EARLY WARNING OF RAINFALL-INDUCED LANDSLIDES AND DEBRIS FLOWS ON MT. BAWAKARAENG, SOUTH SULAWESI, INDONESIA

Hasnawir[1]

ABSTRACT

Rainfall thresholds that form the basis of the landslide warning systems now exist for a few areas in Indonesia. Based on analysis of historical data, threshold performance varies according to precipitation characteristics, and threshold exceed corresponds to a given probability of landslide occurrence. Early warnings of landslides and debris flows that include specific information about affected areas, probability of landslide and debris flow occurrence, and expected timing are technically feasible as illustrated by a case study made on Mt. Bawakaraeng, South Sulawesi, Indonesia. Records from 1997 to 2007 of rainfall data and history of landslides and debris flows were collected from the Ministry of Public Works of the government of Indonesia. The threshold, as defined by the lower boundary of the points representing landslides and debris-triggering rainfall events, is expressed by the equations $I = 41.85D^{-0,85}$ before the large scale landslide on March 26, 2004 and $I = 37.71D^{-0,90}$ after the large scale landslide, where I is the rainfall intensity (mm/hr) and D is the duration of rainfall (hr). According to empirical threshold analysis, the regression curve can be considered as a reliable rainfall intensity-duration threshold for the study area, above which, landslide or debris flow event may occur.

Keywords: Early warning, landslide and debris flow, rainfall thresholds, Mt. Bawakaraeng

I. INTRODUCTION

In recent years landslides and debris flows have caused damage to the natural resources in Indonesia. Losses of lives, destruction of properties, economic losses and adverse impacts to the environment have been caused by these phenomena every year. Particularly in South Sulawesi Province landslides and debris flows have been important issues for mitigation, especially since 2004. A large scale landslide including a debris flow occurred on Mt. Bawakaraeng caldera in year 2004, with a volume of about 232 million m³. The landslide was caused by the collapse of the walls of the caldera resulting in the flow of a large amount of debris with significant damages including 32 deaths and destruction of properties (Tsuchiya *et al.*, 2004).

Moreover, on Mt. Bawakaraeng caldera, the majority of landslides and debris flows have been triggered by intense rainfall (Hasnawir and Kubota, 2009).

Characterization of landslide-triggering rainfall has been used to establish the relation between rainfall and landslides in various parts of the world. The most commonly investigated rainfall parameters in relation to landslide initiation include cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration. Attempts have been made to define thresholds employing various combinations of these parameters. Since the majority of slope failures are triggered by extreme rainfall, a number of researchers (e.g., Campbell, 1975; Cotecchia, 1978; Caine, 1980; Pomeroy, 1984; Cannon and Ellen, 1985; Neary and Swift, 1987; Kim *et al.*, 1991; Wilson *et al.*, 1992; Larsen and Simon, 1993; Wilson and Wieczorek, 1995; Wieczorek, 1996; Terlien, 1998; Crosta, 1998; Crozier, 1999; Glade

[1]Forestry Research Institute of Makassar, Ministry of Forestry of Indonesia
Corresponding Author: wirforest@yahoo.com

1

et al., 2000; Wieczorek *et al.*, 2000; Aleotti, 2004; Guzzetti *et al.*, 2004; Hong *et al.*, 2005; Giannecchini, 2006) have attempted to establish rainfall intensity thresholds so that slope failure predictions could be made accurately. These various works define rainfall threshold in terms of rainfall intensity, duration vs. intensity ratio, cumulative rainfall in a given time, antecedent rainfall vs. daily rainfall ratio, event rainfall vs. yearly average rainfall ratio, and daily rainfall vs. antecedent excess rainfall ratio. Caine (1980) was the first to establish worldwide rainfall threshold values for landslides. Similar threshold values have been proposed for California (e.g., Cannon and Ellen, 1985; Wieczorek, 1987; Wieczorek *et al.*, 2000), the Southern European Alps (Cancelli and Nova, 1985; Ceriani *et al.*, 1992), pre-Alpine regions of Northern Italy (Guzzetti *et al.*, 2004), the Piedmont region of Italy (Aleotti, 2004), Korea (Kim *et al.*, 1991), Southern China (Li and Wang, 1992), Japan (Cotecchia, 1978; Yatabe *et al.*, 1986; Yano, 1990; Hiura *et al.*, 2005) and Puerto Rico (Larsen and Simon, 1993). Recently Dahal and Hasegawa (2008) reviewed representative rainfall thresholds for landslides in the Nepali Himalayas.

