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Heavy Rain Types for Triggering Shallow Landslides in South Korea

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This study aimed to elucidate the differences in the tendency for landslides to occur according to heavy rain types in summer in South Korea. For this, the rainfall intensity–duration (*I–D*) relationship and the differences in *I–D* relationship by three representative heavy rain types (convective rainstorm, monsoon rain and typhoon rain) were analyzed statistically, based on the corresponding hourly rainfall data for 478 shallow landslides occurred through South Korea during 1963–2012. In the quantile regression analysis of the *I–D* relationship for triggering landslides, the regression line of the 50th percentile of each heavy rain type showed notable differences, and convective rainstorms showed the highest rainfall intensity for the same duration, followed by monsoon and typhoon rains. While the difference was remarkable in the rainfall duration range of 4–20 h, it tended to decrease with an increase in the duration, suggesting that the effects of rainfall intensity on landslide occurrence gradually became insignificant due to an increase in soil water content. Rainfall intensity and duration according to heavy rain type revealed a statistically significant difference. Rainfall intensity was the highest in convective rainstorms and the lowest in typhoon rains, whereas rainfall duration was the longest in typhoon rains and the shortest in convective rainstorms. Such a trend is consistent with the characteristics of heavy rain types reported in Korean meteorology studies, clearly indicating that landslides occurring in South Korea were mainly triggered by heavy rains in summer. The results of this study should contribute for establishing landslide warning and evacuation systems when considering the characteristics of heavy rain in the future and suggest the necessity to improve rainfall and landslide prediction techniques during localized convective rainstorms and to provide systematic and proactive warning and evacuation systems.

Key words: duration, heavy rain type, intensity, *I–D* relationship, shallow landslide

INTRODUCTION

Landslides are natural phenomena that shape earth surface including mountain and gentler terrains, and typical mountain sediment disasters often causing damage to human life and property (Sidle and Ochiai, 2006). While numerous factors including climate, topography, geological features, and soil are involved in landslide occurrences (Choi, 1986; Sidle and Ochiai, 2006), rainfall is the major triggering factor (e.g., Iverson, 2000; Wieczorek and Glade, 2005; Dahal and Hasegawa, 2008; Guzzetti *et al*., 2008; Saito *et al*., 2010). Rainfall induces landslides by reducing the shear stress of soil by elevating the pore water pressure and increasing the unit weight of soil clods (Brand, 1981). Therefore, the fundamental relationship between rainfall conditions and landslide occurrence needs to be understood for landslide prediction, and warning and evacuation systems (Keefer *et al*., 1987; Wieczorek and Glade, 2005).

Many studies have analyzed the correlation between rainfall and landslide occurrence using indicators including antecedent rainfall (e.g., Campbell, 1975; Yagi and Yatabe, 1987), daily rainfall (e.g., Hong *et al*., 1990; Kim *et al*., 1991) and rainfall intensity–duration (*I–D*) relationship (e.g., Caine, 1980; Guzzetti *et al*., 2008). Caine (1980) first suggested the rainfall *I–D* threshold for determining the relationship between rainfall and landslides based on the empirical analysis of 73 rainfall cases that caused landslides and debris flows. The method was then modified by other researchers (e.g., Guzzetti *et al*., 2008). While the previously reported *I–D* relationship only showed an average tendency of landslide occurrence (Saito *et al*., 2010), it has been utilized as a comprehensive criterion in estimating landslide occurrence possibility and for warning and evacuation (Keefer *et al*., 1987; Aleotti, 2004; Dahal and Hasegawa, 2008; Guzzetti *et al*., 2008). The *I–D* relationship reflects local climate, geological features, and topography (Saito *et al*., 2010), and includes information regarding landslide types induced by short–term high intensity and long–term low intensity rainfalls (Dahal and Hasegawa, 2008).

Such a relationship between rainfall and landslide occurrence is especially important in Korea. Most of the

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annual precipitation in South Korea occurs from June to September, during the East Asian Monsoon season in summer, with heavy rainfall. Despite the varying soil properties, most landslides occur during this season (Lee *et al*., 2012) because rainfall is the most important landslide–triggering factor (Choi, 1986; Kim and Jung, 2000). The proper operation of landslide warning and evacuation systems is also dependent on rainfall status (Kim *et al*., 2012). Therefore, many studies have investigated landslides by focusing on rainfall (Hong *et al*., 1990; Kim *et al*., 1991; Kim and Jung, 2000; Han, 2001; Kim *et al*., 2012). However, most of these studies have difficulties in confirming landslide occurrence because they relied mainly on daily rainfall data without considering rainfall duration and hourly rainfall characteristics, and thus can perform only in spatially limited regions. Moreover, due to the changes in heavy rainfall characteristics such as frequency and magnitude caused by climate change (Yun, 2006; Moon *et al*., 2011), it is necessary to investigate landslide occurrence characteristics by considering various heavy rainfall characteristics and to provide countermeasures.

