The Influence of Rainfall Amounts Not Exceeding Critical Rainfall on Landslide Occurrence in Japan

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Research Article

Keywords: early-warning system, landslide, critical rainfall, antecedent precipitation index, geological classification

Posted Date: November 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1063753/v1>

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Abstract

Critical rainfall events are used in landslide early-warning systems to predict the occurrence and severity of disasters. In this study, past landslide disasters in Japan were identified for which the critical rainfall set for each 1-km grid was exceeded using historical landslide records, radar-based rainfall data over a 1-km grid, and standard rainfall data collected over the past 17 years. It was determined that nearly equal numbers of rainfall events were identified with higher and lower rainfall amounts than the critical rainfall. The probability that a series of rainfall events would cause a landslide was approximately 1.15% when the critical rainfall was exceeded and 0.09% otherwise, a difference of approximately 10 times. It was also found that even if critical rainfall was not exceeded, in the case of debris flow and slope failures, there was rainfall that exceeded the standard rainfall one or two days before. In the case of landslides, there was rainfall that exceeded the critical rainfall one or two weeks before, and if the critical rainfall was exceeded in another rainfall event, a landslide could occur. The operational evaluation of Japanese LEWSs has a recall value of 0.486 as the accuracy of occurrence prediction, which was related to the fact that almost half of the rainfall events occurred in nonexceedance of the reference rainfall. The specificity was 0.935, known as the accuracy of nonoccurrence prediction, which was also greatly influenced by the TN (true negative) data of nonexceeding rainfall events, which accounted for most of the data.

1. Introduction

Rainfall-induced landslides are important natural hazards and often cause considerable damage to society. To assess the primary causes of landslides, understanding the relation between rainfall and landslide occurrence is necessary. Many studies have focused on quantifying rainfall parameters to empirically derive critical rainfall to understand the regional propensities of landslide occurrences and to develop landslide early warning systems (LEWSs, see Piciullo et al. 2018, Guzzetti et al. 2020, for a detailed review). For example, the first regional LEWS was constructed in Hong Kong in 1977 in response to catastrophic landslide events in 1972 and 1976 that caused many fatalities (Brand et al. 1984, Malone 1988). Since then, many regional LEWSs have operated in the USA (e.g., Wilson et al. 1993, Wilson 2012), Italy (Tiranti and Rabuffetti 2010, Tiranti et al. 2013, 2014), Canada (Jakob et al. 2012), Indonesia (Liao et al. 2010), Taiwan (Wei et al. 2018), and Japan (Osanai et al. 2010). These LEWSs have used many rainfall parameters, such as rainfall intensity, duration, cumulative rainfall, antecedent rainfall, and physical-based rainfall-runoff modes, based on ground rain gauges, weather radar, and satellite rainfall products.

These LEWSs assess the timing of landslides based on an empirical critical rainfall threshold. A key assumption of applying critical rainfall is that the likelihood of landslide occurrence increases with increasing rainfall amounts. However, the application of empirical critical rainfall for LEWSs has an inherent tradeoff relation between overestimation and underestimation with landslide occurrences under rainfall conditions of critical rainfall. Validation of the predictive performance of LEWSs is therefore important to improve LEWSs (Guzzetti et al. 2020). Although many studies have validated the LEWSs for

past heavy rainfall events, no study has validated nationwide landslide events for entire 1-km grids over the long term.

Japan is located in the East Asian monsoon region. The Japanese archipelago is characterized by high-relief topography and complex geological conditions. Heavy rainfall frequently occurs in Japan, especially during the summer monsoon season, causing landslide disasters (Saito et al. 2014). Many studies have analyzed the relations between rainfall parameters and landslide occurrences. For example, early notions of Endo (1970) and Onodera et al. (1974) showed the critical rainfall for landslide occurrences using maximum hourly rainfall and cumulative rainfall. The first nationwide LEWS was developed by the Ministry of Construction in 1984 using hourly rainfall, antecedent rainfall, and effective rainfall (Ministry of Construction 1984, Terada and Nakaya 2001). The Ministry of Land, Infrastructure, and Transport and Tourism in Japan (MLIT) and the Japan Meteorological Agency (JMA) has operated the current Japanese LEWS since 2005 using 60-minute rainfall and the Soil Water Index (SWI, an antecedent precipitation index) (Osanai et al. 2010, see Section 2). Although the Japanese LEWS has been operated for more than 15 years, few studies have validated its predictive performance. The predictive performance of the Japanese LEWS is addressed in this study by analyzing the nationwide landslide inventory ($n > 15,000$) between 2003 and 2020 (17 years) and rainfall data with a spatial resolution of 1 km or 5 km. In particular, this study focuses on the timing of landslides and underestimation of landslide occurrences in terms of the impacts of antecedent rainfall before landslides are induced by rainfall events. In addition, operational evaluation of the critical rainfall was also conducted.

