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Applicability of a rainfall-induced debris flow warning model: A case from Typhoon Khanun in Nantou County, Taiwan, 2023

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Abstract. Nantou County in Taiwan has endured a major earthquake and numerous extreme rainfall events over the past few decades, leading to significant disasters and economic losses due to landslides and debris flows. This study employs the parameter *RI* as the rainfall indicator, defined by the product of the 24-hour cumulative rainfall (*R*) and the hourly rainfall intensity (*I*). An empirical model correlating rainfall return period *T* of *RI* with the probability of debris flow occurrence (*P*) was used. The *P*–*T* model reflects the probability characteristics of debris flow occurrences after the Chi-Chi earthquake and extreme rainfall events and has been applied to the Chenyoulan Stream Watershed (CSW) in Nantou County, Taiwan. In early August 2023, Typhoon Khanun triggered numerous debris flows in Ren'ai Township, Nantou County. This study used the *P*–*T* model to evaluate the probability of debris flow occurrences in Ren'ai Township and examined the model's applicability. The results showed that the peak *RI* in Ren'ai Township reached 933 cm²/h, far exceeding the critical *RI* value of 365 cm²/h for triggering multiple debris flows in the CSW. Consequently, several debris flow events were recorded. The *P*–*T* model, combined with yellow and red risk levels, is reasonable for this case study.

Key words: *rainfall indicator, debris flow occurrence, probability, risk level*

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Применимость модели предупреждения о дождевых селях на примере тайфуна «Ханун» в уезде Наньтоу, Тайвань, 2023 год

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Аннотация. Уезд Наньтоу на Тайване за последние несколько десятилетий пережил сильное землетрясение и многочисленные экстремальные осадки, что привело к значительным бедствиям и экономическим потерям из-за оползней и селевых потоков. В данном исследовании в качестве индикатора осадков используется параметр *RI*, определяемый как произведение 24-часового суммарного количества осадков (*R*) и почасовой интенсивности осадков (*I*). Была использована эмпирическая модель, связывающая период повторяемости осадков *T* с вероятностью возникновения селевых потоков (*P*). Модель *P*–*T* отражает характеристики вероятности возникновения селевых потоков после землетрясения Чи-Чи и экстремальных дождевых явлений и была применена к водосборному бассейну ручья Ченьоулан (CSW) в уезде Наньтоу, Тайвань. В начале августа 2023 г.

[1] Previously.

тайфун «Ханун» вызвал многочисленные селевые потоки в пос. Ренъай в уезде Наньтоу. В данном исследовании использовалась модель *P–T* для оценки вероятности возникновения селевых потоков в пос. Ренъай и изучалась применимость модели. Результаты показали, что пиковое значение *RI* в поселке Ренъай достигло 933 см^2/ч, что значительно превышает критическое значение *RI* в 365 см^2/ч для возникновения многочисленных селевых потоков в CSW. В результате было зарегистрировано несколько селевых потоков. Модель *P–T* в сочетании с желтым и красным уровнями риска показала свою эффективность в рамках данного исследования.

Ключевые слова: *параметр осадков, сход селевых потоков, вероятность, уровень риска*

