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Effectiveness and efficiency of slot-check dam system on debris flow control

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Abstract

Slot-check dam system is commonly used to control sediment transport associated with debris flows and mitigate debris flow hazards. This paper aims to estimate the performance of the slot-check dam system in the field and set up a verification to evaluate the efficiency of a slot-check dam system and each subsystem in debris flow sediment control. Field survey on a group of a series of slot-check dams at Shengou Basin in Yunnan, China reveals that the conserving sediment volume of each dam is related to its relative location in the group, gradually decreasing from upstream to downstream. The cumulative sediment volume within a subsystem of slot-check dams closely related to the characteristics of the catchment controlled by the subsystem. It increases with the controlled catchment area of the most downstream dam in subsystem and the distance from the dam to the upstream most. Evaluation models for the conserving efficiency of a slot-check dam system on debris flow control in a river basin and each subsystem within the group associate to the controlled catchment characteristics have been proposed. The layout principle of a slot-check dam system in a river basin has been developed based on the conserving efficiency of a subsystem of slot-check dams which would allow the slot-check dam system to be designed in a more scientific way.

1 Introduction

Debris flows are widely recognized as one of the dominant geomorphic processes in steep mountainous terrain (Remaître and Malet, 2010). Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction. They can travel long distances in channels with modest slopes and to inundate vast areas. Large debris flows can exceed 10^9 m^3 in volume and release more that 10^{16} J of potential energy, but even commonplace flow of $\sim 10^3$ m^3 can denude vegetation, clog drainage-ways, damage structures and endanger humans (Iverson, 1997).

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One of the most effective techniques to manage debris-flow hazards is to construct series of check dams (Takahashi, 1981; Remaître and Malet, 2010; Chen et al., 2013; Fiebiger, 1997; Heumader, 2000; Huebl and Fiebiger, 2005; Hungr et al., 1987; Mizuyama, 2008). They play an important role in the management and development of a river basin (Busnelli et al., 2001). One of their most common functions is to enhance sediment deposition, reducing the bed gradient and flow velocity in order to check soil erosion within a stream, such as a gully (Castillo et al., 2014).

Two kinds of check dams can be distinguished: closed and open (Busnelli et al., 2001; Li, 1997; Catella et al., 2005). Conventional closed check dams are overflowed by the water discharge and intercept all but the fine particles of the solid material. Hence they are rapidly filled up by the sediment transport. Conversely, open check dams are constructed with suitable openings in the body of the structure, thus part of the sediment is allowed to pass through (Busnelli et al., 2001). Slot-check dam, an open-type check dam with slot shaped openings, has been shown to be efficient in reducing debris flow run-out (Remaître et al., 2008; Jia et al., 2011). If the opening slots of the check dam are large enough, deposition upstream the check dam during ordinary events is negligible, its storage capacity is left available for the very large debris flows (Busnelli et al., 2001; Chen et al., 2013; Li, 1997).

Considerable theoretical and numerical works have been performed on the size, shape and structure of torrential check dams, allowing the definition of general design criteria (Remaître and Malet, 2010; Armanini and Larcher, 2001; Han and Ou, 2004; Jia et al., 2011; Johnson and McCuen, 1989; Lien, 2003; Li, 1997; Catella et al., 2005; Shrestha et al., 2008). Some researchers studied the river bed variations after check dam system construction (Conesa-García et al., 2007; Xu et al., 2004; Zimmermann and Church, 2001). Less research has focused on the optimal number and location of these dams along the debris-flow track (Osti and Egashira, 2008; Hassanli et al., 2009; Remaître and Malet, 2010) as well as the quantitative evaluation on slot-check dam system efficiency in sediment control in the field (Remaître and Malet, 2010). Preliminary study on the efficiency of the subsystem in a slot-check dam group has been

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proposed (Zou et al., 2014). In the study, a new way for the analysis on the efficiency of a slot-check dam group was provided. The conserving efficiency of the subsystem within a slot-dam group was associated with catchment shape characteristics. But it was only focused on the contribution of a subsystem to the whole slot-check dam group. The efficiency of the single slot-check dam and the efficiency of the whole slot-check dam system and its subsystem on the sediment control in a river basin were not evaluated. And it is important that more related catchment characteristics associated with sediment erosion and dam parameters should be considered in the efficiency evaluation. Principle on the layout of a slot-check dam system in a debris flow river basin is also needed to be proposed for the mitigation of debris flow hazards.