The current Japanese critical rainfall that is used to identify occurrence and nonoccurrence setting methods uses the RBF network of Kuramoto et al. (2001) to set nonlinear critical rainfall (Fig. 1). The rainfall indices used are the 60-minute cumulative rainfall as the short-term rainfall index and the soil-water index, which is the sum of water depths of the three-layer tank model parameterized in a basin consisting of three typical geological classifications in Japan (Okada 2005), as the long-term rainfall index. A three-dimensional PBFN output response surface is calculated for each 1-km grid based on the rainfall indices, and the response surface is subtracted from the highest value of the RBFN output to capture the landslide data for LEWS and used as a two-dimensional critical rainfall. As shown in (Osanai et al. 2010), the critical rainfall using RBFN is set for each grid, which reflects the characteristics of the primary factor in each grid, which is referred to here as the in-line method. In addition, nonexceeding rainfall of the critical rainfall was also considered in this paper to study the effect of antecedent rainfall of landslides that occur in small-scale rainfall.

The types of phenomena present in the Japanese landslide data will be explained in the next chapter. In current technical standards, debris flows and spatiotemporally concentrated slope failures (debris avalanches) are extracted from landslide data, and the critical rainfall is set for LEWS (Osanai et al. 2010). The types of phenomena in the Japanese inventory will be explained in the next chapter. Landslides and slope failures in small-scale rainfall were not included in the rainfall standard. In some

PBFN output response surface and the RBFN value, which was calculated based on the 60-minute cumulative rainfall and SWI. RBFN output values ranged from 0 to 1.0, with a value closer to 0 indicating a larger rainfall magnitude and a value closer to 1.0 indicating a smaller rainfall.

3. Materials And Methods

3.1. Landslide disaster data

The disaster data used in this study were based on data collected by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) for the period 2003-2020 for all of Japan. The data was based on the reported date, place and cause of occurrence for each type of debris flow, slope failure and landslide reported by each prefecture. Among these three phenomena, "slope failure" corresponds to "debris avalanche" in the Hungr et al. (2014) classification, and "landslide" corresponds to "slide" and "spread". In this study, the names of the phenomena were used in the original data: debris flow, slope failure, and landslide.

In addition, this study addresses two types of landslides: debris flow and slope failures, which are covered by the Japanese LEWS, and landslides for reference.

Disasters caused by factors other than rainfall, such as earthquakes and snowmelt runoff, were excluded and limited to those caused only by rainfall. In addition, disasters for which the date of occurrence was not clear were excluded. In cases where the date of occurrence of landslides was known but the time of occurrence was not, the time was assigned to evaluate the maximum time the two axes of SWI and 60-minute cumulative rainfall comprehensively were the peak of the rainfall.

In this study, landslides occurring on a smaller scale than those covered by Japanese LEWS are also included to understand the characteristics of landslides occurring in small-scale rainfall due to the influence of antecedent rainfall and the actual situation of landslides occurring in nonexceedance critical rainfall events that have not yet been clarified. (Unlike the disasters used for critical line setting, sporadic landslides that do not occur in a concentrated time and space were also covered.

3.2. Rainfall data

The rainfall-related indices were the 60-minute cumulative rainfall combined meteorological radar and ground rain gauges (Shinpo 2001), SWI, and their RBFN values. The basic characteristics were organized on one-hour intervals from June 2003 to September 2020 for each of the 223,186 grids, which will be discussed later. A series of rainfall events was defined as a rainfall event with an RBFN value of 0.99 or less to exclude extremely small rainfall events and from the start of the event to 24 hours after the end of the event or 24 hours after the event fell below critical rainfall, whichever was later, as shown in Fig. 2.

3.3. Geological data

To analyze whether there is a difference in the relationship between disaster occurrence, rainfall exceedance, and nonexceedance of critical rainfall, the geology of each 1-km grid reflecting latitude and longitude (in Japan, this is called "National Land Numerical Information Tertiary Mesh") was classified using nine geological categories based on geological age (prehistoric, tertiary, and quaternary) and origin (sedimentary, volcanic, and plutonic rock/metamorphic rock), referring to the geological classification of Uchida et al. (2016). The rate of the number of rainfall events not exceeding the critical rainfall to the number of rainfall events was calculated for each geological classification. The geological classification of each grid was based on the AIST Geological Map of Japan (1:200,000) National Institute of Advanced Industrial Science and Technology (AIST) (2019), and the geological feature with the largest area occupied within a grid was treated as the geological feature of that grid.

3.4. Characteristics inventory

The procedure for linking rainfall index data and landslide data to classify rainfall is shown in Fig. 3. Specifically, the number of rainfall events and the number of disasters were calculated from the following two perspectives: pre/postrainfall period, exceeding/nonexceeding critical rainfall (15,151 events for debris flow and slope failures and 1,213 events for landslides).