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Introduction

Extreme rainfall events have caused many countries to face serious debris flow disasters in recent years [*Joshi, Kumar, 2006; Chen, Chuang, 2014; Borga et al, 2014; Wang et al., 2015; Joe, Tongkul, Roslee, 2018; Nam, Lee, Kim, 2019; Gong et al., 2020*]. To avoid or reduce debris flows hazards, monitoring and early warning of debris flows is a concern topic for many researchers. The use of rainfall record to determine the rainfall threshold (critical rainfall) for debris flow occurrence is a commonly used method for debris flow warning [*Destro at al., 2017*]. Accumulated rainfall, rainfall intensity, and rainfall duration are widely used evaluation indicators for rainfall characteristics [*Caine, 1980; Wieczorek, 1987; Jan, Chen, 2005; Shieh et al., 2009; Chen et al., 2011*]. However, the occurrence of debris flows is not only related to the characteristics of rainfall, but also influenced by the terrain, lithology, sediment supplement, and soil cover conditions of a catchment [*Destro at al., 2017; Jan, Chen, 2005; Chen, Jan, 2008*]. This leads to high uncertainty in monitoring and warning the occurrence of debris flows. Especially after extreme rainfall events, there is a significant change in sediment supplement in a catchment area, and the critical rainfall of debris flows will also change accordingly [*Chen et al., 2009; Tang, Zhu, Li, 2009; Chen, 2011; Chen, Ja, Huang, 2013; Pan et al., 2018; Shen, Huang, Tsai, 2020*]. This poses greater challenges for debris flow monitoring and prediction [*Guzzetti et al., 2008; Nikolopoulos, 2014*]. Due to the high uncertainty of debris flow occurrence, some researchers have introduced the concepts of risk and probability to evaluate the occurrence of debris flow [*Chen, Jan, 2008; Chen, Jan, Lee, 2007*]. In Taiwan, soil and water conservation units use an integrated indicator of cumulative rainfall and rainfall intensity, and then differentiate the probability of debris flow occurrence into yellow and red alerts based on the low and high probabilities [*Jan, Lee, 2004*]. Chen and Huang [*2021*] developed a probabilistic model of debris flow occurrence based on rainfall return period *T* (the model of debris flow occurrence probability *P* and *T*) that reflects the effects of long-term rainfall changes and extreme events. This model reflects the probability characteristics of debris flow occurrence after the Chi-Chi earthquake and extreme rainfalls, and was applied to the Chenyoulan Stream Watershed (CSW), Nantou County, Taiwan. The Typhoon Khanun in early August 2023 caused multiple debris flows in Ren'ai Township, Nantou County. This study used the *P-T* model to evaluate the probability of debris flow occurrence in Ren'ai Township and tested the applicability of the model.

Extreme rainfall in the study area

The study area is located in Ren'ai Township, Nantou County, in the mountainous area of central Taiwan. The altitude of this township ranges from 382 to 3560 m (Fig. 1), and according to the data from the Ren'ai Rainfall Station, its annual average rainfall is approximately 2300 mm. From August 3 to 4, 2023, the peripheral circulation of Typhoon Khanun and the strengthening of southwest winds brought record breaking rainfall with accumulated rainfall of 992.5 mm in 48 h to Ren'ai Township, Nantou County, causing multiple debris flows and landslides. Among them, the St. Benedict (SB) gas station in Nanfeng Village (as shown in Figs. 1 and 2), an area affected by the debris flow potential stream with No. “Touxian DF013”, was buried for the 7th time by the debris flow, making it the building with the most times buried by debris flow in Taiwan's history [*ARDWCT, 2023*]. There were four records of this gas station being buried by debris flows in 2000, once in February, twice in April, and once in May, due to sufficient loose sediment supplement within one year after the 921 earthquakes in 1999. Subsequently, during the impact of Typhoon Mindulle and the July 2 flood in 2004 and Typhoon Sinlaku in 2008, the gas station was also buried again due to the heavy rainstorm. Now, Typhoon Khanun in 2023 has buried the SB gas station for the seventh time. The rainfall analysis results show that a breaking heavy rainfall occurred in Ren’ai Township, Nantou County from August 3rd to 4th (Fig. 3). The peak hourly rainfall I = 114 mm/h occurred on August 4th from 15:00 to 16:00. The maximum 24-hour cumulative rainfall R=818mm, which occurs at the peak of the hourly rainfall 24 h before. The peak hourly rainfall and maximum daily cumulative rainfall R_d =644mm on August 4th were both historical records of this rainfall station (Fig. 4), leading to frequent occurrences of debris flows and landslides. These slope hazards were mostly concentrated in the central mountainous area of Taiwan, especially Nantou County being the most severely affected (36, accounting for 78% of the total disaster points), of which 29 occurred in Ren'ai Township. According to the data compiled by the Ministry of Agriculture of Taiwan, Typhoon Khanun caused a total agricultural loss exceeding NT $238 million, of which Nantou County accounted for 73% of the total loss, with a loss amount exceeding NT $173.39 million.

Probabilistic rainfall-induced debris flow warning model

Rainfall index RI

A rainfall index RI was used to develop the model associated with probability of debris flow occurrence. RI is defined as

$$RI = R \times I, \tag{1}$$

where R is the 24-hour cumulative rainfall and I is the hourly rainfall intensity. The RI index has been used to study an extreme rainfall associated with debris flows [*Chen, Jan, Huang, 2013; Chen, Huang, 2021*]. RI > 365 cm^2/h, can be identified as extreme rainfall that triggered multiple debris flows in the CSW [*Chen, Jan, Huang, 2013*].

