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ORIGINAL RESEARCH ARTICLE

Analysis of rain-induced underground debris flow events in mines based on logistic regression models

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Abstract: Rainfall is one of the main external factors triggering debris flows in mines. To investigate the relationship between rainfall and the occurrence of underground debris flows, we selected 249 rainfall events in the study area from 2020 to 2022, including 86 potential underground debris flow events and five large-scale underground debris flow events. A rainfall threshold model for the occurrence of underground debris flows was developed using logistic regression. The model's accuracy, area under the receiver operating characteristic curve, and F1 score were 0.85, 0.9493, and 0.85, respectively, indicating good predictive performance and generalization. The results show that the rainfall thresholds for underground debris flow occurrence can be classified into three risk levels: (i) for p=0.9, the triggering rainfall was 88.6483 mm and the antecedent effective rainfall was 164.9885 mm; (ii) for p=0.7, the triggering rainfall was 78.2563 mm and the antecedent effective rainfall was 145.6473 mm; and (iii) for p=0.5, the triggering rainfall was 71.7336 mm and the antecedent effective rainfall was 133.5076 mm. The research findings provide a theoretical basis for the prevention and control of debris flow events in mines.

Keywords: Underground debris flows; Logistic model; Rainfall threshold; Triggering rainfall; Antecedent effective rainfall; Risk level

1. Introduction

Underground debris flows are a major safety risk in mines using the natural caving method, representing a geological hazard induced by mining activities.[1] Because underground debris flows primarily occur in mines employing the natural caving method and are strongly influenced by the mining methods and activities, they are less recognized and often overlooked than surface debris flows. When the rock mass contains a high amount of mud or fine-grained ore, or when the overlying strata and dust layers are thick, these substances easily form mud under hydraulic action, which then infiltrates underground goaf areas through fissure channels, posing a risk to personnel safety and facility integrity. Although an increasing number of researchers have investigated underground debris flows in recent years, the mechanisms underlying these events remain poorly understood. In particular, the long-term rainfall-induced erosion of the overlying strata and the evolutionary characteristics of debris-flow transport through fissure channels require further in-depth studies.[2,3] Underground debris flows typically originate from the localized fluidization of loose glacial deposits or mining backfill materials.[4] When heavy rainfall or groundwater infiltration raises pore water pressure beyond a critical threshold, the loose material gradually liquefies and flows toward surface subsidence pits, where it further mixes with the abundant loose materials, forming mud. Subsequently, the mud enters the ore body through surface subsidence pits and fissures, forming mud inclusions that ultimately lead to underground debris flow events under the influence of mining activities.[5] Rainfall plays a decisive role in this process.[6] Surface rainfall not only increases groundwater levels and pore water pressure through infiltration but also saturates fissure zones, enhancing permeability and accelerating mud initiation and transport.[1,7-9] Simultaneously, continuous or concentrated rainfall events can produce cumulative effects that couple the surface and groundwater systems and significantly increase the probability and scale of underground debris flows.[10,11] Cabral *et al.*[6] reported a significant linear correlation between debris flow frequency and rainfall, and their analysis of rainfall-triggered and non-rainfall-triggered debris flow events helps assess rainfall duration and intensity thresholds for debris flow occurrence.[12] Identifying rainfall thresholds that trigger debris flows can be an effective measure for preventing and mitigating debris flow events.[13] Therefore, identifying the quantitative relationship between rainfall characteristics and the occurrence of underground debris flows is of great significance for establishing scientific rainfall threshold models and improving mine event early warning systems.

To study the mechanisms underlying underground debris flows, researchers worldwide have conducted physical model experiments, factor analyses, risk assessments, and numerical simulations.[2,14] Niu *et al.*[1,15] explored the formation mechanism of underground debris flows—mud inclusions in mines using the natural collapse method—through physical model experiments, establishing a generalized model of the formation mechanism and expanding the research scope of debris flows. Huang *et al.*[16] studied the catastrophic process of intermittent cement inrush caused by rainfall through physical experiments. To further investigate the correlation between hydraulic action and loose material sources, Chen *et al.*[17] conducted water and sediment inrush experiments, and Zhao and Zhang[18] proposed the relationship between mud viscosity and water content. Zhang *et al.*[19,20] also analyzed the correlation between rainfall and the occurrence of underground debris flows using machine learning methods and classified the hazard level based on rainfall conditions. Castro *et al.*[21] quantified the main risk variables related to mud formation and outbreaks through logistic regression. Regarding the occurrence of underground debris flows, Castro *et al.*[4] indicated that mud may remain dormant for a long time and suddenly mobilize when disturbed. Xue *et al.*[22] also explained that mud enters seepage faults in the mining process, and does not directly enter from the surface and erupt immediately. Zhang *et al.*[3] indicated that underground debris flows are induced by human activities and rainfall, and have the characteristics of being concealed and having dynamic multiphase triggering factors. These studies all indicate that rainfall is one of the most important factors that induce underground debris flows, affecting their formation and flow.

While many scholars have conducted research and analysis on underground debris flows in mines using surface debris flow research techniques and achieved fruitful results, few have directly conducted risk assessments and hazard threshold studies based on the four major factors (triggering mechanisms, discharge points, water, and mud formation) contributing to debris flow formation. Therefore, this study uses a logistic regression model to simulate and analyze rainfall data. Based on the process of rainfall erosion and surface infiltration, a rainfall threshold is established using antecedent effective rainfall and triggering rainfall, and hazard levels are classified. This research can provide a fundamental theoretical basis for the prevention and control of underground debris flows.

