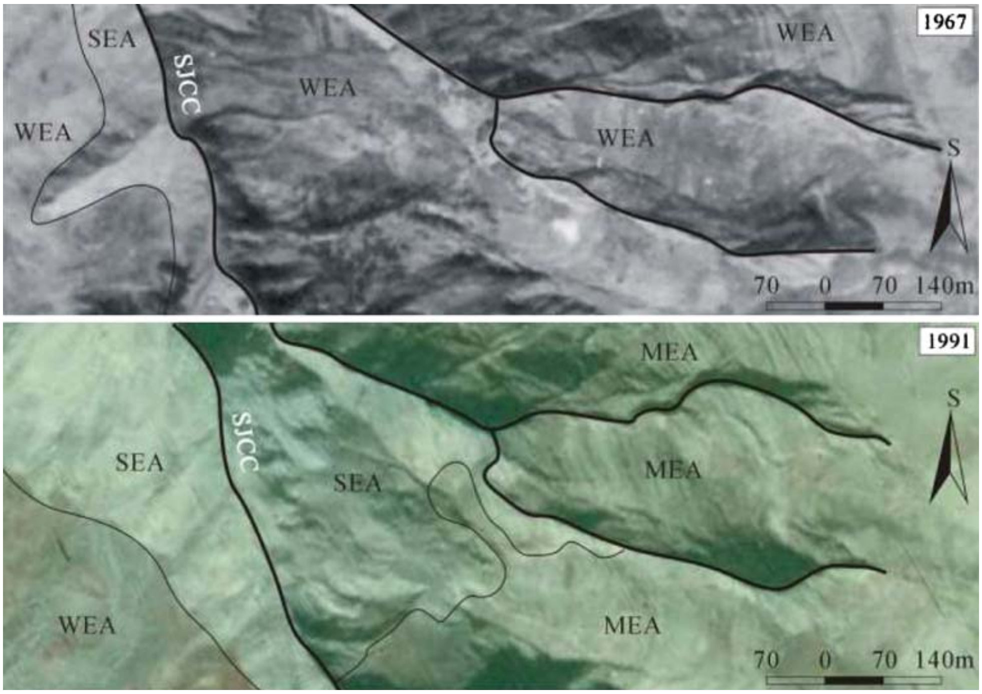


Fig. 10 Comparison of erosion areas showing in aerial photographs on 1967 and 1991 in Sanjiacun channel (*SJCC*), position (1,580E, 2,330N), in upper Menqian Ravine. SEA, MEA and WEA refer to the strong, middle and weak erosion areas, respectively

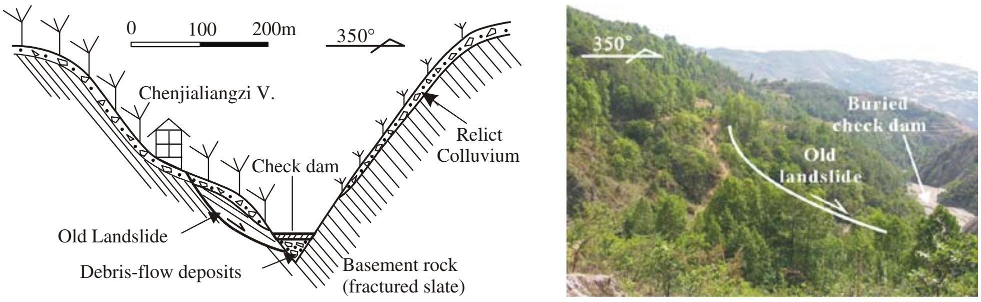


Fig. 11 Cross-section of the bank slopes with a check-dam against an old landslide in Meizishu channel, position (2,560E–670N), near Chenjialiangzi village

Solid contents in water

Figure 12 shows the site photographs taken on 16 November 2002 and on 30 April 2004, respectively. The location of the site photographs is the junction of the Menqian stream and the Duozhao stream merging into the Jiangjia stream (Fig. 12a). Figure 12b shows two different water streams flowing down on 16 November 2002. One water stream was from the Menqian ravine and the other was from the Duozhao ravine. Figure 12c shows the two water streams flowing down on 30 April 2004. It is evident that the water flowing down from the Menqian ravine was turbid while the water flowing down from the Duozhao ravine was clean. The water in the Menqian ravine had much more solid contents than that in the Duozhao ravine. This observation may have shown that the Menqian catchment had severer soil erosion than the Duozhao catchment.

