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Article

Development of Korean Nomograms for Forecasting and Alerting Debris Flows Based on Critical Accumulated Rainfall

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Abstract: Ongoing climate change causes abnormal climate events worldwide such as increasing temperatures and changing rainfall patterns. With South Korea facing growing damage from the increased frequency of localized heavy rains, the country is not an exception. In particular, its steep slope lands, including mountainous areas, are vulnerable to damage from landslides and debris flows. In addition, localized short-term heavy rains that occur in urban areas with extremely high intensity tend to lead a sharp increase in damage from soil-related disasters and cause huge losses of life and property. Currently, South Korea predicts landslides and debris flows using the standards for forecasting landslides and heavy rains. However, as the forecasting is conducted separately for rainfall intensity and accumulated rainfall, this lacks a technique that reflects both amount and intensity of rainfall in an episode of localized heavy rainfall. This study, therefore, aims to develop such a technique by collecting past cases of debris flow occurrences and rainfall events that accompanied debris flows to calculate the rainfall triggering index (RTI) reflecting accumulated rainfall and rainfall intensity. In addition, the RTI is converted into the critical accumulated rainfall (R_c) to use precipitation information and provide real-time forecasting. The study classifies the standards for flow debris forecasting into three levels: ALERT (10%–50%), WARNING (50%–70%), and EMERGENCY (70% or higher), to provide a nomogram for 6 hr, 12 hr, and 24 hr. As a result of applying this classification into the actual cases of Seoul, Chuncheon, and Cheongju, it is found that about 2–4 hr of response time is secured from the point of the Emergency level to the occurrence of debris flows.

Keywords: rainfall intensity; debris flow forecasting; rainfall triggering index (RTI); critical accumulated rainfall (R_c); nomogram

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1. Introduction

Global warming-initiated, abnormal climate events receive great attention worldwide. South Korea, in particular, has faced such events, including increasing temperature and rainfall and a growing number of heavy rain days, for the recent 100 years [1], which has led to natural disasters such as localized heavy rainfall, wind and waves, droughts, and heavy snows. Notably, the summer season from June to September shows a tendency of having an increased number of debris flows [2]. Debris flows are a type of natural disaster that occurs by a complex interaction between flooding from heavy rainfall and ground soil, as well as by a wide range of other factors such as thawing during spring, indiscriminate logging, and forest fire. They are also, commonly, secondary damage from typhoons and localized heavy rains, with the latter being their main cause because of how heavy rainfall brings an increase in flow speed, soil loss, and large-scale movement of rocks that lead to huge disasters [3]. In South Korea, damage from debris flows has been reported frequently nationwide, with examples such as Inje-gun and Pyeongchang-gun of Gangwon-do Province in 2006; Seoul, Chuncheon-si, and Pocheon-si in 2011; Samcheok-si in 2012; Busan-si in 2014; and

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Cheongju-si and Cheonan-si in 2017. For this study, debris flows are seen as mainly from localized heavy rains. In this regard, it requires a thorough understanding of the characteristics of rainfall events that cause debris flows, when establishing an early-warning system for debris flow damage and related planning, maintaining, or managing disaster prevention facilities.

In South Korea, studies on forecasting of debris flows and landslides are mainly about using the related standards provided by the Korea Forest Service and the Korea Meteorological Administration to review their relevance with an analysis of rainfall events that cause debris flows and landslides or to quantitatively calculate the standards. However, studies on debris flow forecasting based on rainfall events have not been actively conducted [4–9].Tables 1 and 2 show the prediction standards for landslides and rainfall, provided by the Korea Forest Service and the Korea Meteorological Administration, respectively. Such standards mainly defined rainfall and accumulated rainfall separately.

South Korea forecasts landslides and debris flows by analyzing rainfall and basin characteristics and using models to calculate the triggering factors. With the current advancement in radar technologies, studies are continuously conducted for predictions using radar data [10–19]. Therefore, the study attempted to establish a method that considers rainfall intensity and accumulated rainfall not as an independent factor but a function. To this end, it modified the RTI calculation method developed by Jan and Lee [20] to support the prediction of debris flows potentially caused by precipitation.

The study used past precipitation data from 80 stations located at the areas that experienced damage from debris flows from 2012 to 2013 for rainfall intensity and accumulated rainfall for each precipitation duration. Based on this, it classified debris flow damages to estimate the rainfall triggering index (RTI). In addition, it calculated the average intensity of the rainfall that causes debris flows. For debris flow prediction, the study classified the prediction standards for accumulated rainfall into ALERT (RTI from 10% to 50%), WARNING (RTI from 50% to 70%), and EMERGENCY (RTI from 70% or higher). The 10%, 50%, and 70% RTIs were divided by the average rainfall intensity to estimate the critical accumulated rainfall (R_c) and its curve by duration. The calculated R_c was applied to the actual cases of Umyeon Mountain of Seoul, Chuncheon of Gangwon-do, and Cheongju-si of Chungcheongbuk-do, where damage actually occurred, to make the debris flow prediction for 24 hr of the rainfall triggering such, which aims to determine its applicability for debris flow prediction.