2. Geological characteristics and underground debris flow hazards in the study area

The study area is located in a large porphyry copper mining district in northwestern Yunnan, China (Figure 1). It is characterized by steep highland terrain with elevations between 3,400 and 4,500 m, where Quaternary glacial deposits, quartz diorite porphyry, and gray slate of the Tumugou Formation are widely exposed. The rock mass is highly fractured, with well-developed faults and joints, resulting in complex hydrogeological conditions. Atmospheric precipitation is the sole source of groundwater recharge, primarily concentrated from July to September. The Quaternary glacial and slope deposits form the main aquifers, but their water-bearing capacity varies significantly across lithologic units.

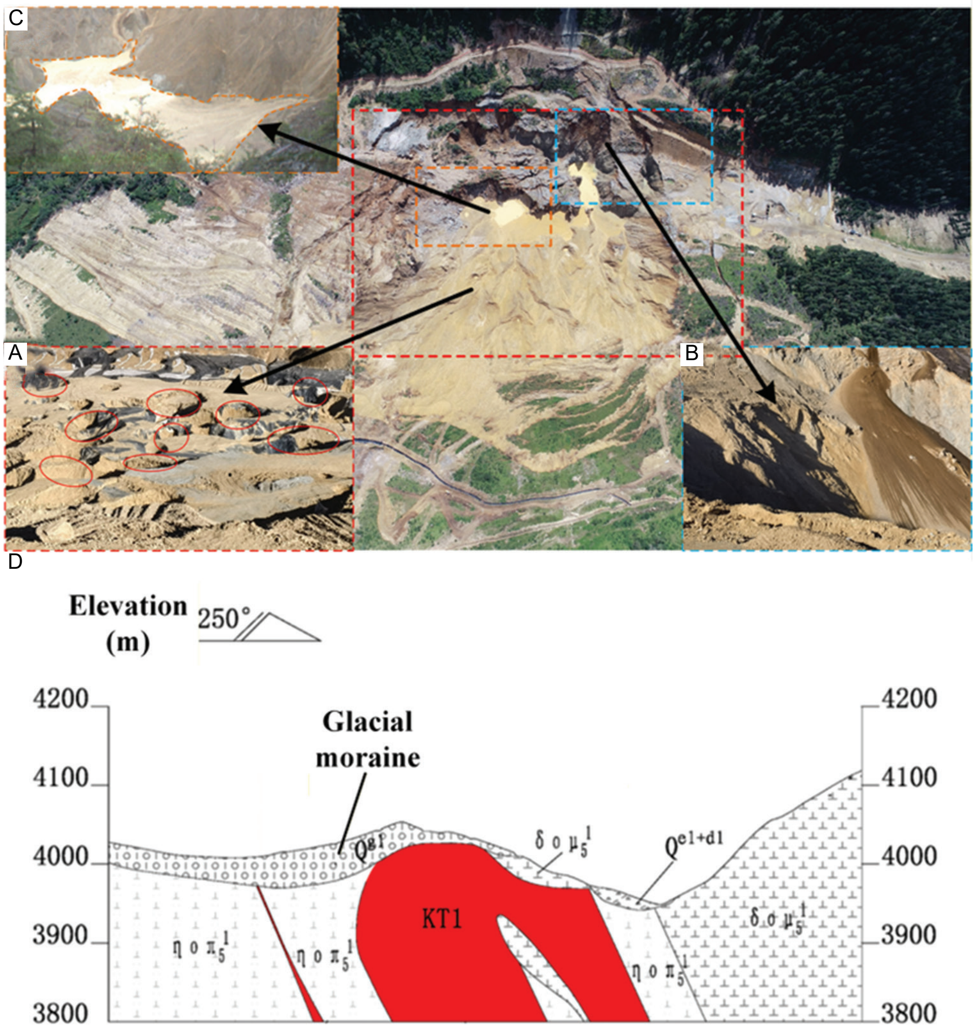

Figure 1. Orthophotography of the study area. (A) Subsidence area and surface sinkholes. (B) Surface glacial till. (C) Sinkhole catchment area. (D) Topographic profile of glacial till distribution.
Source: Image by author.

The mine adopts the natural caving method, in which continuous extraction triggers overburden collapse and large-scale surface subsidence. In fault-rich zones, loose debris and fault gouge gradually form potential channels connecting the surface and underground goaf. During the rainy season, heavy rainfall infiltrates through these channels, washing moraine material and fine sediments into the mined-out voids. This process induces local softening, collapse, and mud accumulation in tunnels, and as mining-induced stress redistributes, these channels expand and interconnect.

Such geological and structural conditions, combined with concentrated rainfall, create a high susceptibility to underground debris flows (Figure 2). Rainwater infiltration raises pore pressure, reduces shear strength, and mobilizes unconsolidated materials along collapse pathways. Once initiated, underground debris flows exhibit sudden onset and rapid, destructive movement within confined spaces, posing severe threats to miners. Overall, rainfall acts as the dominant triggering factor, while the fractured structure and mining-induced voids provide the necessary geological conditions for debris flow development in the study area.

3. Debris flow prediction model based on logistic regression

This study analyzes daily rainfall data over 3 years and investigates the occurrence of underground debris flows. Incomplete data on underground debris flow events are excluded from the analysis. In addition, data on contemporaneous extreme weather events are