Recently, Kim *et al*. (2013) analyzed the *I–D* threshold for triggering landslides based on 478 shallow landslides and hourly rainfall data. In South Korea, heavy rain triggering landslides can be produced by various mechanisms through water exchange between oceans, land and atmosphere (Rha *et al*., 2005), and is largely categorized into monsoon rain, typhoon rain, and convective rainstorm, each of which has different characteristics (Rha *et al*., 2005; Lee *et al*., 2006; Oh *et al*., 2007). The objective of this study was to investigate the *I–D* relationship between landslide occurrence and rainfall, according to the representative Korean heavy rain types (convective rainstorm, monsoon rain and typhoon rain), and its differences using statistical methods. Although we examined the same dataset (478 landslides) as Kim *et al*. (2013) used, our approach has different aspects in that the *I–D* condition was analyzed by differences in heavy rain types.

METEOROLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS IN SOUTH KOREA

South Korea, located in the middle latitudes, is characterized by a temperate climate that is strongly affected by the East Asian Monsoon. According to the observations in the last 30 years, the mean annual temperature is 6.6–16.6°C, and the mean annual precipitation is 825.6–2007.3 mm with substantial regional variation (Korea Meteorological Administration, 2012). Most of the annual precipitation occurs from June to September. In general, the rainfall occurs dominantly as monsoon rain from the end of June to July and as localized convective rainstorms or typhoon rain from August to September (Park *et al*., 2008; Korea Meteorological Administration, 2011a). The mean temperature and precipitation increased by 0.2°C and 3.4%, respectively, during 1981–2010 as compared to 1971–2000, in South Korea (Korea Meteorological Administration, 2011c).

In addition, 64% of the land area consists of mountains and 62.5% of them have a steep slope of above 30° (Korea Research Institute for Human Settlements, 2008). Excluding steep mountains, hilly or low mountains (with weak uplifts due to erosion and weathering over a long period of time) at altitudes of 500 m above sea level account for most of the mountains (National Institute for Disaster Prevention, 2003). In terms of geological features, igneous rocks are the most widely distributed (41%) followed by metamorphic rocks (35%) and sedimentary rocks (24%) (Korea Forest Research Institute, 2010). With respect to geological features and landslide occurrence, sediment runoff owing to a scour phenomenon that includes soil loss accounts for most of the landslides in sedimentary rock regions, while landslides in the form of slope failure mainly occur in granite and gneiss regions (Jeong *et al*., 2011).

METHODS

Data collection

Among the landslides caused by heavy rainfalls from June to September for the 50 years from 1963 to 2012 in Korea, we analyzed 478 shallow landslides with confirmed time and location of occurrence based on local government and media (e.g., online or offline daily newspaper) data. In particular, information of landslide occurrences from 1960 to the 1990s was collected from past daily newspapers provided by the Naver news library (http://newslibrary.naver.com).

For the rainfall data, 163 meteorological stations closest to the landslide occurrences in the Korea Meteorological Administration (KMA; http://www.kma.go.kr) and Water Management Information System (http://www.wamis.go.kr) were selected and hourly rainfall data of the corresponding station was utilized. Average distance and standard deviation from the landslides to the meteorological stations was 4.6 ± 2.9 km.

Data analysis

Based on previous studies (e.g., Lee *et al*., 2006; Oh *et al*., 2007; Jeong and Ryu, 2008), the heavy rain was divided into three types: convective rainstorm, monsoon rain, and typhoon rain. Referring to the 2011 Changma White Book (KMA, 2011a) and the 2011 Typhoon White Book (KMA, 2011b), monsoon and typhoon rains were defined as heavy rains occurring during the monsoon season and during the typhoon impact period, respectively. The other sudden and local occurrences were considered as convective rainstorms. The monsoon periods of 1963–1972 and 2011–2012, which are not reported in the 2011 Changma White Book (KMA, 2011a), were investigated through past newspaper articles and notice of the KMA, respectively.