In order to develop a warning system for landslides and debris flows, an accurate identification of the rainfall condition that triggers landslide and debris flow is needed. Hence the main objectives of the study were to determine empirical rainfall intensity-duration thresholds for landslides and debris flows for Mt. Bawakaraeng caldera of South Sulawesi, Indonesia.

II. METHODOLOGY

A. Study Area

The study area is located in the Mt. Bawakaraeng caldera (Figure 1). The caldera is situated 90 km from Makassar, South Sulawesi and the elevation of Mt. Bawakaraeng is 2,830 m above sea level. The foot of the collapsed caldera is the head water of the Jeneberang river which is connected to the Bili-Bili Dam. The dam was constructed for multi-purpose usage such as drinking water reservoir and hydroelectricity for South Sulawesi. The soil types of the study area

are andosol. According to FAO (2001), soil types which belong to the andosol group are developed from volcanic materials. Most andosols have excellent internal drainage because of their high porosity and their occurrences are predominantly at high elevations. Specific gravity of the soil is 2.70, porosity is estimated as 66.7% - 88.7%. The bulk density of andosols is low, not just in the surface soil where it is typically less than 900 kg/m^3 but values as low as 300 kg/m^3 have been recorded in highly hydrated andosols. The bulk density does not change much over a suction range of 1500 kPa (limited shrink and swell).

In the study area 14% of the land surface has dense forest cover and over 12% of the area has deteriorated from dense to semi-dense forest. The study area and the surrounding areas consist of 50% dry farm land, 40% grass land and about 10% partly paddy field. The vegetation of the mountainous area is composed of natural forest and forest plantation dominated by *Pinus merkusii*. Mountain tops are covered by grass without high trees. The morphology of Mt. Bawakaraeng is characterized by high relief, extreme slopes, high degree of weathering as well as erosion activities such as soil movements and landslides. The basement rocks around Mt. Bawakaraeng area consist of the Tonasa Formation, the Camba Formation, the Baturape-Cindako Volcanic Rocks, extrusive and intrusive rocks and the Lompo-battang Volcanic Formation, which were formed from the Paleogene to the Quaternary period (Sukamto and Supriatna, 1982). The geological map and the stratigraphic column of Mt. Bawakaraeng caldera are shown in Figure 2 and Table 1, respectively. The geological units are described as follows (Ministry of Public Works, 2005).

Tonasa Formation: It consists of limestone and marl of Eocene to Middle Miocene age. Layered limestone has folded structure with less than 25° inclination. Camba Formation: It consists of tuffaceous sandstone, tuff and mudstone and pyroclastic rocks of Late Miocene age. It is widely distributed from Maros district to Jeneponto district, and forms a mountainous area in the middle section of the Jeneberang river. Baturape-Cindako Volcanic Rocks: They were formed by volcanic activity during the Pliocene age. They consist of tuff, lava accompanied by conglomerate and breccia. These rock units are distributed in the vicinity of Mt. Maja in southern

Figure 1. Location map of the study area in Jeneberang watershed, South Sulawesi, Indonesia