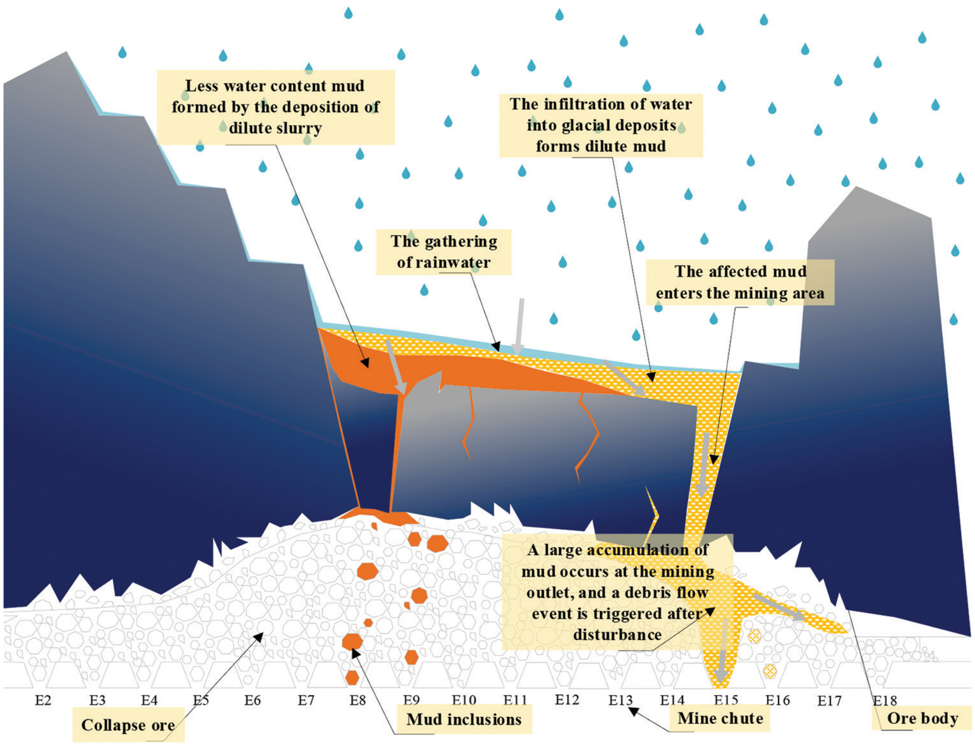

Figure 2. Schematic showing downhole debris flow formation
Source: Image by author.

considered. The analysis examines the 480-h (20-day) period leading up to the event, considers the effective rainfall coefficient, and calculates the effective rainfall amount that triggers the event.[11,23,24] The processes involved in rainfall-induced underground debris flows can be divided into two types:[25]

(i) The first type involves the continuous rainfall that precedes the debris flow events, referring to rainfall accumulated over a defined period before their occurrence. In this mining area, rainfall can cause mud formation in the overlying Quaternary glacial deposits, and the mud is then washed into the collapse pit at the base of the overlying deposits (Figure 1). This process widens the voids between the overlying glacial deposits, increasing pore-water pressure, decreasing effective stress, and reducing shear strength, thereby triggering underground debris flow events.
(ii) The second type involves sudden rainfall, which directly enlarges the mining outlet channel through erosion. This rainfall directly triggers underground debris flows even in the absence of mining disturbances.

It should be noted that only certain rainfall events trigger underground debris flows. Therefore, this study considered induced rainfall, antecedent effective rainfall, and cumulative effective rainfall as the key indicators. A logistic regression model was employed to analyze the rainfall data. The triggering rainfall and pre-event effective rainfall data were divided into training and testing sets to train the logistic regression model. The triggering rainfall and pre-event effective rainfall data were used as inputs, while the occurrence of underground debris flows in the mining area (1 for occurrence and 0 for non-occurrence) was used as the model output. The model's accuracy and generalization were evaluated using performance metrics, such as precision, recall, and F1 score. In addition, the receiver operating characteristic (ROC) curve (a graphical tool for evaluating the performance of the binary classification model) was plotted, and the area under the curve (AUC) (a metric that quantifies the overall performance of the binary classification model) value was calculated to assess the model's performance. Thus, a mathematical model was developed to determine the rainfall threshold for triggering underground debris flows.

3.1. Observed rainfall in the mining area

An analysis was conducted by combining observed rainfall and occurrence data for underground debris flow events in the mining area over a 3-year period. Underground debris flow events without specific time records, specific locations, or rainfall monitoring data were excluded from the analysis. A total of 249 daily rainfall data points from the mining area were selected for the 2020–2022 period. Based on the mining area's meteorological warning system and terrain monitoring system, 86 potential debris flow events (large mud accumulations observed at the mining outlet) and five significant underground debris flow events (i.e., events that have an extensive impact and cause equipment damage) were identified.

Due to the daily resolution limitation of rainfall data in the mining area, rainfall data associated with underground debris flows were extracted from records corresponding to the event dates. Figure 3 presents the daily rainfall data observed in the mining area over a 3-year period, along with the occurrences of debris flow events.

The rainy season in the mining area occurred primarily in July, August, and September, whereas rainfall was relatively low during the other months, and no underground debris flow events were observed. Figure 3 shows that the mining area experiences concentrated, continuous rainfall, which is classified as sustained rainfall. Consequently, the probability of underground debris flow occurrences is higher during the rainy seasons. This indicates that the preceding rainfall plays a significant role in the occurrence of debris flows. Due to the prolonged effect of previous rainfall, the soil gradually saturates, leading to a decrease in the shear strength of the overlying glacial and debris layers. Even on days with minimal or no rainfall, once the cumulative effective rainfall exceeds the critical threshold, underground debris flows can be triggered. In particular, when no rainfall occurs on the day of the debris flows but prolonged rainfall occurred in the preceding period, the accumulated rainfall above the discharge opening can disrupt the equilibrium of the mud slurry, resulting in underground debris flows when mining operations commence. Figures 1 and 2 indicate that preceding rainfall plays a significant role in the occurrence of underground debris flows in the mining area.

3.2. Analysis of debris flow occurrence factors

The occurrence of underground debris flows in mining areas depends on multiple factors, including disturbances and triggering mechanisms. Mining operations are the most significant form of disturbance to the existing equilibrium, leading to underground debris flows within the mine piles. There must also be discharge points through which the slurry enters the mine tunnels. In addition, a water source is needed, which is provided by rainfall. Finally, there must be existing mud-like substances or materials capable of forming mud.