In this study, the aforementioned method was used to cover the warm season (April 1~October 31) period from June 2003 to September 2020. In addition, because disaster data was based on reports from local governments and there was a large amount of data on disasters in populated areas. There were almost no data on disasters in unpopulated areas, areas without houses, plains (less than inclination 2 degrees), and water areas which were excluded from the object, in addition to areas where no critical rainfall was set. As a result, a database combining rainfall data, disaster data, and geological classification data for each 1-km grid was created for 223,186 grides out of 430,054 meshes nationwide excluding these areas. The items in the database are shown in Table 1.

For the calculation of the unknown time data, when the date of occurrence of the disaster was a day with rainfall, it was counted as the minimum RBFN output value timing during rainfall. If the occurrence day was the day after rainfall or the day after falling below the critical rainfall fall, the data was counted as the RBFN minimum time during the immediately preceding rainfall event. If the date of occurrence was two days after the rainfall event or the day after falling below the critical rainfall fall, the data was not counted. The relationship between the time of occurrence of a disaster and the exceedance of the critical rainfall during rainfall was classified according to the timing of the occurrence of the event: pre, during, post, and after the end of the rainfall and the nonrainfall period. The number of rainfall events and the number of disasters occurring during a rainfall event were counted as the number of rainfall events (even if more than one disaster occurs within a 1 km grid in a rainfall event), while the number of disasters occurring after a rainfall event was counted as the number of disasters. The classification of the number of rainfall events and their details are shown in Fig. 4 and Table 2.

3.5. Retrospective rainfall data

To understand the effect of antecedent rainfall on landslide nonexceedance critical rainfall, antecedent rainfall was determined retroactively from the date of occurrence of the disaster. The period for retrieving the antecedent rainfall and the rainfall characteristics to be extracted are shown in Table 3. During the disaster occurrence rainfall event period, the maximum 60-minute cumulative rainfall, the maximum SWI, and the minimum RBFN output values were determined. The time difference between the maximum 60-minute cumulative rainfall and SWI and the time of the disaster event, in addition to the difference between exceeding and falling below the critical rainfall, were also determined for the periods of 28 days and 365 days before the disaster event, respectively. In the case of the search up to 28 days ago and 365 days ago, the rainfall periods including the date of occurrence of the disaster were excluded from the search. In the case of multiple landslides occurring in one rainfall event in a grid, the date and time of the first occurrence was used as the representative.

3.6. Operational evaluation of LEWS in Japan

The accuracy of the estimation of landslide occurrence was confirmed based on inventory and rainfall data during the warm season from June 2003 to September 2020 for debris flow and slope failures, which were the targets of LEWS in Japan. To evaluate the accuracy of the LEWS in Japan, the recall value was calculated as the precision evaluation for occurrence and the specificity as the precision evaluation for nonoccurrence. These values were calculated based on the confusion matrix of the predicted and actual numbers shown in Table 4. Exceeding the critical rainfall that deals with rainfall that was predicted to occur on landslides, nonexceeding critical rainfall deals with rainfall that was not predicted to occur on landslides.

Exceeding rainfall, i.e., was predicted to produce landslides and did, was classified as true positive (TP), and rainfall that did not produce was classified as false-positive (FP), type-I error. Nonexceeding rainfall, i.e., was predicted to not occur on landslides and did not, those that did occur were classified as true negative (TN), and those that did occur were classified as false negative (FN) type-II errors.

Recall is the percentage of correct answers among the actual "occurrences" in the confusion matrix, as shown in Equation (1). Additionally, the specificity in Equation (2) indicates the likelihood of making a correct answer for a nonoccurrence.

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

1

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}}$$

2

4. Results

4.1. Number of rainfall and events

Figure 5 shows the number of disasters for debris flows, slope failures and landslides during the pre/postrainfall period. In terms of the number of disasters that occurred during the pre/postrainfall period, 19.3% of the 15,151 cases of debris flow and slope failure and 27.6% of the 1,213 cases of landslides occurred. Landslides, which were considered to be affected by deep groundwater levels, occurred more than 8% during the pre/postrainfall period.

Tables 5-8 show the results of each case in Table 2, debris flow, slope failure, and landslide, respectively, during the pre/postrainfall period. The unit of the number in the table for the rainfall is the number of rainfall events, and the unit of the number for the pre/postrainfall is the number of events.

The number of debris flows and slope failures in Table 5 is almost the same as the number of rainfall events, with 4,904 rainfall events exceeding critical rainfall and 5,182 rainfall events not exceeding critical rainfall. However, there was a large difference in the number of nonexceeding rainfall events, with 419,894 exceeding the critical rainfall amount and 5,992,232 nonexceeding critical rainfall. The occurrence rate of all events in exceeding critical rainfall based on rainfall events was $4,904/424,888 = 1.15\%$. In contrast, the nonexceeding critical rainfall rate was $5,182/5,997,414 = 0.09\%$, a difference of more than 10 times. For the pre/postrainfall disaster period, nonexceeding rainfall events are by far the most common (Table 6).

