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ORIGINAL ARTICLE

Estimation of the antecedent rainfall period for mass movements in Taiwan

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Abstract

Antecedent rainfall plays an important role in rainfall-induced mass movements. However, it is difficult to define the appropriate period of antecedent rainfall for mass movement assessment. To solve this problem, this study provides a simple approach that combines calibrated antecedent rainfall (CAR) and 24-h rainfall for 283 mass movements that occurred in Taiwan from 2006 to 2013. The 24-h rainfall at the time of each mass movement was compared with the total cumulative rainfall for various periods preceding the event. The lowest correlation was found for the total cumulative rainfall from 15 to 20 days before a mass movement day. The 24-h rainfall was compared with the cumulative CAR values for various days of antecedent rainfall. The effect of cumulative CAR on mass movements increased from 22.0 to 39.7% when the number of days considered was increased from 3 to 30 days. However, the increase became gradual after 15–18 days. In addition, the critical antecedent rainfall conditions occurred within 18 days before mass movements in all cases. These results suggest that the antecedent rainfall of 15–18 days is useful for mass movement assessment in Taiwan. This study also established a critical antecedent rainfall threshold for mass movements in Taiwan that is useful for early warnings: $I_a = 28.7\,D_a^{-1.24}$, where I_a is critical mean rainfall intensity during the antecedent rainfall period up to 18 days (mm/day) and D_a is the length of the antecedent rainfall period. According to the relationship between 24-h rainfall and the critical antecedent rainfall conditions, low antecedent rainfall intensity that continues for a long time leads to a gradual increase in soil moisture such that a small amount of 24-h rainfall can trigger mass movements. On the other hand, high antecedent rainfall intensity for a short time is not enough to increase soil moisture, and a large amount of 24-h rainfall is needed to flush surface materials and cause mass movements.

Keywords Mass movements · Absolute antecedent rainfall · Calibrated antecedent rainfall · Intensity–duration threshold · Critical rainfall · Soil moisture

Introduction

Mass movements such as landslides and debris flows are caused by various factors affecting slope stability (Keefer 1984; Guzzetti et al. 2002; Malamud et al. 2004a, b). Among them, meteorological factors are the primary external force control on the amount of available water for infiltration into soil and rocks (Fukuoka 1980; Crozier 1986; Wieczorek 1996). It is well known that rainfall has dominant effects on triggering mass movements in the mountainous areas of different countries. Rainfall-induced mass movements are now among the most common natural hazards worldwide (Xie et al. 2004; Chang et al. 2008; Pradhan and Lee 2010). The influence of rainfall on mass movements differs substantially, depending upon the mass movement dimensions, kinematics, and materials involved. Usually, shallow mass movements are triggered by high-intensity rainfall within

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a short duration, while most deep-seated mass movements are related to rainfall lasting for a long period (Lumb 1975; Brunsden 1984; Cannon and Ellen 1985; Wieczorek 1987; Crosta 1998; Polemio and Sdao 1999; Flentje et al. 2000; Bonnard and Noverraz 2001; Trigo et al. 2005; Chen et al. 2017). Therefore, to understand the relationship between the initiation of mass movements and rainfall conditions, many previous studies have addressed the rainfall intensities (*I*) and durations (*D*) related to mass movements. Caine (1980) first proposed the *I*–*D* threshold for landslides and debris flows. Keefer et al. (1987) successfully predicted the time of major landslides in a rainstorm event by using the *I*–*D* threshold. In early years, these thresholds were determined manually (Caine 1980; Keefer et al. 1987; Larsen and Simon 1993; Chen et al. 2005). More recently, however, mathematical and/or statistical criteria have been used to objectively determine the threshold. Guzzetti et al. (2007) were the first to propose the Bayesian inference method for determining *I*–*D* thresholds; Brunetti et al. (2010) proposed a frequentist approach; and Saito et al. (2010) adopted the quantile-regression method. The *I*–*D* threshold was established based on the corresponding rainfall events for mass movements. However, many previous studies pointed out that antecedent rainfall also plays an important role in the initiation of mass movements (Glade 1997; Crozier 1999; Glade et al. 2000; Guzzetti et al. 2007, 2008; Dahal and Hasegawa 2008; Chen et al. 2015). The issue of the period of antecedent rainfall is still debated today (Crozier 1986, 1999; Kim et al. 1991; Glade et al. 2000; Aleotti 2004; Dahal and Hasegawa 2008; Khan et al. 2012). Actually, different researchers (Lumb 1975; Pasuto and Silvano 1998; Cardinali et al. 2006) have found that various periods (numbers of days) of antecedent rainfall correlate well with the initiation of mass movement.

Taiwan is highly susceptible to mass movements due to its high-relief topography, complex geological conditions, and frequent heavy storms and earthquakes. Rainfall-induced mass movements in Taiwan have been widely investigated. For example, Chen and Su (2001) pointed out that developed discontinuities on valley sides are the major source of materials for debris flows and that when heavy rainfall leads to increase in soil moisture content and the groundwater table, the safety factor of a slope will drop drastically and failure will occur. Chuang et al. (2009) also found that areas with higher densities of discontinuities in rocks are more prone to rainfall-induced mass movements. Antecedent rainfall has also been found to be one of the most important factors in triggering mass movements in Taiwan (Wu and Chen 2009; Chen et al. 2015). Surprisingly, few studies have discussed the length of the period that should be considered for the antecedent rainfall of mass movements in Taiwan. Currently, the Taiwanese government monitors and predicts possible mass movements using 7 days for antecedent rainfall, but without sufficient justification. Chen et al. (2015) established *I*–*D* thresholds for mass movements in Taiwan and analyzed antecedent rainfall for 7 days before mass movement–rainfall events, following some previous studies of other countries. It is important to clarify the period of antecedent rainfall for mass movements in Taiwan. Therefore, the objectives of this study were to analyze antecedent rainfall conditions to determine the length of the period that should be considered for the antecedent rainfall of mass movements in Taiwan and to establish the antecedent rainfall threshold for mass movements in Taiwan.