For the rainfall analysis, the rainfall continued from the beginning of rainfall to the landslide occurrence was defined as single heavy rainfall event that triggered landslides, and its rainfall duration and mean rainfall intensity were calculated. The single heavy rainfall events were

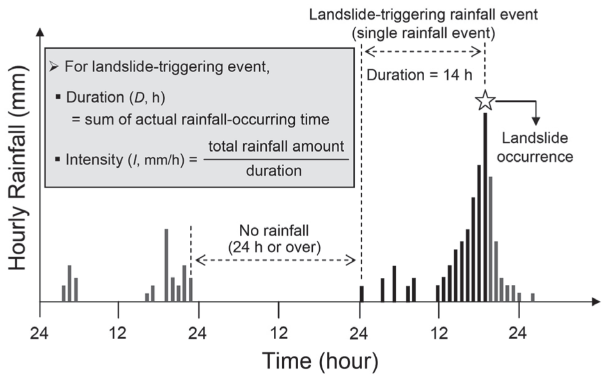

Fig. 1. Definition of rainfall event in this study.

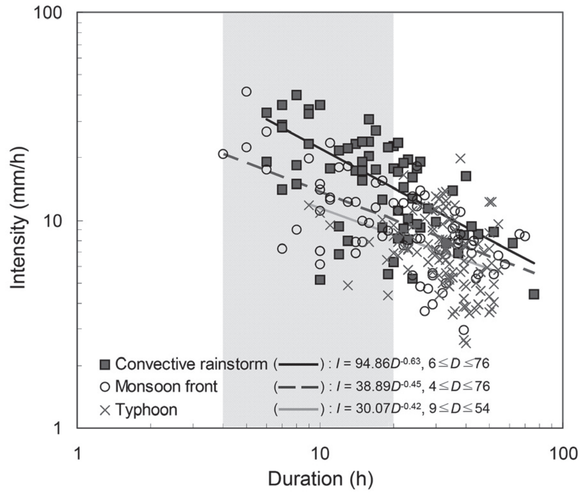

Fig. 2. *I–D* conditions and quantile regression lines of 50th percentile by heavy rain type for triggering shallow landslides in South Korea.

classified as those that had a minimum of 24 h of non–rainfall time before the beginning of rainfall based on the methods defined in previous domestic and international studies (Saito *et al.*, 2010; Yune *et al.*, 2010; Kim *et al.*, 2012). The detailed method is described in Fig. 1.

The following relationship using a power law equation suggested by Caine (1980) was used for the analysis of *I–D* of landslide–triggering rainfall:

$$I = \alpha D^{\beta} \quad (1)$$

where I is mean rainfall intensity (mm/h), D is rainfall duration (h), and both α and β are coefficients. Based on equation (1), a quantile regression analysis (Koenker, 2005) was adopted to compare the differences in *I–D* relationship among landslide–triggering rains. Due to robustness not affected by data distribution and outliers (Koenker, 2005), the quantile regression analysis using conditional quantiles allows more accurate investigation of the tendency (Koenker and Schorfheide, 1994) for landslide occurrence. In this study, we calculated the 50th percentile (Saito *et al.*, 2010).

In addition, we used statistical analysis to examine differences in *I–D* condition among landslide–triggering heavy rains. Prior to the statistical analysis, *I–D* of the heavy rain events were subjected to a normal distribution test (Kolmogorov–Smirnov test). As a result, both rainfall *I–D* were confirmed to have non–normal distribution in the convective rainstorms and the monsoon rain. Therefore, the Kruskall–Wallis test, which is a non–parametric equivalent of one–way ANOVA, was performed. Also, in the presence of significant differences, a post–hoc comparison test (Wilcoxon Rank Sum test) was performed, and then the differences in rainfall *I–D* among landslide–triggering rains were analyzed. All statistical analyses were performed using the statistical program R version 2.12.1. (http://www.r–project.org).