In the normal operation of a mine, daily mining activities at each discharge point are generally consistent; therefore, disturbances and triggering mechanisms were considered as constants in this study.

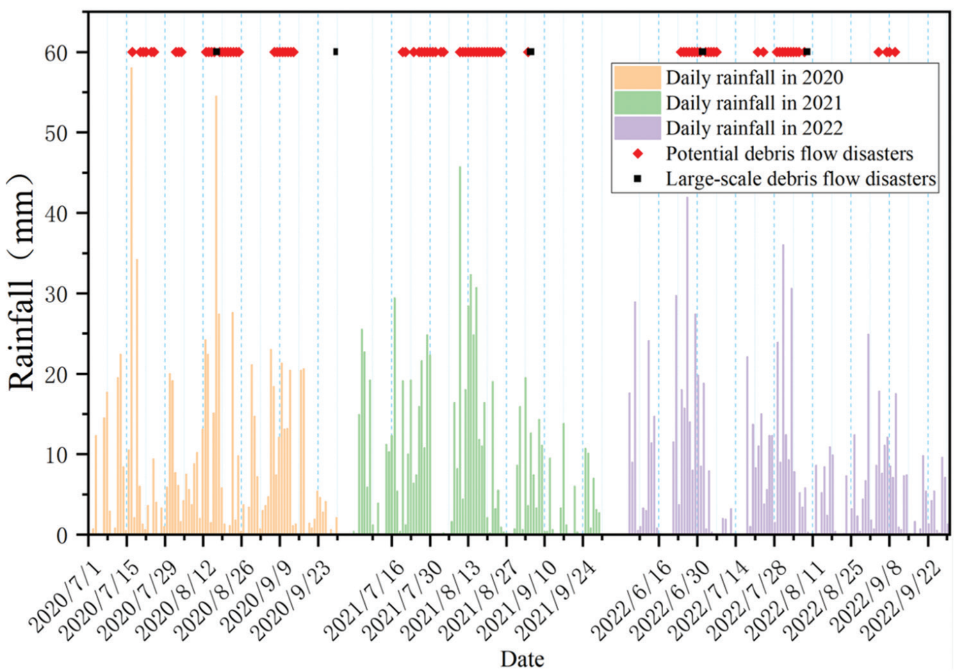

Figure 3. Three-year data of observed rainfall and debris flow occurrence

The discharge points also remained constant in regular mining operations. In the studied mining area, the main source of material for underground mudslides was glacial and debris deposits that provided the conditions for the formation of underground debris flows. In the study area, the overlying glacial and debris layers were eroded by rainfall, forming the material for debris flows. Although the environmental protection measures prevent the overlying glacial and debris layers from being eroded, they inadvertently preserve ample material that may contribute to underground debris flows.

The water source is the most critical factor in the occurrence of underground debris flows, and in this study, water is considered a discrete variable and the primary factor to examine.

3.3. Effective rainfall model

The main factor leading to the displacement and sliding of the upper-level glacial deposits into the collapse pit is the rapid decrease in matric suction of the unsaturated slope due to rainfall infiltration. The initial rainfall events typically increase the voids between particles in the overlying glacial deposit layer, leading to increased pore water pressure, reduced effective stress, and decreased shear strength, thereby triggering the sliding and accumulation of the glacial deposit layer into debris flows. The initial rainfall does not fully contribute to the occurrence of underground debris flows; only certain rainfall events trigger them.[26,27] In this study, the rainfall threshold needed for the occurrence of underground debris flows is analyzed through the combination of effective rainfall and triggering rainfall. Triggering rainfall is the minimum rainfall required to directly trigger underground debris flow events. Initial effective rainfall refers to rainfall that accumulates moisture in the upper-level glacial deposits over a given period, leading to a decrease in shear strength and the occurrence of underground debris flow events. The effective rainfall amount that triggers underground debris flow events serves as an indicator of rainfall-induced underground debris flows, depending on both previous rainfall totals and rainfall on the day of the debris flow.[28] The effective rainfall amount is typically considered a function of the return rainfall index and time.[29] In this study, the cumulative rainfall amount for the 5 days preceding an underground debris flow event, starting from the onset of rainfall, is defined as the triggering rainfall. The expressions for triggering rainfall, the cumulative rainfall before the event, and initial effective rainfall are as follows (Equations 1-3)[30]:

$$X_c = X_1 + X_2 + X_3 + X_4 + X_5 + \sum_{i=6}^{n} k^{i-5} X_i \quad (1)$$

$$X_{a5} = X_1 + X_2 + X_3 + X_4 + X_5 \quad (2)$$

$$X_{a15} = \sum_{i=6}^{n} k^{i-5} X_i \quad (3)$$

where,

X_c: Cumulative effective rainfall, X_1, X_2, X_3...X_i, represent the consecutive daily rainfall amounts recorded 24 h, 48 h, 72 h, and so on, before the rainfall event immediately preceding the event;

k: Rainfall attenuation coefficient ($k \leq 1$), characterizes the ability of the underlying surface to retain rainwater;

X_{a5}: Triggering rainfall;

X_{a15}: Antecedent effective rainfall.

The coefficient of rainfall attenuation, denoted *k*, represents the capacity of the material along the path to retain rainfall and is determined by the overall properties of the soil and rock in the region. Therefore, selecting an appropriate rainfall attenuation coefficient is a key issue in constructing an effective rainfall model. Researchers have proposed a range of rainfall attenuation coefficients from 0.72 to 0.86.[24,30-33] The coefficients $k = 0.8$ and 0.84 were the most widely used in previous studies.[34,35] Considering that the research object is debris flow in underground mines, this study selects a rainfall attenuation coefficient of 0.84 based on previous studies.[23,36,37]

Previous studies have divided the effective time period of antecedent rainfall into 4, 10, 15, and 18 days.[23,24] It has been found that the correlation between the 15-day antecedent effective rainfall and landslide events is the highest.[28] Since this study focuses on underground debris flows in mines, which exhibit delayed occurrence, various factors were considered. Therefore, the time period for rainfall was set as 480 h (20 days) before the occurrence of underground debris flow events. In addition, the triggering rainfall was defined as the sum of rainfall over the previous 5 days.

