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Relationships between natural terrain landslide magnitudes and triggering rainfall based on a large landslide inventory in Hong Kong

Abstract Rain-induced landslides are recognized as one of the most catastrophic hazards on hilly terrains. To develop strategies for landslide risk assessment and management, it is necessary to estimate not only the rainfall threshold for the initiation of landslides, but also the likely magnitudes of landslides triggered by a storm of a given intensity. In this study, the frequency distributions of both open hillside landslides and channelized debris flows in Hong Kong are established on the basis of the Enhanced Natural Terrain Landslide Inventory (ENTLI) with 19,763 records in Hong Kong up to 2013. The landslide magnitudes are measured in terms of the number, scar area, volume, or density of landslides. The mean values of the scar areas and volumes are 55.2 m^2 and 102.0 m^3, respectively, for the open hillside landslides and 91.3 m^2 and 166.5 m^3, respectively, for the channelized debris flows. Empirical correlations between the numbers, scar areas, and volumes of hillside landslides or channelized debris flows and the maximum rolling rainfall intensities of different periods have been derived. The maximum rolling 4- to 24-h rainfall amounts provide better predictions compared with those with the maximum rolling 1-h rainfall. Maximum rolling rainfall intensity-duration thresholds identifying the likely rainfall conditions that yield natural terrain landslides or debris flows of different magnitudes are also proposed. The initiation rainfall thresholds are identified as 75, 90, 100, 120, 150, 180, and 200 mm for the maximum rolling 1-, 2-, 4-, 6-, 8-, 12-, and 24-h rainfall, respectively.

Keywords Landslide · Debris flow · Rainfall threshold · Hazard · Magnitude-frequency

Introduction

A natural terrain slope refers to a slope which has not been modified by human activities substantially. A natural slope often erodes to a level which is relatively stable under normal circumstances. However, if the conditions of the natural slope are changed due to deforestation or heavy rainfall, the slope condition may deteriorate due to further erosion, loss of soil suction or buildup of positive pore-water pressure due to deeper infiltration, washout, or other disturbances, and the slope may fail. Compared with manmade slopes such as cut slopes and fill slopes, natural terrain is relatively more vulnerable to the impact of rainstorms, leading to rainfall-induced landslides (Au 1998; Gao et al. 2015; Tang et al. 2017).

Rain-induced natural terrain landslides have caused a large number of casualties and severe damages in mountainous areas. It is therefore important to forecast the potential of landslides and propose mitigation measures. Assessing the landslide magnitudes and quantifying the triggering rainfall thresholds are essential in developing landslide risk mitigation strategies (Keefer et al. 1987; Guzzetti et al. 2008). When historical landslide records and their corresponding rainfall conditions are available, one can establish relationships between them and apply the relationships for predicting the future landslide hazards.

Many rainfall thresholds to trigger landslides, such as the intensity-duration threshold and the daily/hourly rainfall threshold, have been established for forecasting rainfall-induced landslides in different regions (e.g., Keefer et al. 1987; Chan et al. 2003; Glade et al. 2000; Crosta and Frattini 2001; Guzzetti et al. 2008; Baum and Godt 2010; Huggel et al. 2010; Martelloni et al. 2012; Rosi et al. 2016; Chen et al. 2017). A number of studies on relationships between rainfall and landslides based on historical landslides and rainfall data in Hong Kong have also been conducted (e.g., Lumb 1975; Brand et al. 1984; Premchitt 1991; Kay and Chen 1995; Finlay et al. 1997; Au 1998; Evans et al. 1999; Franks 1999; Pun et al. 1999; Dai and Lee 2001; Ko 2003; Yu 2002; Chau et al. 2004; Wong et al. 2006; Ho 2013; Ko and Lo 2016). Lumb (1975) developed correlations between rainfall and occurrence of landslides, and found that the landslides in Hong Kong heavily depended on the short-period rainfall intensity, with a threshold of 70 mm/h. Finlay et al. (1997) investigated the relationship between the probability of landslide occurrence and rainfall, and determined the rainfall thresholds that cause isolated landslides using the data from 1984 to 1993. The number of landslides was best predicted using 3-h rainfall. Dai and Lee (2001) investigated magnitude-cumulative frequency relationships for landslides and relationships between rainfall and occurrence of landslides. The 12-h rolling rainfall was found to be the best in predicting the number of landslides. The 12-h maximum rolling rainfall value is calculated as the maximum value of rainfall in 12 consecutive hours on a hyetograph. Ko (2003) analyzed natural-terrain landslide data and established an empirical relationship between the landslide density (i.e., cumulative percentage of natural terrain landslides) and the normalized maximum rolling 24-h rainfall (i.e., the ratio of the maximum rolling 24-h rainfall and the location-specific mean annual rainfall). Recently, Ko and Lo (2016) presented a territory-wide rainfall-based landslide susceptibility analysis that took cognizance of the effects of slope angle and bedrock geology.

The previous studies on relationships between landslides and rainfall had targeted to derive the minimum rainfall thresholds that are likely to trigger landslides. Little attention has been paid to the magnitude of landslides under storms of different intensities (Wong et al. 2013). Although these minimum thresholds answer the question whether landslides will occur or not, rainfall thresholds for triggering prescribed magnitudes of landslides are of greater value in assessing landslide risks and developing landslide warning criteria.

In this study, both the natural terrain landslide records and the rainfall records from 1984 to 2013 in Hong Kong are organized. The frequency distributions of the magnitudes of hillside landslides and channelized debris flows, in terms of the number, scar area, volume, or density of the hazards, are established. Year-based correlations between the magnitudes of open hillslope landslides