Study area

The island of Taiwan resulted from collision of the Luzon arc on the Philippine sea plate and the Asian continental margin, with the Philippine Sea plate moving toward the Eurasian Continental plate at a rate of 80 mm/year (Teng 1990; Yu et al. 1997; Dadson et al. 2003). The subduction of the Philippine Sea plate beneath the Eurasian Continental plate resulted in the formation of an active mountain belt called the Central Range, which has over 200 peaks higher than 3000 m above sea level (Ho 1986; Teng 1990). It is also responsible for frequent large earthquakes, and the collision has propagated southward over the past 5 Myr, with marine terrace uplift and exhumation rates of 5–7 mm/year (Li 1976; Willett et al. 2003). Analyses of topographical conditions in Taiwan show that about 32% of Taiwan is above 1000 m and that the slope of mountainous areas is mostly between 30° and 50° (Chen et al. 2015).

The geographic location of Taiwan is between 120°E and 122°E and between 22°N and 25°N, and the boundary between tropical and subtropical-monsoon climates is located in southern Taiwan (Wang and Ho 2002). The average temperature over the Taiwanese lowlands during the wet season (May to October) is above 20 °C, while that during the dry season (November to April) is between 14 and 20 °C. The central and southern parts of Taiwan are mountainous, so the average temperatures are lower there than in other regions of the country (Chen et al. 2015). On average, four typhoons strike Taiwan every year (Wu and Kuo 1999). The heavy, concentrated rainfall results in an average annual rainfall over Taiwan of 2500 mm (Shieh 2000). Approximately 60–80% of the annual rainfall occurs during the wet season (Chen et al. 2015).

Mass movements represent the primary mechanisms of erosion and are important for maintaining balance between erosion and uplift in Taiwan (Dadson et al. 2003). The frequent heavy rainfall and earthquakes lead to mass movements in the mountainous areas in Taiwan. In addition, Taiwan also has a fragile geological environment, and areas that display a high density of geological discontinuity are prone to mass movements (Chen et al. 1999; Chen and Su 2001; Chuang et al. 2009).

Data and methods

Mass movement data

A total of 283 rainfall-induced mass movements were collected from the reports of the Soil and Water Conservation Bureau (SWCB) of Taiwan for the 8-year period of 2006–2013 (Fig. 1). According to the classification of landslides developed by Varnes (1978), all these mass movements belong to the categories of slide (rotational and translational) and flow types. Although mass movements occur frequently in Taiwan due to the frequent large earthquakes and heavy rainfall, no complete record with very detailed information exists. In 2006, the SWCB started to conduct detailed field surveys when mass movements damaged houses and roads so as to prevent secondary disasters and ensure quick recovery. That bureau compiles information on the type, location, and approximate time (accuracy in hours) of each disaster event and publishes annual reports. The occurrence time of each mass movement event is calculated based on real-time videos taken at observation stations, the times at which people report the disasters, and interviews with residents. In addition, some of the 283 mass movement cases may have moved several times in separate periods. In this study, the occurrence time of each mass movement was defined as the time when a mass movement first moved. As these reports sometimes also included mass movements related to triggering factors other than rainfall (e.g., earthquakes), we carefully checked all reports ($n = 314$) and excluded data on events that were not caused by rainfall. The relatively high integrity and consistency of the data collected by the SWCB indicate that at this time, these data are the best available for analyzing the characteristics of rainfall-induced mass movements in Taiwan.

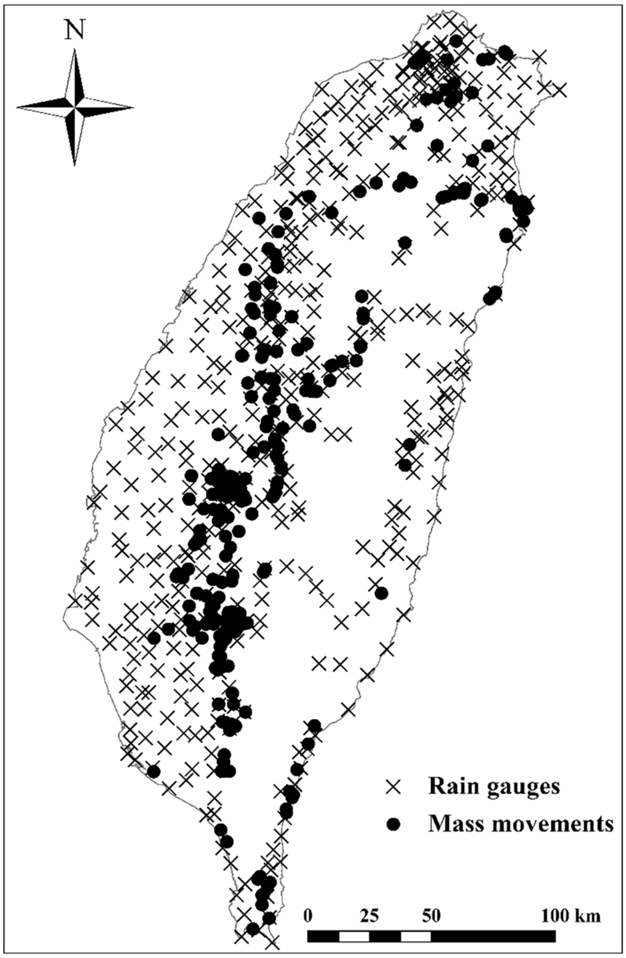


Fig. 1 Rain gauge distribution and mass movements occurring in 2006–2013 in Taiwan

