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Influence of Cumulative Rainfall on the Occurrence of Landslides in Korea

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Abstract

This study presents the impact of cumulative rainfall on landslides, following the analysis of cumulative rainfall for 20 days before the landslide. For the 1520 landslides analyzed, the highest amount of average daily rainfall of 52.9mm occurred the day before the landslide, and the least amount of 6.1mm was experienced 20 days before the landslide. The least number of landslides (263 landslides) occurred when the cumulative rainfall is less than 20mm, and increased to 316 landslides in less than 30mm rainfall, 514 landslides in less than 80mm, 842 landslides in less than 150mm, and 678 landslides in 150mm and above. Considering the landslide occurrence in relation to the cumulative rainfall and the cumulative number of days, 986 landslides (64.9%) of the 1520 landslides were triggered by the 3 days cumulative rainfall for the 100mm rainfall and below, and 60% of landslides at the 5 days cumulative rainfall, indicating that the impact of cumulative rainfall on landslides was high in the 3 days and 5 days cumulative rainfall. More landslides occurred for the 101mm-200mm rainfall at the 10 days cumulative rainfall, more landslides for the 201mm-300mm rainfall at the 14 days cumulative rainfall, and more landslides for the 301mm-400mm rainfall at the 18 days cumulative rainfall. Three typologies of cumulative rainfall triggers are evident in Korea which includes: the early stacked rainfall accumulation type; the long-term intensive rainfall accumulation type; the continuous daily rainfall accumulation type. Cumulative rainfall is thus a major factor causing landslides. It is therefore imperative to take into consideration cumulative rainfall and the cumulative number of days as important triggers of landslides, as this could help contribute in landslide forecasting, thus putting in place measures to minimize the damage caused to life and property by landslides.

Keywords: cumulative number of days, cumulative rainfall, landslide forecasting, landslide triggers

1. Introduction

In recent years, typhoons and torrential rains occurring as a result of climate change have caused landslide disasters, resulting to a lot of damage to human life and property in Korea. In the year 2002, Typhoon RUSA caused the highest losses experienced ever across the country, affecting 321 people with property damage worth about 5.5 billion USD (Kim, Won, & Chung, 2006;National Institute for Disaster Prevention, 2002). Since then, landslide disasters have been recorded almost every year across the country, not confined to a particular area. Annually, an average of 60 fatalities and damage to life and property valued at 500-1 000 million US Dollars can be attributed to landslides in Korea (Lee & Hencher, 2014).

Significant damage is caused by landslides, thus it is imperative to conduct landslide factor analysis and landslide assessment (Choi, 1986; Ma, 1990; 1992; 2001), as well as to put in place landslide forecasting and harm reduction systems (Kang, Jung, Ma, & Chung, 1999; Ministry of Sci. and Tec., 2006; Emergency management agency, 2008; Ma, Jeong, & Park, 2008) so as to ensure the management of landslides.

A combination of factors such as topography, geology, earthquakes and rainfall act together to cause landslides. The occurrence of landslides also varies according to slopes and vegetation type (Ma, 2014). However, rainfall has been noted to be a major factor that causes/triggers landslides (Dai & Lee, 2001). Rainfall intensity may trigger the occurrence of landslides regardless of the geological and hydrological conditions of the area (Brand, 1985).

Many studies have been carried out on the occurrence of landslides with respect to rainfall characteristics such as cumulative rainfall, continuous rainfall, antecedent rainfall and rainfall intensity. Usually, over 8% of landslide disasters have occurred following a daily torrential rainfall that exceeds 100mm (Im, 2009). A constant and continuous rainfall intensity that prolongs for a long period of time usually results to landslides (Caine, 1980). Most landslides in Korea are triggered by intense rainfall during typhoons and seasonal rain fronts from June to September (Lee & Hencher, 2014).

In the case of Hong Kong, landslides occur when the daily rainfall exceeds 100mm and the cumulative rainfall for 15 days exceeds 350mm (Lumb, 1975). The destructive landslide at the Nagano Prefecture of Japan occurred when the day before the landslide had 1mm of rainfall while the previous days before the landslide had a cumulative rainfall amount of 49mm (Mauri, Sato, & Watanabe, 1997; Sassa, 1997).