This paper is aimed at evaluating the efficiency of the slot-check dam system and its subsystem in sediment control for the river basin. A quantitative method is proposed for estimating the efficiency of slot-check dam system in debris flow hazards mitigation. The layout principle of a slot-check dam system in a river basin is analyzed based on the efficiency of a subsystem of slot-check dams on sediment control.

2 Study area

The study area is Shengou Basin in Dongchuan district, Kunming in China. Shengou Basin is a tributary of the right bank of Xiaojiang River, and a typical debris-flow gully in the mountainous regions of southwestern China (Fig. 1). It covers an area of about 32 km^2 and is located in the northeastern Dongchuan district, extending 103°09′07″–103°15′00″ E and 26°04′47″–26°09′03″ N. The basic parameters of Shengou Basin are listed in Table 1.

Shengou Basin pertains to a subtropical monsoon climate zone with distinct dry and wet seasons, vertical zoning and regional heavy rainstorm. It has an annual rainfall 600–1200 mm in the river valley and 700 mm in the alpine region. The precipitation in the rainy season from May to October accounts for 88 % of total annual precipitation. Rainstorm and rain shower accounted for above half of the total annual precipitation.

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The centers of rainstorms mainly occurred at the zone from 2500 to 3000 m in the river basin. The annual rate of rainstorm is 0.8–1.5 times per year, maximum rainfall intensity reached 123.6 mm in 24 h, 63.4 mm in 1 h and 20.8 mm in 10 min.

The water discharge in the river trench is about 0.5 $m^3 s^{-1}$. Water level would suddenly arise if rainstorm occurs and the flow discharge could be large than 100 $m^3 s^{-1}$. The peak discharge of flood with return year of 50 years is 169.2 $m^3 s^{-1}$. Debris flows would properly occur in the rivers under the rainstorm with return year of 10 years.

Debris flows threaten the safety of more than 12 000 people living in Shengou Basin. The outburst of debris flow may damage the highway and railway at the downstream area and block Dabai river which Shengou river flows into. In order to control sediment transport and mitigate debris flow hazards, a slot-check dam group with a series of five dams had been built in 2010 at the upper region of Shengou Basin (Figs. 1 and 2). The main characteristics of the slot-check dams are listed in Table 2.

3 Methodology

This research aims to assess the effectiveness of the chain of check-dams and a individual check dam through field survey and analytical study. Field survey had been conducted to investigate the performance of the slot-check dams. The effectiveness of the series of slot-check dams in sediment control has been verified from its stability resistant to the impact of debris flows, soil conservation function and downstream erosion prevention. The efficiency to assess the function of the mitigation project has been represented by several quantitative evaluation parameters. And the methodology of the derivation of efficiency has been given in the follows.

3.1 Efficiency of the slot-check dam system in sediment control

The efficiency of an individual check dam in the entire chain of check dams $\eta_{\mathrm{d}i}$:

$$\eta_{\mathrm{d}i} = \frac{v_i}{\sum v_n} = \frac{v_i}{V_n}. \tag{1}$$

The efficiency of subsystem in the slot-check dam system η_{subs} is to be established to assess the role of a dam and the subsystem in the whole dam system. It can be represented by the ratio of the accumulated volume of deposit stored within the subsystem $\sum v_i$ to the total sediment volume stored within the dam group $\sum v_n$:

$$\eta_{\mathrm{subs}i} = \frac{\sum v_i}{\sum v_n} = \frac{V_i}{V_n}. \tag{2}$$

The efficiency of a slot-check dam system in mitigating debris flow η_{sys} is to be established to assess the role of the dam system in mitigating debris flow and sediment control at the river basin. It can be represented by the ratio of the volume of sediment stored within the storage of the dam group $\sum v_i$ to the possible surface erosion volume of the region V_0:

$$\eta_{\mathrm{sys}i} = \frac{\sum v_i}{V_0} = \frac{V_i}{V_0}. \tag{3}$$

Since the sediment volume in the river basin is related to the characteristics of the catchment area and the rainfall factor in the area, the possible surface erosion volume of the region can be calculated as:

$$V_0 = f(R_\mathrm{a}, \Delta_p) \tag{4}$$

where R_a is the rainfall factor of debris flow in the river basin,

$$R_\mathrm{a} = \frac{nI_\mathrm{r}}{I_\mathrm{a}} \tag{5}$$

where I_r is the critical rainstorm intensity per 24 h that induced debris flow in the river basin, n is the frequency of the related rainstorm, I_a is the average annual rainfall intensity per 24 h, and Δ_p is the sediment volume base according to the characteristics of the catchment area,