Table 1.Columnar section of the geological units around Mt. Bawakaraeng caldera

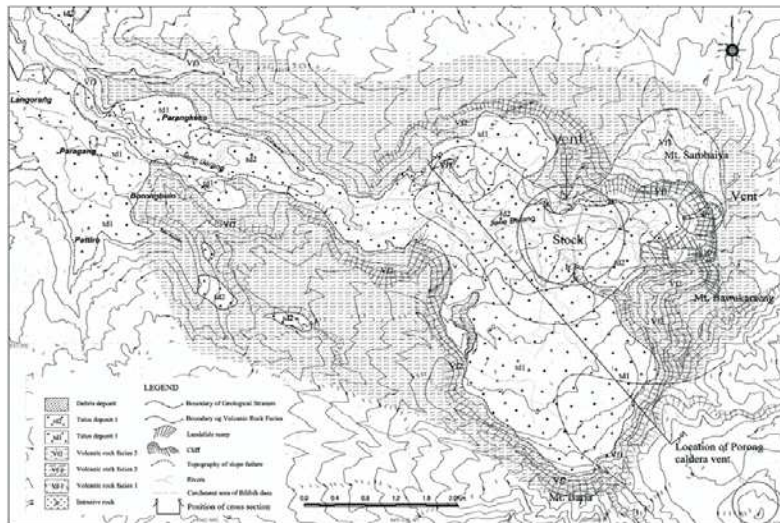| Age			Formation	Symbol	Description
Quaternary	Holocene		Riverbed Deposit	rd	This stratum consists of gravel, sand and clay. The surface of deposit along the Jeneberang river is covered with debris flow deposit more than 10 m in depth at its maximum.
			Talus Deposit-2	td2	This stratum consists of fallen rocks, detritus, soil and sand formed by collapse. Talus deposit formed by the latest caldera wall collapse accumulated from the hem part of the slope collapse to the downstream area of Lengkese village along the Jeneberang river.
			Terrace Deposit-2	tr2	This stratum consists of gravel, sand and clay. Terrace plain has a height of 5 to 20 m above the present riverbed.
	Pleistocene		Terrace Deposit-1	tr1	This stratum consists of gravel, sand and clay. Terrace plain has a height of 50 to 75 m above the present riverbed.
			Talus Deposit-1	td1	This stratum consists of fallen rocks, detritus, soil and sand. This deposit is widely distributed along ancient Jeneberang river (present Kausisi river), forming terrace plain with a height of 50 to 100 m above the present Jeneberang riverbed. It is deemed that this stratum was formed by debris flow which occurred in the Pleistocene age.
		LompobattangVolcanics	Volcanic Rocks Facies-3	Vf3	This stratum is distributed at the edge part of the volcano body, and consists of pyroclastic-sedimentary rocks which are composed of lapilli tuff, pumice tuff, volcanic breccia and volcanic conglomerate.
			Volcanic Rocks Facies-2	Vf2	This stratum is distributed in the whole area of the volcano body, and forming the alternation of volcanic layer. Volcanic layer consists of basalt-andesite lava, and pyroclastic rocks which are composed of volcanic breccia and tuff. In this facies, the amount of lava is superior to that of pyroclastic rocks. And the continuity of lava is high, and the thickness of lava is mainly more than 20 m. The rock-mass has columnar joints with intervals of 30 to 200 cm, but the hardness of the lava rock is comparatively high.
			Volcanic Rocks Facies-1	Vf1	This stratum is distributed around the vent, and forming the alternation of volcanic layer. Volcanic layer consists of pyroclastic rocks which are composed of vent breccia, volcanic breccia and tuff, and lava. But in this facies, the continuity of lava is low, and the rock-mass like a lens is formed. Low cementation sedimentary rocks are contained at the boundary part of the volcanic layers that were formed intermittently. From these points, the strength of rock -mass is relatively low.
			Intrusive Rock	Ir	This stratum consists of dasite that were supplied from magma, and is distributed as effusive rock and stock around the caldera. Dasite is mainly composed of Plagioclase, Quartz, and Pyroxene with a diameter of 1 to 10 mm, and shows light gray color. The notable feature of dasite is to easily deteriorate the rock quality by weathering.