RESULTS

I–D relationship by heavy rain type for triggering landslides

The *I–D* relationship of landslide–triggering heavy rains for the past 50 years in Korea is shown in Fig. 2. In the *I–D* relationship of all the landslide–triggering heavy rains, rainfall intensity tended to gradually decrease as rainfall duration increased. The ranges for landslide–triggering heavy rains were 4.42–40.13 mm/h and 6–76 h for convective rainstorms, 2.96–41.70 mm/h and 4–70 h for monsoon rains, and 2.55–19.80 mm/h and 9–54 h for typhoon rains, respectively. In particular, for rainfall durations of less than 20 h (shaded part of Fig. 2), landslides caused by convective rainstorms and monsoon rains accounted for 56% and 45%, respectively, while landslides due to typhoon rains accounted for only 4%.

The quantile regression analysis of heavy rain types in the *I–D* relationship showed the differences in the regression lines of the 50th percentile. Among the landslide–triggering heavy rains, convective rainstorms showed the highest rainfall intensity followed by monsoon rains and typhoon rains for the same rainfall duration, and the difference was remarkable particularly for rainfall durations of less than 20 h. The regression lines of the 50th percentile according to each heavy rain type are as follows:

For convective rainstorms, $I = 94.86D^{-0.63}$ $(6 \leq D \leq 76)$
For monsoon rains, $I = 38.89D^{-0.45}$ $(4 \leq D \leq 76)$
For typhoon rains, $I = 30.07D^{-0.42}$ $(9 \leq D \leq 54)$

According to the above equation, at the 50th percentile, among the landslide–triggering heavy rains, convective rainstorms, monsoon rains, and typhoon rains exhibit rainfall intensities of 23.76 mm/h, 14.47 mm/h, and 11.95 mm/h, respectively, during short rainfall durations (e.g., 9 h), and 0.69 mm/h, 6.46 mm/h, and 5.63 mm/h, respectively, during relatively long rainfall durations (e.g., 54 h), showing that the difference decreased as the rainfall duration increased.

Differences in intensity and duration by heavy rain type for triggering landslides

The results of analyzing differences in rainfall intensity among the landslide–triggering heavy rains are shown in Fig. 3. The mean rainfall intensity (± standard error) of landslide–triggering heavy rain was found to be the highest for convective rainstorms (16.75 (± 1.03) mm/h), followed by monsoon rains (10.71 (± 0.71) mm/h), and typhoon rains (7.47 (± 0.14) mm/h), indicating a statistically significant difference at the 95% confidence level ($p < 0.001$).

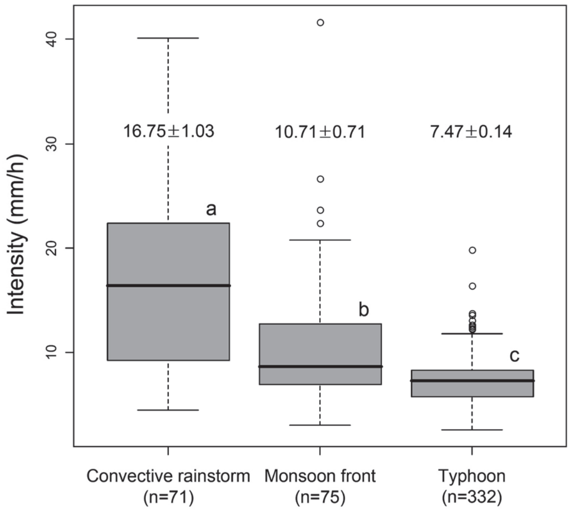

Fig. 3. Box–and–whisker plots of rainfall intensity by heavy rain type for triggering shallow landslides. For the box plots, thick solid lines indicates the median value and box ends are the upper and lower quartiles. The whiskers represent the maximum and minimum values excluding outliers (defined as values at a distance 1.5 times the interquartile range) and open circles are outliers. Significant differences (p<0.05) from Wilcoxon Rank Sum test following Kruskall–Wallis test are indicated with constrasting letters (a, b, c) above the box. Values above each box indicate mean ± standard errors.