In Italy`s Imperia area, rainfall of 1,000mm recorded for a 45 days cumulative rainfall period, initiated landslides after 8-10 hours of rainfall having an intensity of 8-10mm per hour (Guzzetti et al. 2004). In Kangwon-do area of Korea, a cumulative high rainfall that occurred the day before and during the day of the landslide was the main cause of the landslide that had huge debris flow (Park, 2008). Yune et al. (2010) noted that cumulative rainfall of 3 days to 7 days before the occurrence of a landslide as well as the intensity of rainfall are the main causes of landslides.

It is difficult to predict the time of occurrence of a landslide since it usually occurs unexpectedly. There is the need to assess rainfall characteristics such as the rainfall characteristics on the day of the landslide, cumulative rainfall and rainfall intensity as well as their interaction with other factors to ascertain the main cause of a landslide.

Therefore, the present study is to analyze the impact of the cumulative rainfall for 20 days before the day of the landslide, to assess the characteristics of rainfall and rainfall accumulation that cause landslides in accordance with the cumulative number of rainy and non-rainy days. This will enable us identify the typologies of cumulative rainfall triggers.

2. Materials and Methods

2.1 Test Site

The test site includes the vicinities of 7 cities and 8 provincial areas (Seoul, Busan, Ulsan, Gwangju, Daegu, Daejeon Metropolitan City, Incheon Metropolitan City, Gyeongnam, Gyeongbuk , South Jeolla Province, North Jeolla Province, South Chungcheong Province, North Chungcheong Province, Gyeonggi, Gangwon Province) in South Korea. South Korea is a peninsular situated between China and Japan. It is generally mountainous with over 70% of the total area made of mountains and uplands. It has mean annual temperatures of 10^{o}C ranging from -15^{o}C in winter to 30^{o}C in summer, average annual rainfall of 1 200mm, with over 60% of this rainfall occurring between June and August (Lee & Hencher, 2014). The terrain is as well vulnerable to flash floods associated with severe rainfall because of the orographic effect (Yoon & Bae, 2012). These areas experience Typhoons which usually pass over South Korea in late summer especially in August, associated with torrential rains. The Korean Peninsula largely comprises mountains and ridges, which are denudation remnants of deformed basement rocks, sedimentary successions, and plutonic and volcanic rocks, concealing a long history of crustal deformation. Sedimentary rocks are important constituents of the crust in the Korean Peninsula (Sung, 2013). Generally, the rock composition of Korea include 40% metamorphic rock, 35% igneous rock, and 25% sedimentary rock, with landslides especially rock failures such as in road construction sites mostly occurring in areas made of metamorphic and sedimentary rocks (Park & Han, 2008), and debris flows highly occur in areas of metamorphic rocks (Ma, 2010).

2.2 Landslide Data

Landslide data for this study is the compiled data on landslides that occurred from 1991 to 2012 in Korea. The landslides analyzed in this study are those mostly triggered by intense rainfall during typhoons and seasonal rain fronts, such as debris flows, mudflows, land creep etc. which are common landslide types in Korea. Local governments identified and recorded the exact time and day the landslides occurred and the area of occurrence.

Within the study period, in Gyeongsangnam-do area, the cities of Busan and Ulsan had 525 landslides analyzed out of 1208 recorded; In Gyeongsangbuk-do, Daegu Metropolitan City had 294 landslides out of 2,142 recorded; in Jeollanam-do, the city of Gwangju had 39 landslides out of 44 recorded; the North Jeolla Province had 216 landslides out of the 429 recorded; in Chungcheongnam-do, the city of Daejeon had 124 landslides out of the 1,017 recorded; North Chungcheong Province had 165 landslides out of the 299 recorded; in Gyeonggi-do, the city of Seoul had 35 landslides out of 549 recorded. In the other provinces, 122 landslides were examined among the 2,208 recorded. Double landslides occurred in some areas, thus landslide analysis was done by identifying the exact date and time the 1520 landslides analyzed in this study occurred. Only the landslides that had adequate available data were analyzed in this study, as many of the landslides occurred several years ago.

2.3 Rainfall Data Collection

Cumulative rainfall data for a 20 days period prior to the landslide was collected from the weather service website (www.kma.go.kr), Regional Automatic Weather Stations (AWS, Automatic Weathering System) and the National Comprehensive Water Resources Management System (WAMIS). Gauge rainfall data and radar rainfall data are generally obtained in the areas. The hourly and daily rainfall data obtained was then analyzed. The cumulative daily rainfall data for a 20 days period before the landslide is shown in Figure 1. The rainfall data was limited to 20 days cumulative period since this duration most remarkably triggers and influences the characteristic landslide types of the area.