Rainfall data

In Taiwan, more than 400 rain gauges for recording hourly rainfall data have been installed by Taiwan's Central Weather Bureau (Fig. 1). These rain gauges are the tipping-bucket type, which can automatically record data. Despite the abundance of rain gauges in Taiwan, relatively few rain gauges have been installed in mountainous areas; hence, rain gauges are not always located close enough to mass movement sites. For this reason, we selected the nearest five rain gauges for each mass movement and conducted a kriging interpolation using the ordinary kriging and the spherical semivariogram model to estimate rainfall at each mass movement location. This study separated rainfall into 24-h rainfall at mass movements (cumulative rainfall from 24 h before mass movements) and antecedent rainfall (precipitated earlier than 24 h before mass movements). Furthermore, by separating the antecedent rainfall every 24 h as the daily antecedent rainfall (Fig. 2), we were able to calculate the absolute antecedent rainfall (AAR) for various days as below:

$$\mathrm{AAR}_x = R_1 + R_2 + \cdots + R_n \tag{1}$$

where AAR_x is the cumulative absolute antecedent rainfall for day x, R_1 is the daily rainfall for the day before x, and R_n is the daily rainfall for the nth day before day x.

Calibrated antecedent rainfall (CAR)

The absolute total amount of antecedent rainfall during a long period will not provide a complete effect on mass movements. Its effect decreases over time due to drainage, evapotranspiration, and other processes (Canuti et al. 1985; Crozier 1986, 1999; Glade et al. 2000). To consider this decreased effect of antecedent rainfall over time on mass

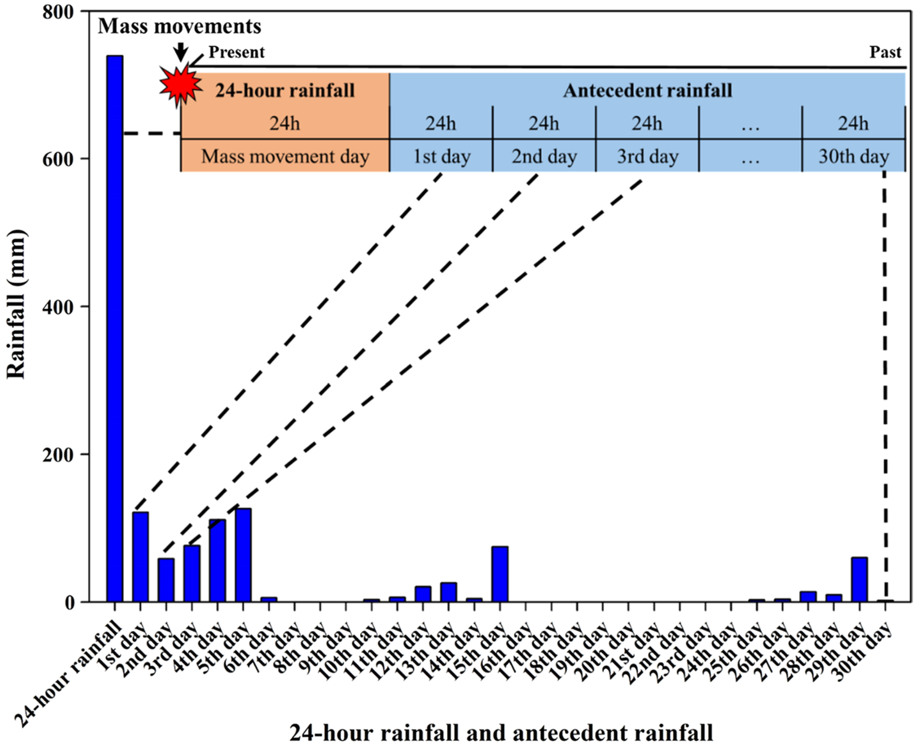


Fig. 2 Definitions of 24-h rainfall and antecedent rainfall for mass movements

movements, Crozier (1986) proposed that calibrated antecedent rainfall can be calculated as below:

$$\mathrm{CAR}_x = KR_1 + K^2R_2 + \cdots + K^nR_n, \quad (2)$$

where CAR_x is the calibrated antecedent rainfall for day x, and K is an empirical parameter depending on characteristics of the draining capacity and hydrology of an area (Capecchi and Focardi 1988). In general, the K value ranges between 0.8 and 0.9. However, the government of Taiwan usually uses a K value of 0.7 because they only assess the antecedent rainfall of 7 days before mass movements (Soil and Water Conservation Bureau 2016). Previous studies pointed out that a K value of 0.9 is best for assessing 30-day antecedent rainfall before the day of mass movements (Marques et al. 2008; Khan et al. 2012). This study used calibrated antecedent rainfall with a K value of 0.9 for the following analyses.