Moreover, three bottles of water samples were taken near the junction of the two ravines on 30 April 2004. The analytical result indicates that the water sample from the Menqian ravine had 0.5% clastic materials by weight. The water sample from the Duozhao ravine had almost zero clastic materials. The water sample from the Jiangjia stream stream had 0.6% clastic materials in weight. Again, the water from Menqian ravine had much more solid particles than the water from Duozhao ravine, which may have shown that Menqian catchment had severer soil erosion than Duozhao catchment.

Comparison of surface erosion rates in the upstream areas

Severe slope surface erosions have also occurred in the upstream areas of the Menqian and Duozhao ravines. Aerial photographs taken in 1967 and 1991 are used to illustrate the surface erosions and to compare the differences in the erosion rates of the two ravines. Figure 5 of ESM shows the 1967 and 1991 aerial photographs in Dahei channel in the Menqian upstream area. More channels can be observed on the 1991 photograph. Figure 13 shows the 1967 and 1991 aerial photographs in Mashanao channel in the Menqian upstream area. The eroded area in the 1991 photograph can be observed much closer to the road. Figure 6 of ESM shows the 1967 and 1991 aerial photographs in Jianjiaodi channel in the Duozhao upstream area. The 1991 photograph has less barren areas than the 1967 photograph, which indicates a slower erosion rate. Furthermore, the erosion distances and rates over the 24 years are estimated from each pair of the photographs in Fig. 13, Figs. 5 and 6 of ESM. The results are given in Table 4. From Table 4, it is evident that the erosion rates in Menqian upstream areas are greatly higher than those in Duozhao upstream areas.

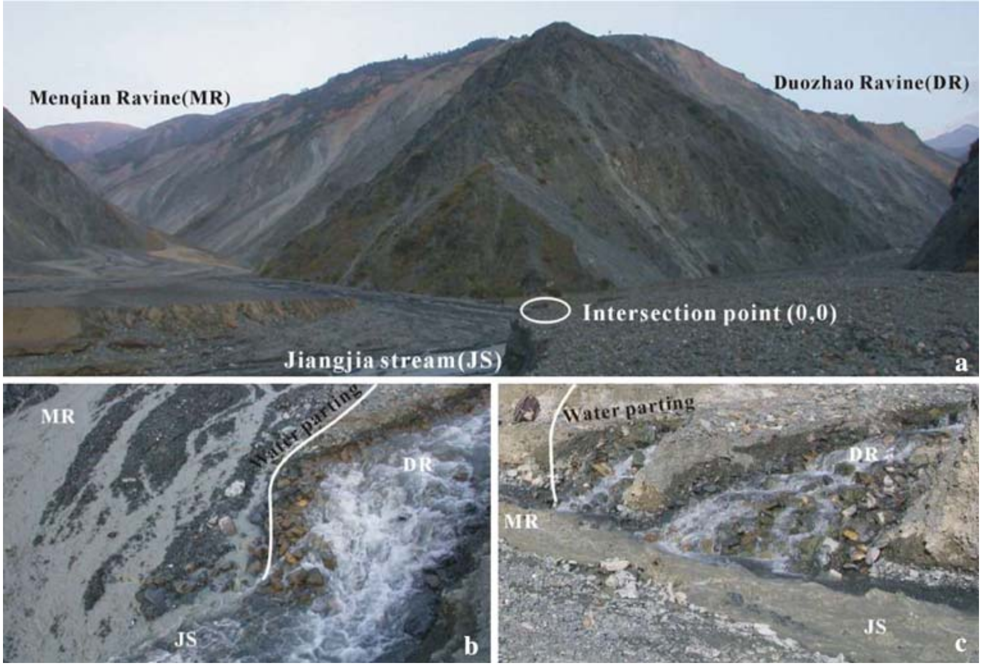


Fig. 12 Comparison in water flows from Menqian and Duozhao ravines. **a** Site photograph showing intersection area of Menqian and Duozhao ravines in Jiangjia stream; **b** site photograph showing the mud water flow from Menqian ravine and the clean water flow from Duozhao ravine, position A (0E, 0N) on 16 November 2002; **c** site photograph showing the junction of mud water flow from Menqian ravine with the clean water flow from Duozhao ravine, position A (0E, 0N) on 2 May 2004