2.4 Description of Analysis

Rainfall data from gauges nearest to the sites were analyzed since gauges are usually considered to provide accurate "point" measurements as well as analysis of rainfall data from radars, since high-resolution radars are useful to obtain additional information on the areal distribution of rainfall field in the mountainous regions (Gabella et al. 2005). Data analysis was done with IBM SPSS Statistics 21.

The relationship between cumulative rainfall-landslide was analyzed for each of the 1520 landslides examined in this study. Daily rainfall ranges in the 20 days cumulative period were defined as follows; ≤100mm, 101mm-200mm, 201mm-300mm, 301mm-400mm, 401mm-500mm, 501mm-600mm, and 601mm-700mm, and the relationship between the rainfall amounts-cumulative days of rainfall-landslides were analyzed (Figure 3).

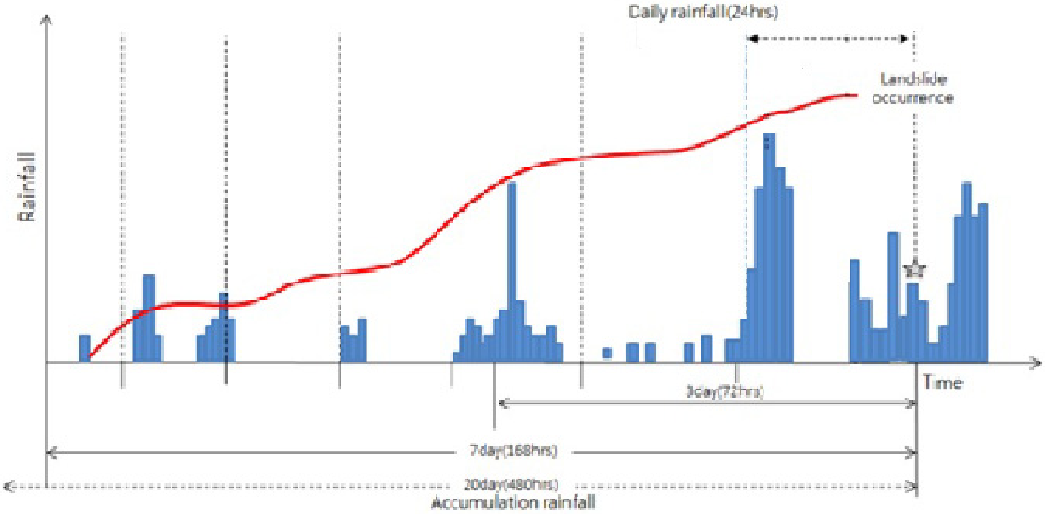


Figure 1. The characteristics of rainfall events by landslide occurrence in a 20 days period

3. Results

3.1 The Characteristics of Rainfall Prior to Landslides

The relationship between cumulative rainfall and landslide occurrence was done to ascertain the effect of rainfall on landslides. For the 1520 landslides analyzed in this study, considering a 20 days cumulative rainfall period before the landslide, the total number of days for the occurrence of all the landslides is 30400 (1520 × 20 = 30400) days. Rainfall occurred on 50.6% of the days, whereas there was no rainfall on 49.4% of the total number of days (Table 1). The results show that cumulative rainfall of within 10 days prior to the landslide, contributed greatly to landslides as more landslides occurred within this period. Prolonged precipitation thus plays an important role in landslide occurrence. Rainfall duration and cumulative rainfall thus significantly influence landslides.

Table 1. The number of rainy and non-rainy days during 20 days before landslide

Characteristics of days	Number of days
Total number of days before landslide	30,400
Rainy days	15,681(50.6%)
Non-rainy days	14,719(49.4%)
Average rainy days	10.3

For the 1520 landslides analyzed, generally, the amount of rainfall increased the days before the landslide than the further previous days in the 20 day cumulative rainfall period before the landslide. One day before the landslide, the amount of rainfall was 385mm, 420mm 2 days before, 265mm 3 days before, 380mm 4 days before, and a decreasing trend experienced after the 4th day to 132mm at the 20th day before the landslide. The highest amount of average daily rainfall of 52.9mm occurred the day before the landslide, 22.8mm 2 days before, 21.9mm 6 days before. The least amount of average rainfall of 6.1mm was experienced on the 20th day before the landslide (Figure 2). 150mm of rainfall and above occurred on more days than 300mm of rainfall and above.