The P–T model

An empirical model correlating T with the probability of debris flow occurrence (P) has been proposed by Chen and Huang [*Chen, Huang, 2021*]. The P–T model reflects the probability characteristics of debris flow occurrences after the Chi-Chi earthquake and extreme rainfall events and has been applied to CSW in Nantou County, Taiwan. Due to the lack of sufficient debris flow data in Ren'ai Township, Nantou County to establish the P-T relationship, this study used the empirical relationship from CSW in the same county for analysis. The P–T relationship of the unaffected by extreme events period is:

$$P = 1 - e^{-0.20\left(\frac{T}{0.46}\right)^{0.99}}. \tag{2}$$

In which

$$T = (RI/180)^{2.38} + 0.97. \tag{3}$$

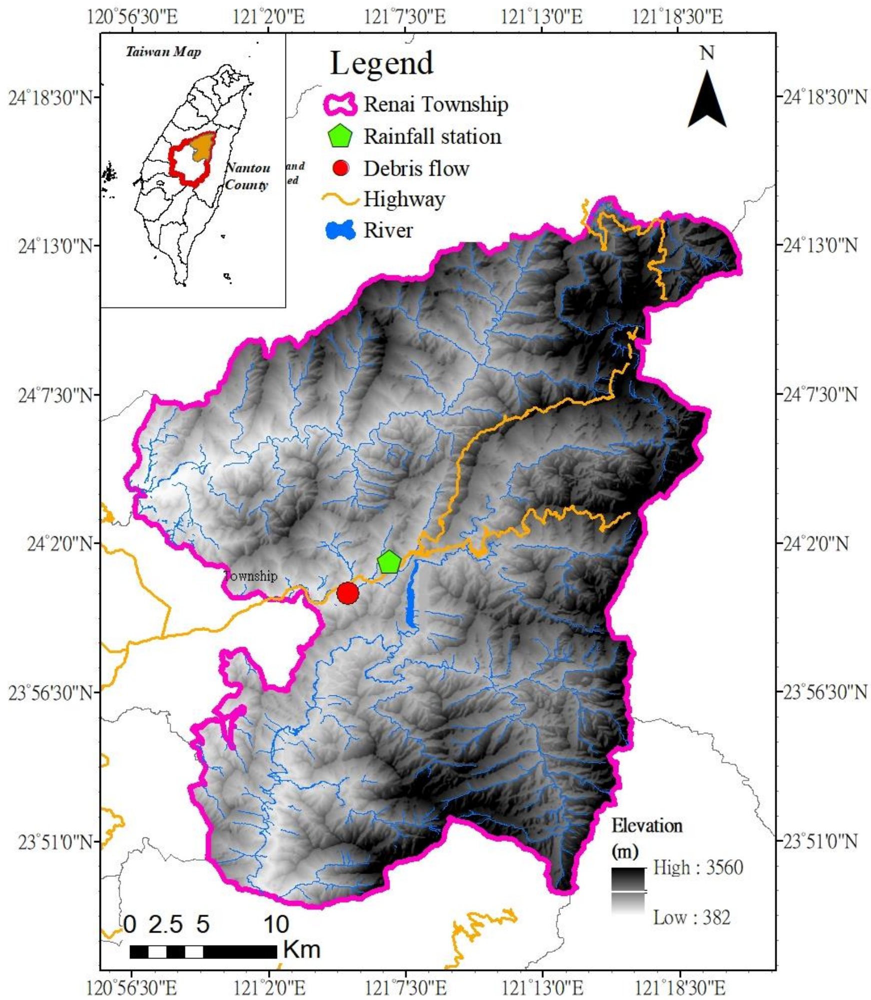

Fig. 1. The study area in Ren'ai Township, Nantou County. The red circle symbol showing the debris flow event at The St. Benedict (SB) gas station

a) b) c)

Fig. 2. St. Benedict (SB) gas station (No. "Touxian DF013" potential debris flow stream) in Nanfeng Village has been buried seven times by debris flows, making it the most buried building in Taiwan history [*ARDWCT*, *2023*]: a – the first debris flow hazard at the SB gas station in the rainstorm in Feb. 2000 after the 921 earthquakes in 1999 (provided by J.D. Shieh on Feb. 28, 2000 [*ARDWCT*, *2023*]); b – the sixth debris flow hazard at the SB gas station during Typhoon Sinlaku in 2008 (provided by S.C. Huang on Sept. 23, 2008 [*ARDWCT*, *2023*]); c – Fifteen years later, from Aug. 3rd to 4th, 2023, Typhoon Khanun's outer circulation caused the SB gas station to be buried for the seventh time by debris flow (from CTS TV image)

The P–T model (Eqs. (2) and (3)) was used to calculate the probability of debris flow occurrences in Ren'ai Township and examined the model's applicability. P was determined when the rainfall index RI >30 cm²/h.