3.4. Logistic regression model of debris flow occurrence

Logistic regression is widely used to analyze rainfall conditions associated with landslides and debris flow events.[38] In the case of underground debris flow events, from a statistical perspective, the factors that influence their occurrence can be treated as independent variables, while the occurrence or non-occurrence of underground debris flows can be treated as the dependent variable for classification. Since rainfall factors are discrete variables, this study applies logistic regression to analyze the data.[39]

Assuming that the probability of underground debris flow occurring in the mining area is p, where p ranges from 0 to 1, the probability of underground debris flow not occurring is $1-p$. The logistic regression value for underground debris flow is $p/(1-p)$. Taking the natural logarithm, the independent variables are X_1, X_2,...., X_k where X_1 represents the rainfall of the current day, X_2 represents the rainfall of the previous day, and so on. If the dependent variable is the probability of underground debris flow occurrence (p), then the logistic regression equation can be expressed as follows (Equations 4 and 5)[40]:

$$\ln\frac{p}{1-p}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\cdots+\beta_kX_k \quad (4)$$

where β_1, β_2,⋯, β_k are regression coefficients. From Equation (IV), we can derive:

$$p=\frac{e^{\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k}}{1+e^{\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k}} \quad (5)$$

Using Equation (5), it is possible to quantitatively predict the probability of rainfall-induced underground debris flow events.

4. Result

4.1. Analysis of initiated rainfall and preliminary effective rainfall

The daily rainfall data from 2020 to 2022 were used in this study, and the values of the triggering rainfall (X_{a5}), previous effective rainfall (X_{a15}), and cumulative effective rainfall (X_c) were calculated for each day. The data for X_{a5}, X_{a15} and X_c are shown in Figures 4-6, respectively.

This study initially analyzed the daily rainfall data from the mining area for the years 2020–2022. The triggering rainfall and cumulative effective rainfall for each day were examined, leading to the selection of 249 rainfall events. Among them, 86 events were identified as potential underground debris flow events, and five events were classified as large-scale underground debris flow events. Figures 4-6 show that underground debris flow events occur most frequently during periods with high cumulative effective rainfall, whereas they rarely occur during periods with low triggering rainfall and previous effective rainfall. Selecting triggering rainfall and previous effective rainfall as key factors ensures the accuracy of the predicted rainfall threshold model for underground debris flows based on binary logistic regression.

Using the triggering rainfall (X_{a5}) and antecedent effective rainfall (X_{a15}) as independent variables and the occurrence of underground debris flow (1 or 0, i.e., binary categories) as the dependent variable, a regression equation was established based on the selected 249 data points. The data were divided into a training set (70%) and a test set (30%). Across regression analysis, the probability model for predicting underground debris flow occurrence was obtained as follows (Equation 6):

$$p=\frac{e^{(0.1299*X_{a5}+0.0698*X_{a15}-9.3182)}}{1+e^{(0.1299*X_{a5}+0.0698*X_{a15}-9.3182)}} \quad (6)$$

The predicted results are shown in Figure 7, demonstrating a high level of accuracy in the classification results.

4.2. Logistic regression model test

To verify the accuracy and practicality of the underground debris flow prediction probability model, we selected five representative large-scale underground debris flow events as samples from 91 potential and large-scale underground debris flow events. We used the Python random sample function with a fixed random seed to randomly select five non-triggering events from the dataset that do not include underground debris flow events. The calculated results were obtained by substituting the rainfall factors into Equation (6). These results demonstrate good agreement between the predicted probabilities and the actual occurrences (Table 1).

This study used a logistic regression model to predict the rainfall threshold for triggering underground debris flows and evaluated its performance by plotting the ROC curve and calculating the AUC value. A total of 249 data samples were used for model training and testing, with 70% for training and 30% for testing. The ROC curve is shown in Figure 8. The model exhibited varying true-positive and false-positive rates across thresholds. The AUC, which represents the area under the ROC curve, typically ranges from 0.5 to 1.0. A higher AUC indicates better model performance. In this study, the model's AUC was 0.9493, indicating good performance.

This study also used precision, recall, and F1 score to evaluate model accuracy and generalization ability. The