$$\Delta_p = \alpha_0 A_0 L_0 \tag{6}$$

where α_0 is the shape factor, that is associated with the erosion ability of debris flows in the river basin,

$$\alpha_0 = \frac{A_0}{L_0^2} \tag{7}$$

$$V_0 = \lambda R_a \alpha_0 A_0 L_0 \tag{8}$$

where λ is the volume coefficient, that is a dimensionless parameter. Substitute Eq. (7) into Eq. (8) then,

$$V_0 = \lambda R_a \frac{A_0^2}{L_0}. \tag{9}$$

Intuitively, the cumulative sediment volume stored upstream each dam is related to the characteristics of the catchment area, the rainfall factor in the area R_a and the geometry of the opening slots of dam M_d:

$$V_i = f(R_a, \Delta_{pi}, M_{di}) \tag{10}$$

where

$$\Delta_{pi} = \alpha_i A_{ci} L_{ci} \tag{11}$$

$$M_{di} = (1 - \varepsilon_i \varphi_i) \tag{12}$$

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where α_i is the shape coefficient,

$$\alpha_i = \frac{A_{ci}}{L_{ci}^2} \tag{13}$$

$$V_i = \lambda R_a \alpha_i A_{ci} L_{ci} (1 - \varepsilon_i \varphi_i). \tag{14}$$

Substitute Eq. (13) into Eq. (14), then accumulate deposit volume in a subsystem is:

$$V_i = \lambda R_a \frac{A_{ci}^2}{L_{ci}} (1 - \varepsilon_i \varphi_i) \tag{15}$$

where A_{ci} is catchment area controlled by slot-check dam; L_{ci} is distance from the dam to the most upstream point of the region; ε_i is the open rate of the dam; φ_i is the coefficient of transport capacity of the slot-check dam, related to the opening size of the slot of check dam to the representative particle size of debris flow, $0 < \varphi_i < 1$.

Ikeya and Uehara (1980), Mizuyama et al. (1988) and Itoh et al. (2011) studied various types of open-type dams and pointed out that the debris flow will be trapped when the ratio of representative particle size of debris flow to the post spacing is larger than its closure threshold. Here from the experimental tests, we introduce K (Eq. 16) as the closure coefficient of openings in slot-check dam. When $K \geq 1$, sediments of debris flow would filled the small opening slots in the check dam and gradually deposit within the slot-check dam storage. In this condition, almost no discharge through openings of the dam occurs. On the other hand, debris flow discharge from the large slots.

$$K = 2.5 \sqrt{\frac{\gamma}{\gamma_w}} \frac{D_{90}}{b_{\min}} \tag{16}$$

where γ is the density of debris flow; D_{90} is the 90 % particle size of the debris flow; $b_{\min}$ is the minimum width of the opening size.

(i) for small slot ($K \geq 1$):

$$\varphi_i = 0. \tag{17}$$

Substitute Eqs. (17) and (15) into Eq. (2), then the conservation efficiency of a subsystem of dams in the whole system can be calculated as:

$$\eta_{\mathrm{subs}i} = \frac{\sum_{j=1}^{i} A_{\mathrm{c}j}^2 / L_{\mathrm{c}j}}{\sum_{j=1}^{n} A_{\mathrm{c}j}^2 / L_{\mathrm{c}j}}. \tag{18}$$

Substitute Eqs. (17), (9) and (15) into Eq. (3), then the efficiency of the subsystem on erosion control at a river basin:

$$\eta_{\mathrm{sys}i} = \frac{\sum A_{\mathrm{c}i}^2 / L_{\mathrm{c}i}}{A_0^2 / L_0}. \tag{19}$$

(ii) for large slot ($K < 1$):

$$\varphi_i \neq 0. \tag{20}$$

For a stony debris flow,

$$\varphi_i = 0.11 \left(\frac{B_{\min}}{D_{95}} - 1 \right)^{0.36} C_a^{-0.93} \tag{21}$$

where $B_{\min}$ is the minimum space of slots, C_a is the sediment concentration at the peak discharge occurring at the front part of the debris flow and D_{95} is 95 % grain size (Mizuyama et al., 1995).

