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Rerearch Article

Rainfall–triggered landslide warning for Viet Nam using an antecedent rainfall index

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Abstract: This study is conducted to perform the rain–induced landslide warning for Viet Nam using an antecedent rainfall index (ARI) integrated with a landslide susceptibility map. The method used ARI 95th quantile as the warning threshold according to the suggestion of several previous studies. The results testing for the 6 historical landslide events indicated that the ARI values at the 95th quantile are more proper for the landslide events that are triggered by rainfall occurring on a small scale, whereas with respect to rain events happening on a large scale, the area under warning is widespread which leads to false alarm a lot. The warning area is reduced significantly when the 99th quantile is used as the warning threshold, which results in a decrease in the false alarm ratio. However, the warnings could not detect the landslide events that are triggered by rainfall occurring on a small scale. These results recommend that the ARI values at the 95th quantile should be used as the threshold for landslide warning with respect to the heavy rainfall events happening on a small scale, meanwhile, for the heavy rainfall events that occur on a large scale, the 99th quantile is a better choice.

Keywords: Rainfall–triggered landslide warning; ARI; Landslide susceptibility map.

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1. Introduction

Landslides are dangerous natural disasters occurring frequently and commonly around the world, causing thousands of human losses and the destruction of local infrastructures every year. The threats of landslides go up with the relentless development of the mountain areas. Landslide alerts or early warnings could provide helpful information for disaster managers and emergency planners to make robust decisions in mitigating the landslide damages [1–3].

The landslides could be triggered by several factors, such as rainfall, snowmelt, earthquakes, human activities, and so on. Precipitation is the most common ones among these factors. Landslides triggered by rainfall are usually because of the rise of the negative pore–water pressure which reduces the soil shear strength and causes the slope failures. This kind of landslide often follows a long period of high soil moisture in the lower zone and is then triggered by intense rainfall. Given rainfall is able to demonstrate both the antecedent soil water content and recent rainfall conditions, it is widely used to define the threshold for the occurrence of landslides by applying an empirical method. Most of the previous studies define rainfall threshold as a line that is identified visually [4] or by statistical approaches (e.g Bayesian inference [5–6] and the frequentist method [7] to separates the occurrence or non–occurrence of landslides. The most popular features used to categorize rain events are precipitation intensity–duration (ID) and accumulated event precipitation–rain duration (ED). Numerous rainfall thresholds were suggested and applied for landslide warning [8–11]. Despite they are the key tool in landslide warning systems, their deficiencies are often realized and discussed. For instance, the antecedent soil moisture or the recent rainfall information in some studies is not obviously taken into account in the threshold identification. For rainfall events happening in short durations, they seem to ignore the antecedent soil moisture information. Meanwhile, with respect to the rainfall event occurring in long durations, in spite of it implicitly contains the antecedent soil moisture information, it could not illustrate the relationship between rainfall events and landslides, because there might be the highest amount of rainfall which trigger landslides, antedated by a rainfall period which is able to lead to the slope to failure [12]. Nevertheless, the intensity computed from such a long period would flatten the intensity peak, neglecting the importance of the rainfall trigger.

To more manifest consider the antecedent soil moisture condition and the recent rainfall, numerous studies were conducted to obtain the rainfall thresholds which consider both the antecedent soil moisture condition and the rainfall trigger. They integrate the antecedent soil moisture condition into the determination of thresholds. In some systems of landslide warning, the antecedent accumulated precipitation over a period is used to simulate soil moisture condition which is associated with the recent rainfall amounts to obtain the landslide–triggered thresholds. For instance, the threshold proposed in [13] is identified by using the recent 3–day rainfall and the antecedent 15–day rainfall, whereas [14] take into account the recent daily rainfall and the antecedent 3–day rainfall information. [15] implemented an Antecedent Rainfall Index (ARI) to express implicitly the antecedent soil moisture condition by using the 7–day recent rainfall.