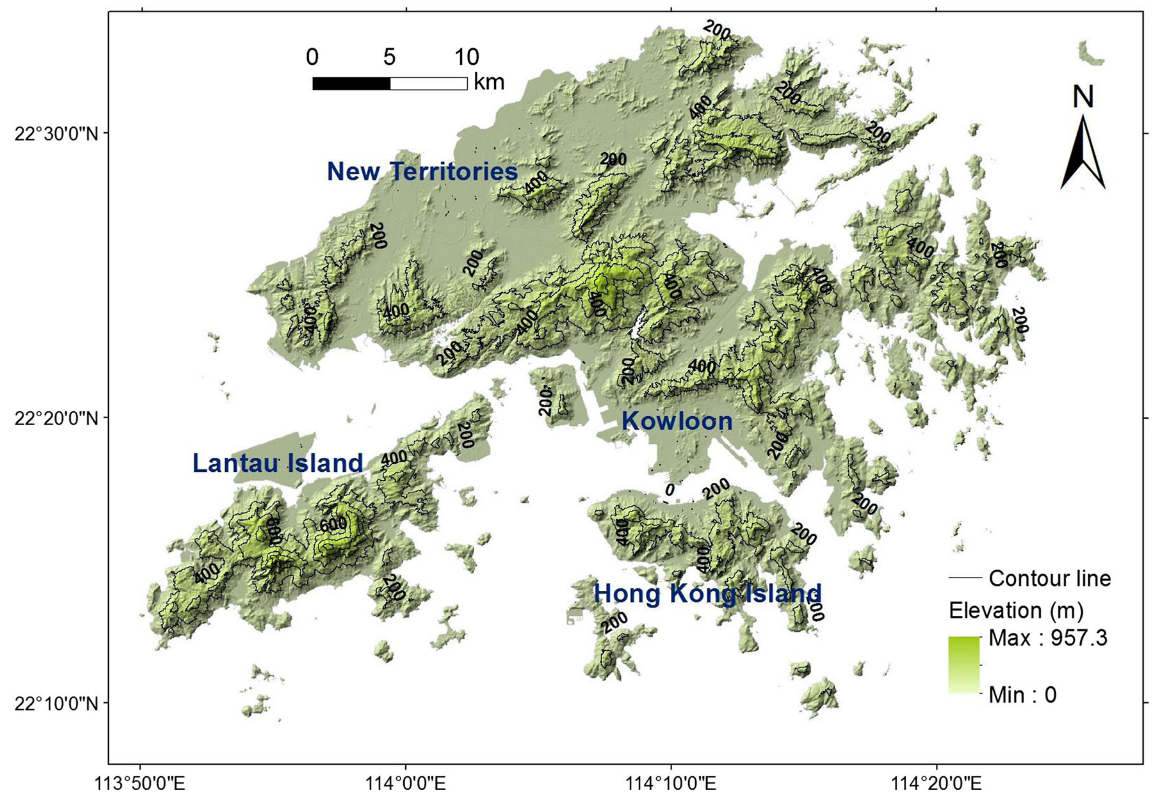

Fig. 1 Topography of Hong Kong

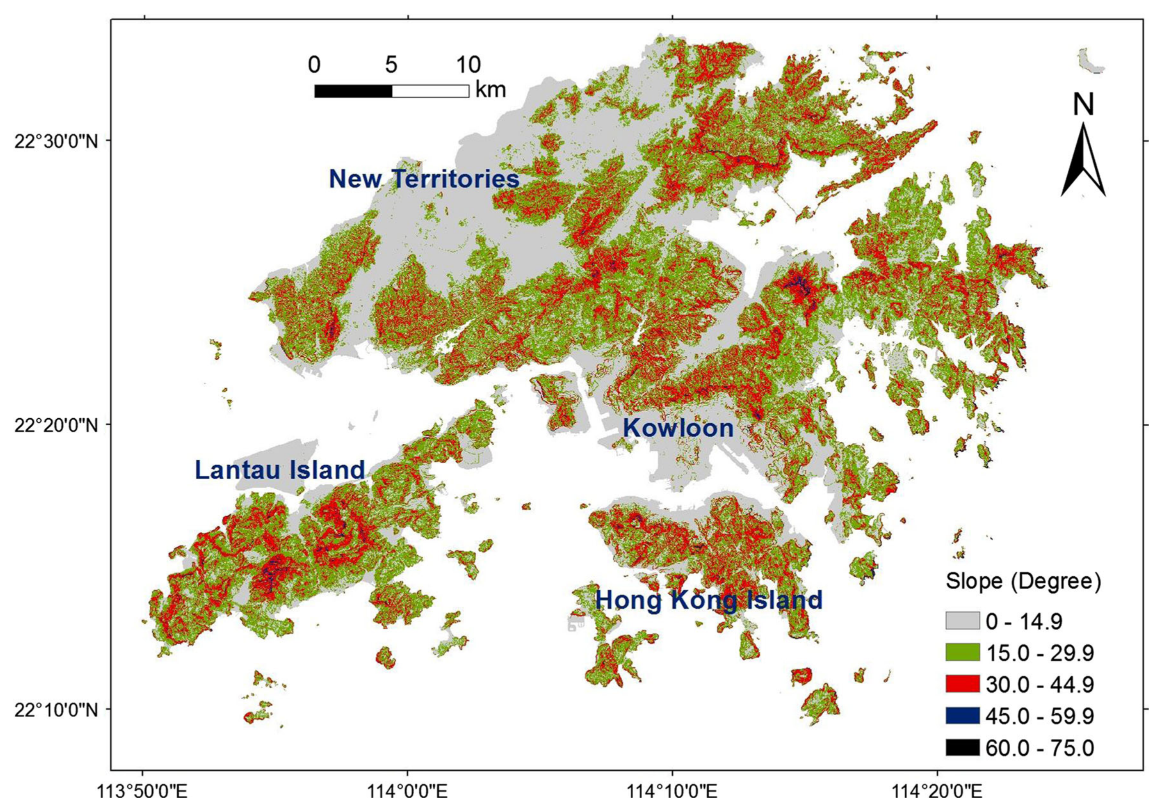

Fig. 2 Sloping angles of Hong Kong

Table 1 Maximum rolling 1-, 4-, 12-, and 24-h rainfall during 1984–2013

Year	Maximum rolling 1-h rainfall (mm)	Maximum rolling 4-h rainfall (mm)	Maximum rolling 12-h rainfall (mm)	Maximum rolling 24-h rainfall (mm)
1984	112.0	227.0	244.0	251.5
1985	132.5	227.0	231.0	305.5
1986	101.5	197.0	248.5	314.5
1987	96.0	165.5	251.0	320.0
1988	79.0	157.5	182.5	282.0
1989	105.0	194.5	408.5	566.0
1990	91.0	161.0	193.5	276.0
1991	77.5	112.5	190.0	197.5
1992	144.5	243.0	385.0	386.5
1993	117.0	285.0	575.5	742.0
1994	211.5	365.0	793.5	956.0
1995	112.0	223.5	353.0	468.0
1996	95.0	173.5	210.0	353.0
1997	128.5	262.5	435.0	800.0
1998	98.0	218.5	374.5	562.0
1999	120.5	230.5	366.0	565.0
2000	126.5	348.5	484.0	525.5
2001	132.0	230.5	312.0	323.0
2002	139.0	225.5	302.0	438.0
2003	135.0	290.5	428.5	505.0
2004	95.5	177.5	225.0	246.5
2005	117.0	196.5	337.5	570.0
2006	166.5	236.0	322.5	391.0
2007	89.5	130.0	189.5	229.0
2008	153.5	384.0	485.5	622.5
2009	97.5	169.5	207.0	250.5
2010	139.5	261.0	267.0	286.5
2011	116.5	183.0	235.5	236.5
2012	98.5	173.5	273.5	428.0
2013	153.5	207.5	262.5	323.0
Average	119.4	221.9	325.8	424.0

and channelized debris flows and the maximum rolling rainfall intensity are derived, and rainfall thresholds for triggering landslides and debris flows of different magnitudes are developed.

Study area

Hong Kong has a subtropical climate characterized by distinguished dry and wet seasons. About 85% of the annual rainfall is recorded during the wet season from April to October (AECOM and Lin 2015). Rainfall intensities of 50–100 mm/h or 250–350 mm/day are common (Ko and Lo 2016). Severe storms with hourly rainfall exceeding 200 mm/h and daily rainfall exceeding 900 mm have also been recorded. Storms with high intensity and short duration in Hong Kong are typically associated with southwest monsoons or tropical cyclones. Indeed, a rainstorm with a rolling 24-h rainfall of over 300 mm anywhere in Hong Kong, or if it has resulted in fatal landslides, is recognized as a significant rainstorm (Ko and Lo 2016).

Hong Kong has a total land area of about 1100 km^2. The topography of Hong Kong comprises steep mountainous areas and dissected valleys. The highest point is Tai Mo Shan (957 m) in New Territories. Other prominent topographic features include Victoria Peak (552 m) on Hong Kong Island and Lantau Peak (934 m) on Lantau Island. Natural terrain occupies about 60% of the land, a large proportion of which is steeply sloping. Intense urban developments have taken place in the foothill areas that are relatively flat.

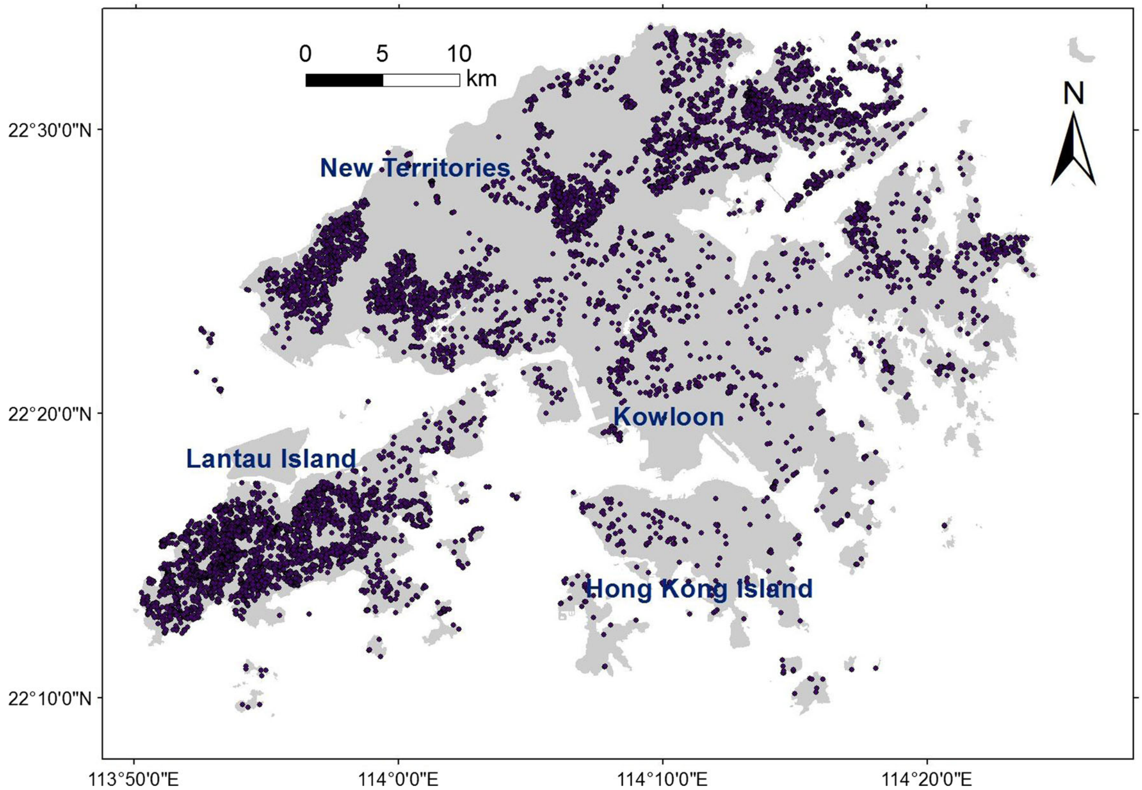

Fig. 3 Enhanced natural terrain landslide inventory during 1984–2013 (extracted from ENTLI)

LiDAR data covering the entire Hong Kong was acquired in January 2011. The vertical accuracy of this data set is ± 0.1 m, and the horizontal accuracy is ± 0.5 m. The ground surface elevation on the GIS platform is shown in Fig. 1. The slope angles can be obtained from a digital elevation model (DEM) and are shown in Fig. 2. The slopes are rather steep, ranging from 0 to 75°. Seventy-five percent of the natural terrain is steeper than 15°, and over 30% is steeper than 30°. The low-elevation areas are densely populated, especially the northern Hong Kong Island and Kowloon. Even relatively small slope failures may cause severe consequences.