Substitute Eqs. (21) and (15) into Eq. (2), then the conservation efficiency of a subsystem of dams in the whole system can be calculated as:

$$\eta_{\mathrm{subs}i} = \frac{\sum_{j=1}^{i} A_{\mathrm{c}j}^2 (1 - \varepsilon_j \varphi_j) / L_{\mathrm{c}j}}{\sum_{j=1}^{n} A_{\mathrm{c}j}^2 (1 - \varepsilon_j \varphi_j) / L_{\mathrm{c}j}}. \tag{22}$$

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Substitute Eqs. (21), (9) and (15) into Eq. (3), then the efficiency of the slot-check dam system on erosion control at a river basin:

$$\eta_{\mathrm{sys}i} = \frac{\sum A_{ci}^2 (1-\varepsilon_i \varphi_i)/L_{ci}}{A_0^2/L_0}. \tag{23}$$

3.2 Optimal design of the layout of a slot-check dam system

The optimal layout of the slot-check dam system is essential in the dam system design. Figure 7 shows the outline of slot-check dam system design for debris flow hazard mitigation. The layout could be developed based on the characteristics of the controlled catchment area of the subsystem, storage capacity of a single dam, required total reservation of sediments and the appropriate dam sites. Based on the efficiency evaluation model, the efficiency of the whole designed dam system in sediment control in the basin and a subsystem in the group can be estimated. That can provide a quantitative base for counter calculation and comparison the optimal layouts. Actually, the dam system to be designed in a river basin is not closed but an open system which is just a subsystem for a more extended system. As shown in Fig. 8, after the design or plan of a layout of a system, a new dam system can also be added or inserted into the existed old system without breaking the original arrangement. And the controlled catchment area as well as the distant to upstream most of a subsystem can be calculated as:

$$\begin{cases} A_{c1} = a_1 \\ A_{c2} = a_1 + a_2 \\ A_{c3} = a_1 + a_2 + a_3 \\ A_{ci} = a_1 + a_2 + a_3 + \cdots + a_i = \sum_{j=1}^{i} a_j \\ A_{ci+1} = a_1 + a_2 + a_3 + \cdots + a_i + a_{i+1} = \sum_{j=1}^{i+1} a_j \end{cases} \tag{24}$$

$$\eta_{\mathrm{sys}i+1} = \frac{R_{\mathrm{adesign}} \sum A_{ci}^2 (1-\varepsilon_i \varphi_i)/L_{ci}}{R_{\mathrm{a}} A_0^2/L_0} \tag{25}$$

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where R_{adesign} is the rainfall factor with the designed return year of debris flow.

$$v_{i+1} = V_{i+1} - V_i = \sum v_{i+1} - \sum v_i \tag{26}$$

where v_{i+1} is the storage capacity of the single dam with the number $i+1$ in the dam system.

4 Results and discussion

Field survey had been conducted to investigate the performance of the slot-check dams. The effectiveness of the series of slot-check dams in sediment control has been verified from its stability resistant to the impact of debris flows, soil conservation function and downstream erosion prevention (Fig. 2). Figure 2 shows the performance of the five slot-check dams with a continuous layout from the upstream (Fig. 1) in Shengou Basin. Each slot-check dam had played an effective role in erosion conservation as a certain amount volume of sediments deposited within the storage of each dam. The dams successfully resisted to the impact of debris flows since they were running in good condition without damage in dam body or dam foundation.

The construction of check dams in a gully reach causes a flow perturbation upstream and downstream of each structure. It creates a backwater effect by increasing the water depth immediately upstream of the structure (Castillo et al., 2014). An equilibrium regime of sediment deposit formed upstream each dam after encountering a transient subcritical state due to dam block (Fig. 3).

For dam-filling conditions, a hydraulic jump habitually occurs and a flow drop downstream of the check dam also produces (Castillo et al., 2014). Except for the upstream source, the sediments stored within each couple of check dams mainly come from the bank and the lateral slope on both sides of the gully, rather than from the bed. From the field investigation, the base of each check dam is not exposed. No apparent downstream bed erosion has been observed expect the partial erosion in the preventing rib downstream the first dam (Fig. 4).

Figure 5 shows the sketch of equilibrium deposit within the slot-check dam system. Equilibrium deposits had been blocked and formed upstream each dam. Debris flow sediments with different volume were blocked by the dam at each step and deposited within the dam group. It shows that the sediment conserving function of a dam largely depends on its relative location in the group.

