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An assessment framework for the mitigation effects of check dams on debris flow

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ABSTRACT

Debris flow can be very destructive, especially in areas of dense population on mountain foothills. Check dams are constructed across drainage channels and are beneficial for reducing flow velocity and soil erosion, as well as controlling debris flows. On July 26, 1987, a destructive debris flow occurred in a watershed north of Tehran, Iran. A series of check dams were constructed in the watershed to mitigate the hazards of future debris flow due to the importance of the region. This study first proposes a procedure to estimate the volume of the sediments in a debris flow from the calculated volume of an equivalent regular flood. The procedure to estimate the sediments volume is employed in a framework to assess the effects of constructed check dams for a similar debris flow in the region. The framework considers the unfilled storage of the check dams for estimating the volume of the sediments in each catchment. Field measurements were implemented to estimate the available storage of check dams. The volume of sediments in two cases was estimated: 1) the debris flow in 1987 and 2) a probable debris flow at current time considering the available storage of constructed check dams. The comparison shows that the volume of sediments reaching the outlet of the watershed decreased 13% as the effect of check dams in trapping sediments. Applying the proposed framework to this case study shows its ability in assessment of check dams' impact on debris flow.

1. Introduction

Debris flow is a gravity driven flow of sediment and water mixture that occurs suddenly in mountainous areas. This phenomenon can be very destructive and damaging, especially in areas of dense population on mountain foothills (Alimohammadlou et al. 2013; Banihabib and Iranpoor 2015). Although considerable progress has been achieved in improving the knowledge about debris flows (Arnáez et al. 2015; Blasone et al. 2014; Iverson 1997; Takahashi 2007), there are still many questions regarding the mechanisms of debris flows mainly because many parameters change rapidly during a debris flow due to erosion and deposition along the flow path (Hassan-Esfahani and Banihabib 2016; Schürch et al. 2011). Estimating the volume of sediments in a debris flow is a key question among them.

Structural, biological, and management measures have been proposed to mitigate debris flow hazards. Among structural measures, check dams have been implemented throughout the world as part of watershed management plans. Check dams are constructed across drainage channels and are beneficial for reducing flow velocity and soil erosion, as well as capturing sediments. Even old check dams, which have been filled up with deposits of previous debris flows, can be useful in controlling debris flows by reducing channel bed gradient using trapped deposits.

A number of studies analyzed the constructive effects of check dams on debris flow (Liu 1992; Liu et al. 2013; Remaître et al. 2008). There are also some reported cases of check dam failures. Wang (2013) reports a debris flow in China claiming 1700 lives which destroyed or severely damaged all nine check dams along its path because of their inability to resist the fluid pressure of the debris flow or the impact force of individual boulders.

To investigate debris flow hazards and the effectiveness of check dams, estimating the volume of debris flow and sediments deposited by debris flow is a necessary step. Debris flow volumes are generally estimated based on empirical, physical, geomorphological, and numerical methods (Bianco and Franzi 2000; Bovis and Jakob 1999; Gartner et al. 2008; Gatwood et al. 2000; Guo et al. 2016; Hungr et al. 1984; Jakob et al. 2005; Marchi and D'Agostino 2004; Milne et al. 2012; Pak and Lee 2008; Van Asch and Van Steijn 1991). Rickenmann (1999) provides a comprehensive review of empirical relationships for debris flows. However, these methods are either very expensive to implement or

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requires historical data of debris flows to be collected. An alternative procedure to estimate debris flow volume is proposed in this study. The proposed method uses a Rainfall-Runoff model to simulate "fluid flow" in the study area. The relations described by (Takahashi 2007) are applied to estimate debris flow and sediments volumes from the results obtained by Rainfall-Runoff model.

The approach of estimating sediments volume is employed in a framework to assess the mitigation effects of check dams in a potential debris flow in a watershed north of Tehran, Iran. The region experienced a strong debris flow on July 26, 1987 and due to the social, political and economical importance of the region, a number of check dams were built in the watershed in the years following the event. Although the framework does not address the complex dynamics of debris flows, it can be used in the absence of historical data or for implementing a preliminary debris flow assessment.

2. Study area

The study area is Tajrish watershed in north of Tehran, the capital city of Iran with a metropolitan area of over 10 million inhabitants. Tajrish watershed is a mountainous region that contains two sub-watersheds called Darband and Golabdareh. Mount Toochal has an elevation of 3957 m and is located in this watershed. Table 1 summarizes the main characteristics of Darband and Golabdareh sub-watersheds, which are further divided into 10 and 23 catchments, respectively, as shown in Fig. 1.