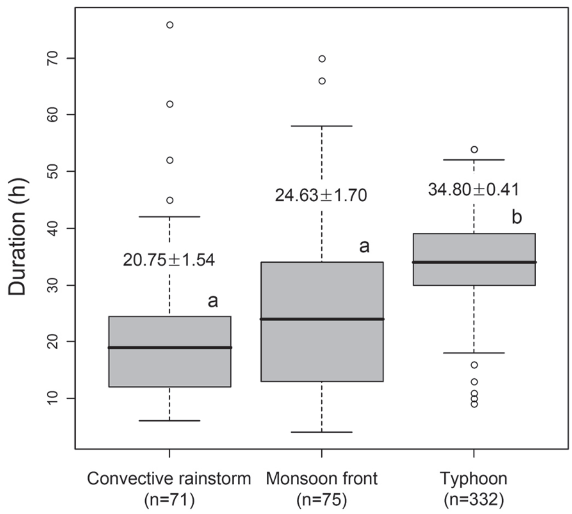

Fig. 4. Box–and–whisker plots of rainfall duration by heavy rain type for triggering shallow landslides. For the box plots, thick solid lines indicates the median value and box ends are the upper and lower quartiles. The whiskers represent the maximum and minimum values excluding outliers (defined as values at a distance 1.5 times the interquartile range) and open circles are outliers. Significant differences (p<0.05) from Wilcoxon Rank Sum test following Kruskall–Wallis test are indicated with constrasting letters (a, b) above the box. Values above each box indicate mean ± standard errors.

Statistical analysis results of differences in rainfall duration among the landslide–triggering heavy rains are shown in Fig. 4. The mean rainfall duration of landslide–triggering heavy rain was longest for typhoon rains (34.80 (± 0.41) h), followed by monsoon rains (24.63 (± 1.70) h), and convective rainstorms (20.75 (± 1.54) h). Significant differences between monsoon rains and convective rainstorms were not observed at the 95% confidence level ($p > 0.05$), but typhoon rains showed a significant difference between them at the 95% confidence level ($p < 0.001$).

DISCUSSION

Several studies (Oh *et al.*, 2007; Jeong and Ryu, 2008) on characteristics of heavy rain types during summer in Korea reported that the convective rainstorms had relatively short rainfall durations and occurred in limited areas as compared with monsoon or typhoon rains. In general, convective rainstorms show higher rainfall intensity as compared with monsoon and typhoon rains (Rha *et al.*, 2005; Lee *et al.*,2006) due to a short–lived mesoscale convective systems that generate convective rainstorms inducing a large amount of rainfall within a short time (Jeong and Ryu, 2008). During monsoon period, rainfall occurs in relatively extended areas for a longer period due to a stationary front as compared with localized convective rainstorms (Jeong and Ryu, 2008). Typhoon rain generally continues for more than 24 h as the typhoon approached South Korea (Oh *et al.*, 2007).

In this study, the *I–D* of the heavy rain types seem to reflect very well in the tendency for landslides to occur. In particular, more than 50% of the landslides were triggered by convective rainstorms, which occurred in the duration of 4–20 h, indicating that the landslides occurred under relatively higher rainfall intensities with shorter durations as compared with monsoon and typhoon rains (Fig. 2), and there was a statistically significant difference between the three heavy rain types (Figs. 3 and 4). This result may be attributable to the difference in the rainfall kinetic energy or raindrop size associated with rainfall intensity. Rainfall kinetic energy or raindrop size was positively correlated with rainfall intensity in terms of rainfall erosivity (Cerdà, 1997; Jayawardena and Rezaur, 2000; Nanko *et al.*, 2008). However, as this study only analyzed the average tendency for landslide occurrence and its differences based on the *I–D* relationship, there was a limitation that the results do not reflect peak rainfall intensity or rainfall intensity at the time of landslide occurrence (Saito *et al.*, 2010; Jemec and Komac, 2013). For example, the peak rainfall intensity is high for all heavy rain types (Fig. 5), whereas *I–D* relationship showed a distinct negative correlation (Fig. 2). In particular, typhoon–triggering landslides occurred under lower intensity and longer duration (Fig. 2), but the peak rainfall intensity appeared at relatively longer duration (Fig. 5), as reported by Lee *et al.* (2006).

Differences in rainfall intensity of landslide–triggering heavy rains showed a gradual decrease with an increase in rainfall duration (Fig. 2), suggesting that cumulative

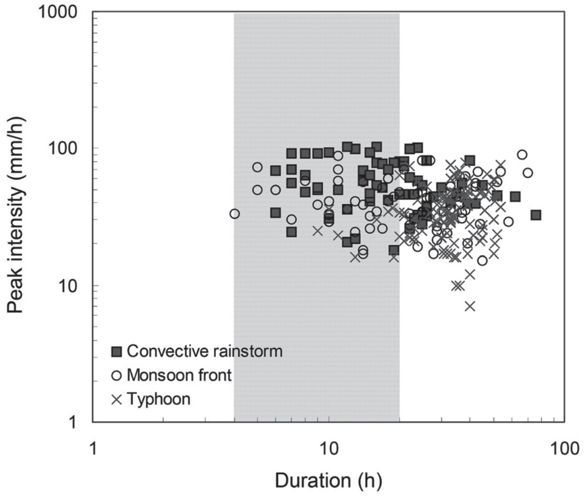

Fig. 5. Relationship between peak rainfall intensity and duration from the beginning of rainfall to landslide occurrence by heavy rain type.