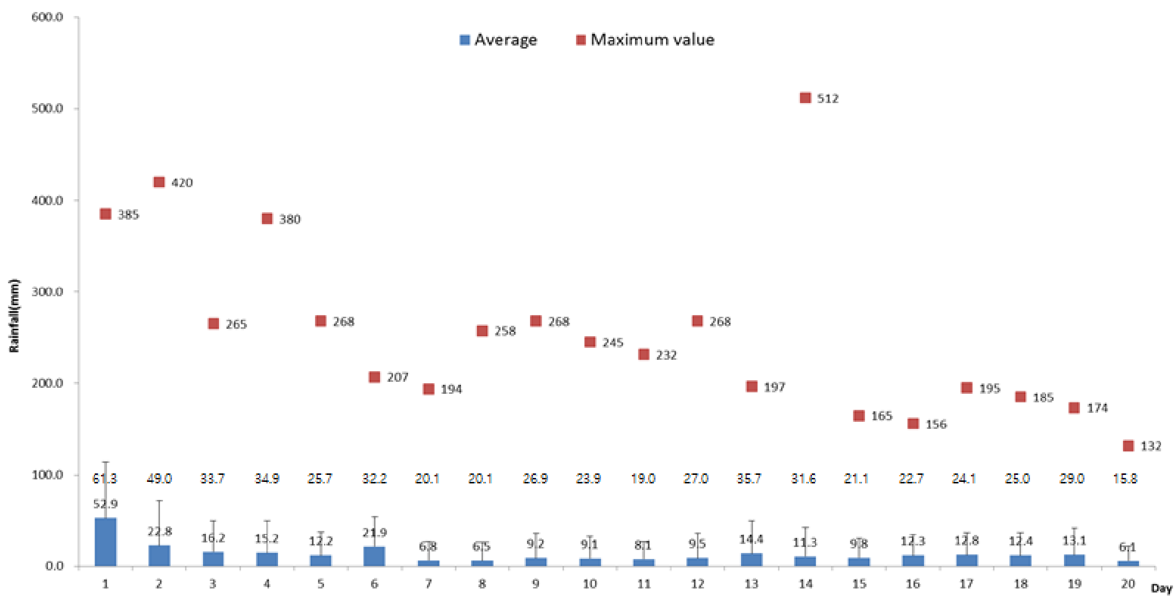


Figure 2. Daily rainfall during 20 days before landslide

3.2 Landslides Occurrence Due to the Cumulative Number of Rainy Days and Cumulative Rainfall

The least number of landslides (263) occurred when the cumulative rainfall is less than 20mm, and increased as the cumulative rainfall increased with 842 landslides occurring when the cumulative rainfall was less than 150 mm (Table 2).

Table 2. The Number of landslide by rainfall accumulation

Rainfall accumulation	Number of landslides	Total
<20mm	263	1520
≥20mm	1257	
<30mm	316	1520
≥30mm	1204	

<80mm	514	1520
≥80mm	1006	
<150mm	842	1520
≥150mm	678	

In addition to the role of cumulative rainfall on landslides occurrence, the number of landslides also varied according to the cumulative number of days, as landslide occurrence was highly influenced by the cumulative number of days of rainfall close to its occurrence (Figure 3). The number of landslides reduced as the number of days before the landslide increased (Figure 3). For the 100mm of rainfall and below, the highest and more frequent numbers of landslides (1251 of the 1520 landslides analyzed) were recorded the day before the landslide. Torrential rainfall with very high intensity occurred 1 day before the landslide which resulted in severe landslides, thus high intensity rainfall of about 100mm within 24 hours triggers the occurrence of landslides. 1191 landslides were recorded for 2 days before the landslide, 986 landslides 3 days before, 901 landslides 4 days before, 845 landslides 5 days before, thus influence on the number of landslides decreased over time. The 6 day triggered 609 landslides accounting to just 40.1% of the 1520 landslides analyzed, further indicating a drastic decline in the number of landslides with increase in days in the 20 days cumulative rainfall period.