Governed by the subtropical rainfall conditions and the hilly terrains, large areas of the natural terrain in Hong Kong may be susceptible to open hillslope landslides, resulting in serious consequences. For example, on 8 June 1972, the Po Shan Road landslide and the Sau Mau Ping landslide killed 138 people in a single day. In Hong Kong, The materials from slope failures mainly include saprolite, colluvium, and weathered rock. Some of these detached materials may develop into channelized debris flows with great destructive power (Zhang et al. 2014; Gao et al. 2016; Chen et al. 2016).

Available data

Automatic raingauge network

The Hong Kong Observatory (HKO) and the Geotechnical Engineering Office (GEO) have installed 110 automatic raingauges in Hong Kong since the early 1980s. The raingauge network provides real-time rainfall data at a 5-min interval. Based on readings from these raingauges, the maximum rolling 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-h rainfall in each year from 1984 to 2013 has been obtained. The maximum rolling 1-, 4-, 12-, and 24-h rainfall from 1984 to 2013 is listed in Table 1. Among a majority of years from 1984 to 2013, there was at least one significant rainstorm in a year. Probable maximum precipitation (PMP) is frequently used to quantify the magnitudes of storms, especially for extreme storm events (AECOM and Lin 2015). In 2008, the maximum rolling 4-h rainfall reached 384 mm, which has a return period of 1100 years, corresponding to 60–67% of the 4-h PMP; the maximum rolling 24-h rainfall was 622.5 mm, with a return period of 200 years, corresponding to 33–41% of the 24-h PMP. The spatial variations and correlations of three large storms in Hong Kong are described by Gao et al. (2017).

Historical year-based landslides

Numerous natural-terrain landslides have been recorded in Hong Kong in the past. GEO compiled an inventory of historical landslides in Hong Kong in the mid-1990s, which was known as Natural Terrain Landslide Inventory (NTLI) (King 1999). Since then, GEO has enhanced NTLI based on both high- and low-flight aerial photographs and expanded the inventory on an annual basis (GEO 1996; Maunsell-Fugro Joint Venture 2007). The ENTLI contains records of 19,763 recent natural terrain landslides and debris flows that occurred in the period of 1924–2013, and 89,571 relict natural terrain landslides.

In ENTLI, recent landslides are visible landslide incidents since 1924 that can be identified from aerial photographs with confirmed year of occurrence. Relict landslides occurred earlier

Table 2 Summary of numbers of landslide records during 1984–2013

Year	Open hillslope landslides	Channelized debris flows	Total number
1984	43	6	49
1985	55	17	72
1986	95	23	118
1987	35	9	44
1988	28	21	49
1989	384	285	669
1990	43	14	57
1991	18	3	21
1992	317	180	497
1993	933	780	1713
1994	563	243	806
1995	137	20	157
1996	72	26	98
1997	257	106	363
1998	308	78	386
1999	518	421	939
2000	706	205	911
2001	205	93	298
2002	44	22	66
2003	214	93	307
2004	22	5	27
2005	136	108	244
2006	63	24	87
2007	113	23	136
2008	1629	1488	3117
2009	48	16	64
2010	85	19	104
2011	34	5	39
2012	119	4	123
2013	47	14	61
Total	7271	4351	11,622

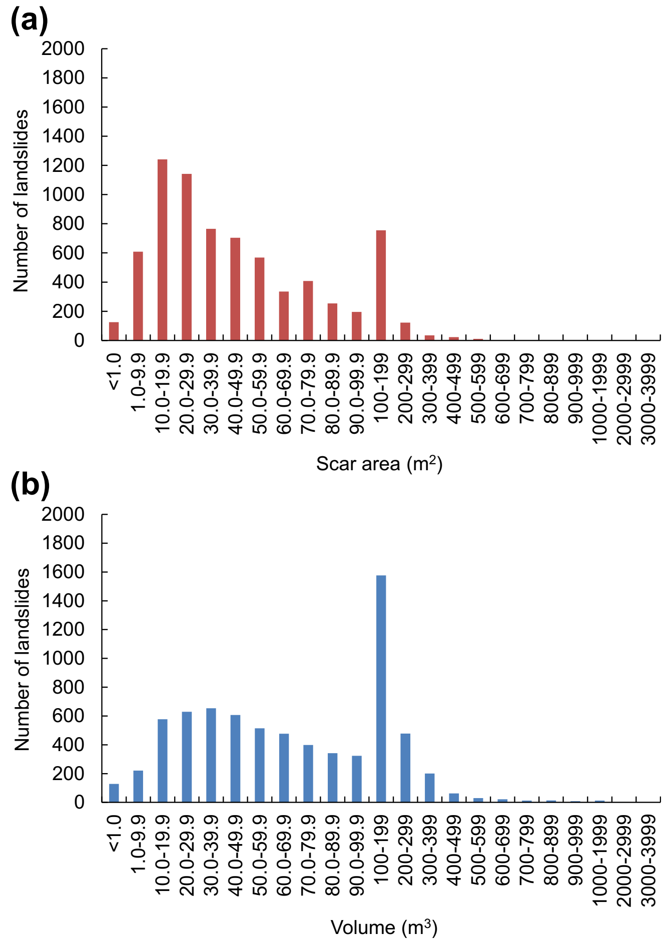

Fig. 4 Frequency distributions of **a** scar area and **b** volume of open hillslope landslides

than the time scale of aerial photos, but are identifiable in aerial photos based on indication of morphological features. The ENTLI has a resolution of 0.1 m, which is very accurate. The greatest error of the inventory results from both the subjective nature of aerial photo interpretation and the vegetation cover. Since 1984, GEO documented major landslides in open reports, which minimized chances of misidentification. Since data after 1984 are more reliable, only 11,622 records in the past 30 years since 1984 are examined and the relict landslides are not considered in this study.

The inventory data of historical natural terrain landslides were compiled into a point shapefile on the GIS platform. The information collated and compiled into the attribute tables for each entry includes occurrence year, landslide crown location, landslide classification, any actions taken for a particular landslide, average width and length of the landslide main scarp, runout distance, and elevations of the crown and toe, vegetation cover, slope angle, etc. The inventory of natural terrain landslides from 1984 to 2013 is shown in Fig. 3. Landslides are densely distributed over the territory of Hong Kong. The landslide types are classified into open hillslope failure (O), channelized debris flow (C), or coastal slope failure (S). The open hillslope landslides include block glides, block slumps, hillslope debris slides, debris avalanches, and debris flows (Varnes 1978), which are wholly on the open hillslope and are not channelized along a stream course. Open hillslope landslides may develop into channelized debris flows, which are characterized as a detached mass sliding downstream along a gully.

Open hillslope landslides and channelized debris flows are the two most common natural terrain landslide types in Hong Kong (Ko 2003; Wong et al. 2013; Ng et al. 2002) and are studied separately in this paper.