For landslides, as shown in Tables 7 and 8, the number of disasters was less than 1/10 of the number of debris flows and slope failures, but the ratio of exceeding rainfall to nonexceeding rainfall was similar, indicating the same trend. The trend in the number of disasters occurring pre/postrainfall periods was similar, with the number of disasters occurring in nonexceeding rainfall events being far greater than those occurring in exceeding rainfall events.

Although the occurrence rate based on the number of rainfall events was more than 10 times greater for exceeding rainfall events than for nonexceeding critical rainfall events, the fact that occurrence in nonexceeding rainfall events was not infrequent suggests that it is important to examine the impact of retrospective rainfall events.

4.2. Relationship between geology, number of events, and critical rainfall

To analyze the relationship between disaster occurrence, geological classification, and exceeding/nonexceeding critical rainfall, the ratio of the number of rainfalls in exceeding/nonexceeding critical rainfalls to the number of rainfalls in two cases, debris flow, slope failure, and landslide, was determined for each geological classification using nine geological classifications based on geological

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ilure" here refers to "debris avalanche" in Hungr's et al. (2014)

classification, while "landslide" corresponds to "slide" and "spread". The ratio of the number of rainfall events exceeding/not exceeding the critical rainfall for debris flow and slope failure and the compositional ratio of each geological category are shown in Fig. 6(a)-(d) show those for landslides.

For debris flow and slope failure, the highest percentage of rainfall occurrence was in the Quaternary sedimentary rocks. Although the plains are excluded from the target grid of this study, because the disaster data was based on disaster reporting, the most common geology in the compositional rate was still Quaternary sedimentary rock, which accounts for approximately 1/4 of the total. This may also be because the area has a large population exposed to hazards close to urban areas such as terrace cliffs and hillsides. For sedimentary and volcanic rocks, the disaster occurrence rate increases with increasing geological age, regardless of whether the critical rainfall is exceeded, which may indicate the degree of solidification in the case of sedimentary rocks and the susceptibility to disasters in the volcanic ash layer in the case of volcanic rocks. Although the compositional rate of tertiary geological units in metamorphic rocks and Paleozoic rocks was small, the disaster occurrence rainfall rate was above the average because it does not exceed the critical rainfall, indicating that the geology was prone to disasters.

For landslides, unlike debris flows and slope failures, a larger-than-average rate of occurrence rainfall rate occurred in Tertiary sedimentary rocks and in Plutonic rocks and Metamorphic rocks of the Mesozoic/Paleozoic Era, which is consistent with the fact that landslides are more common in these geological regions.

4.3. Effect of antecedent rainfall

Figures 7(a)-(c) and 8(a)-(c) show the frequency distributions of rainfall indices for the maximum 60-minute cumulative rainfall, maximum SWI, and minimum RBFN output values until the end of the occurrence rainfall for the nonexceeding critical rainfall for debris flow and slope failure and landslide, respectively, and the number and percentage of exceeding critical rainfall for each category. In addition, Table 9 shows the statistical data of these rainfall indicators. Distribution of these rain indices maximum value of debris flow and slope failure, and landslides were all highly variable, the number of rainfall occurrences was higher in the categories of 20-40 mm/60 min for maximum 60-minute cumulative rainfall, 100-200 mm for maximum SWI, and 0.9 or higher for minimum RBFN output value. However, these were the nonexceeding critical rainfall events, and therefore, these indices were not very large. Additionally, as shown in Table 9, there is little difference in the statistical characteristics of those rainfall indices for the 28-day and 365-day periods. For debris flow and slope failure, landslides with nonexceeding critical rainfall, the maximum 60-minute cumulative rainfall and SWI, minimum RBFN output value and the rate of exceeding critical rainfall (number of exceeding critical rainfall/number of total rainfalls) for the period of 28 days back from the date of disaster occurrence, excluding the disaster of rainfall period, were searched. In addition, the timing of those maximum or minimum rainfall indices was also investigated.

Figure 9(a)-(f) show histograms of the maximum rainfall indices from the previous 28 days to the end of

time difference between the minimum RBFN output values. Similarly, the landslide results are shown in Fig. 10(a)-(f). In addition, Figs. 11(a)-(f) and 12(a)-(f) show the results of debris flow and slope failures in the 365-day time series, respectively.

In the case of debris flow and slope failure, 100% of the cases exceeded critical rainfall one or two days before, but only a small percentage of the cases experienced rainfall exceeding critical rainfall three days to four weeks before, which means that the critical rainfall a few days before was the one that should be considered in the previous period. In addition, due to the small number of cases, it was not possible to ascertain the rainfall indices that should be considered in the previous rainfall period, since only a few cases had both large 60-minute cumulative rainfall and SWI. However, in the case of landslides, it should be noted that there are many rainfalls of such a scale that critical rainfalls were exceeded in the period from 7 days to 2 weeks prior to the event. As a result of examining the effects of antecedent rainfall retrospectively up to the 28th, it should be noted that debris flow and slope failure were more likely to occur with nonexceeding critical rainfall if there was significant rainfall that exceeded critical rainfall by approximately two days and landslides by one to two weeks prior to the event.