Comparing 24-h rainfall and antecedent rainfall

Antecedent rainfall plays a significant role in triggering mass movements because it gradually increases the ground water level, soil moisture, and pore water pressure (Wieczorek and Glade 2005). To determine the effect of antecedent rainfall on mass movements, this study compared the 24-h rainfall at mass movements with the total cumulative rainfall (including 24-h rainfall and antecedent rainfall) from different numbers of days before mass movements. The correlation coefficients between them became lower when the considered days of antecedent rainfall increased because the effect of antecedent rainfall increased (Dahal and Hasegawa 2008). In addition, this study also analyzed the scattered population of 24-h rainfall at mass movements and cumulative antecedent rainfall of various numbers of days before the mass movement day. The area of the plot was divided into two halves by a diagonal line to distinguish x-axis- and y-axis-biased scattering. The divider line in the plot indicated that 24-h rainfall and antecedent rainfall were the same at the time of mass movements. This line acts as a guideline to whether 24-h or antecedent rainfall regulates mass movements (Dahal and Hasegawa 2008). In this study, the cumulative antecedent rainfalls of 3, 7, 10, 15, 20, and 30 days before mass movements were used. Then we calculated proportions for the cases regulated by 24-h rainfall and the cases regulated by antecedent rainfall among the 283 mass movement events, and those values were used as the effects of 24-h rainfall and antecedent rainfall, respectively.

Critical rainfall threshold of antecedent rainfall

An established rainfall threshold for mass movements from antecedent rainfall can provide information for early warnings because possible mass movements can be identified at an earlier stage by their antecedent conditions. The most popular rainfall threshold worldwide is the rainfall intensity–duration (*I*–*D*) threshold, which is identified on an *I*–*D* plot as the minimum rainfall total for which a mass movement could occur (e.g., Chen et al. 2015). Although many different methods have been proposed (Guzzetti et al. 2007;

Brunetti et al. 2010; Saito et al. 2010; Chen et al. 2015), the general form of the relationship between rainfall intensity and duration is:

$$I = \alpha D^{-\beta}, \tag{3}$$

where α is a scaling constant (intercept) and β is the shape parameter (slope).

In order to establish the critical rainfall threshold from antecedent rainfall, this study used the highest calibrated mean rainfall intensity during the antecedent rainfall period (I_a) and the length of the antecedent rainfall period (D_a) to establish the intensity–duration relationship. For each mass movement event, we calculated the average rainfall intensities corresponding to different days of antecedent rainfall to determine the maximum average rainfall intensity, which is used as I_a, and the number of corresponding days of antecedent rainfall, which is used as the D_a. Then the frequentist statistical method was adopted, with 5% defined as the critical I_a–D_a threshold for mass movements (Chen et al. 2015).

Results

Rainfall conditions for mass movements

The 24-h rainfall for the 283 mass movements in 2006–2013 ranged from 38.5 to 1252.6 mm, with an average of 490.4 mm. *AAR* of 30 days before the mass movement day was 96.9–1496.7 mm, with an average of 497.7 mm. After calibration, CAR of 30 days was between 28.6 and 842.0 mm with an average of 259.2 mm (Table 1). The lowest 24-h rainfall (38.5 mm) was for the case of a 100-m^2 landslide that occurred in 2013 with high AAR of 841.5 mm and high CAR of 337.4 mm. Despite the small amount of 24-h rainfall, the large amount of antecedent rainfall destabilized the slopes, resulting in a landslide when there was almost no rainfall. The lowest AAR of 30 days (96.9 mm) was for the case of a 5×10^3-m^2 landslide that occurred in 2008 after 24-h rainfall of 283.7 mm. The roles of factors other than rainfall appear to be important. We found from the report that the lithology of the landslide location was sedimentary rocks and it had a slope of 45–60°, resulting in a landslide despite the small impact of corresponding and antecedent rainfall. The lowest CAR of 30 days (28.6 mm) was for the case of a debris flow that occurred in 2007 with a high 24-h rainfall of 313.5 mm. The debris flow occurred 1 h after the peak rainfall intensity of 50 mm/h. The high rainfall intensity flushed surface materials and caused the debris flow despite the small amount of antecedent rainfall. Overall, for about 76.7% of mass movements, the ratio of cumulative AAR of 30 days and 24-h rainfall was between 0.5 and 2.0. Even after calibration, 49.1% of mass movements still had ratios above 0.5 (Fig. 3). This large amount of antecedent rainfall contributed to the occurrence of mass movement. The trends of the percentage of mass movement events in different ranges of ratios of cumulative antecedent rainfall of 30 days and 24-h rainfall for AAR and CAR were very similar. However, the percentages in the range of the ratios for AAR and CAR, 0–0.5, were quite different. This means that using AAR to estimate antecedent rainfall will lead to overestimation in many cases. This also indicates the necessity of using CAR on the estimation of antecedent rainfall, which can account for the decrease in the antecedent rainfall effect over time due to drainage, evapotranspiration, and other processes.

Table 1 24-h rainfall and 30-day cumulative antecedent rainfall for mass movements

Rainfall conditions	24-h (mm)	AAR (mm)	CAR (mm)
Average	490.4	497.7	259.2
Max.	1252.6	1496.7	842.0
Min.	38.5	96.9	28.6

Comparing 24-h rainfall and antecedent rainfall

Figure 4 shows the results of 24-h rainfall correlated with the total cumulative rainfall amounts from 3, 7, 10, 15, 20, and 30 days before the mass movement day. The scattered data show relevant correlation coefficients of $r^2 = 0.919$, 0.896, 0.893, 0.891, 0.891, and 0.893 for 3-, 7-, 10-, 15-, 20-, and 30-day intervals, respectively. The correlation coefficients were lower when the number of days of cumulative rainfall was higher. The lowest correlations appeared at the 15- and 20-day intervals.