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2. Materials and Methods

To analyze the influence from the interlinkage between accumulated rainfall and rainfall intensity, the study collected the precipitation data of 80 areas that experienced debris flow damage in Gangwon-do from 2012 to 2013 and used the precipitation amount by duration with a maximum of 24 hr in which debris flows occurred. Based on this, the RTI, an index for accumulated rainfall and rainfall intensity was calculated for 6 hr, 12 hr, and 24 hr, respectively. Furthermore, the study estimated an average rainfall intensity at the time of debris flow occurrence before using the RCI equation to calculate R_c for each duration (6 hr, 12 hr, and 24 hr). The R_c of 10%, 50%, and 70% was then used with the occurrence probability to define the three risk levels. In addition, based on actual damage cases, the study developed a nomogram for continuous precipitation to verify its applicability for debris flow forecasting (Figure 1).

3. Theoretical Background

3.1. Debris Flow

A debris flow refers to the dynamic phenomenon where soil, rocks, and floating substances flow down a slope by gravity with changes in their shape and sizes. The term “debris flow” was first mentioned in a book of Austria-born geologist Stiny [21], who defined such as a moving mass from flooding at mountainous areas that contains large amounts of floating matters and soil. Sharpe [22], however, differentiated debris flows from debris avalanches in his United States–based studies, with the former as a movement of soil and rocks saturated with water at a water channel with a steep slope, and the latter as a phenomenon where fragmented soil of an upper layer at a steep slope flow fast, similar to a snow avalanche. As shown in Figure 2, the path of debris flows comprises three zones: initiation, transportation, and deposition [23]. Because debris flows have pressure 4–5 times higher than that of flooding water, given that they are mixed with soil and rocks, their external force is 10 times higher than that of flooding water when conflicting with facilities [24].

Major factors that have influence on the occurrence of debris flows include topographic factors (slope angle, slope impact, and facilities to reduce the flow of pumice stones and soil), geographical factors (depth of soil layers and characteristics of top soil), and hydrological factors (amount of precipitation). Among such factors, precipitation increases pore water pressure and soil weight and leads to erosion and scour of the surface. The analysis of scales and accumulated rainfall indicates that an area with 200 mm or higher of precipitation and 20 mm/hr of rainfall intensity will face severe damage with increasing frequency (Figure 3). This result suggests that areas with low vulnerability may experience a higher probability of debris flow occurrence, in a precipitation episode with a certain level and intensity. Therefore, for the precipitation that triggers a debris flow, it is standard to consider both accumulated rainfall and rainfall intensity observed at the time of its occurrence.

3.2. Estimation of Critical Accumulated Rainfall Using RTI

The RTI model developed by Jan and Lee [20] was designed to predict debris flows triggered by rainfall in real time. For the RTI calculation, rainfall intensity (I) and accumulated rainfall (R_t) are used as follows.

$$RTI = I \times R_t \tag{1}$$

In the equation above, I indicates rainfall intensity (mm/hr) and R_t is the accumulated rainfall (mm) observed shortly before the occurrence of debris flows. Out of the rainfall episodes for up to seven days, the one that continues for 24 hr with a direct influence on debris flows is considered as antecedent rainfall. The study used the rainfall accumulated for continuous 6 hr, 12 hr, and 24 hr to estimate the RTI. Because rainfall has a direct impact on the occurrence of debris flows, especially its accumulation and intensity, the existing system for forecasting landslides uses prediction for accumulated rainfall and rainfall intensity and daily precipitation, whereas the RTI is calculated with accumulated rainfall and rainfall intensity to consider both the amount and intensity. However,

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the RTI can be difficult to understand for communities where debris flow–related damage is expected, as it is only a combination of rainfall intensity and accumulated rainfall and does not directly deliver the information about a risk level of debris flow. Therefore, the RTI was converted into critical accumulated rainfall (R_t) to aid understanding in the provided forecasting. Because the RTI focused on damage in Taiwan during the country's developed stage, it showed a gap for the rainfall and intensity of South Korea. Therefore, the study changed the level to 10%, 50%, and 70%, taking into consideration the flood forecasting standards provided by the Flood Control Office [25]. Figure 4 shows the definition of RTI and R_c.