For the results of the 365-day retrospective analysis, as shown in Fig. 11, there were no large peaks in the exceeding critical rainfall rate, and the number of exceeding critical rainfall events was large 40 weeks ago, but this was due to the rainfall period of the previous year, and in effect, the influence of rainfall prior to 28 days was considered to be negligible.

In the case of landslides, as in the case of debris flow and slope failure, there was no significant exceeding critical rainfall for the period prior to one or two weeks, and the exceeding critical rainfall 40 weeks prior was considered to be due to the rainfall of the previous year.

4.4. Result of Operational evaluation of LEWS in Japan

Table 10 shows the operational results in Japan based on the number of rainfall events and disasters in exceeding/not exceeding critical rainfall for debris flows and slope failure from June 2003 to September 2020, including landslides caused by small rainfall events. The recall as the occurrence accuracy of LEWS was 0.486, which was not so high, yet the specificity for the nonoccurrence accuracy of LEWS as 0.935, which means that LEWS can correctly predict the nonoccurrence of LEWS. However, these results were related to the probability of a landslide occurring as extremely low even under rainfall conditions that have the potential to cause a landslide, and it was considered realistic to evaluate the operational performance of the LEWS on a 1-km grid basis in terms of recall.

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} = \frac{4,904}{4,904 + 5,182} = 0.486$$

3

$$\text{Specificity} = \frac{\text{TN}}{\text{TN} + \text{FP}} = \frac{5,992,232}{5,992,232 + 419,984} = 0.935$$

5. Discussion

5.1. LEWS performance evaluation and geological characteristics

The analysis of the critical rainfall based on the rainfall events confirms that it was a "transition line". The separability of the so-called "threshold" was evaluated by the event occurrence rate around this inflection, regardless of the number of dimensions. Since the magnification of rainfall as an incentive was 15 times higher than the critical rainfall, the incentive was interpreted as an amplification of the occurrence potential of the predisposing factor on the corresponding grid, and the knowledge on the applied geological predisposition can be integrated more effectively by superimposing the judgment for disaster prevention.

Since the multiplier for rainfall as an incentive was 15 times the critical rainfall, the incentive was interpreted as an amplification of the occurrence potential of the primary factor on the corresponding grid. By superimposing disaster response decisions, knowledge about primary factors in terms of geological predisposition can be integrated more effectively.

A coupled analysis of the relationship between disaster occurrence and geology and rainfall occurrence showed that, reflecting the geological composition and population distribution of Japan, inventories of debris flows and slope failures were more common in Quaternary sedimentary rocks, and the disaster occurrence rate was higher in sedimentary rocks and volcanic rocks with a more recent geological age. Compared to the Quaternary sedimentary rocks, the relatively Plutonic and Metamorphic rocks had more failure cases (false negative) in nonexceeding critical rainfall, which posed an issue for LEWS. It was also confirmed that the geological view of landslide occurrence reflected the distribution of event occurrence.

5.2. Antecedent rainfall for LEWS

Due to its high suitability across the country, Japan has adopted a frequency-based approach to criteria development that combines short-term and long-term rainfall indices and learns from a database of past long-term rainfall. Although the method reflects such a large amount of technological accumulation, approximately half of the disaster events do not exceed critical rainfall, and furthermore, almost 10–30% of the events are outside of rainfall events. As a result, it was confirmed that the fast-moving debris flow and slope failures had a certain amount of rainfall one to two days before the rainfall period, and the relatively slow-moving landslides (slide, slip, spread) had a certain amount of rainfall of one to two weeks during the 28-day period. In the case of reflecting the residual moisture in the ground for such a long period of time, slope hydrological experience shows that simply reducing the diminishing rate of the antecedent rainfall index as in the past may significantly increase the false alarm (false-positive), which may greatly affect the practical reliability of LEWS. For example, this problem cannot be avoided by using

Loading [MathJax]/jax/output/CommonHTML/jax.js hods of Hong Kong (24-hour total rainfall), which operates a

comparable LEWS, or other countries that use 2-4 days of total rainfall and its probability value. Therefore, rather than improving the hydrological model, it would be more effective to consider a method to appropriately learn the rainfall history during the affected period as an operational rule to reduce the negative impact of reducing the effectiveness of LEWS. In addition, since the search was conducted 52 weeks previous in this study, it could be concluded from the data handled that there was no need to consider the warm season history of one year ago. Limiting the period of time considered in past rainfall history to approximately 28 days was very significant for the development and operation of LEWSs.

5.3. Quality of inventory and future subject

In this analysis, the occurrence rate was calculated by incentive factors alone because a series judgment system was adopted that does not include both primary factors and incentive factors at the same time. In addition, because of the operational indicators and critical rainfall, the evaluation relied on rainfall data available in Japan and inventories.

Geology was represented as a factor affecting the risk of the primary factors by the AIST geology data of approximately 1 km². The appropriateness of reflecting detailed local geology in grid-scale assessments needs to be re-examined in the future. Additionally, how to make the topographic factor representative at 1 km² could be an applied geomorphology issue.