The results of the relationship between 24-h rainfall at mass movements and cumulative *CAR* of various days (3, 7, 10, 15, 20, and 30 days) for antecedent rainfall are plotted in Fig. 5. The divider line in each graph acts as a guideline to whether 24-h rainfall or cumulative CAR regulated mass movements. As shown in Fig. 5, when 3-day cumulative *CAR* before the mass movement day was plotted against 24-h rainfall at mass movements, nearly 78.0% of mass movements were biased toward the y-axis (i.e., 24-h rainfall at mass movements), which means that, out of 283 mass movement events, 78.0% of the events occurred under the influence of 24-h rainfall. This effect decreases to 66.0, 64.5, 61.4, 61.0, and 60.3% for 7, 10, 15, 20, and 30 days of cumulative CAR, respectively.

Critical antecedent rainfall threshold

As previously stated, this study adopted the frequentist method to establish the critical antecedent I_a–D_a thresholds

Fig. 3 Percentage of mass movement events in different ranges of ratios of cumulative antecedent rainfall of 30 days and 24-h rainfall

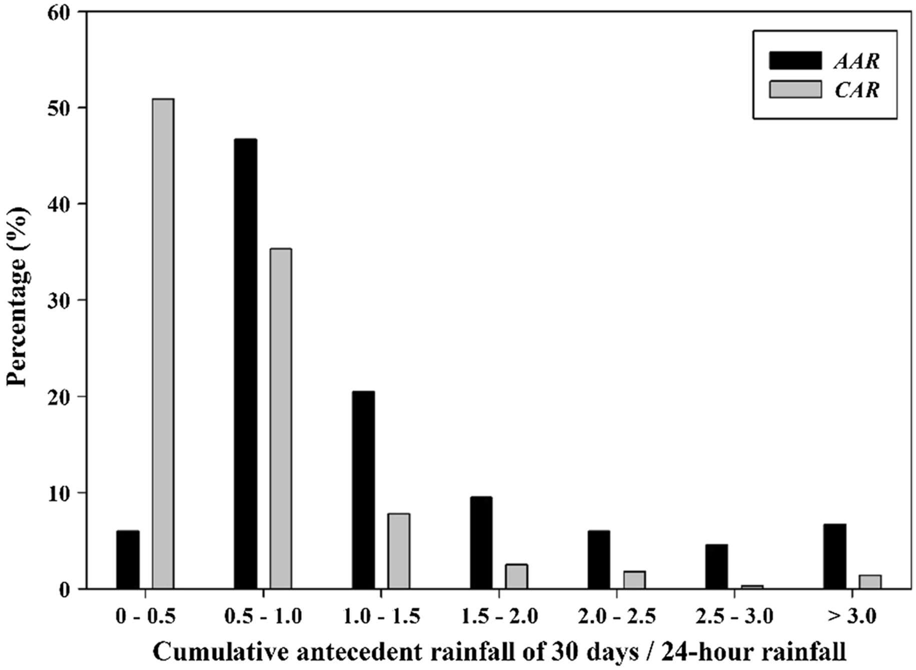
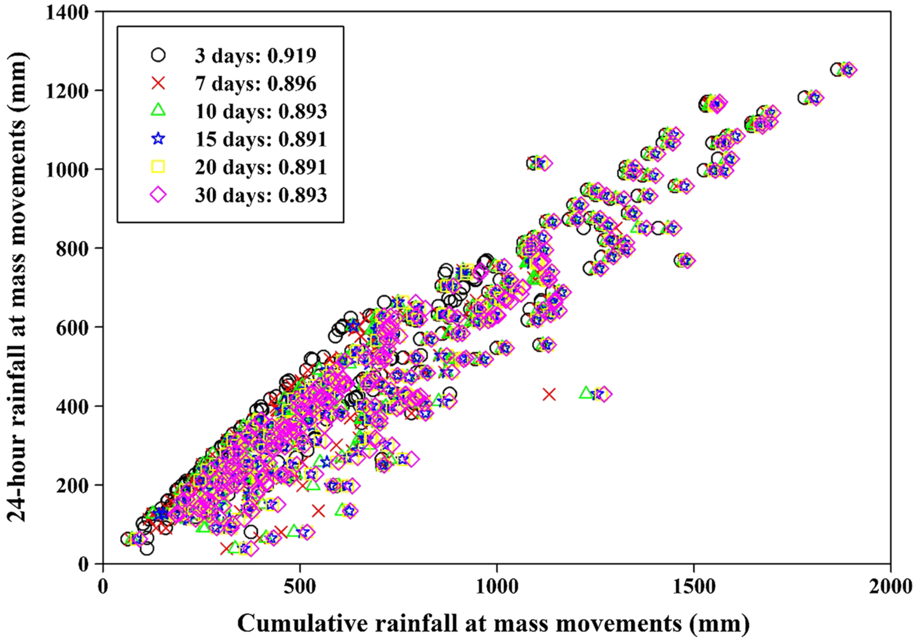


Fig. 4 Relationship between 24-h rainfall at mass movements and total rainfall considered for various numbers of days before the mass movement day. Correlation coefficients for various days are also shown in the legend



for mass movements (Fig. 6). The resultant equation for this threshold is as follows:

$$I_a = 28.7D_a^{-1.24}\left(1 \le D_a \le 18 \text{ days}\right). \quad (4)$$

The equation indicates that both short-duration (e.g., 1 day) and high-intensity (e.g., > 28.7 mm/day) critical antecedent rainfall can contribute to mass movements. However, long-duration (e.g., 18 days) and low-intensity (e.g., > 0.8 mm/day) critical antecedent rainfall may also contribute to mass movements. In addition, the critical rainfall conditions for these mass movements are within 18 days.