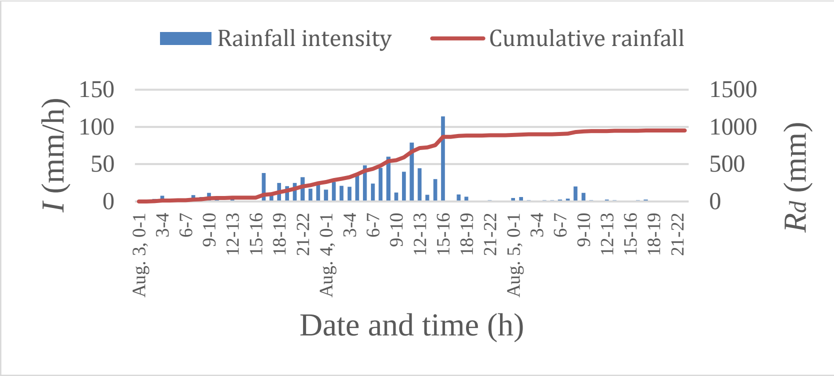

Fig. 3. Changes in hourly and cumulative rainfall at Ren'ai rainfall station. The cumulative rainfall from August 3rd to August 5th was 933 mm

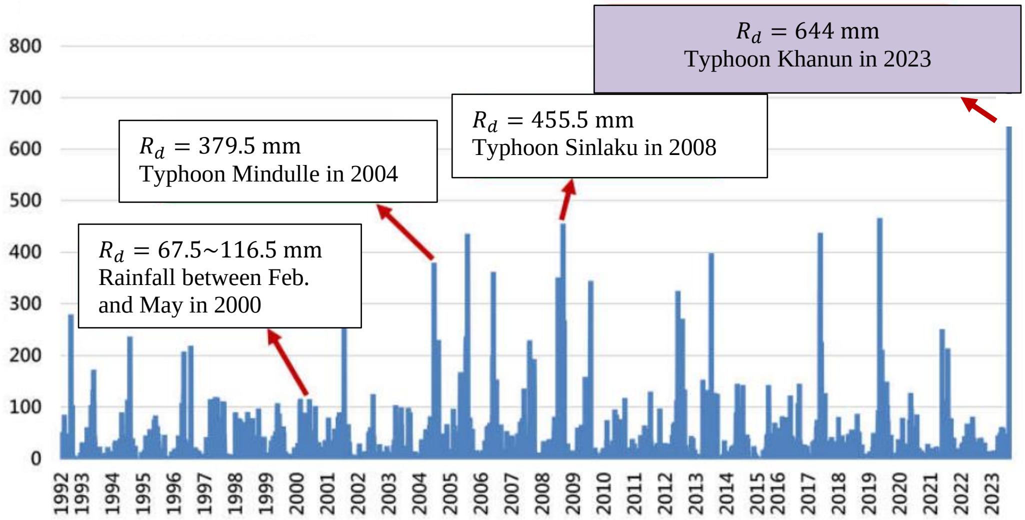

Fig. 4. Time series of daily cumulative rainfall R_d at Ren 'ai rainfall station, Ren 'ai Township, Nantou County (Source: Central Meteorological Administration; Drawn by: National Science and Technology Center for Disaster Prevention and Rescue (modified after [*Huang et al., 2023*])

Debris flow warning

Based on the temporal variation of rainfall data, the probability of debris flow occurrence *P* can be calculated using Eqs (2) and (3). In the application of early warning for debris flows, it is recommended to distinguish the risk levels into yellow and red. When P >0.5, the yellow risk level enters the warning state until the subsequent 6 h of rainfall result in P <0.5. When P >0.7, enter the red risk level that needs to be evacuated, and adjust to the yellow risk level until the subsequent 6 h of rainfall make P <0.7.