For the 101mm-200mm of rainfall, there was a sharp increase in the number of landslides from the 5 days to the 6 days cumulative rainfall, as 636 landslides were triggered for the 6 days cumulative rainfall, 661 landslides for the 7 days cumulative rainfall, 666 for the 10 days cumulative rainfall, after which the number of landslides declined with almost equal numbers up to 20 days cumulative rainfall (Figure 3). For the 201mm-300mm of rainfall, 208 landslides were triggered for the 10 days cumulative rainfall, with a sharp increase at the 11 days cumulative rainfall with 343 landslides, after which, a decrease with relatively uniform number of landslides occurred. For the 301mm-400mm rainfall, the 18 days cumulative rainfall had the highest number of 258 landslides. Also, a few landslides were triggered for the over 1000mm rainfall at the 20 days cumulative rainfall.

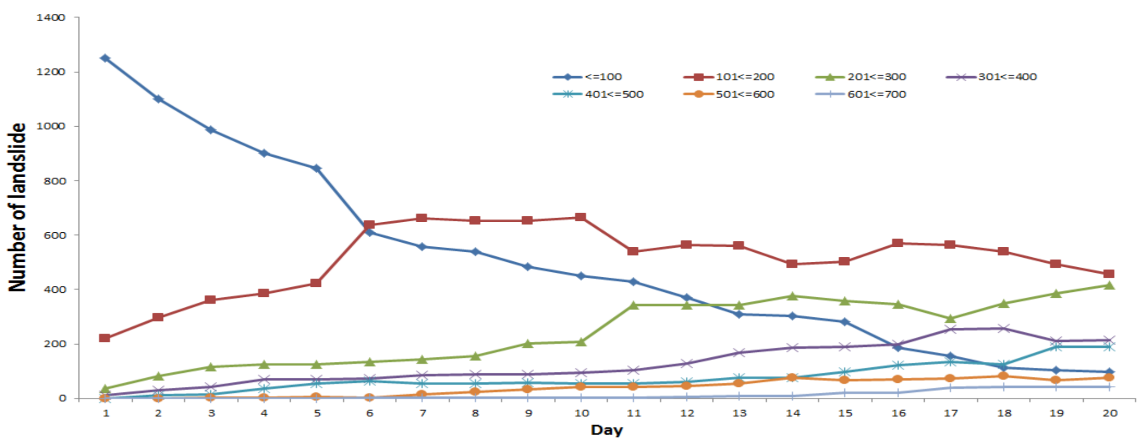
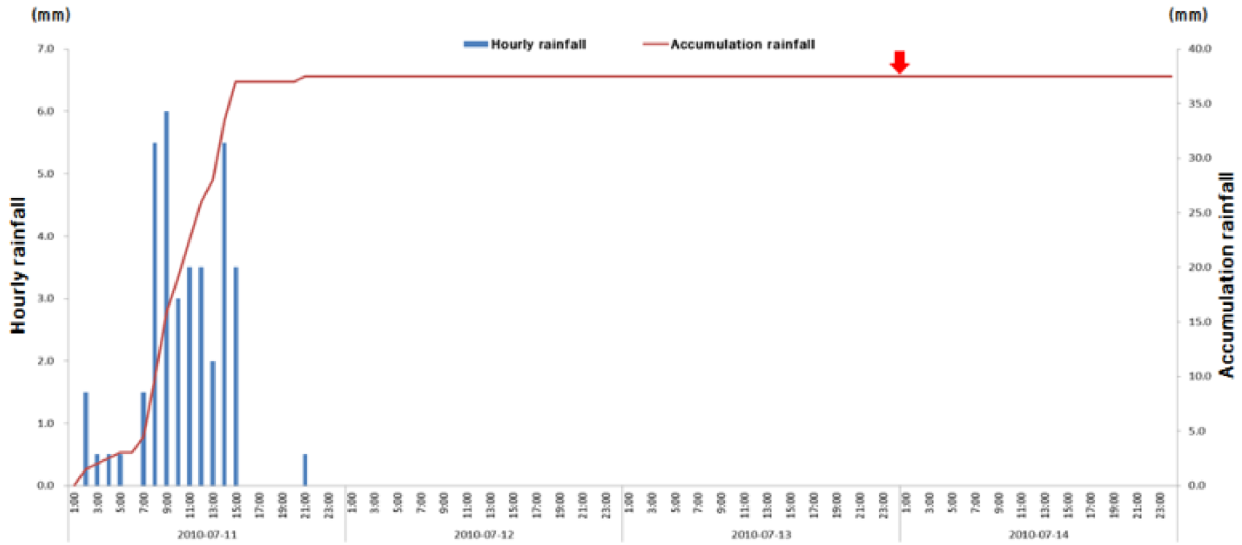