Frequency of landslides

The numbers of open hillslope landslides and channelized debris flows during 1984–2013 are listed in Table 2. In total 11,622 open

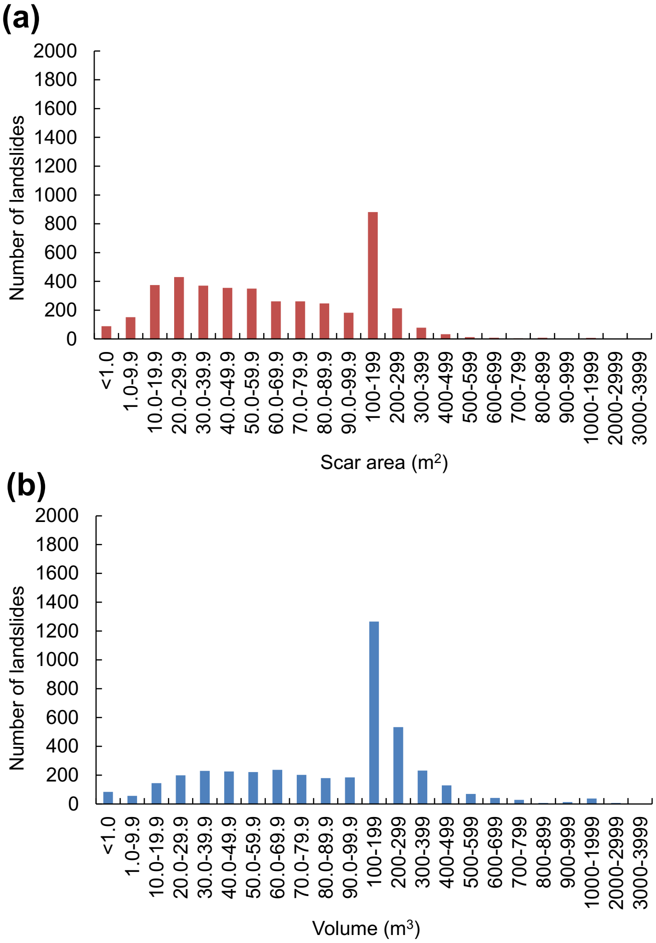

Fig. 5 Frequency distributions of **a** scar area and **b** volume of channelized debris flows

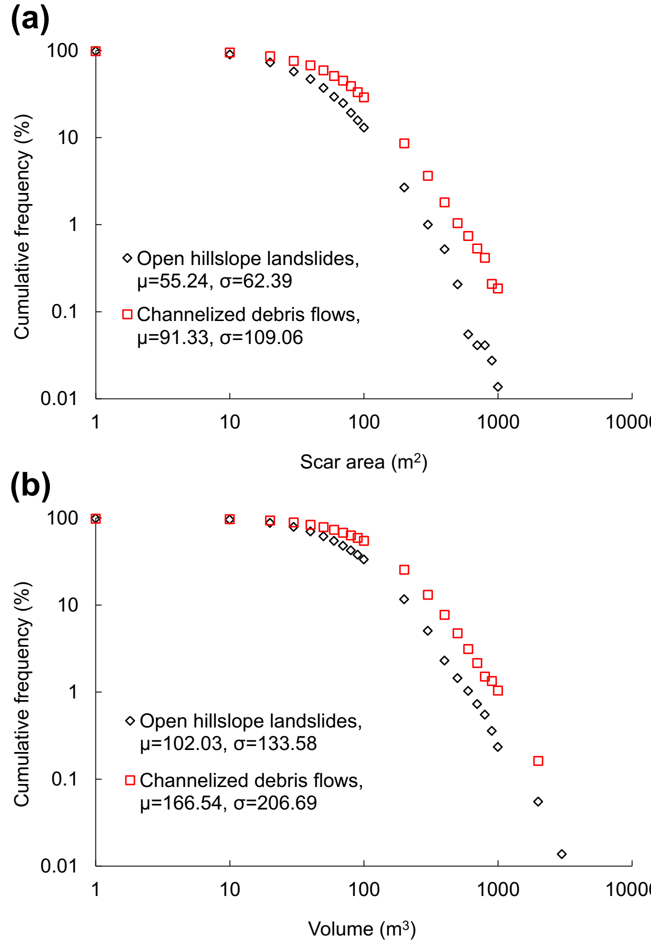

Fig. 6 Cumulative frequency: **a** scar area and **b** volume relationship of landslides. μ = mean value, σ = standard deviation

hillslope landslides and channelized debris flows were recorded. There were 6 years in which more than 500 landslides were triggered annually: 3117 landslides in 2008, and more than 500 landslides in 1989, 1993, 1994, 1999, and 2000. Open hillslope landslides took larger proportions than channelized debris flows. The numbers of channelized debris flows in these years were relatively large as well.

The data on landslide scar area and volume enables us to determine the frequency distribution of the magnitudes of landslides. The landslide scar area is computed as the product of the landslide scar width and length. The landslide volume is calculated as the landslide scar area multiplied by the average failure depth. The failure depth is considered to be negatively correlated with the slope angle, and is between 1.5 and 2.0 m according to previous field investigations (Au 1998). Those landslide cases with no width or length records are excluded in this study.

Figures 4 and 5 show the frequency histograms of open hillslope landslides and debris flows in terms of scar area and volume, respectively. There are 1241 and 1142 recorded open hillslope landslides and channelized debris flows with scar areas of 10–20 and 20–30 m^2, respectively. Approximately 10% of the open hillslope landslides are estimated to have a source area of 100–200 m^2, and 22% of the open hillslope landslides have a volume in the range of 100–200 m^3. There are approximately 20% of the debris flows with source areas ranging from 100 to 200 m^2, and 29% of the debris flows with volumes of 100–200 m^3. The mean values of the scar areas are 55.24 and 91.33 m^2, and the mean values of the volumes are 102.03 and 166.54 m^3 for the open hillslope landslides and channelized debris flows, respectively. The corresponding standard deviations are 62.39 and 109.06 m^2 for scar area, and 133.58 and 206.69 m^3 for volume, respectively.

The frequency-magnitude distribution is detected to be a power-law type according to previous studies (e.g., Hungr et al. 1999; Dai and Lee 2001). The distribution is analogous to the Gutenberg-Richter law, being a straight line in a log-log space:

$$\mathrm{Log}N = A + BM \quad (1)$$

where N is the number of landslides; M is the magnitude measured on a logarithmic scale; and A and B are coefficients. It states that the logarithm of the number of landslides N exceeding a given magnitude M is linearly related to the logarithmical magnitude.

With reference to the Gutenberg-Richter law, the cumulative frequency-volume distributions for both the open hillslope

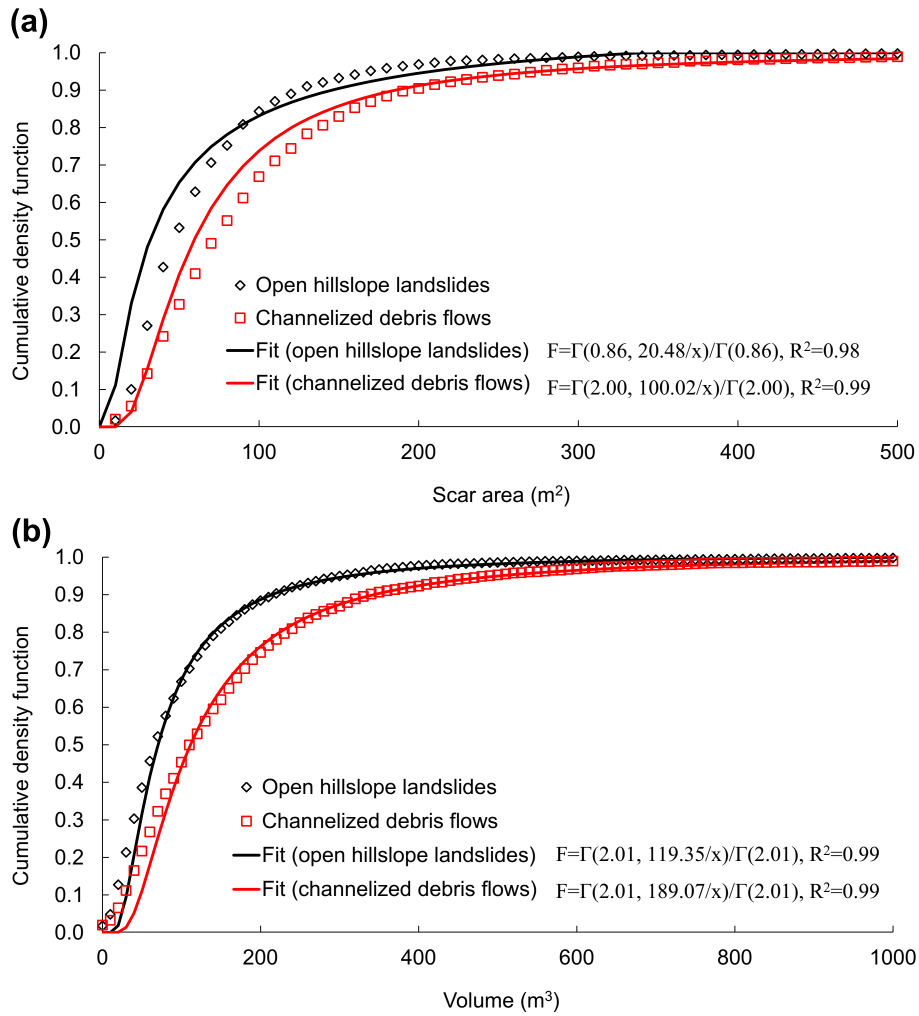

Fig. 7 Cumulative density functions and curves fitted using a regularized gamma function for **a** scar area and **b** volume of landslides

landslides and the channelized debris flows are plotted in Fig. 6. Approximately 87% of the open hillslope landslides have scar areas less than 100 m², and 67% of the open hillslope landslides have volumes less than 100 m³. Approximately 71% of the channelized debris flows have scar areas less than 100 m², and 45% of the channelized debris flows have volumes less than 100 m³. The relationships for both scar areas and volumes in Fig. 6a, b appear to be linear on a logarithmic scale when the scar areas and volumes are larger than 200 m² or 200 m³.