Discussion

Affected days of antecedent rainfall

We can find from Fig. 3 that, for most of the 283 mass movements, the amount of antecedent rainfall was very high and

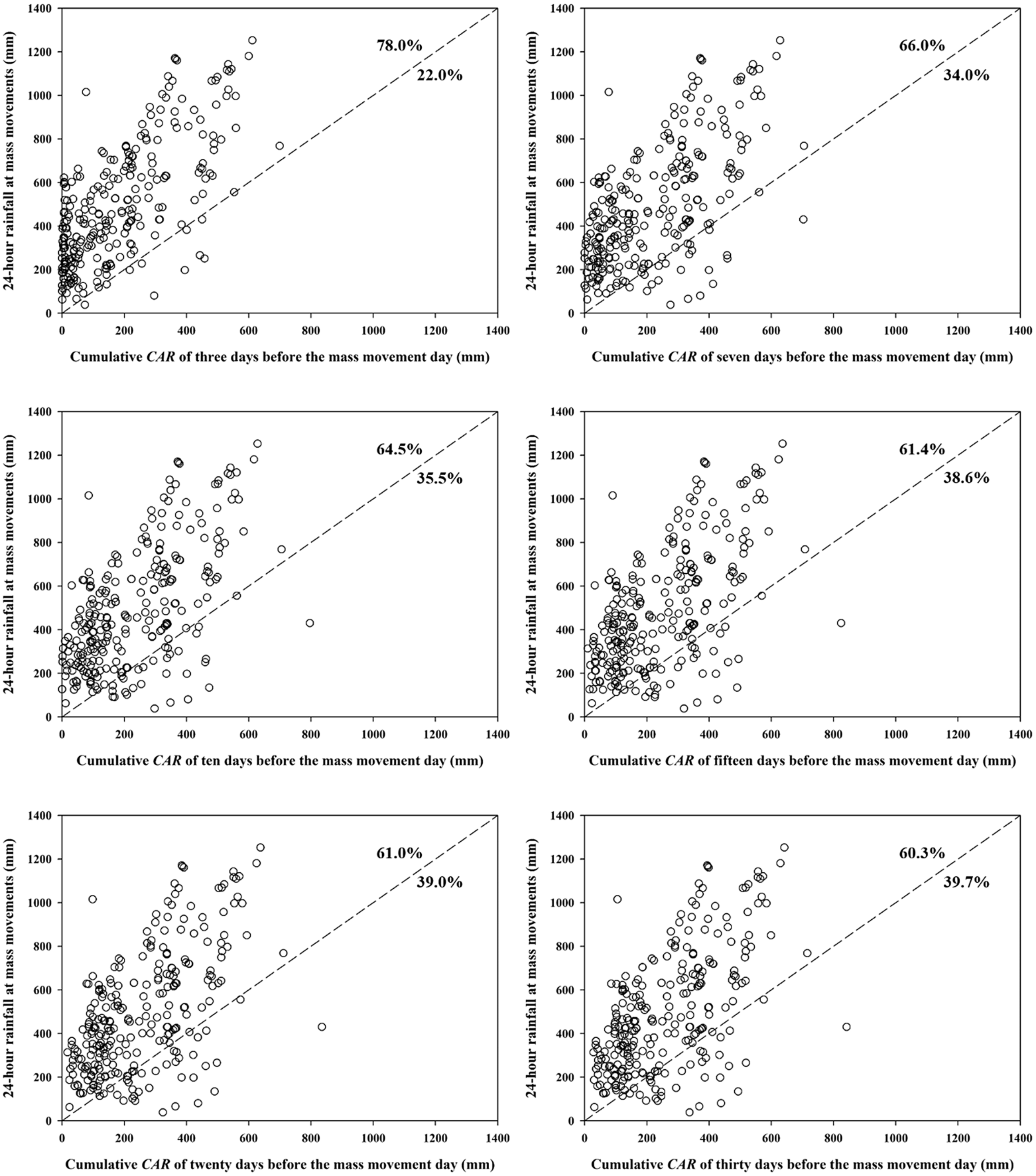


Fig. 5 Relationship between 24-h rainfall at mass movements and various days (3, 7, 10, 15, 20, and 30 days) of cumulative CAR. Dashed line represents that 24-h rainfall and cumulative CAR are the same at mass movements. Values show the percentage of 24-h rainfall and cumulative CAR regulating mass movements

sometimes higher than the amount of 24-h rainfall at mass movements. Although the antecedent rainfall was attenuated over time, there was still a significant effect of antecedent rainfall on mass movements after taking into consideration the calibration. These results imply the importance of antecedent rainfall in triggering mass movements due to its effect