Source: Ministry of Public Works, 2005

Figure 2. Detailed geological map of Mt. Bawakaraeng caldera
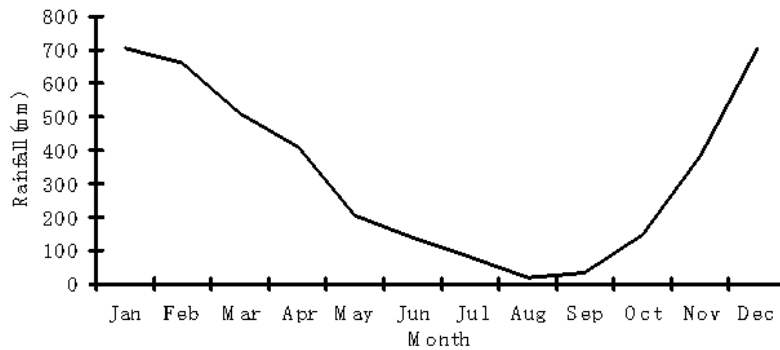Source: Ministry of Public Works (2005)

Figure 3. Average monthly rainfall at the study area
Source: Analysed data

part of Gowa and in the vicinity of the right tributary of the Jeneberang river.

Extrusive and Intrusive Rocks: Basalt, andesite and diorites of Late Miocene to Pliocene age are distributed as dike, sill and stock rock. They crop out as small rock bodies associated with sedimentary and volcanic rocks. They are distributed in Maros and Jeneponto districts. Lompobattang Volcanic Formation: It consists of andesitic volcanic rocks of Pleistocene age with lava, pyroclastic rocks and secondary deposit. The central portion of Porong Caldera (Figure 2) consists of a vent which comprises of effusive rocks. The volcanic rocks are distributed around the eastern portion of the Gowa district and cover the mountainous area in the headwaters of the Jeneberang river (Ministry of Public Works, 2005).

The rainfall in the study area is not well distributed. The average monthly rainfall ranges from 18 mm in August to 710 mm in December. High intensity rainfall usually occurs from December to March. There are two distinct seasons i.e. dry and wet. The dry season lasts from April to October with 25% of the annual rainfall. The remaining 75% of the annual rainfall occurs throughout November to March, and has its maximum during the Monsoon. Average annual rainfall is estimated at 4000 mm. Average monthly rainfall is about 333 mm (Figure 3). From 1975 to 2005 the annual mean temperature, the mean daily evaporation throughout the year, the mean monthly relative humidity, and the mean monthly wind velocity were 22.8°C, 4.1 mm, 80.9% and 1.1 m/s, respectively. Evapotranspiration loss is up to 1,497 mm per year, that is about 50 - 25% of the

annual rainfall (Ministry of Public Works, 2005).

B. Methods

In general, two types of rainfall thresholds can be established; empirical and physical thresholds (Aleotti, 2004). The empirical thresholds refer to relational values based on statistical analysis of the relationship between rainfall and landslide occurrences (Campbell, 1975; Caine, 1980; Larsen and Simon, 1993; Crozier, 1999; Guzzetti *et al.*, 2004). Physical thresholds are usually described with the help of hydrologic and stability models that take into account different parameters such as relationships between rainfall and pore-water pressure, suction, infiltration, slope morphology, and bedrock structures (Montgomery and Dietrich, 1994; Crosta, 1998; Terlien, 1998; Crosta and Frattini, 2001; Jakob and Weatherly, 2003). Antecedent rainfall (Crozier, 1999; Rahardjo *et al.*, 2001) also plays an important role in the determination of rainfall thresholds. Conventionally, critical precipitation indicates the amount of rainfall from the time ("zero point") in which a sharp increase in rainfall intensity is observed which is triggering off the (first) landslide (Figure 4). This increase results in a significant break in the slope of the rainfall's cumulative curve.