Since the overwhelming majority of the historical natural terrain landslides are small ones, the cumulative density functions of the scar areas and volumes of both open hillslope landslides and channelized debris flows are fitted using a regularized gamma function (Malamud et al. 2004):

$$F(x;\alpha,\beta) = \frac{\Gamma\left(\alpha,\frac{\beta}{x}\right)}{\Gamma(\alpha)} \qquad (2)$$

where α and β are parameters and obtained using least-squares fitting, and x is a variable describing the landslide scar area or volume in this study. Its corresponding probability density function is an inverse gamma distribution:

$$f(x;\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{-\alpha-1} \exp\left(-\frac{\beta}{x}\right) \qquad (3)$$

Figure 7 shows the cumulative density functions and fitting curves for the scar areas and volumes of both open hillslope landslides and channelized debris flows. The estimated α and β values for the scar areas and volumes of the open hillslope landslides are 0.86, 20.48, and 2.00, 100.02, respectively. The corresponding values for the channelized debris flows are 2.01, 119.35, and 2.01, 189.07, respectively.

Landslide magnitude-based triggering rainfall thresholds

Relationship between landslide magnitudes and rainfall intensity

The relationships between the occurrence of landslides and maximum rolling rainfall intensity in different durations are evaluated using linear regression analysis. The threshold of maximum rolling rainfall for the initiation of natural terrain landslides is

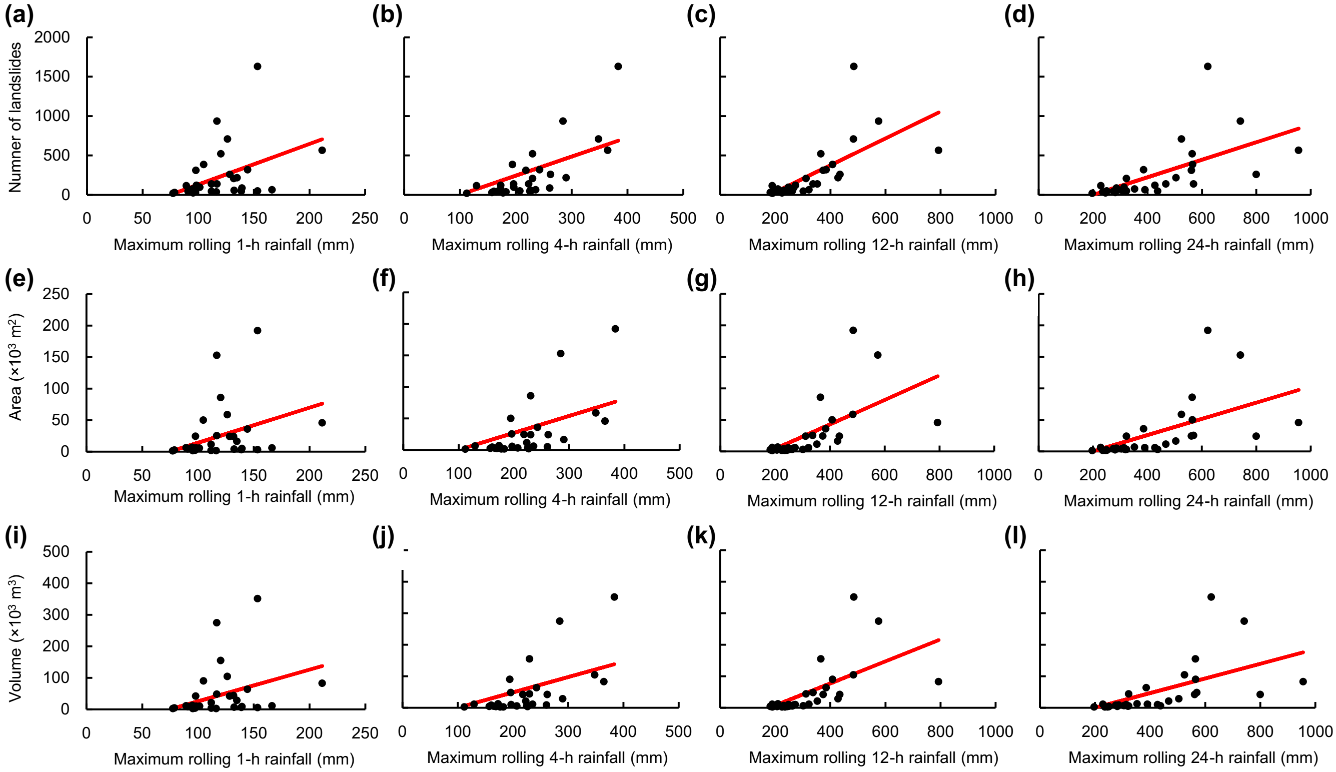

Fig. 8 Relationships between maximum rolling 1-, 4-, 12-, and 24-h rainfall and numbers (**a**–**d**), scar areas (**e**–**h**), and estimated volumes (**i**–**l**) of open hillslope landslides

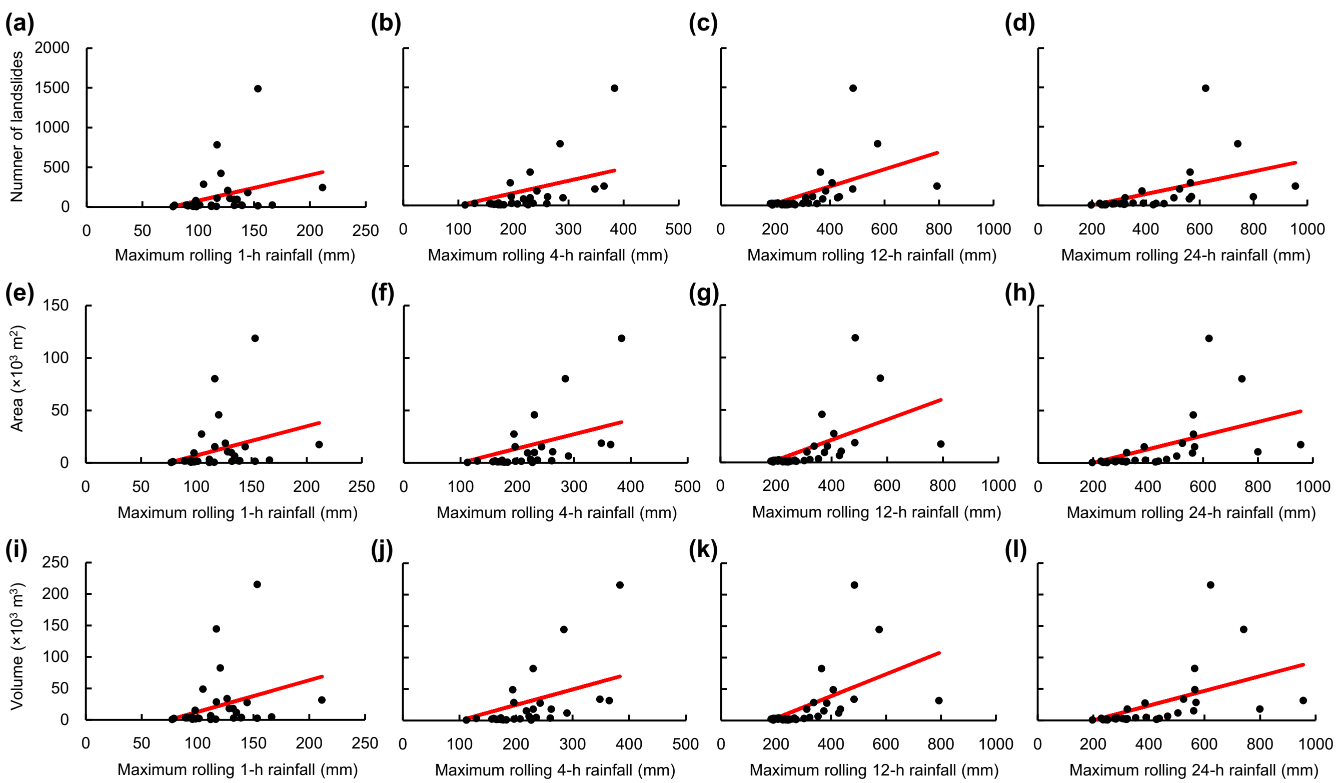

Fig. 9 Relationships between maximum rolling 1-, 4-, 12-, and 24-h rainfall and numbers (**a**–**d**), scar areas (**e**–**h**), and estimated volumes (**i**–**l**) of channelized debris flows