Characteristics of deposits upstream the dams were measured on 29 November 2012 and the efficiency of each dam was estimated (Table 3). From the comparison of the effective height of dam and the deposit height, all five dams are not completely used up with remaining capacity for subsequent sediment conservation. Although the dams have blocked a great amount of sediments, the largest dam efficiency is not more than sixty percent. Since the slope of deposit is slower than the original channel slope (Fig. 3), storage per height at upper layer is larger than that at lower layer in the dam reservior.

The volume of deposit stored within each slot-check dam storage and the accumulated volume of deposits upstream each dam are related to the control catchment area at that point and the distance from the dam to the most upstream point in the catchment (Fig. 6). The volume within the dam storage initially increases with the increase of its controlled catchment area (Fig. 6a). But after the volume increases to a maximum value at a dam located at the midstream, it decreases with the controlled catchment area. However, the accumulated volume upstream the slot check dam always increases with the controlled area, initially it increases sharply, then slightly and gradually approaches to a stable value. About 60 % of sediment has been blocked upstream the third dam in the dam system.

The relationship between the sediment deposit volume upstream the slot-check dam and the distance from the dam to the first dam is similar (Fig. 6b). The accumulated deposit volume upstream the slot check dam approaches to a stable value when the dam sits far away from the first dam in the group.

The efficiency of slot-check dam system associated with the characteristics of the catchment mountain is listed in Table 4. The conserving efficiency of a slot-check dam

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system on debris flow control in a river basin and each subsystem within the group are associated with the related catchment characteristics. Since the movable sediments volume in Shengou Basin is about $6.017 \times 10^5\ \mathrm{m}^3$, the efficiency of the whole dam system in sediment control in the basin is calculated and compared with the results of the evaluation model.

According to Table 4, the efficiency of each individual dam in the group is different. For an optimal design, (1) the individual dam height or the storage capacity should be determined according to its efficiency in the group $\eta_{\mathrm{d}i}$. (2) To make sure the difference between two connected subsystems efficiency $\eta_{\mathrm{subs}i}$ is more or less the same. (3) Since the system efficiency in the basin is about 20 %, more mitigation projects or methods should be added in order to prevent debris flow hazards to greater extent.

5 Conclusions

Slot-check dam system, an interconnected defense system, shows its significant effectiveness in sediment transport control associated with debris flows.

1. Field survey had been conducted to investigate the performance of the slot-check dams in Shengou Basin. The dams successfully resisted to the impact of debris flows since they were running in good condition without damage in dam body or dam foundation. Each slot-check dam had played an effective role in erosion conservation as a certain amount volume of sediments deposited within the storage of each dam.

2. The conserving efficiency of a slot-check dam system on debris flow control in a river basin and each subsystem within the group are associated with their related catchment parameters. The conserving sediment volume of each dam is related to its relative location and catchment area in the group, gradually decreasing from upstream to downstream.

3. Quantitative method were proposed for estimating the efficiency of slot-check dam system based on the rainfall factor, shape factor and related dam parameters. The data obtained in the Shengou Basin has been come up with a quantitative example of optimal design of the slot-check dam system. The dam height and location in the basin can be better determined based on the evaluation of dam system efficiency, so that they works at maximum efficiency.

Further study and more field data in different river basins are needed to promote the application of the efficiency evaluation model.

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Table 1. Main characteristics of Shengou Basin.

River basin	Catchment area A (km^2)	Main stream length L (km)	Average width B (m)	Relative altitude H_m (m)	Average slope S (%)	Debris flow $Q_{p=0.5\,\%}$ (m^3 s^{-1})	Debris flow $Q_{p=1\,\%}$ (m^3 s^{-1})	Debris flow $Q_{p=2\,\%}$ (m^3 s^{-1})
Shengou	31.77	13.55	51.20	2520.00	20.30	318.22	282.86	247.51

Table 2. Basic parameters of the slot-check dams.

Dam	Length of dam L_d (m)	Effective height of dam H_d (m)	Height of drainage hole in dam h (m)	Width of drainage hole in dam b (m)	Design discharge Q_{proj} ($m^3 s^{-1}$)
a	63.9	8.0	0.50	0.40	96.55
b	79.0	12.0	0.40	0.40	96.55
c	65.5	10.0	0.40	0.40	96.55
d	100.0	10.5	0.50	0.40	96.55
e	62.0	6.0	0.50	0.40	96.55

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Table 3. Deposits upstream each slot-check dam measured on 29 November 2012.