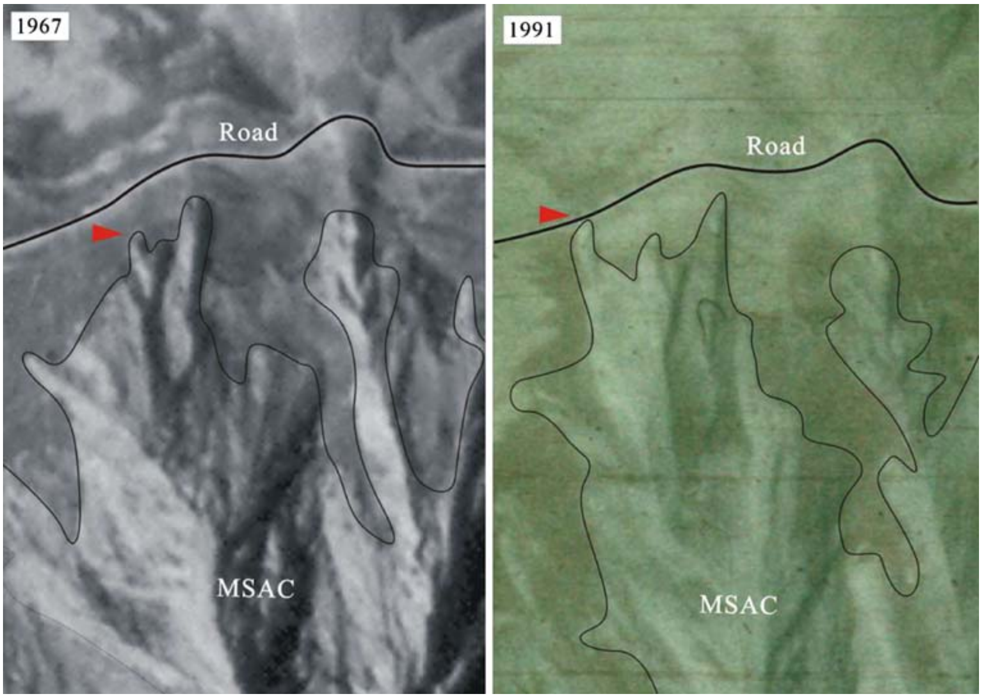


Fig. 13 Aerial photographs in 1967 (**a**) and 1991 (**b**) for fast erosion rate in Mashanao channel (*MSAC*), position (3,650E, 3,150N), upstream of Menqian

Table 4 Surface erosion rates on the upstream areas of Menqian and Duozhao ravines

Area	Menqian				Duozhao
Reference mark for calculation	Dahei Road	Mashanao Road	Mizhishan road and house	Pingzidi road	Jianjiaodi road
Eroded distance (m) from 1967 to 1991	65–70	45–50	35–40	65–70	5–10
Overall erosion rate (m/year) from 1967 to 1991	2.7	1.9	1.5	2.7	0.3

Comparison of erosion amounts

As shown in Fig. 2, the check-dams were concentrated within the middle stream (i.e., Meizishu and Daqishu channels) of Duozhao ravine. Therefore, the lower and upstream areas can be the source areas for offering rich debris so that debris flows can still occur in Duozhao ravine. Yang (1997) reported that the annual sediment transportations in 1979 from Menqian and Duozhao contributed respectively about 60 and 30% of the total sediments in Jiangjia stream.

Furthermore, the field investigation and the annual data of sediment transportations in Jiangjia stream from 1965 to 1998 has indicated that the proportion of sediments from Duozhao have greatly decreased since the construction of the check-dams (Wang et al. 2000 and Fig. 14). The amount of sediments from Duozhao is much less that that from Menqian.

Slope vegetation coverage

Slope vegetation coverage can be used as an index to evaluate the function of the check-dams. A slope has to be stable for a long time for its slope surface to be covered with grass and trees (GEO 1994). The higher the vegetation and tree coverage on a slope, the longer the slope stable, and the higher the Factor of Safety (FOS, which means the ratio of theoretical sliding force on a sliding plane to actual sliding force, simplified as FOS) of that slope.