It cannot be denied that the evaluation of this study was affected by changes in data quality over time due to the improvement of the analysis scheme for radar AMeDAS analytical rainfall, the scale of each year and disaster event, and the reliability of various reports from different prefectures.

There is room for the unique reporting of landslide categories in Japan and improvement in the use of remote sensing in the future, as it could not cover the cases of disasters that occurred in the backcountry without people knowing. In addition, the majority of landslides in snow-covered cold regions occur during the snowmelt season, so it is necessary to consider the "cold weather" period in the future.

6. Conclusions

A coupled analysis of the relationship between disaster occurrence and geology and rainfall occurrence showed that the geological characteristics of Japan, especially the distribution of disaster events, were remarkable and that the rainfall history of LEWS was affected by this distribution.

In this study, based on 17 years of analytical rainfall and soil rainfall index data from 2003 to 2020 and disaster data based on disaster reports, in/out of the series of rainfall, the number of disaster occurrences/number of disaster occurrence rainfalls in exceeding/nonexceeding critical rainfall, and the occurrence rainfall rate by geology were confirmed in a 1-km grid unit.

A total of 19.3% of the total number of debris flows and slope failures and 27.6% of the total number of landslides were disasters of the pre/postrainfall period. In the case of debris flow and slope failures, the
Loading [MathJax]/jax/output/CommonHTML/jax.js not exceeding critical rainfall were almost the same, yet the

occurrence rate was more than 10 times higher when the rainfall was exceeding. The occurrence rate for rainfall exceeding the critical rainfall based on the number of rainfall events was 1.15%, while the occurrence rate for nonexceeding rainfall was 0.09%, a difference of more than 10 times.

The geology with the highest occurrence rate of debris flow and slope failure was Quaternary sedimentary rocks, and the occurrence rate of sedimentary and volcanic rocks increased with age. In terms of landslides, the occurrence rate in Tertiary sedimentary rocks and in Plutonic rocks and Metamorphic rocks of the Mesozoic/Paleozoic Era was higher than average, which was consistent with the characteristics of landslides in Japan.

Since there were many landslides that occurred in nonexceeding critical rainfall, and these may be affected by the antecedent rainfall, the maximum values of 60-minute cumulative rainfall, and SWI were confirmed back to 28 days and 365 days. In the case of debris flow and slope failures, the exceedance rate was 100% when the critical rainfall was exceeded one or two days ago, and it was determined that the critical rainfall a few days ago was the previous period's rainfall that should be considered. In the case of landslides, landslides were more likely to experience nonexceeding critical rainfall if there was a large amount of rainfall that exceeds rainfall within the period of one to two weeks before the landslide.

For the operational evaluation of the critical rainfall, in the case of debris flow and slope failure, which are the subject of the LEWS in Japan, the recall for the occurrence was 0.486, which was related to the fact that almost half of the cases occur in nonexceeding critical rainfall. The specificity as the accuracy for nonoccurrence was 0.935, which was affected by the nonoccurrence of nonexceedance rainfall data (true negative) that account for most of the data. For the operational performance of the LEWS, it was considered realistic to evaluate it on the basis of recall.

Operational evaluation of LEWSs as disaster warnings has been performed for significant disaster cases and at the regional level. However, there has been no long-term analysis of actual disasters on a national scale with high resolution in both time and space. The comprehensive evaluation in this study clarified issues in LEWS evaluation that could not be confirmed in case studies and regional-level evaluations.

Even with the critical rainfall based on short-term and long-term rainfall indices (antecedent rainfall indices) optimized for the occurrence rainfall, the number of occurrence rainfall events corresponding to nonexceeding critical rainfall events accounts for half of the total number of occurrence rainfall events. There were data limitations in discriminating between occurrence and nonoccurrence based on rainfall observations alone (errors in hypothesis testing (i.e., striking out to predict "occurrence" even though the event has not occurred (false-positive), type I error), missing the event even though it has occurred (false negative), type II error), and setting the optimal threshold between the two). Therefore, to ensure LEWS, it was essential to cascade regional observations and local monitoring of individual locations, in addition to monitoring with national rainfall indicators.

In Japan, there is room for a multilayered decision-making system to reflect antecedent rainfall

the single rainfall period. Even now, simple resetting of

antecedent rainfall by using a highly continuous rainfall index (SWI) is avoided, and weaknesses that effectively return to near initial values after a certain no rainfall period are the same as the weakness of the simple integrated rainfall method and the effective rainfall method. In the case of landslides (sliding or spreading), it is also necessary to add a decision method that considers rainfall history over a period of 7 days to 2 weeks. However, practically no effect of the rainfall history prior to the 28th was confirmed. Therefore, it is not necessary to include the effects of the previous year's heavy rains, for example. To develop and select long-term rainfall indices, it is sufficient to include a history of 28 days or less.