Dam	Height of deposit upstream the dam H_s (m)	Volume of deposit upstream the dam V_s (10^3 m^3)	Effective height of dam H_d (m)	Efficiency of each dam $\eta_{selfi} \doteq H_s^2/H_d^2$
a	2.90	7.20	8.00	0.13
b	6.20	26.40	12.00	0.27
c	7.40	32.80	10.00	0.55
d	6.10	29.00	10.50	0.34
e	4.60	14.50	6.00	0.59

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Table 4. The efficiency and associated catchment parameters of each slot-check dam system.

Dam	Controlled catchment area A_{ci} (km^2)	Distance to most upstream point L_{ci} (km)	Deposit volume upstream a dam v_i (10^3 m^3)	Cumulative deposit volume in the subsystem V_i (10^3 m^3)	Individual dam efficiency in the group η_{di}	Subsystem efficiency in the group η_{subsi}	Subsystem efficiency in the group (model) $\overline{\eta}_{subsi}$	System efficiency in the basin η_{sysi}	System efficiency in the basin (model) $\overline{\eta}_{sysi}$
a	4.24	1.97	7.20	7.20	0.07	0.07	0.16	0.01	0.03
b	5.60	2.46	26.40	33.60	0.24	0.31	0.42	0.06	0.08
c	7.41	3.06	32.80	66.40	0.30	0.60	0.53	0.11	0.10
d	10.32	3.80	29.00	95.40	0.26	0.87	0.74	0.16	0.14
e	15.26	4.91	14.50	109.90	0.13	1.00	1.00	0.18	0.19

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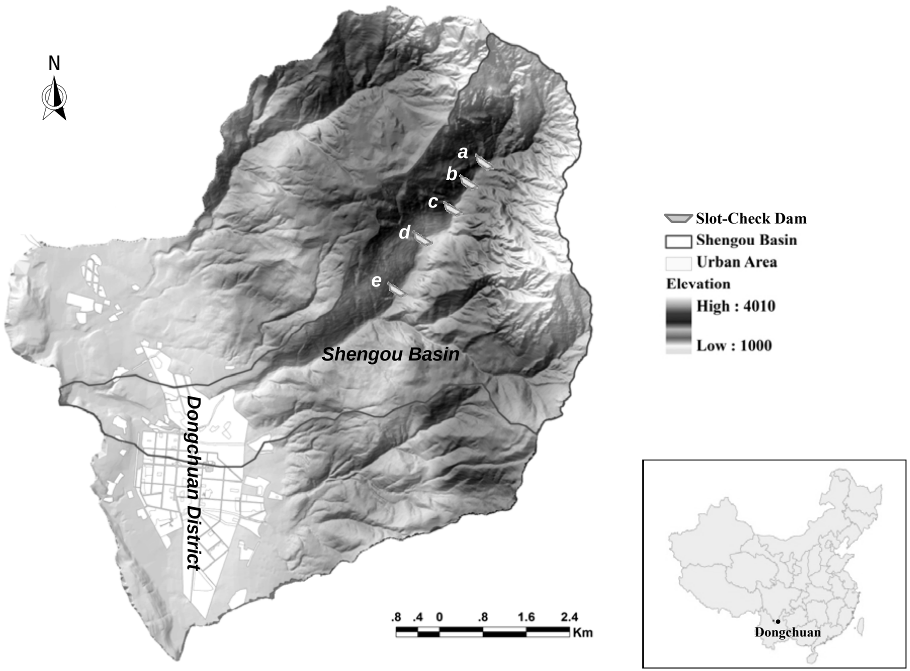

Figure 1. The slot-check dam system in Shengou Basin.