In Viet Nam, the operational landslide warnings are performed by overlapping precipitation and landslide susceptibility maps. The operational warning method uses the most recent 12 hours of observed rainfall associated with a 6–hour rainfall forecast which is the maximum value among the three numerical weather prediction models being launched in operation to establish a precipitation distribution map. In this way, the rainfall used is determined as the triggering rainfall, whereas the antecedent wetness condition is not under consideration. This could lead to a missing warning because landslide happens occasionally even without heavy rain. Therefore, this study is conducted to test the applicability of a state–of–art method that considers both recent rainfall and antecedent wetness condition for operational landslide warning in Viet Nam.

2. Materials and Methods

2.1. Data collection

Daily precipitation data at 186 meteorological stations over the whole Viet Nam from 1991 to 2020 derived from Viet Nam Meteorological and Hydrological Administration (VNMHA) are collected to calculate ARI values. Due to the landslide susceptibility map (LSM) developed by Viet Nam Institute of Geosciences and Mineral resources (VIGMR) (hereafter referred to as VIGMR–LSM) has been completed for 15 provinces located in mountainous areas of the north of Viet Nam, and Thanh Hoa and Nghe An provinces and not covering the whole Viet Nam yet, another LSM obtained from NASA (https://gpm.nasa.gov/landslides/projects.html) (hereafter referred to as NASA–LSM) is collected to fill up the LSM missing area. The locations of 186 meteorological stations, VIGMR–LSM and NASA–LSM are displayed in Figure 1. The VIGMR–LSM and NASA–LSM are saved in raster format and have different spatial resolutions which are about 22.5 m and 1 km, respectively. Therefore, in order to merge the two maps and in service of landslide warning at the 1km scale, the VIGMR–LSM is converted to the resolution of 1 km. Eventually, a complete LSM map covering the whole Viet Nam is made by overlapping the two layers with the priority for VIGMR–LSM.

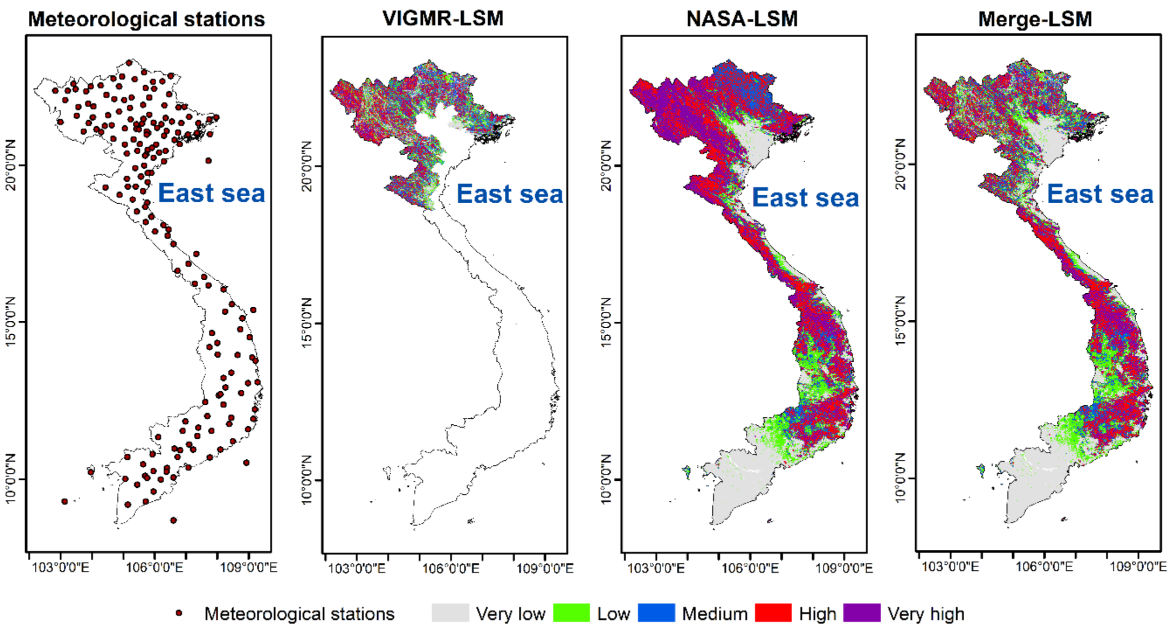

Figure 1. Location of the meteorological stations and landslide susceptibility maps.