Results

According to the change in the probability line of debris flow occurrence (the red line in Fig. 5), the probability *P* of debris flow occurrence exceeded 0.5 after 5:00 on August 4th, entering the yellow warning zone of debris flow. By 8:00, *P* had exceeded 0.7, entering the red warning zone of debris flow. The *RI* value was 495 cm^2/h between 11:00 and 12:00, exceeding the rainfall standard for triggering multiple debris flows (*RI* = 365 cm^2/h). The corresponding probability of debris flow occurrence reaches 0.99. Although the rainfall slightly eased in the 3 to 4 h after *RI* = 495 cm^2/h, the rainfall intensity reached a peak of 114 mm/h from 15:00 to 16:00, and *RI* surged to 933 cm^2/h and the probability of debris flow occurrence once again reach 0.99. According to relevant media reports and on-site investigations, multiple debris flows appeared in the study area in the evening after the peak hour rainfall. Debris flows submerged gas station, roads, and houses but fortunately did not cause any deaths. The results of this study showed that the *P–T* model is reasonable to calculate the probability of debris flow occurrence and distinguish the risk levels of yellow warning and red evacuation, which can effectively mitigate the occurrence of debris flow hazards. However, in the years following the extreme rainfall event of Typhoon Khanun, the rainfall threshold for triggering debris flows may decrease, and the probability of such events may increase. Therefore, it is necessary to adjust the rainfall warning model for a debris flow after this event.

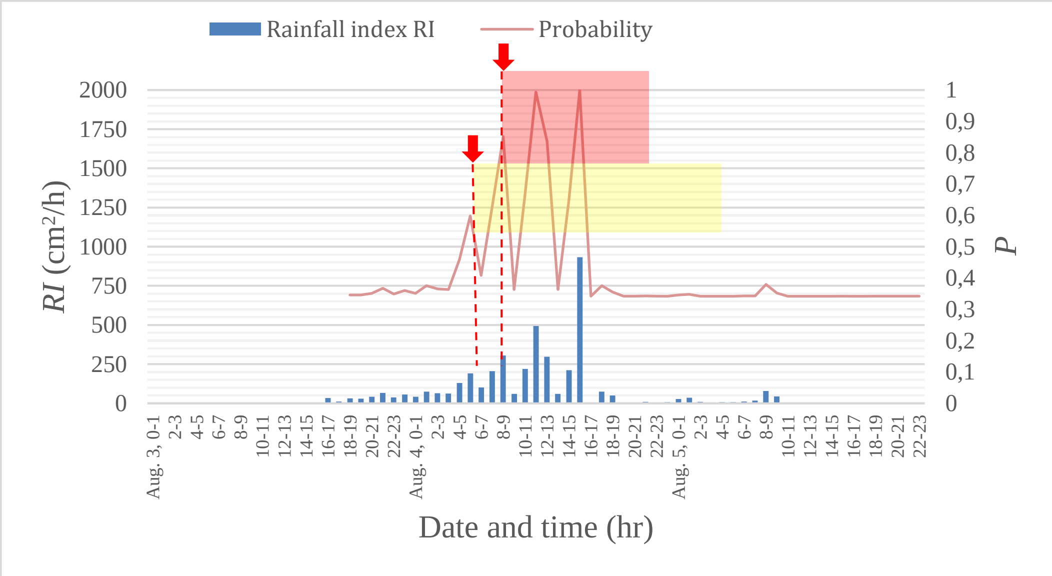

Fig. 5. Changes in rainfall index *RI* and probability *P* of debris flow occurrence. *P* was predicted when the rainfall index *RI* >30 cm²/h. According to the predicted *P*, different warning levels were proposed, with a yellow warning level of 0.5<*P*<0.7 and a red evacuating level of *P* >0.7.

Conclusions

This study used the *P–T* model to evaluate the probability of debris flow occurrence in Ren'ai Township, Nantou County, Taiwan, and examined the applicability of the model. The *P–T* model is based on the relationship between the rainfall index *RI* and its rainfall return period *T*, and combined with the Weibull function to establish a model between RI and the probability of debris flow occurrence. This model has effectively assessed the probability of debris flows occurring in CSW in Nantou County, Taiwan. In the case study of Renai Township, Typhoon Khanun brought record breaking rainfall, with a maximum hourly rainfall of 114 mm/h and a maximum cumulative rainfall of 818 mm within 24 h, resulting in multiple debris flow events. The results showed that the *P–T* model calculated the probability of debris flow occurrence in this study area, distinguished the risk levels of yellow warning and red evacuation, and effectively mitigating the occurrence of debris flow hazards.

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