The empirical thresholds type was selected for this study. Records of rainfall data and history of landslide or debris flow were collected from the Ministry of Public Works of the government of Indonesia (2005) and the Hazama-Brantas, J.O (2007). No study has been conducted on the
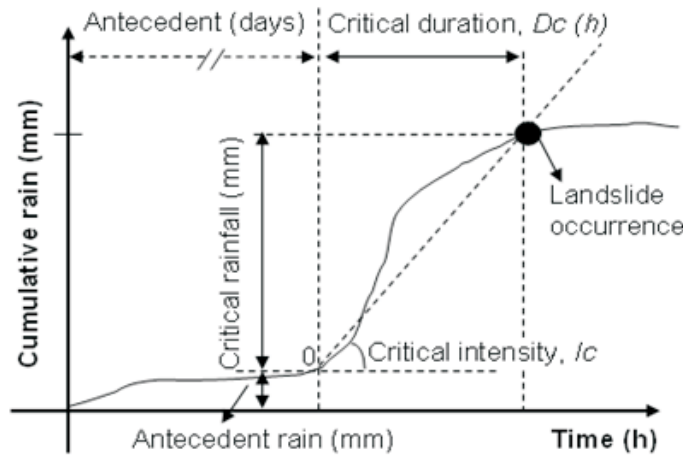

Figure 4. Rainfall parameters in relation to landslide initiation include cumulative, antecedent, intensity and duration of rainfall
Source: Aleotti (2004)

Table 2. Cases of landslides and debris flows in Mt. Bawakaraeng caldera from 1997 to 2007

No	Date	Event	No	Date	Event
1	23-01-1997	Debris flow	12	09-06-2004	Debris flow
2	25-02-1999	Debris flow	13	08-07-2004	Debris flow
3	26-01-2000	Debris flow	14	26-01-2005	Debris flow
4	27-02-2001	Debris flow	15	12-03-2005	Debris flow
5	25-02-2001	Debris flow	16	17-04-2005	Debris flow
6	13-12-2002	Debris flow	17	07-07-2005	Debris flow
7	05-03-2003	Debris flow	18	26-11-2005	Debris flow
8	26-03-2004	Landslide	19	08-02-2007	Landslide
9	16-04-2004	Debris flow	20	16-02-2007	Debris flow
10	03-05-2004	Debris flow	21	27-12-2007	Debris flow
11	07-06-2004	Debris flow			

Remarks: No. 1 to 7 are cases before the large scale landslide. No. 8 is the large scale landslide. No. 9 to 21 are cases after the large scale landslide.

relationship between rainfall and landslides or debris flows before the occurrence of the large scale landslide on March 26, 2004. The existing data indicates that there is a coincidence between the times of the landslides or debris flows with the rainfall events.

We used data for twenty one cases of landslides or debris flows; rainfall intensity-duration before and after the large scale landslide on March 26, 2004 at Mt. Bawakaraeng caldera (Table 2). The reported landslides and debris flows from 1997 to 2007 were analyzed in the upper Jeneberang watershed. Empirical rainfall intensity-duration thresholds for landslides and debris flows were calculated using linear regression analysis which related rainfall intensity and the duration.

III. RESULT AND DISCUSSION

Twenty one cases of landslides or debris flows and rainfall intensity-duration before and after the large scale landslide in March 26, 2004 at Mt. Bawakaraeng caldera were analyzed for rainfall thresholds (Table 3). The regression equation of rainfall intensity-duration before the large scale landslide was $I = 41.85D^{-0,85}$ and the regression equation of rainfall-duration after the large scale landslide was $I = 37.71D^{-0,90}$, where I is the rainfall intensity in mm/hr and D is the duration of rainfall in hr (Figure 5 and 6). Particularly, the critical intensity (I_c) and the critical duration (D_c) are parameters, which indicate the amount of rainfall and time that trigger the landslide or the

Table 3. Cases of landslides-debris flows and rainfall duration-intensity in Mt. Bawakaraeng caldera from 1997 to 2007

No	Date	Duration (D, hr)	Intensity (I, mm/hr)	No	Date	Duration (D, hr)	Intensity (I, mm/hr)
1	23-01-1997	4	16.8	12	09-06-2004	10	5.0
2	25-02-1999	6	7.0	13	08-07-2004	1	41.0
3	26-01-2000	90	1.1	14	26-01-2005	7	11.7
4	27-02-2001	120	0.8	15	12-03-2005	6	15.0
5	25-02-2001	50	2.0	16	17-04-2005	5	8.5
6	13-12-2002	6	7.0	17	07-07-2005	150	0.4
7	05-03-2003	8	7.0	18	26-11-2005	70	1.0
8	26-03-2004	350	0.2	19	08-02-2007	250	0.3
9	16-04-2004	6	15.0	20	16-02-2007	3	20
10	03-05-2004	350	0.2	21	27-12-2007	57	7.5
11	07-06-2004	6	7.3				