Declarations

Funding

We have not received any financial support for this research.

Competing Interests

The authors have no conflicts of interest to declare.

Availability of data and material

The data used in this study are non-public.

Code availability

The code used in this study are non-public.

Authors' contributions

The role of each author in this paper is as follows.

Soichi Kaihara: Specifics of the analysis of this study, data analysis, and interpretation of the results

Noriko Tadakuma: Data analysis for this study.

Hitoshi Saito: Provide ideas for the direction of this study and interpret the results of the analysis

Hiroaki Nakaya: Provide ideas and data for consideration in this study.

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Tables

Table 1. Description of the sediment disaster database.

Item	Contents
Date and time	Hourly date and time during the target period
Soil water index	Hourly soil water index value
60-minute cumulative rainfall	Hourly 60-minute cumulative rainfall value
Output value of RBFN*	Output value of RBFN that caliculated based on RBFN response surface, 60-minute cumulative rainfal and soil rainfall index
Continuous rainfall period	A series of rainfall period separated by 24 hours of non-rainfall period or non-exceedance of standard rainfall period
Continuous rainfall period (No rainfall period including)	The above period plus 24 hour no rainfall period
Exceedance/nonxceeding of standard rainfall	Exceedance/nonxceedance of standard rainfall classification that determined by 60-minute cumulative rainfal and soil rainfall index
* Radial Basis Function Network	

Table 2. Rainfall and sediment disaster data used in this study.

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Category	
①	Number of disaster rainfall exceedance critical rainfall disaster during rainfall period
②	Number of disaster rainfall nonexceedance critical rainfall disaster during rainfall period
③	Number of non-occurrences rainfall exceedance critical rainfall
④	Number of non-occurrences rainfall non-exceedance critical rainfall
⑤	Number of disasters exceeding critical rainfall Pre/Postrainfall period
⑥	Number of disasters non-exceeding critical rainfall Pre/Post rainfall period
⑦	Number of time unknown disasters Pre/Post rainfall period
* No rainfall period is defined as the period that no rain and 24hour after exceeded critical rainfall.	

Table 3. Time required to extract historical rainfall and rainfall index data using the maximum rainfall index.

Search category	Maximum index search period for rainfall	Target of rain index
During rainfall period	From the occurrence time to start of the rainfall	Maximum 60-minute cumulative rainfall, maximum SWI, minimum RBFN output value
Up to previous 28 days	During rainfall prior to disaster occurrence rainfall from previous 28 days	Maximum 60-minute cumulative rainfall, maximum SWI, minimum RBFN output value and time-lag of these indexes and excess condition of critical rainfall
Up to previous 365 days	During rainfall prior to disaster occurrence rainfall from previous 365 days	ditto

Table 4. Definition of confusion matrix.

		Prediction	
		Occurrences	Non-occurrences
Actual	Occurrences	TP (True Positive)	FN (False Negative) (type-II error)
	Non occurrences	FP (False Positive) (type-I error)	TN (True Negative)

Table 5. Numbers of rainfall debris flows and slope failures that occurred during rainfall events.

Timing	Disaster	Critical rainfall	Number of rainfall		Total
			Exceedance	Non exceedance	
During rainfall period	Occurrence	①Exceedance	4,904		10,086
		②Nonexceedance		5,182	
	Nonoccurrence	③Exceedance	419,984		6,412,216
		④Nonexceedance		5,992,232	
Total			424,888	5,997,414	6,422,302

Table 6. Numbers of debris flow events and slope failures that occurred during the pre/postrainfall period.

Timing	Disaster	Critical rainfall	Number of disasters		Total
			Exceedance	Non exceedance	
Pre/Postrainfall period	Occurrence	⑤Exceedance	91		2,931
		⑥Nonexceedance		2,128	
		⑦Time unknown	712		
Total			803	2,128	2,931

Table 7. Numbers of rainfall landslides that occurred during rainfall events.

Timing	Disaster	Critical rainfall	Number of rainfall		Total
			Exceedance	Non exceedance	
During rainfall period	Occurrence	①Exceedance	344		823
		②Nonexceedance		479	
	Nonoccurrence	③Exceedance	424,544		6,421,479
		④Nonexceedance		5,996,935	
Total			424,888	5,997,414	6,422,302

Table 8. Numbers of landslide events that occurred during the pre/postrainfall period.

Timing	Disaster	Critical rainfall	Number of disasters		Total
			Exceedance	Non exceedance	
Pre/Postrainfall period	Occurrence	⑤Exceedance	10		335
		⑥Nonexceedance		152	
		⑦Time unknown	173		
Total			183	152	335

Table 9. Means and standard deviation (SD) of 60-minute cumulative rainfall and SWI used for designated search durations.

Index	Past 365 days	Past 28 days	During rainfall
Average of maximum 60 minutes cumulative rainfall (mm/60min)	40.0	34.5	33.5
Standard deviation of maximum 60 minutes cumulative rainfall (mm/60min)	13.6	13.1	15.1
Average of maximum soil Water Index (mm)	155.9	135.7	155.7
Standard deviation of maximum soil Water Index (mm)	50.6	46.1	47.8

Table 10. Operational evaluation during the warm weather period from June 2003 through September 2020.