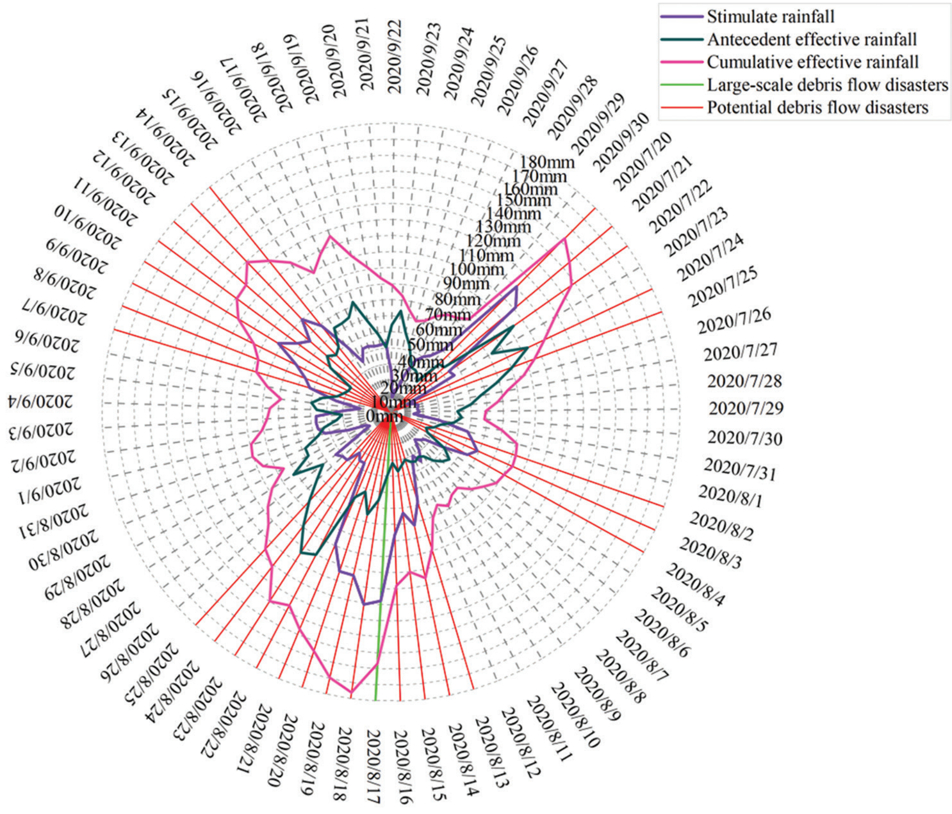

Figure 4. Rainfall data in 2020

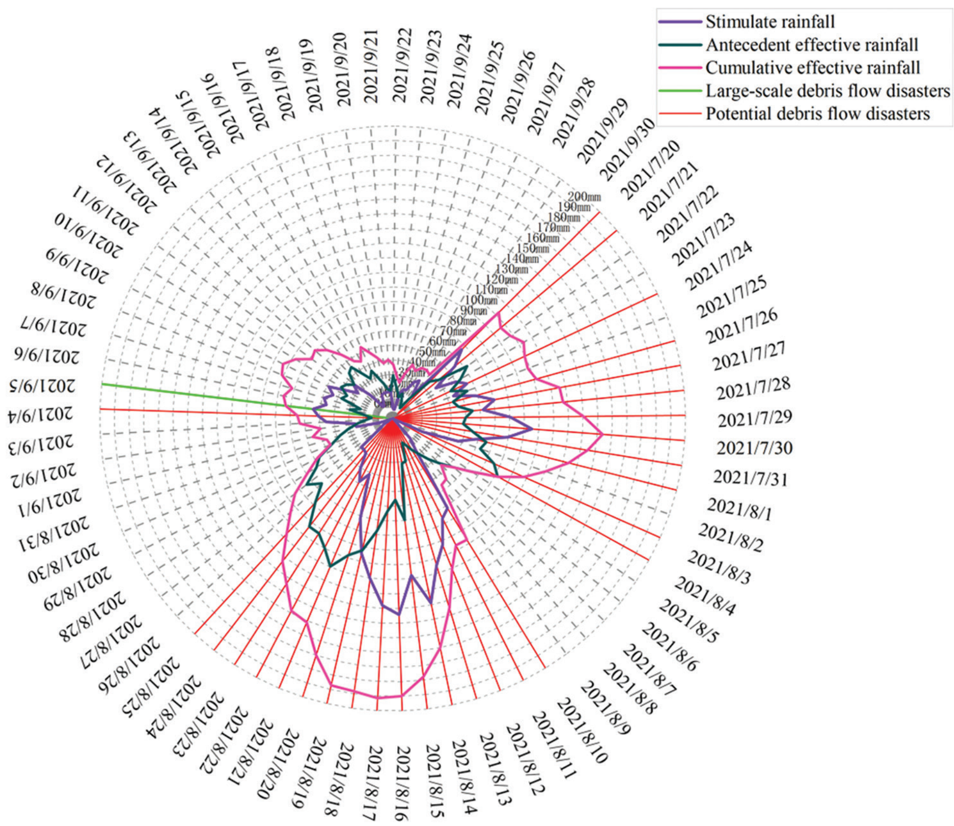

Figure 5. Rainfall data in 2021

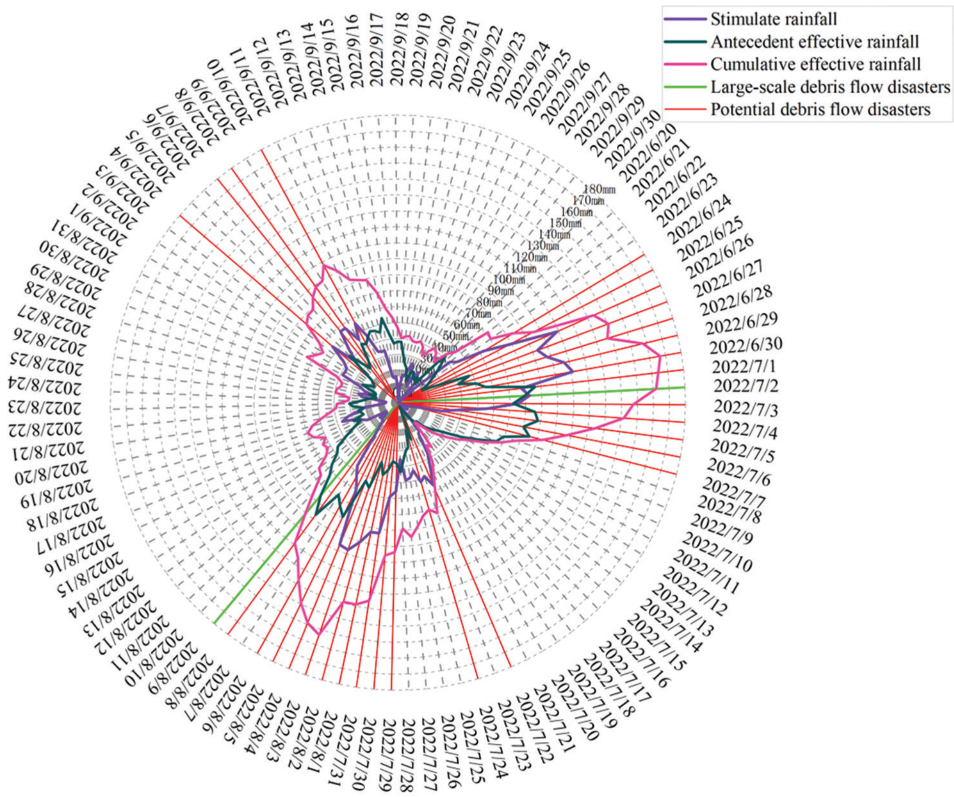

Figure 6. Rainfall data in 2022

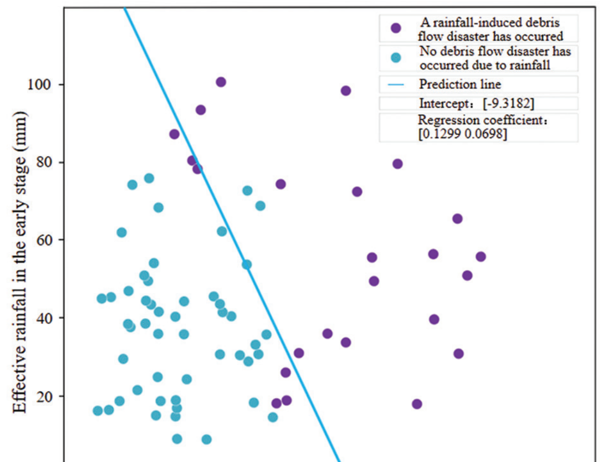

Figure 7. Rainfall threshold prediction results

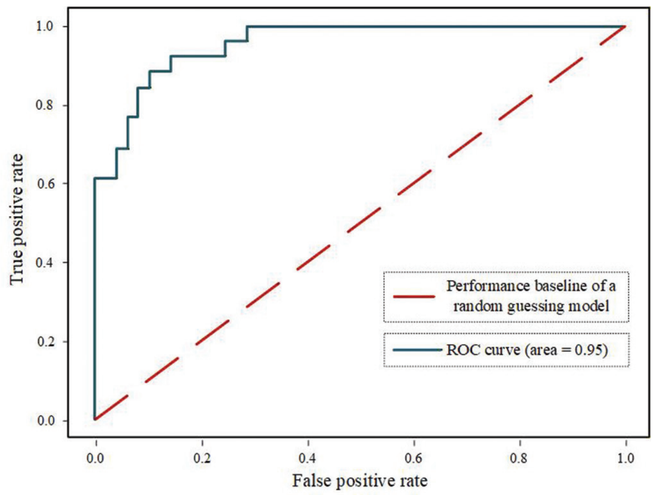

Figure 8. Receiver operating characteristic curve

logistic regression model was evaluated for accuracy and generalization performance using the test set. The evaluation results are presented in Table 2, with the model achieving an accuracy of 0.85 and an AUC of 0.9493, indicating strong accuracy and generalization.

4.3. Analysis of the critical threshold of debris flow induced by rainfall

In this study, a logistic regression model was employed, using both the triggering rainfall and antecedent effective rainfall as key factors, to predict the rainfall threshold for inducing underground debris flows. By setting probability values of p=0.1, 0.5, 0.7, and 0.9 as the critical threshold points for predicting

Table 1. Predicted values for ten selected samples

Serial number	Triggering rainfall (mm)	Antecedent effective rainfall (mm)	Occurrence of underground debris flow (1 for occurrence; 0 for non-occurrence)	Probability of occurrence prediction (%)
1	117.7	39.2556	1	99.98
2	82.2	29.2177	1	96.77
3	40.9	93.3279	1	92.48
4	82.5	79.4154	1	99.90
5	56.3	41.5185	1	70.95
6	37.8	33.1492	0	10.97
7	19.2	49.7670	0	3.39
8	0.3	82.0182	0	2.78
9	7.0	61.8276	0	1.64
10	45.1	4.7366	0	4.19

Table 2. Evaluation of the logistic regression model

Variables	Accuracy	Recall	F1
0 (non-occurrence)	0.85	0.94	0.89
1 (occurrence)	0.86	0.69	0.77
Accuracy	—	—	0.85
Macro average	0.85	0.82	0.83