Remarks: No. 1 to 7 are cases before the large scale landslide. No. 8 is the case when the large scale landslide occurred. No. 9 to 21 are cases after the large scale landslide. No. 20 and 21 were large scale debris flows with volumes of about 7.8 million m³, and 7.0 million m³ respectively.
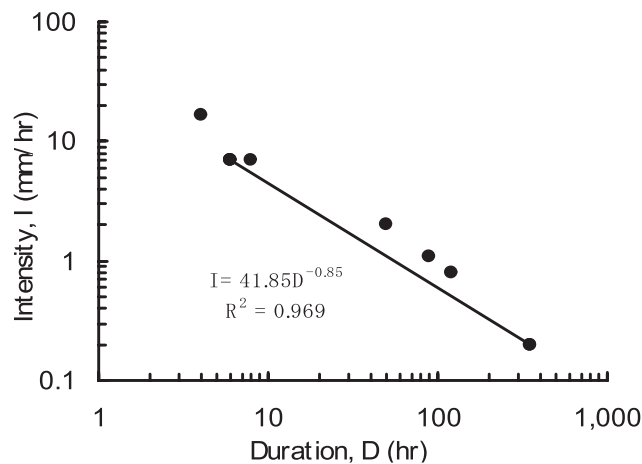

Figure 5. Rainfall intensity-duration threshold curve for landslide in the Mt. Bawakaraengcaldera, Indonesia. This is the threshold before the large scale landslide on March 26, 2004 (Table 2, No 1 to 8)
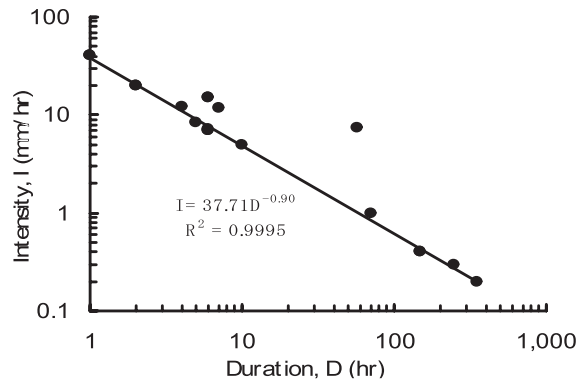
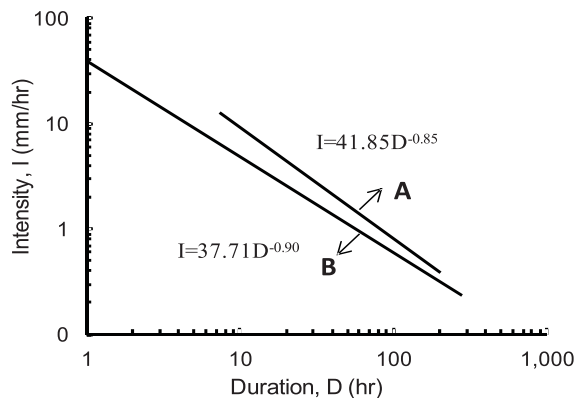Figure 6. Rainfall intensity-duration threshold curve for landslide in the Mt. Bawakaraeng caldera, Indonesia

Figure 7. "A" indicates the threshold before and "B" indicates the threshold after the large scale landslide

debris flow. The regression analysis shows that rainfall intensity increases exponentially as the duration decreases. According to empirical threshold analysis, the regression curve can be considered as a reliable rainfall intensity-duration threshold for the study area, above which, landslide or debris flow events may occur. However the regression value of rainfall intensity-duration before a large scale landslide was higher than after the landslide (Figure 7). After the large scale landslide in Mt. Bawakaraeng caldera, the geomorphology of the caldera has changed. The caldera has become more susceptible to debris flows and landslides due to less intense rainfall as compared to the case prior to the large scale landslide.