Figure 3. The number of landslides relative to the cumulative days of rainfall

986 landslides (64.9%) of the 1520 landslides were triggered in the 3 days cumulative rainfall for the 100mm rainfall and below, and 60% of landslides at the 5 days cumulative rainfall, indicating that the impact of cumulative rainfall on landslides was high in the 3 days and 5 days cumulative rainfall. More landslides were triggered for the 101mm-200mm rainfall at the 10 days cumulative rainfall, more landslides for the 201mm-300mm rainfall at the 14 days cumulative rainfall, and more landslides for the 301mm-400mm rainfall at the 18 days cumulative rainfall (Figure 3).

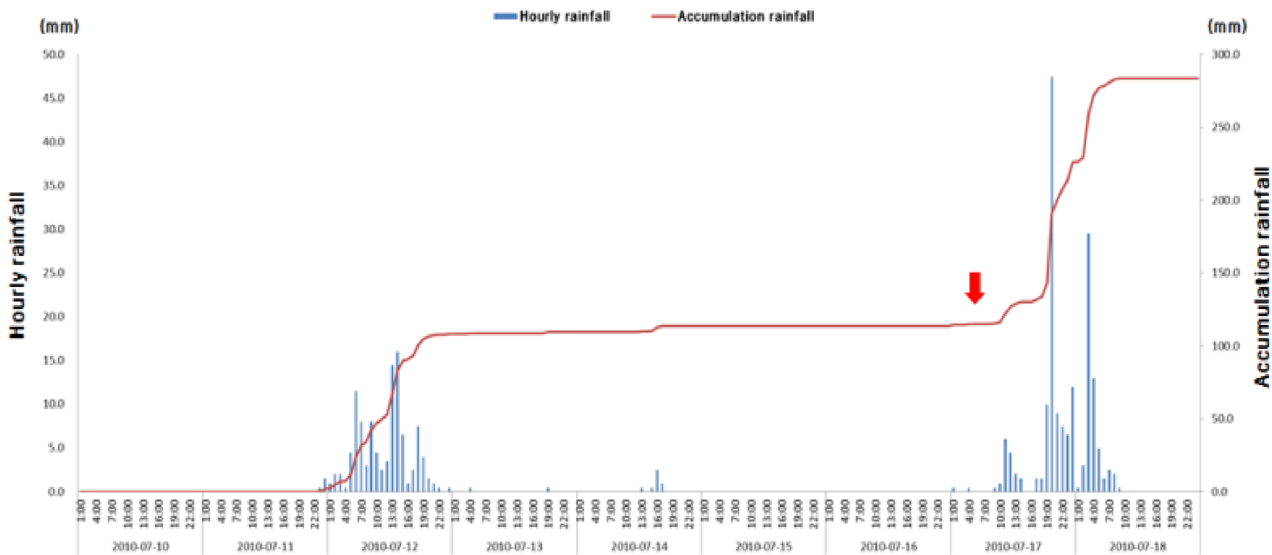
3.3 Typologies of Cumulative Rainfall Triggers

Three typologies of cumulative rainfall triggers are evident in Korea, which include; short-term, long-term, and continuous (Figure 4). These typologies are related to the cumulative rainfall and the cumulative number of days (Figure 3). From 1-5 days cumulative rainfall for the $\leq$ 100mm rainfall daily gives early rainfall accumulation landslide e.g. the July 17, 2010, landslide in Gyeongsangbuk-do, goryeong county, goryeongeup due to cumulative rainfall of 3 days prior to the landslide (Figure 4 a).