4. Result and Discussion

4.1. Collection and Analysis of Debris Flow-Triggering Rainfall Data

In South Korea, mountainous areas account for 60% of its territory. Because most of them are concentrated in Gangwon-do, debris flow damage is frequently reported for the province. In this regard, the study collected data on the debris flow–triggering rainfall from 80 stations for 2012 to 2013 in Gangwon-do, where debris flows easily occur, and calculated accumulated rainfall and rainfall intensity at the site of damage occurrence (Table 3). Figure 5 shows the points of debris flows and the current status of precipitation monitoring stations. Figures 6 and 7 show dispersion of the maximum accumulated rainfall and rainfall intensity for 6 hr, 12 hr, and 24 hr at the 80 stations in the damaged areas.

4.2. Development of Nomogram for Debris Flow Prediction, Using RTI and R_c

The study used rainfall information from the 80 stations mentioned above to calculate the RTIs by phase (Alert, Warning, and Emergency) for each rainfall duration (6 hr, 12 hr, and 24 hr). The RTIs were estimated as 600 (10%), 1,350 (50%), and 2,321 (70%) for the 6 continuous hours; 494 (10%), 1,496 (50%), and 1,900 (70%) for the 12 hours; and 570 (10%), 950 (50%), 1,442 (70%) for the 24 hours. Table 4 summarizes the calculated RTIs and accumulated rainfall and rainfall intensity for each duration.

Prior to forecasting debris flow, related standards should be established. In South Korea, flood forecasting is made, wherein flood levels are standardized with 50% to 70% of the planned levels, in general, applied for the warning and alerting. As explained above, the study referred to the flood forecasting standards of the Flood Control Office [25], with the following set for each level: 10% to 50% of the occurrence possibility for Alert, 50% to 70% for Warning, and 70% or higher for Emergency. Furthermore, the study classified three forecasting levels for the durations of 6 hr, 12 hr, and 24 hr. Figure 8 shows events of the 80 stations in relation with RTIs, whereas Figures 9 to 11 show graphs of the RTI estimations.

RTIs are not information obtained directly from rainfall. Moreover, most people find RTIs difficult to understand and use. Therefore, the study converted RTIs to R_c to aid understanding. To estimate values, average rainfall intensity was used for each duration. R_c that corresponds to the average rainfall intensity is shown in Table 4. Figure 12 shows RTIs for 10%, 50%, and 70% calculated from Figures 9 to 11 and R_c estimation graphs.

The study developed a nomogram for debris flow prediction by rainfall duration, using the critical accumulated rainfall (R_c) for each occurrence possibility (10%, 50%, and 70%) and duration (6 hr, 12 hr, and 24 hr). As shown in Figure 13, a nomogram is a graph of debris flow forecasting levels for the rainfall accumulated from the start to 24 hr of the duration. For each duration, the debris flow forecasting levels (Alert, Warning, and Emergency) are classified with different colors to aid the visual expression of each level by duration of accumulated rainfall.

4.3. Review on Applicability of Debris Flow Nomogram with Actual Cases

To review applicability of the debris flow nomogram that the study developed, it applied the nomogram to cases of damage caused in the past by debris flows. The representative cases include Umyeon Mountain of Seoul in 2011, Chuncheon-si of Gangwon-do in 2011, and Cheongju-si of

Chungcheongbuk-do in 2017. The study estimated the response time before the damage occurrence by forecasting debris flows with the actual precipitation data for the cases. The case of Umyeon Mountain where debris flows occurred at 10:00 in July 27, 2011, resulted in 18 deaths and the evacuation of 400 people. In 2011, Chuncheon-si of Gangwon-do experienced debris flows that occurred at 24:00 and caused 13 deaths and 26 injuries. The case of Cheongju-si of Chungcheongbuk-do occurred at 11:00 on July 16, 2017, causing two deaths. Figure 14 shows the photos of damaged areas taken at those times.

The results of debris flow forecasting with the nomogram the study developed are as follows.

4.3.1. Case 1: Umyeon Mountain, Seoul

For the case of Umyeon Mountain of Seoul, it started raining at 17:00 on July 26 and recorded the maximum accumulated rainfall 307mm (Figure 15) until 16:00 on July 27 with damage occurring at 9:00 on July 27. The debris flow forecasting results were Alert for 18:00 on July 26, Warning for 19:00 of the same day, and Emergency for 5:00 on July 27 (Figure 16). Based on this, it can be assumed that damage occurs after the Emergency level. Therefore, it is estimated that 4 hr of response time is secured prior to damage occurrence. When forecasting is made additionally for the Warning level, the response time that can be secured is estimated as 7 hr.

Regarding the comparison analysis with the alerting standards of the Korea Forest Service and the Korea Meteorological Administration, the former provided the same level of risk; however, it produced the Alarm level for 18:00 of July 26 and 2:00 of July 27, which are some hours before the damage occurrence, with its response time delayed for an hour. On the other hand, the latter provided the Alarm level for 19:00 of July 26, which is some hours before the damage occurrence, and issued the alert for 24:00, which is 3 hr passed the actual damage occurrence (Table 5).