This is the threshold after the large scale landslide on March 26, 2004 (Table 2, No 9 to 21).

Compared to the global threshold (Crosta and Frattini, 2001), the Mt. Bawakaraeng caldera needs high intensity rainfall for landslides to occur, but when compared to the Himalaya threshold (Dahal and Hasegawa, 2008), the Mt. Bawakaraeng caldera needs lower intensity rainfall for landslides to occur (Table 4 and Figure 8).

The susceptibility of the area for the occurrence of landslides or debris flows before and after the large scale landslide was quite different (Figure 6, 7 and 8). The number of cases especially of debris flows appeared more after the large scale landslide on March 26, 2004 than before the landslide. Therefore, the warning from this study will operate more effectively if it is used for the standard rainfall for the warning after the large scale landslide on March 26, 2004.

Currently, to reduce the subsequent landslides or debris flows in the study area, a pilot project under the cooperation of Japanese and Indonesian goverment have been conducted for hazard mitigation. For debris basins surrounded by residential developments, the capability to remove material may be on a 24-hours basis during storms. Also seven Sabo Dams were constructed in the Mt. Bawakaraeng caldera area.

7

Table 4.Some examples of rainfall-duration threshold equations for global, regional and local scales

Researches	Area	Equation
1. Caine (1980)	World	$I \quad 14.82 D^{0.39}$
2. Cancelli and Nova (1985)	Valtellina,northern Italy	$I \quad 44.67 D^{0.78}$
3. Ceriani et al.(1992)	North Italy	$I \quad 20.10 D^{0.55}$
4. Larsen and Simon(1993)	Porte Rico, Caribbean Sea	$I \quad 91.46 D^{82}$
5. Wieczorek (1987)	California	$I \quad 1.7 \quad 9D^{1}$
6. Crosta and Frattini (2001)	World	$I \quad 0.48 \quad 7.2D^{1}$
7. Aleotti (2004)	Piedmont region, Italy	$I \quad 19 D^{0.50}$
8. Dahal and Hasegawa (2008)	Himalaya, Nepal	$I \quad 73.90 D^{0.79}$
9. Present study	Mt. Bawakaraeng	$I \quad 41.85 D^{0.85} (A) \qquad I \quad 37.71 D^{0.90} (B)$

Remarks: (A) indicates the threshold before and (B) indicates the threshold after the large scale landslide
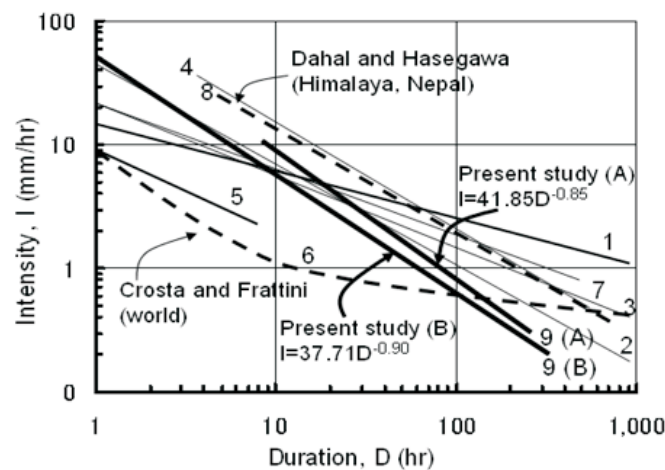

Figure 8. Comparison of the landslide-triggering rainfall intensity-duration thresholds from various studies with the present study before (A) and after (B) the large scale landslide on March 26, 2004

IV. CONCLUSION

The present study shows that the susceptibility of the area for the occurrence of landslides or debris flows before and after the large scale landslide (March 26, 2004) was quite different. The regression value of rainfall intensity-duration before a large scale landslide was higher than after the large scale landslide. Therefore, the rainfall warning will be more effective if the rainfall warning threshold after the large scale landslide is used. The regression curve can be considered as a reliable rainfall intensity-duration threshold for the study area, above which, landslide or debris flow events may occur.

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