2.2. Landslide warning through the integration between ARI and LSM

The ARI calculates a weighted average of the most recent 7 days of rainfall, containing the current date as shown in Eq. (1):

$$ARI = \frac{\sum_{t=0}^{6} w_t P_t}{\sum_{t=0}^{6} w_t} \quad (1)$$

where t is the number of days before the current day, P_t is the rainfall amount at time t, and $w_t=(t+1)^{-2}$ is weight of day t. According to this weighting method, the contribution of rainfall amount to trigger landslide would decrease when t increase.

This study utilizes the 30–year record of continuous daily rainfall at 186 meteorological stations and calculates ARI. In near real–time, the ARI value of the most recent 7 days of rainfall is calculated and then is compared with the ARI threshold which is defined as 95th quantile. It is noted that the 95th ARI quantile is determined based on non–zero rainfall. It means the days that are no rain would be excluded from the calculation. The warning or no warning would be decided based on a decision tree framework which is displayed in Figure 2. It integrates the ARI index with a landslide susceptibility map. The ARI index is calculated every 6 hours at each station sites and then is interpolated to a 1x1 km grid using an inverse distance weighting method (IDW). The grided–ARI is compared against the ARI threshold. If it is lower than this value, no warning is issued but if the ARI value is higher than the threshold, then the landslide susceptibility map is under consideration. No warning is issued if the susceptibility value is very low or low, whereas if susceptibility is medium, high or very high, the nowcasts of caution, warning and danger are issued, respectively.

3. Results and Discussion

The applicability of the method for landslide warning in Viet Nam is tested for 6 landslide events occurring on 05 August 2016 at Bat Xat, Lao Cai, 03 August 2017 at Mu Cang Chai, Yen Bai, 03 August 2018 at Quan Son, Thanh Hoa, 03 October 2020 at Phong Dien, Thua Thien Hue, 18 October 2020 at Huong Hoa, Quang Tri, and 28 October 2020 at Nam Tra My, Quang Nam. In which, the two first events occurred because of the heavy rainfall events on a small scale, whereas the other ones are on a large scale. These are very dangerous landslide events that are responsible for the death of hundreds of persons and the destruction of hundreds of houses and infrastructure. The results of ARI calculation for the six events are shown in Figure 3, whereas maps of landslide warning using ARI 95th as threshold are indicated in Figure 4. The results show that by using ARI 95th as a warning threshold, the applied method could catch the locations of landslide occurrence of all landslide events and put them under high (warning) or very high (danger) possibility of occurrence. This is because the locations of landslide occurrence are in the high susceptibility areas (Figure 1) and the values of ARI at the 95th quantile are quite low (Figure 5).