4.3.2. Case 2: Chuncheon, Gangwon-do

In the Chuncheon area, the rainfall started at 1:00 of July 27, and the 230 mm of maximum accumulated rainfall was recorded until 24:00 of the same day (Figure 17). The damage occurred at 24:00 of July 27, and forecasting for debris flows was made on 4:00 for Alert, 19:00 for Warning, and 21:00 for Emergency (Figure 18). With the application of the Emergency level, it was found that 4 hr of response time was secured prior to the damage occurrence, and with the additional forecasting for the Warning level, a total of 6 hr of the time was secured. Regarding the comparison analysis with the alerting standards of the Korea Forest Service and the Korea Meteorological Administration, the former provided the same risk level; however, it produced the Alarm level for 19:00 of July 27 and for 21:00 of July 27 again before the actual damage occurrence. The standards of the latter issued Alarm from 1:00 of July 27, which is some hours before the damage occurrence. This is a level lower, compared to the actual risk level of Warning at the time of damage occurrence (Table 6).

4.3.3. Case 3: Cheongju, Chungcheongbuk-do

In the Chuncheon area, the rainfall started at 1:00 of July 16, and the 290 mm of maximum accumulated rainfall was recorded until 14:00 of the same day (Figure 19). The damage occurred at 11:00 of July 16, and forecasting for debris flows was made at 8:00 for Warning and 9:00 for Emergency (Figure 20). With the application of the Emergency level, it was found that 2 hr of response time was secured prior to the damage occurrence, and with the additional forecasting for the warning level, a total of 3 hr of the time was secured. Regarding the comparison analysis with the alerting standards of the Korea Forest Service and the Korea Meteorological Administration, similar tendency risk levels were shown for all three alerting standards (Table 7).

5. Conclusion

The study collected precipitation data targeting the areas that experience damage from debris flows from 2012 to 2013, and developed the debris flow nomogram that reflects both accumulated rainfall and rainfall intensity. It used the two elements observed shortly before the occurrence of debris flows to estimate RTIs and set the three levels according to the possibility of debris flow occurrence: 10% to 50% for Alert, 50% to 70% for Warning, and 70% or higher for Emergency. In addition, to help the understanding of the residents in the areas where debris flows can occur, the study converted RTIs to actual accumulated rainfall values (R_c) for use in forecasting. In this study, the debris flow nomogram was developed for each duration (6 hr, 12 hr, and 24 hr) and applied to actual cases of debris flow damage for Umyeon Mountain of Seoul, Inje-si of Gangwon-do, and Cheongju-si of Chungcheongbuk-do.

As a result, the use of the nomogram for debris flow forecasting that the study developed could secure sufficient response time for the cases of Umyeon Mountain of Seoul and Chuncheon of Gangwon-do, where rainfall continues for long durations, and the case of Cheongju of Chungcheongbuk-do where heavy rain is localized. Results for each case are summarized as follows.

1) In the case of Umyeon Mountain of Seoul, 280 mm of the rain that continued for 17 hr caused the occurrence of debris flows. The results of using the nomogram in forecasting debris flows for the Emergency level showed that it could secure 4 hr of the response time. When the forecasting was made additionally for the Warning level, a total of 7 hr of the response time could be secured to ensure reactive actions.
2) In the case of Chuncheon of Gangwon-do, 260 mm of the rain for about 24 hr caused the occurrence of debris flows. The results of using the nomogram in forecasting debris flows showed that it could secure 4 hr of the response time. In addition to the forecasting for the Warning level, a total of 6 hr of the response time could be secured.
3) In the case of Cheongju of Chungcheongbuk-do, 290 mm of the rain for about 11 hr caused the occurrence of debris flows. The results of using the nomogram in forecasting debris flows showed that it could secure 2 hr of the response time. With addition to the forecasting for the Warning level, a total of 3 hr of the response time could be secured.

The results above suggest that the debris flow forecasting nomogram provided by the study is applicable for the actual forecasting on debris flow damages that can be caused by the long-term increase in rainfall and short-term, localized heavy rain. Meanwhile, in the cases of Seoul and Chuncheon, the forecasting standards of the Korean Meteorological Administration and the Korean Forest Service led to the indiscriminate issuance of alerts at the starting point of rainfall. However, the forecasting with the nomogram of the study is expected to support the understanding of rainfall value by general users with a visual representation of the risk level, and allow a proper prediction or response system to the situation.

Because of the diverse causes of debris flows, precipitation-related factors are not enough in determining debris flow occurrence. Therefore, it is crucial to provide the standards that ordinary people can use to make decisions even without expert knowledge. As rainfall is considered the most common factor that causes debris flows, it is expected that the forecasting on debris flows using the nomogram can support the easier interpretation of general users for debris flows. In addition, the forecasting that uses the nomogram the study developed and radar rainfall information can prevent debris flow damage in real time.

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