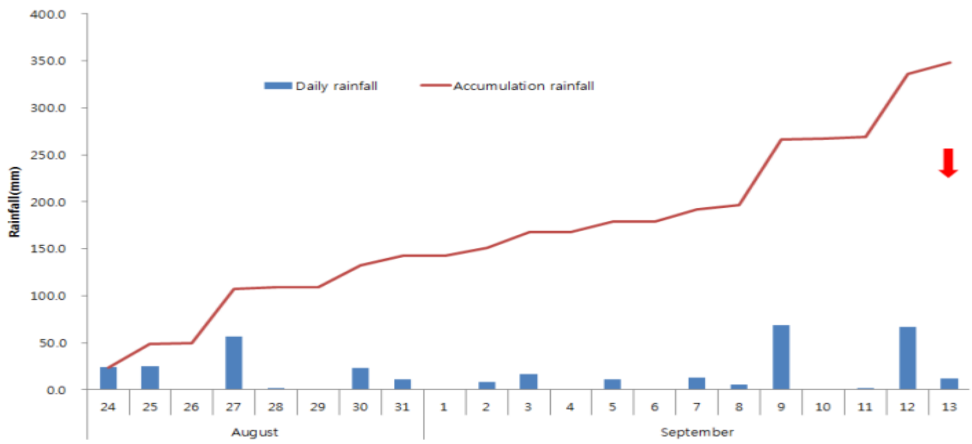
(a) Type of early rainfall accumulation (Ⅰ)

High intensity rainfall with cumulative rainfall of up to 10 days before the landslide (daily rainfall of 101mm-200mm at the 10 day before the landslide) triggers long-term intensive rainfall accumulation landslides e.g. the July 14, 2010 Unandong Iljikmyeon Andong, Gyeongsangbuk-do landslide, were intensive rainfall occurred a few days before the landslide (cumulative rainfall of 101mm-270mm on the 6-10 days before the landslide), were with about 15mm of rainfall the day of the landslide, the landslide was triggered following the saturated soil as a result of previous days cumulative rainfall (Figure 4 b).



(b) Type of Long-term intensive rainfall accumulation (Ⅱ)

Cumulative rainfall of up to 20 days before the landslide (daily rainfall of about 301mm-400mm on the 15-20 days before the landslide), with continuous daily rainfall that reduces up to the day of the landslide triggers continuous daily rainfall accumulation landslides e.g. the September 13, 2003 North Gyeongsang Province, Bonghwa County, Socheon-myeon hyeondongri landslide, were continuous daily rainfall for 20 days before the landslide that accumulated in the soil (with cumulative rainfall of more than 100mm on 18-20 days before the landslide and cumulative rainfall of 300mm-400mm for the 20 days period prior to the landslide) triggering the landslide(Figure 4 c).



(c) Type of Continued daily rainfall accumulation(III)

Figure 4. The typologies of cumulative rainfall triggers

4. Discussion

Many studies show that cumulative rainfall significantly causes the occurrence of landslides (Lumb, 1975; Guzzetti et al. 2004). This hypothesis is in line with the results of this study. It is therefore imperative to analyze the cumulative rainfall and the cumulative number of days before the landslide to ascertain how they contribute to landslides.

The present study involves analysis of a huge number of landslides, some of which occurred over 25 years ago. The study therefore took into consideration the available data for the landslides. The study focused on how cumulative rainfall and cumulative number of days of rainfall influence landslides. There is need for further studies on current landslides in Korea, to analyze the influence of other rainfall parameters on landslides with defined thresholds. Such studies would also provide location maps of the landslides, as well as the underlying bedrock.

In the present study, the amount of rainfall was higher the days before the landslide, and a decreasing trend experienced after the 4th day to 132mm at the 20th day before the landslide. Also, the highest amount of average daily rainfall of 52.9cm occurred the day before the landslide, and the least amount of average rainfall of 6.1mm was experienced on the 20th day before the landslide (Figure 2). Relatively, the least number of landslides (263) occurred when the cumulative rainfall is less than 20mm, and increased as the cumulative rainfall increased with 842 landslides occurring when the cumulative rainfall was about 150 mm (Table 2), thus confirming the influence of cumulative rainfall on landslides. This is similar to the case of the South Gyeongsang Province, Korea, where cumulative rainfall of over 230mm caused landslides (Kim et al., 2011). Au (1993) observed that slope failures are likely to occur when the 24 hour rainfall is more than 70 mm, and sometimes occur when the rainfall is as low as 50 mm.