		Prediction	
		Occurrences	Nonoccurrences
Actual	Occurrences	4,904	5,182
	Non occurrences	419,984	5,992,232

Figures

Figure 1

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Three-dimensional RBFN output response surface based on 60-minute cumulative rainfall and SWI (soil water index) (left) and an example of a two-dimensional critical rainfall based on the response surface (right)

Figure 2

Definition of continuous rainfall period

Figure 3

Procedure used to classify disaster incident data

		Disasters (Time known)	Disasters (Time unknown)		
Exceedance of critical rainfall	① ・During rainfall period ・Exceedance of critical rainfall ・Counting by the number of rainfall	⑤ ・Pre/Postrainfall period ・Exceedance of critical rainfall ・Counting by Number of events (not number of rainfall)	⑦ ・Pre/Postrainfall period ・Time unknown ・Counting by Number of events (not number of rainfall) ・Even if disaster during rainfall period, ・Time unknown events more than specified RBFN output value is counted here.	Exceedance of critical rainfall	Non-exceedance of critical rainfall
	② ・During rainfall period ・Nonexceedance of critical rainfall ・Counting by the number of rainfall	⑥ ・Pre/Postrainfall period ・Non-exceedance of critical rainfall ・Counting by Number of events (not number of rainfall)			
		Disasters (Time known)	Disasters (Time unknown)		
※ Exceedance /nonexceedance is determined by the series of rainfall period (including norainfall periods).					
※ Rainfall events for which the number of rainfall is counted: Rainfall with the minimum RBFN value of less than 0.99					
※ RBFN value of time unknown disasters are assigned the lowest value and time during rainfall.					

Exceedance of critical rainfall	③ • Exceedance of critical rainfall • Counting by the number of rainfall	Exceedance of critical rainfall
Nonexceedance of critical rainfall	④ • Non-exceedance of critical rainfall • Counting by Number of events (not number of rainfall)	Non-exceedance of critical rainfall

Figure 4

Schematic diagram of the procedure used to classify rainfall events associated with sediment disasters
Definition of classifying landslide rainfall (above) and definition of classifying without event rainfall (below)

Numbers of sediment disaster-related events relative to critical rainfall: (a) debris flow and slope failure, (b) landslide

Figure 6

Sediment disasters occurring at rainfall ratios lower or higher than the critical rainfall for each geological classification (a) Higher than the critical rainfall (debris flow and slope failure), (b) Lower than the critical rainfall (debris flow and slope failure), (c) Higher than the critical rainfall (landslide), and (d) Lower than the critical rainfall (landslide)

Figure 7

Histogram of the maximum rainfall index for a series of debris flow and slope failure events (a) 60-minute cumulative rainfall. (b) Maximum SWI. (c) Minimum RBFN output value

Figure 8

Histogram of the maximum rainfall index for a series of landslide events (a) Maximum 60-minute cumulative rainfall. (b) Maximum SWI (c) Minimum RBFN output value

Figure 9

Histogram of the maximum rainfall indices from the previous 28 days to the end of the rainfall prior to debris flow and slope failure occurrence and the critical rainfall exceeding rate. The time difference between the minimum RBFN output values is shown. (a) Maximum 60-minute cumulative rainfall. (b) Time difference between maximum 60-minute cumulative rainfall. (c) Maximum SWI. (d) Time difference

between maximum SWI. (e) Minimum RBFN output values. (f) Time difference between minimum RBFN output values

Figure 10

Histogram of the maximum rainfall index from the previous 28 days to the end of the rainfall prior to landslide occurrence and the critical rainfall exceeding rate. The time difference between the minimum 60-minute cumulative rainfall. (b) Time difference between

maximum 60-minute cumulative rainfall and (c) maximum soil water index. (d) Time difference between maximum soil water index values. (e) Minimum RBFN output values. (f) Time difference between minimum RBFN output values

Figure 11

Histogram of the maximum rainfall index from 1 year before to the end of the rainfall prior to debris flow and slope failure occurrence and the critical rainfall exceeding rate. The time difference between minimum RBFN output values is shown. (a) Maximum 60-minute cumulative rainfall. (b) Time difference between minimum RBFN output values is shown. (c) Maximum SWI. (d) Time difference between minimum RBFN output values

maximum SWI values. (e) Minimum RBFN output values. (f) Time difference between minimum RBFN output values

Figure 12

Histogram of the maximum rainfall index from 1 year before disaster to the end of the rainfall prior to landslide. occurrence and the critical rainfall exceeding rate, the time difference between minimum RBFN

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maximum 60-minute cumulative rainfall. (c) Maximum SWI. (d) Time difference between maximum SWI values. (e) Minimum RBFN output values. (f) Time difference between minimum RBFN output values