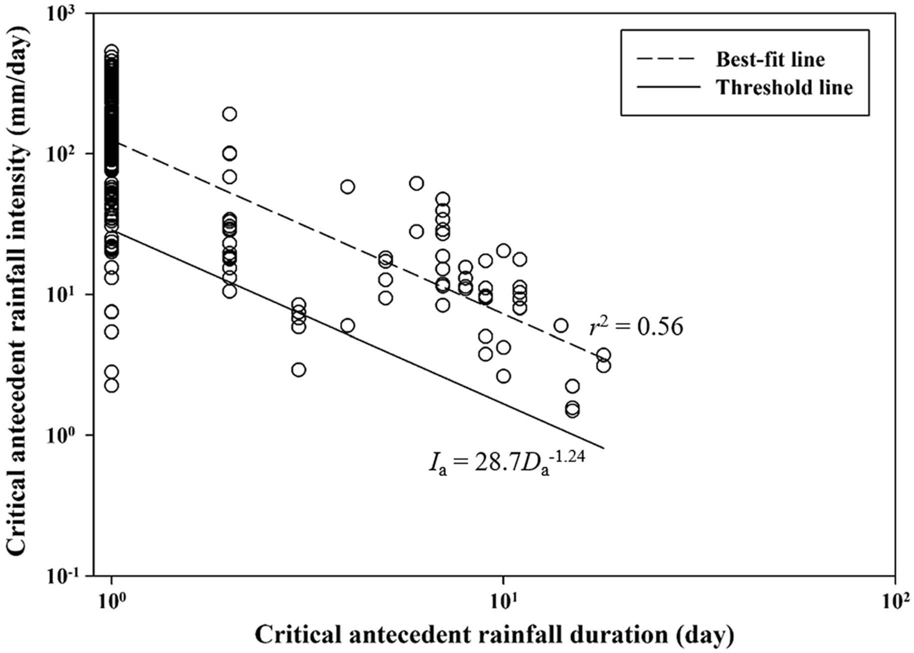


Fig. 6 Critical antecedent *I–D* correlation and threshold for mass movements, with the correlation coefficient value of best-fit line and the equation of threshold line

on ground water conditions and soil moisture (Crosta 1998; Terlien 1998; Wieczorek and Glade 2005; Jakob 2006; Wu and Chen 2009). However, a key difficulty inherent in antecedent rainfall is the definition of the period of accumulation of precipitation to accurately assess the effect of antecedent rainfall. Previous studies around the world have shown different considerations of periods for defining antecedent rainfall. They usually considered 3, 7, 10, 15, and 30 days (Crozier 1986, 1999; Kim et al. 1991; Glade et al. 2000; Aleotti 2004; Dahal and Hasegawa 2008; Khan et al. 2012). Chleborad (2003) considered 18 days (3 days of mass movement event rainfall and 15 days of antecedent rainfall). Some studies also found the best correlation with mass movement occurrence for 15-day (Lumb 1975; Pasuto and Silvano 1998) and 3–4 month antecedent rainfall (Cardinali et al. 2006).

For Taiwan, the above problem has been addressed by this study. Figure 4 shows that the correlation coefficients were lower when the number of considered days for antecedent rainfall increased. The reason for this decrease is the effect of antecedent rainfall. If only a few days were considered for antecedent rainfall, the 24-h rainfall occupied a large proportion of the cumulative rainfall at mass movements, and the correlation coefficient was high. On the other hand, if more days for antecedent rainfall were considered, the proportion of antecedent rainfall of the total cumulative rainfall increased and the correlation coefficient was lower. The lowest values appeared when 15 and 20 days of antecedent rainfall were considered. This trend means that periods of 15–20 days can be used to assess the highest effect of antecedent rainfall on mass movements. Figure 5 shows whether 24-h rainfall or cumulative CAR regulated the mass movements. The effect of cumulative CAR increased from 22.0 to 39.7% when the number of days considered for cumulative CAR was increased from 3 days to 30 days. However, this increase was not stable and became gradual after 15–18 days (Fig. 7). From the critical antecedent rainfall conditions (Fig. 6), we can also find that, in all cases, the highest rainfall intensity occurred within 18 days of the mass movement day. All these results suggest that antecedent rainfall of 15–18 days is useful for mass movement assessment in Taiwan.

Relationship between 24-h rainfall and antecedent rainfall

Figure 5 shows that, with the consideration of 15–18 days for antecedent rainfall, still about 61.0% of the mass movements were regulated by 24-h rainfall. This percentage means that, in most cases, 24-h rainfall plays the key role in triggering mass movements. Therefore, identifying the relationship between 24-h rainfall and antecedent rainfall is quite important for assessing mass movements. Figure 8 shows the relationship between 24-h rainfall at mass movements and critical antecedent rainfall duration. There is a slight negative correlation between them ($r^2 = 0.2$). This means that for a long antecedent rainfall period, soil moisture rises sufficiently high for the occurrence of mass movement, even with a relatively small amount of 24-h rainfall. On the other hand, for a short antecedent rainfall period, a relatively large amount of 24-h rainfall is needed to trigger mass movements because of the low soil moisture. As noted, previous studies