Weighted average	0.85	0.85	0.85

the occurrence of underground debris flows, the expression for the rainfall threshold can be derived from Equation (6) (Equations 7-10):

$$X_{a5} = -0.5373X_{a15}+54.8189 \quad (7)$$

$$X_{a5} = -0.5373X_{a15}+71.7336 \quad (8)$$

$$X_{a5} = -0.5373X_{a15}+78.2563 \quad (9)$$

$$X_{a5} = -0.5373X_{a15}+88.6483 \quad (10)$$

Where X_{a5} represents the triggering rainfall for underground debris flow and X_{a15} represents the antecedent effective rainfall for underground debris flow. The four different thresholds mentioned above (p=0.1, 0.5, 0.7, 0.9) are plotted in Figure 9.

The four thresholds are shown in Figure 9. When p=0.1, underground debris flow events were unlikely to occur. When the relationship between the triggering rainfall (X_{a5}) and the antecedent effective rainfall (X_{a15}) followed Equation (8), the probability of underground debris flow occurrence was 50%. The critical thresholds for the triggering rainfall and antecedent effective rainfall at this point were 71.7336 mm and 133.5076 mm, respectively. When the relationship between the triggering rainfall and antecedent effective rainfall followed Equation (9), the probability of underground debris flow occurrence was 70%. The critical thresholds for the triggering rainfall and antecedent effective rainfall at this point were 78.2563 mm and 145.6473 mm, respectively. Finally, when the relationship between the triggering rainfall and antecedent effective rainfall followed Equation (10), the probability of underground debris flow occurrence was 90%. The critical thresholds for the triggering rainfall and antecedent effective rainfall at this point were 88.6483 mm and 164.9885 mm, respectively.