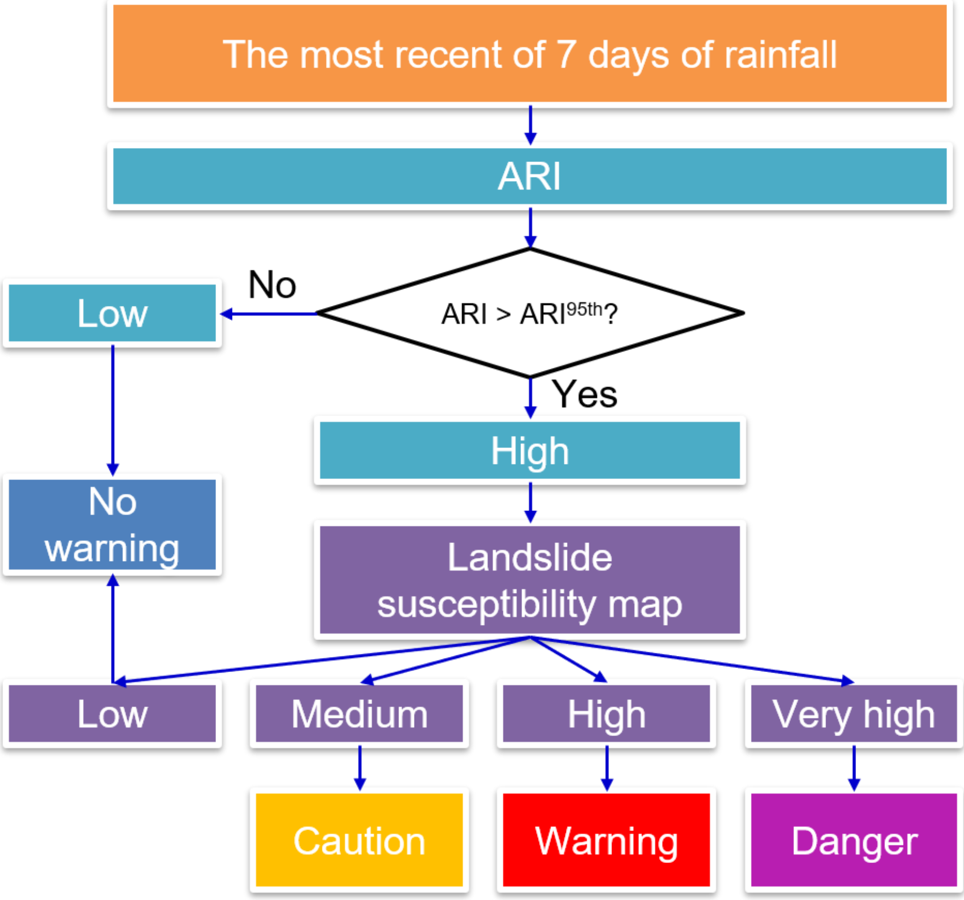

Figure 2. Decision tree structure for generating near real–time landslide nowcasts.

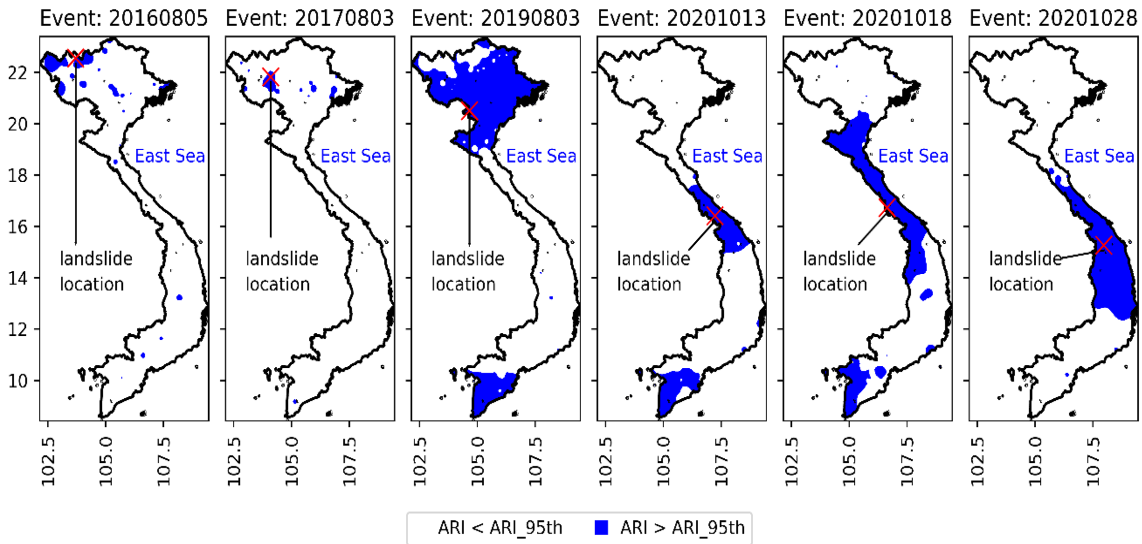

Figure 3. Maps of the ARI higher than ARI 95th for the 6 events.