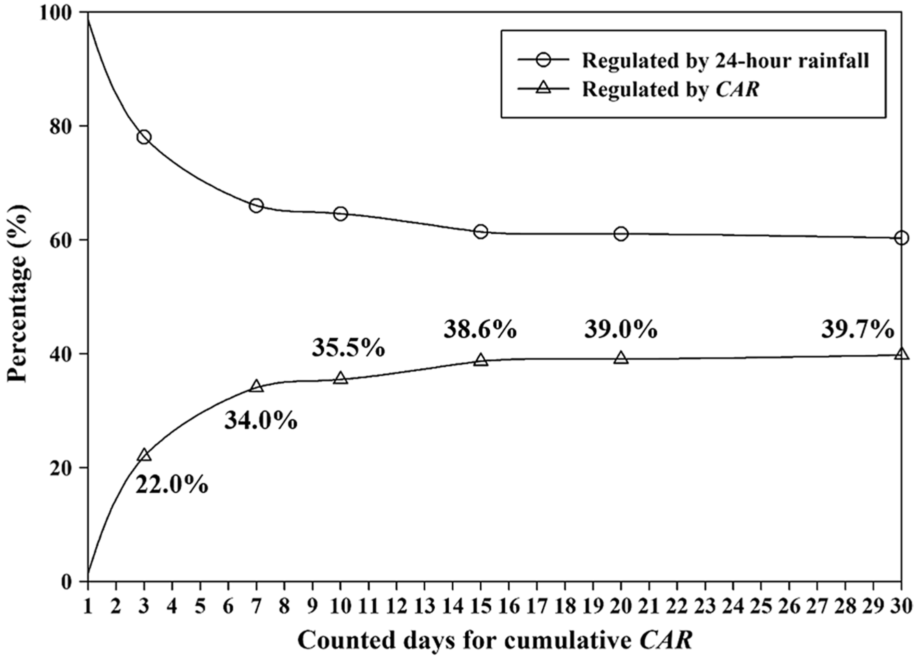


Fig. 7 Percentages of mass movement events regulated by 24-h rainfall and *CAR* with variation of the number of days considered for cumulative *CAR*

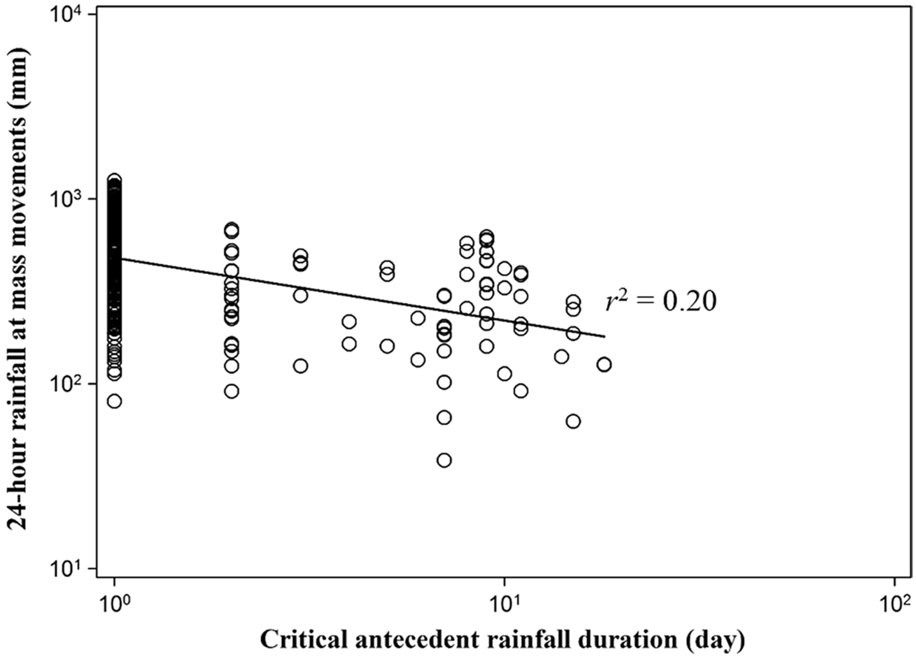


Fig. 8 Relationship between 24-h rainfall at mass movements and critical antecedent rainfall duration, with the correlation coefficient

have pointed out that short-duration and high-intensity rainfall events can trigger mass movements, while long-duration and low-intensity rainfall events may also trigger mass movements (Guzzetti et al. 2007; Dahal and Hasegawa 2008; Saito et al. 2010; Chen et al. 2015). Those findings are consistent with the results of this study. Figure 6 indicates that the long critical antecedent rainfall duration is usually followed with relatively low rainfall intensity, suggesting that even if the antecedent rainfall intensity is low, continuous rain for a long period leads to gradual increases in groundwater level, soil moisture, and pore water pressure sufficient for the occurrence of mass movements, with even a small amount of 24-h rainfall. On the other hand, high antecedent rainfall intensity for only a short period is not sufficient to increase soil moisture to flush surface materials and cause mass movements. Chen et al. (2017) pointed out that shallow mass movements could be caused by high-intensity rainfall within a short duration. In contrast, large mass movements need a higher groundwater level, soil moisture content, and pore water pressure, which arise only after prolonged rainfall. Therefore, the level of rainfall intensity and durations of antecedent and corresponding rainfall may be associated with different types of mass movements, and the observations of this study will provide useful information for further studies on this issue.

Conclusions

This study analyzed the 24-h rainfall and antecedent rainfall of 283 rainfall-induced mass movements that occurred from 2006 to 2013 in Taiwan. The combined use of CAR and 24-h rainfall allowed us to successfully determine the number of days of antecedent rainfall needed for triggering mass movements. In Taiwan, 15–18 days before the mass movement day should be considered as antecedent rainfall for correctly assessing mass movements. The critical antecedent rainfall conditions also occurred within the 18 days preceding the mass movement day in all cases. This study also established the critical antecedent intensity–duration threshold for mass movements in Taiwan. According to the relationship, low antecedent rainfall intensity continuing for a long period leads to gradual increases in groundwater level, soil moisture, and pore water pressure, and then a small amount of 24-h rainfall can trigger mass movements. On the other hand, high antecedent rainfall intensity for a short period is not sufficient to increase soil moisture, and a large amount of 24-h rainfall is needed to cause mass movements. The approach used in this study to determine the antecedent rainfall period may be applied to other areas to help researchers assess mass movement disasters in more detail.

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