Table 5 gives the percentages of the vegetation coverages in Menqian and Duozhao upstream areas in 1967 and 1991. The data in Table 5 indicate that from 1967 to 1991, the percentage of the vegetation coverage in Sanjiacun channel (SJCC) decreased from 46.1 to 16.9%, and the percentage in Mashan'ao channel (MSAC) decreased from 36.2 to 27.4%. However, the percentage of vegetation

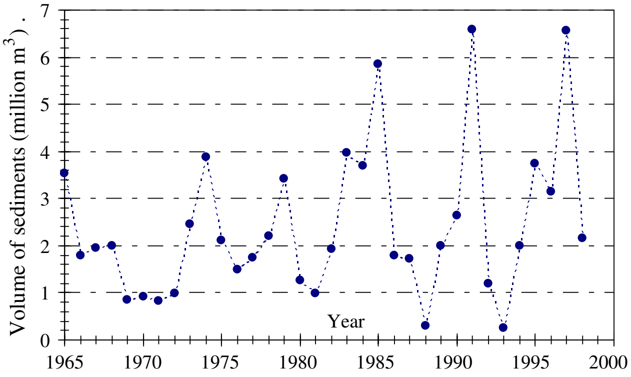


Fig. 14 Annual volume of sediments of debris flows in Jiangjia stream from 1965 to 1998 (after Wang et al. 2000)

Table 5 Percentage of slope vegetation coverage on the upstream areas of Menqian and Duozhao ravines in 1967 and 1991

Year area	Percentage of slope vegetation coverage (%)							
	SJCC (Fig. 10)			MSAC (Fig. 13)			JJDC (Fig. 6 of ESM)	
	SEZ	HEZ	WEZ	SEZ	HEZ	WEZ	SEZ + HEZ	WEZ
1967	53.9		46.1	45.8	18.0	36.2	36.4	63.6
1991	48.1	37.0	14.9	50.3	22.4	27.4	13.0	87.0

The SEZ, HEZ and WEZ refer to the serious erosion zone, high erosion zone and weak erosion zone, respectively

coverage in Jianjiaodi channel (JJDC) of the Duozhao increased from 63.6 to 87.0% over the 24 years.

The present site inspections in 2002 and 2004 further show that Duozhao has a much higher percentage of areas with good vegetation cover than Menqian, as shown in Figs. 4, 5, 9, 11, Figs. 3c and 4 of ESM.

Summary and conclusions

In the above, the authors have presented the investigation results of the 25 years field performance of the 51 pointed random rubble check-dams in Jiangjia stream with respect to their function in erosion prevention. The investigation results are presented with the comparisons of the Duozhao and Menqian catchments in the following four aspects: bed gradient, bank slope stability, surface erosion rate and vegetation coverage. The two catchments are the main catchments in Jiangjia stream where numerous events of large debris flows have happened.

Menqian ravine does not have any check-dams and other erosion structures. The strong erosion has deepened the ravine base level and made the bed gradient steeper. Its bank slopes have become more and more unstable and suffered severe slips and collapses over the time. Villages and plants could not grow well on the bank slopes. More and more slope areas have not been covered with vegetations.

On the other hand, Duozhao ravine has a series of check-dams in the middle channel area to prevent its bed from further erosion since 1979. The bed gradient has become gentler due to permanent deposits of debris above each of the check-dams. The deposits have also stabilized the bank slopes from failure. Vegetation has significantly restored on the bank slopes and the amount of debris sediments has been reduced greatly.

Over the 25 years performance, the check-dams have been effective and played an important role in the erosion mitigation. They have effectively uplifted the base level of erosion along debris-flow channel bed. They have reduced the bed gradient and slowed down the debris-flow velocity and dissipated the flow energy accordingly. They have protected the channel bed and bank slopes, and stabilized the slopes and facilitated the growth of the vegetations.

The 25 years good performance of the 44 check-dams has also demonstrated that the design and construction of the random rubble check-dams with cement mortar pointing are adequate although eight of them were destroyed by debris flows over the years. Dry packed random rubble check-dams can be easily destroyed by debris flows. Check-dams made of local random rubble stones pointed with cement mortar are a cost effective measure in preventing soil erosion and occurrence of debris flow events.

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