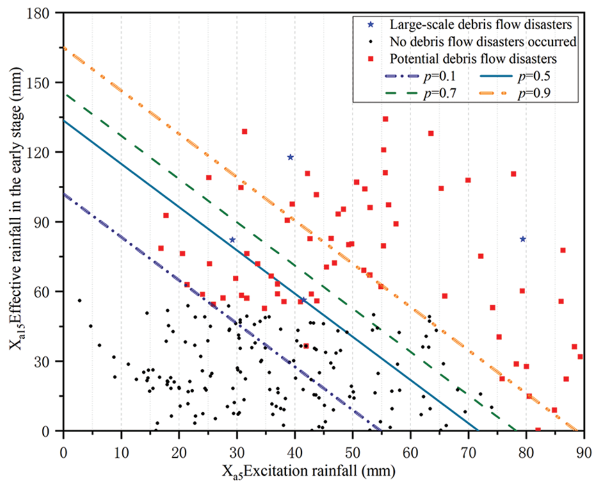

Figure 9. The relationship between triggering rainfall, antecedent effective rainfall, and the occurrence of debris flow

According to the probability and frequency of underground debris flow occurrence induced by rainfall, the critical thresholds can be divided into three risk levels, where level one indicates the highest risk:

i. For a level three warning, the critical thresholds for the triggering rainfall and antecedent effective rainfall were 71.7336 mm and 133.5076 mm

ii. For a level two warning, the critical thresholds for the triggering rainfall and antecedent effective rainfall were 78.2563 mm and 145.6473 mm
iii. For a level one warning, the critical thresholds for the triggering rainfall and antecedent effective rainfall were 88.6483 mm and 164.9885 mm.

5. Discussion

This study establishes a rainfall threshold model for underground debris flows in high-altitude mining areas, providing new insights into the coupling effect of triggering rainfall and antecedent effective rainfall under confined subsurface conditions. Compared to previous empirical or qualitative analyses, the main advantage of this study lies in its quantitative framework, which combines actual monitoring data with a logistic regression model to identify the probabilistic rainfall threshold for debris flow occurrence. The high performance of the model (AUC = 0.9493, F1 = 85%) demonstrates that the proposed method effectively captures the probabilistic relationship between rainfall conditions and debris flow occurrence. Furthermore, by decomposing cumulative rainfall into two physically meaningful components—triggering rainfall and antecedent effective rainfall—this study clearly elucidates the hydrological mechanism of underground debris flow occurrence. This method can be directly applied to underground mining operations, establishing early-warning standards based on real-time rainfall data, providing a quantitative basis for event prevention and safety management in deep mining environments. In addition, this study extends the rainfall threshold concept, traditionally applied to surface debris flows and landslides, to underground debris flows, thereby broadening the theoretical framework for rainfall-induced geological hazards.

Despite the model's promising performance, this study has several limitations. The logistic model primarily focuses on rainfall parameters and does not explicitly incorporate other influencing factors, such as lithology and permeability, the geometry of the collapse channel, temporal variations in mine drainage and pore-pressure response, and mining activities such as blasting vibrations. These factors significantly alter the hydrological pathways and failure mechanisms of underground debris flows. Furthermore, the limited number of observed events restricts the model's statistical robustness; additional long-term monitoring data can further improve the reliability of the derived thresholds. Therefore, future research should focus on integrating multiple data sources—including *in situ* pore pressure measurements, groundwater hydrological simulations, and physical model experiments—to better characterize the internal evolution of rainfall infiltration and stress redistribution. Combining machine learning with hydraulic-mechanical models can help elucidate the progressive failure process and improve prediction accuracy. Moreover, exploring the applicability of the proposed model under different geological and mining conditions is crucial for developing a universal rainfall threshold standard for underground debris flow prediction.

Despite the remarkable performance of the logistic regression model in the study area (AUC = 0.9493), as a statistical method, its thresholds (e.g., the 71.7336 mm triggering rainfall corresponding to p=0.5) are essentially derived from local hydrogeological conditions (such as Quaternary glacial till infiltration and fracture channels), making it difficult to directly apply them to areas with difference subsurface and surface conditions. In fact, the rainfall threshold for triggering debris flows is significantly influenced by climate, geomorphology, and soil characteristics, varying by 30–50% under different hydrological conditions. For example, while the p=0.5 threshold represents a neutral probability (50% chance of occurrence), it may need to be adjusted to p=0.6 in areas with high permeability to reduce false alarms. Therefore, this model is not suitable for cross-regional application. It is recommended to recalibrate the parameters using local rainfall event data before application to adapt to specific hydrogeological heterogeneity. Future research could integrate multi-regional datasets or physical hydrological models to develop an adaptive threshold framework and improve generalization.

6. Conclusion

One major factor controlling underground debris flows is rainfall conditions. This study identifies triggering rainfall and antecedent effective rainfall as key factors and develops a binary logistic regression model to predict rainfall thresholds for underground debris flows. The model exhibited remarkable accuracy, with a precision rate of 85%. The model also demonstrated good performance with a recall and F1 score of 82% and 85%, respectively, and an AUC of 0.9493. The derived rainfall thresholds aligned well with observed conditions, providing a reliable basis for early warning of underground debris flows in mining areas. Based on the research results, rainfall-induced debris flows in mines can be classified into three risk levels—level 1, level 2, and level 3—according to the triggering rainfall and the effective rainfall in the preceding period. This provides a theoretical basis for the prevention and control of debris flow events in mines.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of data

The data for this study are available upon reasonable request from the corresponding author.

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