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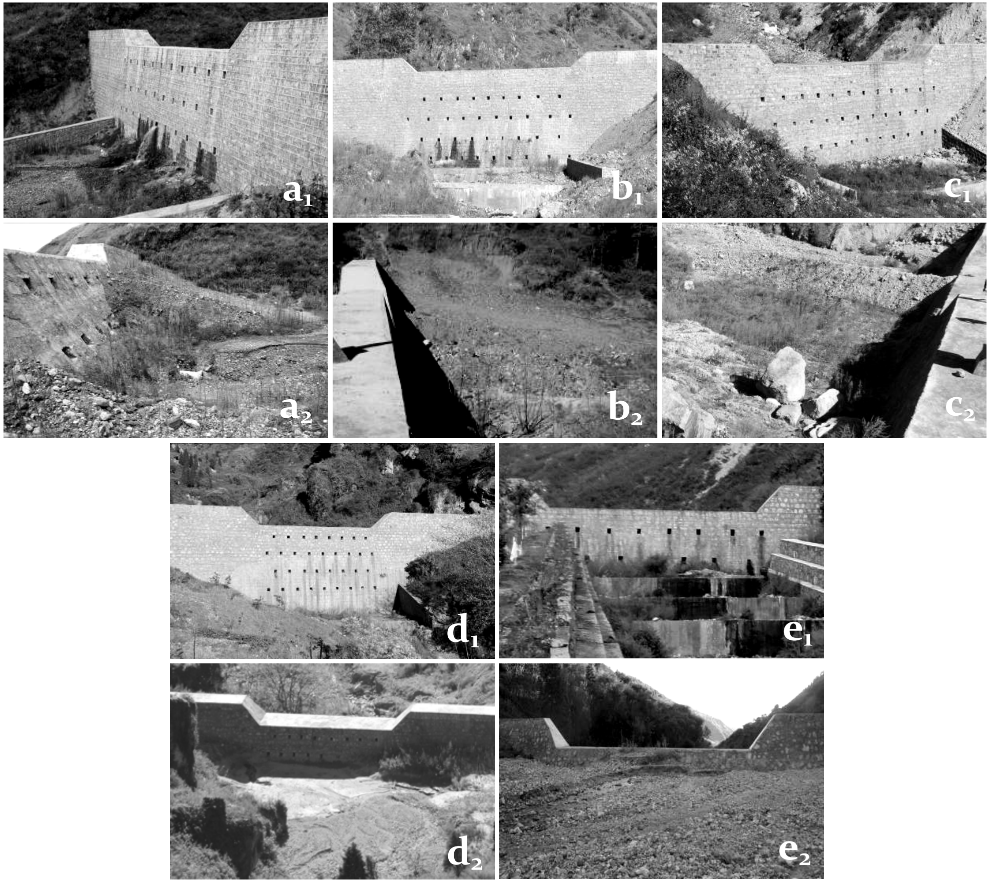

Figure 2. Performance of slot-check dams in Shengou Basin on 29 November 2012. **(a_1–e_1)** View from the downstream, and **(a_2–e_2)** view from the upstream of the five check dams.

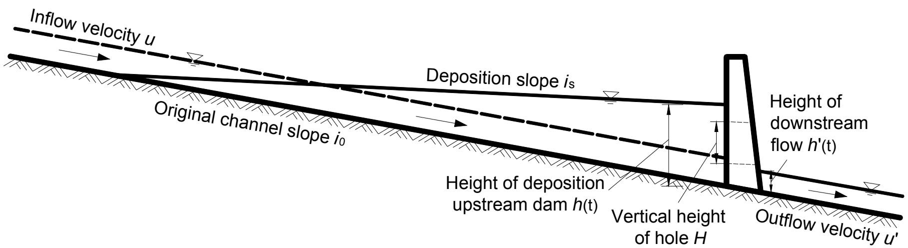

Figure 3. Debris flow sediment deposit upstream a slot-check dam.

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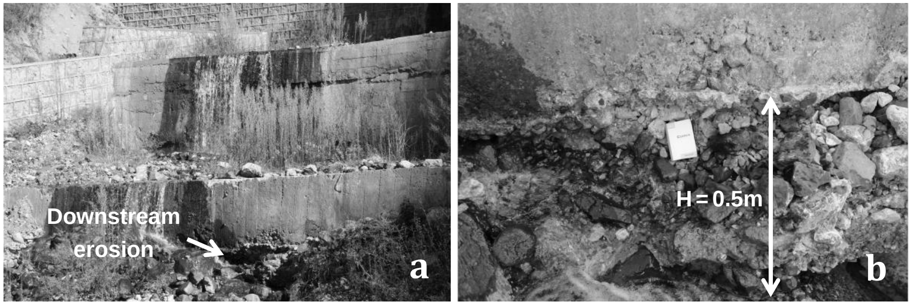

Figure 4. Downstream erosion at the toe of the first slot-check dam.