The number of landslides also varied according to the cumulative number of days of rainfall, as landslide occurrence was highly influenced by the cumulative number of days of rainfall close to its occurrence (Figure 3). For the 100mm of rainfall and below, the highest and more frequent numbers of landslides (1251 of the 1520 landslides analyzed) were triggered the day before the landslide. Torrential rainfall with very high intensity occurred 1 day before the landslide which resulted in severe landslides. According to Kim et al. (2013), with 24 hours rainfall duration, landslide have 50% probability of occurrence with rainfall of 212.9mm, while with 363.8mm cumulative rainfall, landslides have 90% probability of occurrence. However, in the current study, for the 100mm rainfall and below, the day before the landslide triggered the highest number of landslides (Figure 3). Also, in the current study, 986 landslides (64.9%) of the 1520 landslides were triggered by the 3 days cumulative rainfall for the 100mm rainfall and below, and 60% of landslides at the 5 days cumulative rainfall, consistent with Yune et al. (2010), who noted that 3 days cumulative rainfall and the rainfall intensity the previous 7 days before the landslide are significant causes of landslides.

More landslides were triggered for the 101mm-200mm rainfall at the 10 days cumulative rainfall, more landslides for the 201mm-300mm rainfall at the 14 days cumulative rainfall, and more landslides for the 301mm-400mm rainfall at the 18 days cumulative rainfall (Figure 3). Maurizio & Francesco (1999) concluded that, cumulative rainfall of 10 to 90 days is necessary for landslide occurrence. This study therefore shows that cumulative rainfall of different characteristics influence the occurrence of different landslides. Three typologies of cumulative rainfall triggers thus occur in Korea (Figure 4). The result of this study is similar to what obtains in some regions of the world. For instance, in the case of Hong Kong, landslides occur when the daily rainfall exceeds 100mm and the cumulative rainfall for 15 days exceeds 350mm (Lumb, 1975), whereas in Italy`s Imperia Province, rainfall of 1,000mm recorded for a 45 days cumulative rainfall period, initiated landslides after 8-10 hours of rainfall having an intensity of 8-10mm per hour (Guzzetti et al. 2004). Also, in Naples, Italy Pozzano area, total rainfall of 160mm resulted in landslides, were over 800mm of rainfall (over 69% of annual rainfall in the area) occurred within 4 months (Calcaterra & Santos, 2004). The characteristics of rainfall therefore significantly causes landslide (Hong et al., 1990). In line with the identified typologies of cumulative rainfall triggers, landslides may thus still occur even if there was less rainfall in the previous 7 days before the landslide (Yagi & Yatabe, 1987), depending on the rainfall characteristics. In Sao Miguel Island in the Azores Islands, heavy rainfall that occur over a short period and low rainfall that occur over a long period cause landslides (Marques et al., 2008). Landslides are thus affected by several factors such as rainfall duration, rainfall intensity, and cumulative rainfall that occurred previous days before the landslide. Lumb (1975) remarked that disastrous landslides are caused for 24 hours rainfall of 100mm when the cumulative rainfall is over 200mm.

Cumulative rainfall and the cumulative number of days of rainfall are thus major factors that trigger the occurrence of landslides, and this is as well dependent on the terrain. Rainfall acts in combination with several factors, such as slope and geology to cause landslides. Considering several rainfall events or one rainfall event and the cumulative rainfall, it is usually difficult to estimate exactly what caused the landslide. There are also local and regional landslides that do not occur and/or occur under the same rainfall conditions. Critical analysis of the landslide and rainfall characteristics of the area is therefore imperative in determining the cause of the landslide.

In this study, analysis of cumulative rainfall and cumulative number of days are major causes of landslides. Continuous record and analysis of cumulative rainfall is required to aid in the prediction of the possible occurrence of landslides. Thus, noting and analyzing the cumulative rainfall and the cumulative number of days should be considered as major landslide triggering factors, and information on this can contribute in landslide forecasting, thus enabling the putting in place of measures to minimize the damage caused to life and property by landslides.

5. Conclusion

Landslide disasters usually affect life and property, thus resulting in significant losses. Many factors influence the occurrence of landslides, but of prime importance are the factors of cumulative rainfall and the cumulative number of days. Rainfall characteristics therefore determine the type of landslide that would occur. Thus, a consistent analysis and monitoring of cumulative rainfall and the cumulative number of days of rainfall is imperative, to guide in the forecasting of landslides, since these are important landslide triggers. The three typologies of cumulative rainfall triggers in Korea identified in this study (i.e. the early rainfall accumulation type; the long-term intensive rainfall accumulation type; the continuous daily rainfall accumulation type) indicate that landslides are triggered by both immediate and long-term rainfall events. Thus, it is imperative to take into consideration cumulative rainfall and the cumulative number of days of rainfall as major landslide triggers, to contribute in landslides forecasting, and implementing strategies to minimize the damage caused to life and property by landslides.

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