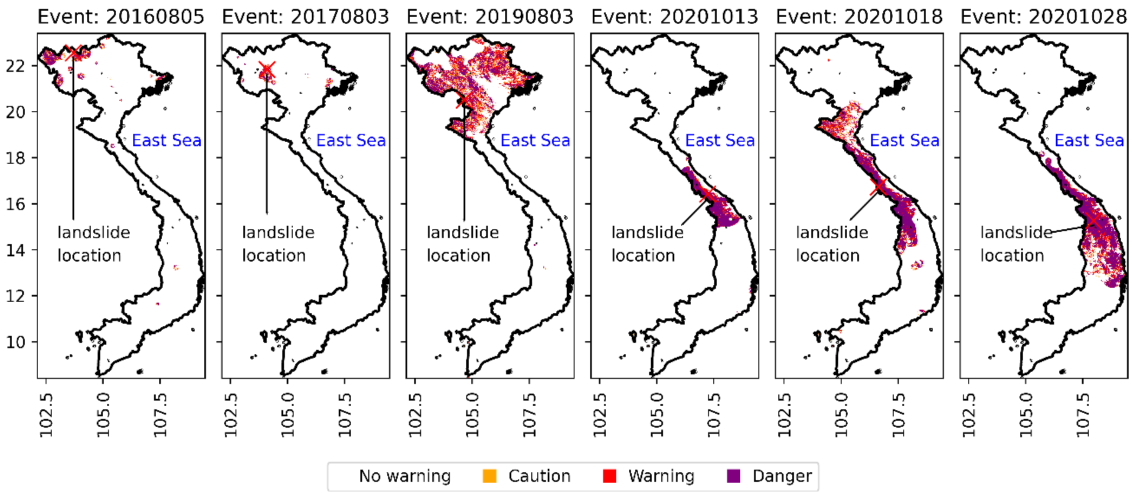

Figure 4. Maps of the regions under landslide warning for the 6 events using ARI 95th as threshold.