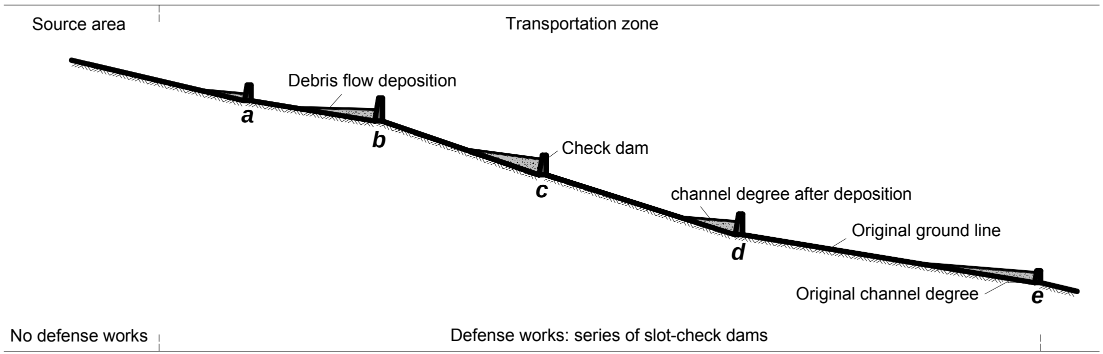

Figure 5. Sketch of equilibrium deposit within the slot-check dam system.

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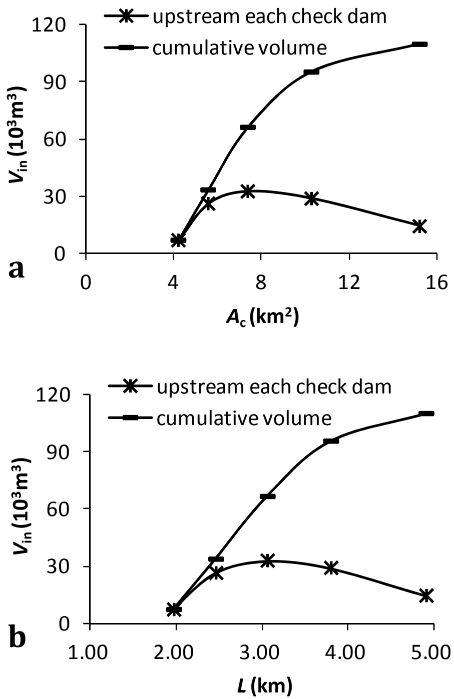

Figure 6. Relationship between the volumes of sediment stored upstream the slot-check dam. **(a)** The drained catchment area; **(b)** the position of the check dam along the river.

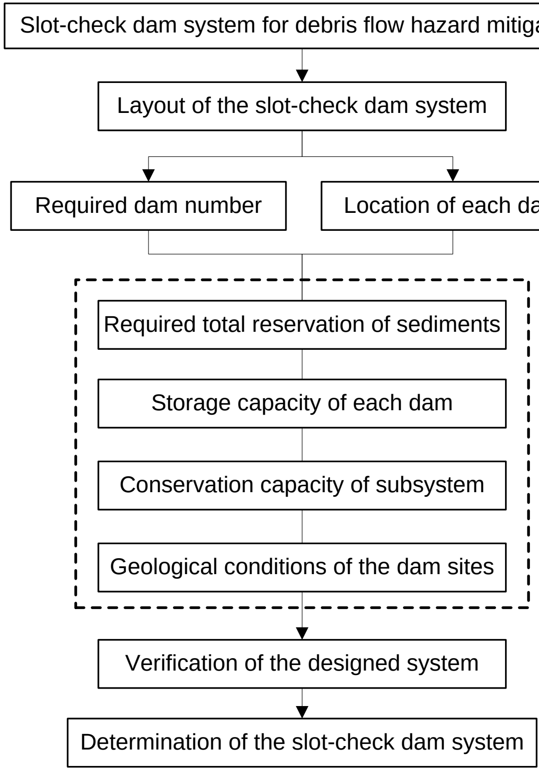

Figure 7. Design procedure of slot-check dam system for debris flow hazard mitigation.

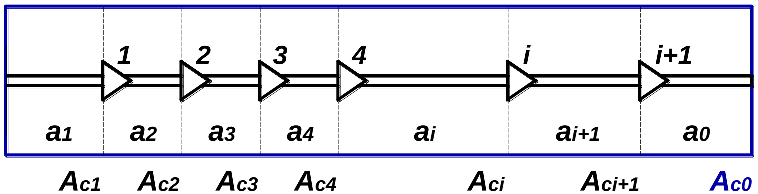

Figure 8. Controlled catchment area of each subsystem.

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