Table 3 Summary of mean maximum rolling rainfall thresholds

	Minimum threshold (mm)	Mean maximum rolling rainfall threshold (mm)					
		Number of open hillslope landslides			Number of channelized debris flows		
		> 500	100–500	< 100	> 500	100–500	< 100
Max. rolling 1-h rainfall	75	146	117	112	135	132	113
Max. rolling 2-h rainfall	90	215	162	154	217	178	157
Max. rolling 4-h rainfall	100	323	218	189	335	252	199
Max. rolling 5-h rainfall	110	355	234	199	377	275	210
Max. rolling 6-h rainfall	120	400	246	213	425	300	222
Max. rolling 8-h rainfall	150	451	281	226	462	349	240
Max. rolling 12-h rainfall	180	541	333	244	531	435	261
Max. rolling 24-h rainfall	200	682	452	310	682	600	328

identified as the minimum values of the rainfall listed in Table 1. In this study, the lower bounds of the maximum rolling 1-, 2-, 4-, 6-, 12-, and 24-h rainfall amounts are 75, 90, 100, 120, 180, and 200 mm, respectively.

Figure 8 shows the correlations between the numbers, areas, and volumes of open hillslope landslides and the maximum rolling 1-, 4-, 8-, and 24-h rainfall amounts from 1984 to 2013, and Fig. 9 shows the corresponding correlations for channelized debris flows. In these two figures, each of the linear correlations is fitted with a fixed intercept, defined as the minimum threshold in Table 3. The R^2 of the fitted regression lines is listed in Table 4. The occurrence of landslides is in general positively correlated to the rainfall intensity. The heavier the rainfall is, the more landslides are likely to occur. However, large differences in the number of landslides are observed for storms of similar intensities, especially for heavy rainfall events. The heavy rainfall events should be discriminated from the minor ones.

The empirical correlations in Figs. 8 and 9 may be subjected to large uncertainties when used to predict the occurrence of landslides under intense rainfall events. One uncertainty is the rainfall pattern. The recorded number of landslides in 2008 was 3117. Using the relationships with the maximum rolling 4- and 24-h rainfall in this study, however, the estimated landslide numbers are only 1131 and 773, respectively. Hence, it is important to consider the temporal rainfall profile in terms of intensity and duration to make the correlations more reliable.

With reference to Table 4, the coefficients of determination associated with the maximum rolling 1-h rainfall are the smallest. Extreme landslide numbers were recorded in 1993 and 2008, but the rolling hourly rainfall values in these 2 years were not distinct. On the contrary, the largest hourly rainfall intensity occurred in 1994, with which the deviation between the prediction and the recorded number is not large. The relationship between the maximum rolling 1-h rainfall and landslide occurrence appears to be rather complex as 1-h rainfall misses some important information such as antecedent rainfall.

The occurrence of landslides is more related with the maximum rolling 4- to 24-h rainfall indicated by larger R^2 values in Table 4. Both the occurrence, the scar areas, and the volumes of landslides can be better represented using a proper temporal rainfall profile with durations from 4 to 24 h. Intense rainfall lasting for a relatively prolonged period, 4 to 24 h, is the most dominant factor for triggering a large number of open hillslope landslides or channelized debris flows. According to previous studies (Lumb 1975; Brand et al. 1984; Dai and Lee 2001), antecedent rainfall is not a major factor as the vast majority of

Table 4 Summary of coefficients of determination R^2 of the regression between rainfall and landslides

	Open hillslope landslides			Channelized debris flows		
	Number	Area	Volume	Number	Area	Volume
Max. rolling 1-h rainfall	0.13	0.07	0.07	0.08	0.06	0.06
Max. rolling 2-h rainfall	0.27	0.18	0.18	0.18	0.16	0.16
Max. rolling 4-h rainfall	0.45	0.34	0.33	0.28	0.27	0.27
Max. rolling 5-h rainfall	0.49	0.38	0.38	0.31	0.31	0.31
Max. rolling 6-h rainfall	0.51	0.42	0.41	0.33	0.33	0.33
Max. rolling 8-h rainfall	0.52	0.42	0.42	0.31	0.33	0.33
Max. rolling 12-h rainfall	0.47	0.39	0.38	0.28	0.30	0.29
Max. rolling 24-h rainfall	0.39	0.35	0.34	0.25	0.28	0.27

Note: The values indicate the R^2 of the linear regression lines in Figs. 8 and 9. For example, the R^2 of the regression line for number of open hillslope landslides versus maximum rolling 1-h rainfall is 0.13

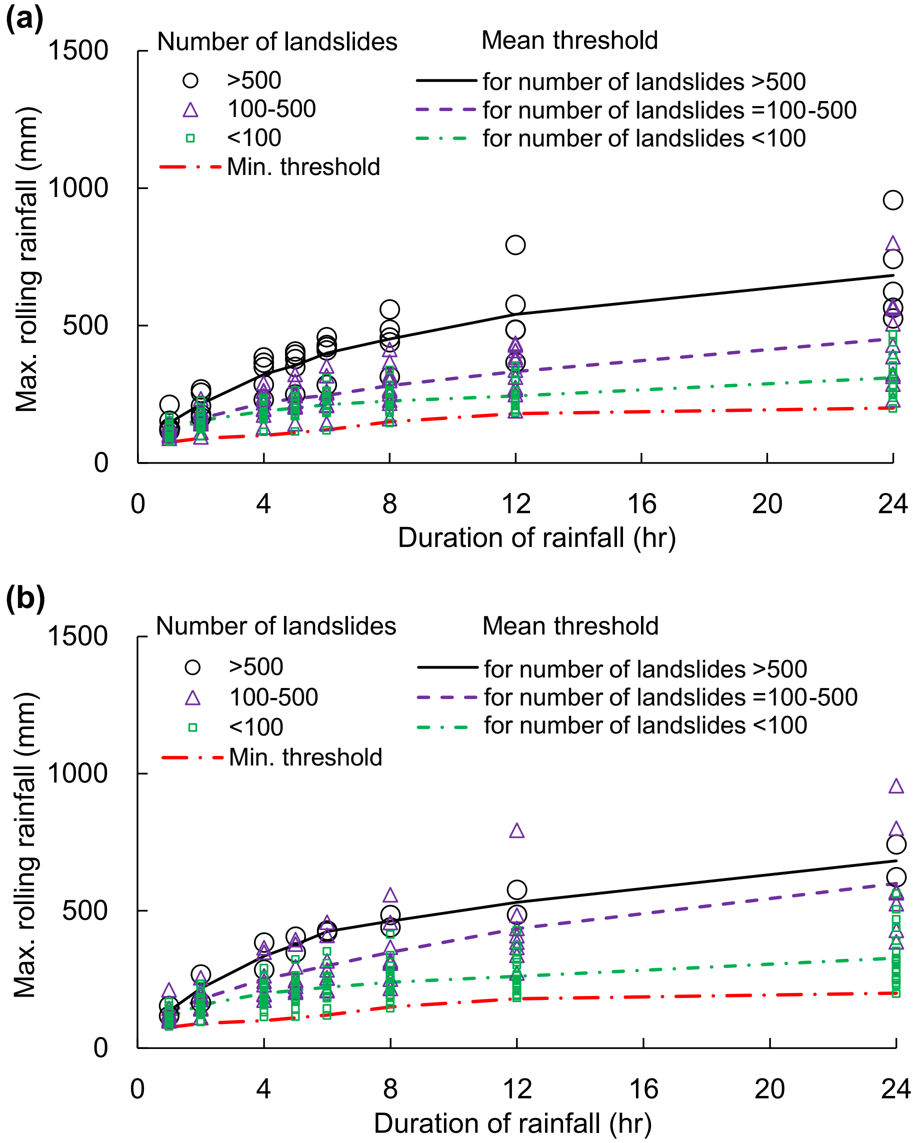

Fig. 10 Maximum rolling rainfall thresholds for triggering **a** open hillslope landslides and **b** channelized debris flows

landslides in Hong Kong were induced by localized short-duration storms of high intensity. The antecedent rainfall effect might have been eliminated after a few hours of intense rainfall.