Being upstream of Tehran, Tajrish watershed is among the critical watersheds in Iran. The outlet of watershed is very close to Tajrish square, now a populated area in Tehran. Due to having steep mountains, Tajrish watershed is subject to debris flows by flush storms. On July 26, 1987, a disastrous debris flow occurred in Darband and Golabdareh sub-watersheds and before long it reached Tajrish square. The precipitation gages in the region recorded 29.5 mm of rainfall in the event. The debris flow claimed 300 lives and caused substantial economic losses. The day after the tragedy, people could see a very huge boulder in the middle of Tajrish square. Considering the necessity of preventing similar disasters, a series of 245 check dams were built in the sub-watersheds during 1999–2001.

3. Methodology and results

Before describing the methodology, we reiterate the difference between terms "fluid flow" and "debris flow" in this study. We use the term fluid flow to refer to a regular flood without significant amounts of debris. Hydrologic modeling system HEC-HMS (William and Matthew 2010), as a rainfall-runoff model, has been widely used to quantify fluid flow. Assuming little debris in the flood, we employ HEC-HMS model in this study to quantify the volume and peak of fluid flow based on recorded rainfall in the region. The equations presented in the next sections are then applied on estimated values of fluid flow to estimate debris flow and sediments volume).

Subsequent sections briefly explain the relations to estimate sediments volume, propose a procedure to estimate sediments volume in the 1987 debris flow, and detail the framework to quantify a potential debris flow at current time and assess the mitigation effects of check dams.

3.1. Equations to estimate debris flow and sediments volumes from fluid flow volume

Takahashi (2007) derived Eq. (1) for a water-saturated uniform bed:

$$Q_t = \frac{C_*}{C_* - C_{df}} Q_o \tag{1}$$

where Q_t is the discharge of debris flow, Q_o is the discharge of the supplied water from upstream (or discharge of "fluid flow" as we explained before), C_* is the maximum possible concentration of sediments in channel bed and C_{df} is sediment concentration in equilibrium condition of debris flow. The maximum possible value of C_{df} is C_*.

As mentioned earlier, in the present study, the results of HEC-HMS model, which actually simulates fluid flow part of a debris flow, is used to estimate Q_o in Eq. (1). We define P coefficient as the ratio of debris flow discharge (Q_t) and fluid flow discharge (Q_o):

$$P = \frac{Q_t}{Q_o} \tag{2}$$

In our proposed procedure to estimate sediment volume, P is used to convert fluid flow discharge (and volume) into debris flow discharge (and volume). Banihabib and Masumi (1999) verified this equation for Masoleh watershed in north of Iran. By substituting Eq. (2) into Eq. (1), Eq. (1) can be rewritten as:

$$P = \frac{C_*}{C_* - C_{df}} \tag{3a}$$

The values reported in the literature for C_* for uniform natural grains is about 0.65 (Takahashi 2007). We considered C_* equal to 0.6 in our study based on our field experiments. So, Eq. (3a) is rewritten as:

$$P = \frac{0.6}{0.6 - C_{df}} \tag{3b}$$

On the other hand, experimental debris flows on erodible beds shows that the sediment concentration (C_{df}) in equilibrium condition of debris flow is not dependent on the discharge but mainly on the bed slope (tanθ) (Takahashi 2007). Takahashi (2007, Equation 2.24, page 46) derived the relation between tanθ and C_{df} as:

$$C_{df} = \frac{\rho \tan\theta}{(\sigma - \rho)(\tan\varphi - \tan\theta)} \tag{4a}$$

where σ is particle density, ρ is fluid density, and ϕ is internal friction angle. Assuming ρ and σ as 1 g/cm^3 and 2.65 g/cm^3, respectively, Eq. (4a) can be rewritten as:

$$C_{df} = \frac{\tan\theta}{1.65(\tan\varphi - \tan\theta)} \tag{4b}$$

Also, bed slope (tanθ) can be estimated using topographic maps as:

$$\tan\theta = \frac{\Delta h}{\Delta L} \tag{5}$$

where Δh is the elevation difference of the channel, and ΔL is channel length. Eq. (4b) implies that as the channel slope (tanθ) becomes

Table 1
Characteristics of the sub-watersheds in Tajrish watershed.

Sub-watershed	Area (ha)	Average elevation (m)	Drainage density (km/km^2)	Channel length (m)	Mean basin slope
Darband	254	2678	7.47	8900	25.6%
Golabdareh	739	2278	6.04	6240	24.4%