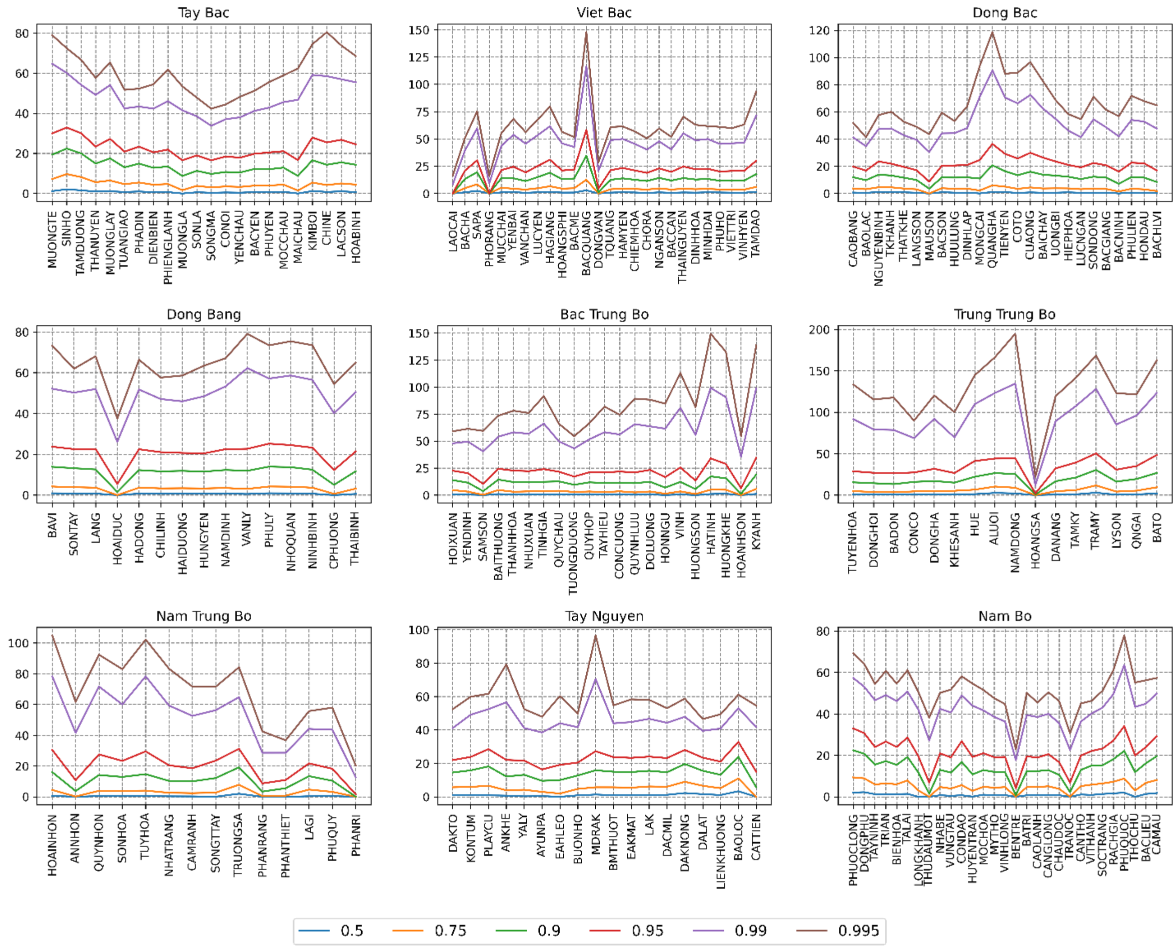

Figure 5. Variation of ARI value according to various quantiles at 186 meteorological stations.

In order to investigate the effect of threshold selection on the result of landslide warning, this study employs analyzing the variation of ARI values according to different quantiles and the warning area corresponding to the quantiles. Figure 5 illustrates the variation of ARI value according to various quantiles at 186 meteorological stations. The 50th, 75th, and 90th ARI values are lower than 20 mm at most of the stations. These values are too small with the landslide situation in Viet Nam, so they should be eliminated in the threshold determination.

Using these quantiles as a warning threshold would cause an increase in false alarms. The ARI values at the 95th quantile fluctuate around 22–25 mm, they are still quite small. This happens due to most of the days in the year have no rain or little rain. On the other hand, the ARI values at the 99th quantile are relatively proper for the condition in Viet Nam, but as shown in Figure 6, the landslide warning using this quantile as the threshold cannot catch the two first events, so it leads to a missing warning. Similarly, there is no point under the warning in the two first events when the 99.5th quantile is chosen. In this case, the warning area for the other events is reduced significantly compared to that of using the 0.95th and 0.99th quantiles. This result could decrease the false alarm ratio; however, it is vulnerable due to the occurrence of landslides containing much uncertainty. Additionally, the ARI values at this quantile are seems to be quite high.