Maximum rolling rainfall thresholds for triggering different magnitudes of landslides

The quantification of landslide magnitude is essential for landslide risk assessment and management. The numbers of both open hillslope landslides and channelized debris flows from 1984 to 2013 are divided into three categories, namely, more than 500, between 500 and 100, and less than 100. The maximum rolling rainfall thresholds for triggering natural terrain landslides of different numbers are established using the mean values of the triggering rainfall and plotted in Fig. 10. These maximum rolling rainfall thresholds for a certain range of landslide volumes do not represent the minimum values of rainfall that may possibly trigger the landslides of specified scar areas or volumes, but are the mean maximum rolling rainfall values corresponding to the specified numbers of landslides. The mean maximum rolling rainfall values are also listed in Table 3. If the maximum rolling 4-h rainfall reaches 330 mm, the numbers of open hillslope landslides and channelized debris flows may both exceed 500. The minimum thresholds are identified as 75, 90, 100, 110, 120, 150, 180, and 200 mm for the maximum rolling 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-h rainfall amounts, respectively. The minimum 1- and 24-h thresholds are consistent with those reported by Brand et al. (1984) and Premchitt (1991). Brand et al. (1984) reported that an hourly intensity of about 70 mm/h appears to be the threshold above which landslides will occur. Premchitt (1991) indicated that landslides are almost certain to occur when the 24-h rainfall exceeds 200 mm.

The rainfall thresholds for the occurrence of channelized debris flows are generally larger than those for the occurrence

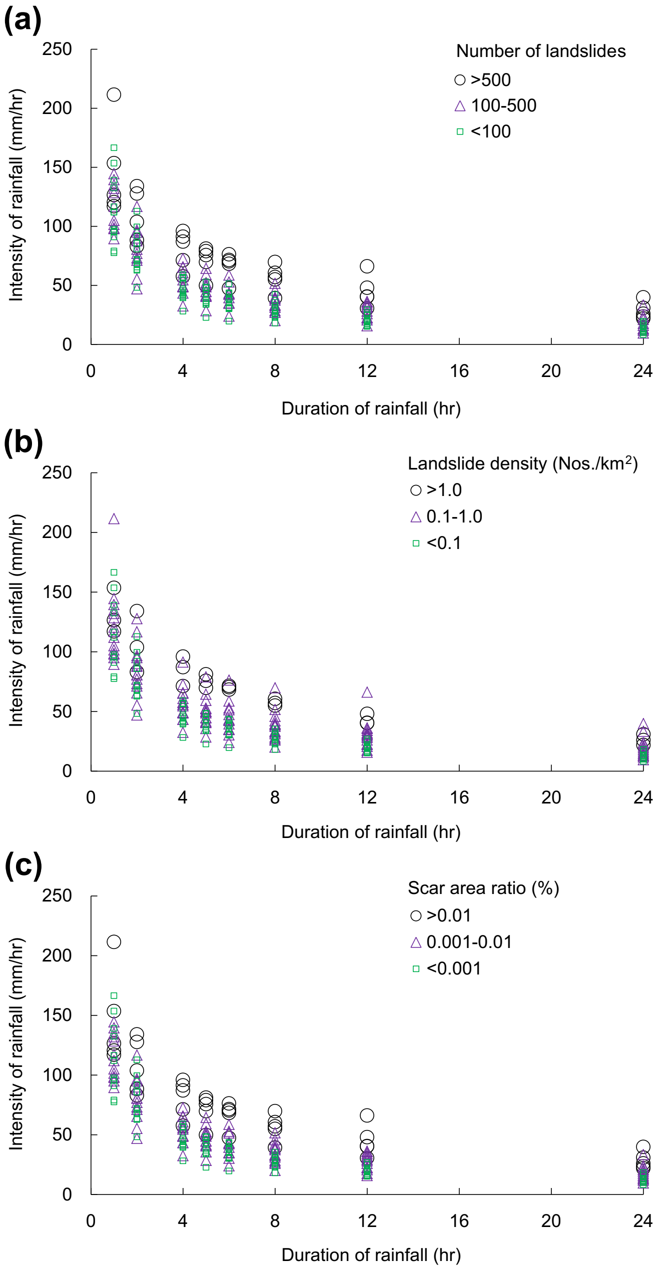

Fig. 11 Maximum rolling rainfall-open hillslope landslide magnitude relationships. **a** Number. **b** Density of occurrence. **c** Scar area ratio

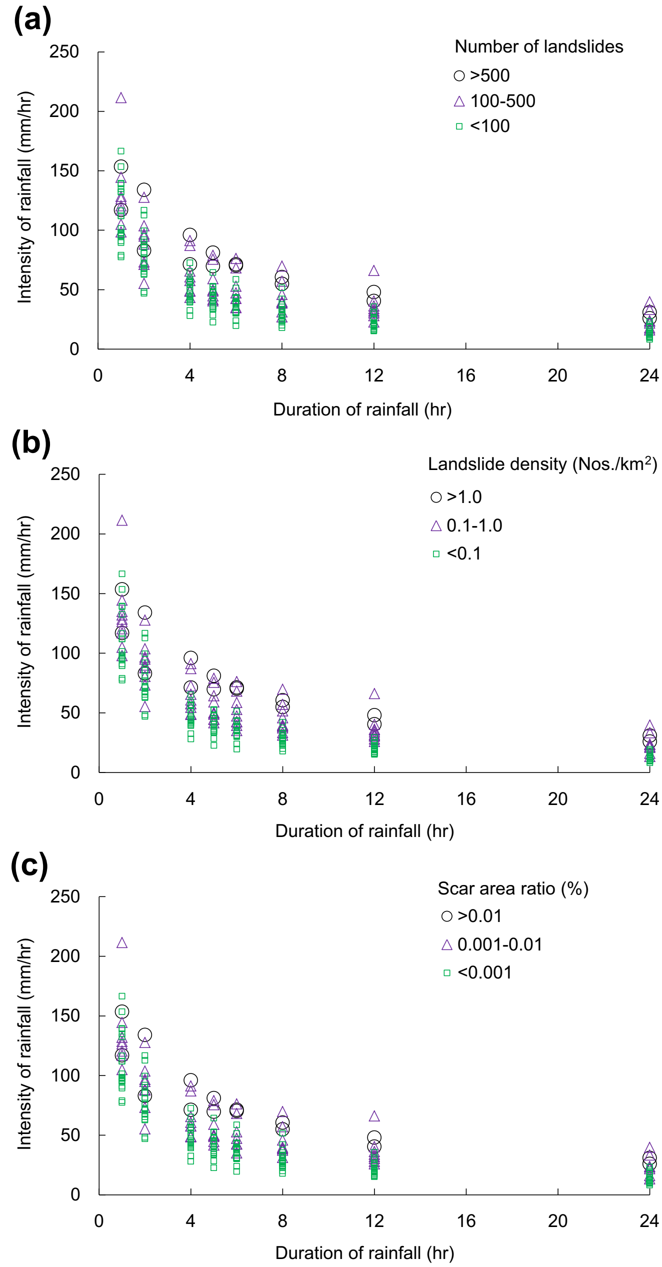

Fig. 12 Maximum rolling rainfall-channelized debris flow magnitude relationships. **a** Number. **b** Density of occurrence. **c** Scar area ratio

of open hillslope landslides. The threshold for triggering more than 100 channelized debris flows is quite close to that for triggering more than 500 landslides. Their mechanisms account for this difference: the occurrence of open hillslope landslides is one condition for the development of channelized debris flows. Open hillslope landslides in Hong Kong initiate typically from shallow slope failures, which are often caused by changes in pore-water pressure by rainwater infiltration (Au 1998; Gao et al. 2015). Some of the shallow slope failures develop into mobile debris flows, which march down the hill and enter a gully, entraining pre-existing materials there. Given high-intensity rainfall over a long period, large flash floods may also develop on mid mountains, entraining the loose materials newly or previously accumulated along the overland flow paths. Under such large rainstorm events, the number of channelized debris flows with much enlarged destructive power could increase with rainfall intensity nonlinearly. More attention should be paid to channelized debris flows under such circumstances.