rainfall increases as rainfall continues resulting in an increase in soil water contents (Chae and Kim, 2012), and therefore, the effects of rainfall intensity on landslide occurrence gradually becomes insignificant. While it is expected that the effects of rainfall duration on increases in soil water content differ according to rainfall patterns (e.g., Tsai, 2008), geological features, or soil thickness, analyzing these factors is out of the scope of this study.

Nevertheless, the *I–D* relationship is an important factor capable of affecting the spatial distribution and scale of landslides and debris flows. Crosta and Frattini (2000) explained the relationship between the *I–D* condition and frequency and density of debris flows caused by each event. Dahal and Hasegawa (2008) reported that shallow landslides occurred under short–term high rainfall intensity and large–scale landslides under long–term low rainfall intensity. Khan *et al*. (2012) stated that heavy rain events with many corresponding landslides causing damage to human life were characterized by short duration and high rainfall intensity. In particular, landslides in Mt. Umyeon in Seoul, and in Mt. Majeok in Chuncheon, Gangwon–do, South Korea, which caused large–scale damage to human life in July 2011, were mainly caused by the short–term convective rainstorms of 325 mm (mean rainfall intensity of 23.2 mm/h) for 14 h and 201 mm (mean rainfall intensity of 28.7 mm/h) for 7 h, respectively (Kim *et al*., 2012). Also, rainfall duration was a factor that influenced the frequency of landslide occurrence (Chae and Kim, 2012) and was considered to be a crucial parameter for the prediction of landslide occurrences in real–time monitoring systems (Chen *et al*., 2005).

SUMMARY AND CONCLUSIONS

In the present study, the types of heavy rain in summer were classified into convective rainstorms, monsoon rains, and typhoon rains, and the differences in rainfall *I–D* with respect to landslide occurrence were then statistically analyzed. The quantile regression analysis with respect to the *I–D* relationship for triggering landslides resulted in a notable difference for each heavy rain type in the 50th percentile regression lines, and convective rainstorms showed the highest rainfall intensity for the same duration, followed by monsoon rains and typhoon rains. The difference was noticeable in the rainfall duration of 4–20 h and gradually decreased with increase in rainfall duration, indicating that the impact of rainfall intensity gradually decreases with an increase in soil water content. In addition, mean *I–D* among landslide–triggering heavy rains showed a statistically significant difference. Rainfall intensity was the highest in convective rainstorms and the lowest in typhoon rains, while the duration was the longest in typhoon rains and the shortest in convective rainstorms. These results indicate that the characteristics of the heavy rain types reflected in landslide occurrences and the main triggering factor of landslides in Korea is the heavy rain in summer. Although this study did not consider peak rainfall intensity or rainfall intensity at the time of landslide occurrence, and geomorphological and geological features, the results of this study clearly show the differences in landslide occurrence tendency according to the *I–D* of landslide–triggering heavy rains. Therefore, the results of this study should contribute for establishing landslide warning and evacuation systems when considering heavy rain characteristics in the future.

Summer rainfall in South Korea has increased in recent years, and a major reason for this is the increase in occurrence frequency of localized convective rainstorms in August–September, after the monsoon front period (Yun, 2006; Moon *et al*., 2011). Given this situation, the frequency and risk of landslides caused by convective rainstorms are expected to substantially increase in the future. Because localized convective rainstorms form rapidly and occur in limited areas for a short time, space–time prediction is difficult, and therefore, requires a more careful meteorological observation (Rha *et al*., 2005; Jeong and Ryu, 2008). Given the fact that landslide warning and evacuation primarily focuses on rainfall and is, therefore, dependent on weather forecasts, prediction of landslides caused by localized convective rainstorms with high intensity and short duration, and time–space uncertainties is limited. It is therefore necessary to improve rainfall and landslide prediction techniques during localized convective rainstorms and to establish and manage systematic and proactive warning and evacuation systems.

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