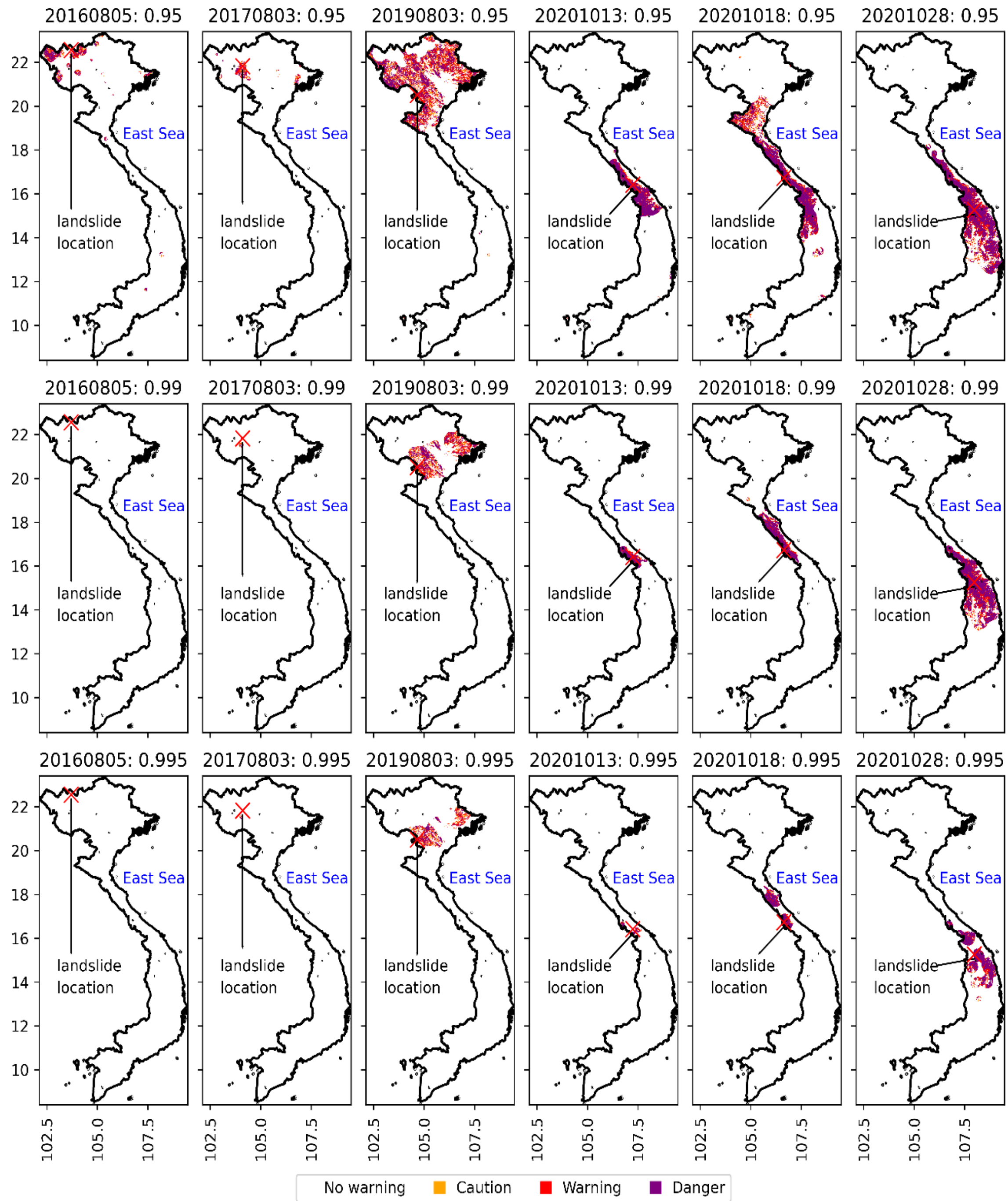

Figure 6. Variations of landslide warning area according to the change of ARI quantiles during the 6 landslide events.

Based on the above analysis, we suggest that for the rain events at a small scale, the ARI value at the 95th quantile should be selected as the warning threshold, whereas the ARI value at the 99th value would be a better choice with respect to the rain events at a large scale. Of course, these recommendations are based on the testing results of the 6 landslide events only. To achieve the best threshold used for landslide warning in Viet Nam, it is very crucial to test the method for a lot of other landslide events in the past and for the upcoming rainy season as well.

4. Conclusion

This study evaluated the applicability of a method which is the integration of an antecedent rainfall index and landslide susceptibility map for landslide warning in Viet Nam. The method used ARI 95th quantile as the warning threshold according to the suggestion of several previous studies. The results testing for the 6 historical landslide events indicated the viability of the method for landslide warning in Viet Nam. It is realized that the ARI values at the 95th quantile are more proper for the landslide events that are triggered by rainfall occurring on a small scale, whereas with respect to rain events happening on a large scale, the area under warning is widespread which leads to false alarm a lot. The warning area is reduced dramatically when the 99th quantile is used as the warning threshold, which results in a decrease in the false alarm ratio. However, the warnings could not detect the landslide events that are triggered by rainfall occurring on a small scale. These results recommend that the ARI values at the 95th quantile should be used as the threshold for landslide warning with respect to the heavy rainfall events happening on a small scale, meanwhile, for the heavy rainfall events that occur on a large scale, the 99th quantile is a better choice.

The results and recommendations above are the consequence of applying the method for only 6 landslide events. It is able to vary when the number of landslide events increases. Hence, it is very essential to include much more events in the selection of rainfall threshold. It is also noted that the LSM used for the provinces from Ha Tinh to the south is extracted from a global landslide susceptibility map that includes much uncertainty. Besides, the number of stations used in this study is quite sparse, which leads to many errors when the rainfall data are interpolated to a 1x1 km grid. Thus, further studies should be conducted to complete the LSM developed by VIGMR and to exploit the rainfall data at automatic stations as well as include much more landslide events.

Author contribution statement: Calculation and coding; manuscript writing and editing: H.M.N.; manuscript editing; methodology; results analysis and discussions: H.M.N., T.D.P., V.K.M., V.D.H.; data processing and analysis: N.P.N.

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