Intensity-duration thresholds for triggering different magnitudes of landslides

The rainfall intensity-duration records for the numbers of open hillslope landslides and channelized debris flows are presented in Figs. 11a and 12a, respectively. The natural terrain area in Hong

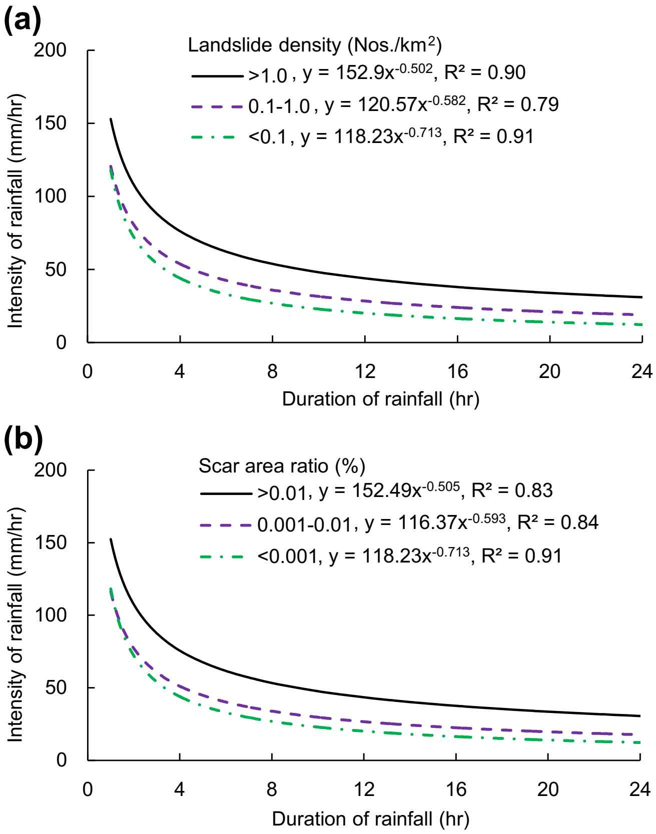

Fig. 13 Maximum rolling rainfall thresholds for triggering open hillslope landslides of **a** density of occurrence and **b** scar area ratio

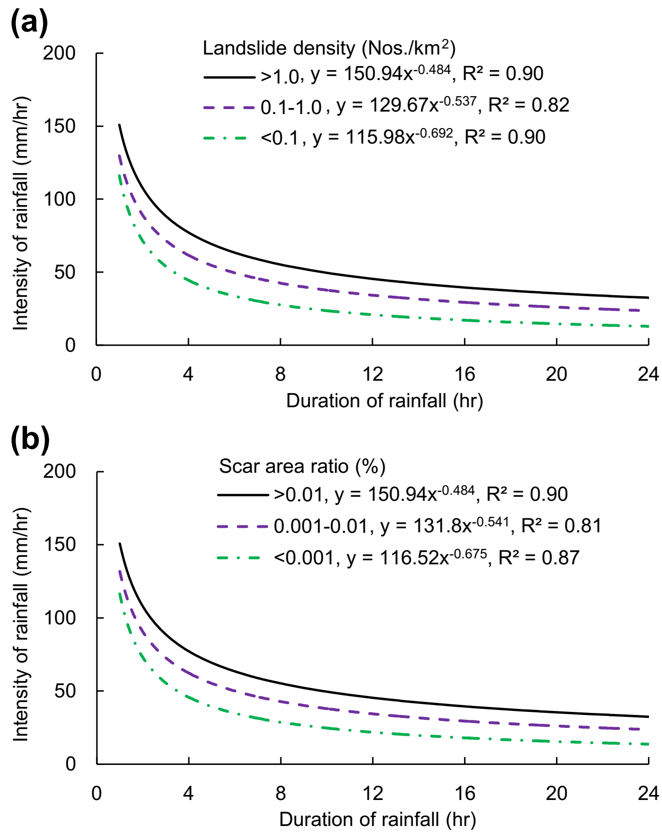

Fig. 14 Maximum rolling rainfall thresholds for triggering channelized debris flows of **a** density of occurrence and **b** scar area ratio

Kong is about 660 km^2. The landslide density in number of landslides per square kilometer can be calculated accordingly. Figures 11b and 12b depict the rainfall intensity-duration relationships for three levels of landslide densities. Since the scar areas of historical landslides in each year have been obtained, the scar area ratio per year can also be computed as the total scarp area divided by the total natural terrain area. Figures 11c and 12c present the intensity-duration relationships associated with three scar area ratios for open hillslope landslides and channelized debris flows, respectively. The rainfall intensity-duration relationships for landslide density and scar area ratio are similar.

The curves defining the rainfall intensity-duration thresholds can be fitted using a power law (e.g., Caine 1980; Guzzetti et al. 2008):

$$I = a \cdot D^{-b} \tag{4}$$

where a and b are the scale and shape of the power law curve; I is the rainfall intensity in millimeters per hour; and D is the duration in hours, ranging from 1 to 24 h. Note that the rainfall intensity here is calculated by the maximum rolling rainfall divided by its corresponding duration, which denotes the highest rainfall intensity across the entire territory of Hong Kong. Estimated a and b values are obtained using least squares fitting.

The proposed rainfall threshold curves for three different categories of density and scar area ratio for open hillslope landslides and channelized debris flows are shown in Figs. 13 and 14, respectively. These thresholds in the figures do not represent the minimum values of rainfall that may possibly trigger the landslides of the specified scar areas or volumes, but are the mean rainfall values corresponding to the specified scar areas or volumes. The R^2 for each intensity-duration threshold is quite large, ranging from 0.79 to 0.91; hence, these estimated rainfall threshold curves are associated with a high degree of confidence. These empirical thresholds can be viewed as a family of composite thresholds that are of significance to landslide risk management. When compared with the threshold curve for open and channelized debris flows derived by Jibson (1989), for which coefficients a and b are 41.83 and 0.58, respectively, the composite rainfall thresholds for Hong Kong in this study are significantly higher.

Limitations

The rainfall-landslide correlation studies in this paper are subject to several limitations:

1. The rainfall-landslide magnitude correlations and rainfall thresholds in this paper are developed only for natural terrain landslides. In the future, similar relationships for manmade slope failures should be developed.
2. The correlations and thresholds are considered in regional scale in a statistical sense. The raw temporal information stored in the landslide inventory does not allow a precise link

between rainfall and landslide occurrence. Spatial variations at local scale, particularly information on site-specific rainfall, lithology, topography, and geology, should be considered in the future (e.g., Gao et al. 2017; Xiao et al. 2017).

3. The correlations and thresholds are based on 30 years of records, and should be updated when more data is available. More precise validation work should be conducted in the future (Giannecchini et al. 2012; Martelloni et al. 2012; Segoni et al. 2014; Gariano et al. 2015; Piciullo et al. 2017) based on future rain-induced landslide events.
4. One should be cautious when extending these empirical relationships to future extreme storms not covered by the historic data during the period of 1984–2013. Hazard interactions may develop in a large storm, and cascading hazards of greater destruction power may be generated from such interactions (Zhang et al. 2014; Zhang et al. 2016).
5. Rainfall-landslide correlations based on long-term landslide records may not be applicable to regions recently stricken by strong earthquakes. In such regions, the rainfall thresholds may change rapidly due to changing material supply and topography, restoration of vegetation, and other factors (Chen et al. 2014; Zhang et al. 2013, 2016; Shen et al. 2017; Zhang and Zhang 2017).

Conclusions

In this study, the magnitudes and triggering rainfall thresholds of the open hillslope landslides and channelized debris flows in Hong Kong during the period of 1984–2013 are assessed based on the Enhanced Natural Terrain Landslide Inventory (ENTLI) with 19,763 records. These empirical correlations and triggering rainfall thresholds are essential to landslide risk management. Based on the study, the following conclusions can be drawn:

1. The frequency distributions of both the open hillslope landslides and the channelized debris flows in Hong Kong are established. Approximately 87% of the open hillslope landslides have scar areas less than 100 m^2, and 67% of the open hillslope landslides have volumes less than 100 m^3. Approximately 71% of the channelized debris flows have scar areas less than 100 m^2, and 45% of the channelized debris flows have volumes less than 100 m^3. The mean values of the scar areas and volumes of the open hillslope landslides are 55.2 m^2 and 102.0 m^3, respectively, and those for the channelized debris flows are 91.3 m^2 and 166.5 m^3, respectively.
2. Linear correlations combining landslide occurrences, scar areas, volumes, and maximum rolling rainfall in different periods have been derived. The rainfall intensity-duration thresholds for identifying the likely rainfall conditions that yield natural terrain landslides of certain magnitudes have also been proposed. The rainfall thresholds are quantified for three levels of landslide magnitudes for both open hillslope landslides and channelized debris flows.
3. To improve the accuracy of the rainfall-landslide magnitude correlations, maximum rolling rainfall with relatively prolonged profiles need to be included. The maximum rolling 4- to 24-h rainfall amounts are found to provide better predictions for the numbers, scar areas, and volumes of landslides compared with those with the maximum rolling 1-h rainfall.
4. The minimum rainfall thresholds for initializing landslides are identified as 75, 90, 100, 110, 120, 150, 180, and 200 mm for the maximum rolling 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-h rainfall, respectively. If the maximum rolling 4-h rainfall reaches 330 mm, statistically more than 500 open hillslope landslides and 500 channelized debris flows can occur in Hong Kong.

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