Debris flow hazard assessment of the Eryang River watershed based on numerical simulation

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Abstract. The middle reach of Taohe River, in the south part of Gansu Province, China is severely threatened by debris flow hazard. Eryang River is an important branch of Taohe River. On May 10, 2012, many debris flows were triggered by extreme heavy rainfall (1% frequency), resulting in serious losses of human lives and properties. In order to recognize the hazard of debris flows in small watersheds, six key debris flow gullies in Eryang watershed, Lalonggou, Zhalonggou, Yizigou, Jiehagou, Lalugou, Paizuigou, were selected as the research area. The numerical simulation software FLO-2D was used to analyze the debris flow movement and accumulation characteristics of each debris flow gully under the actual ’5.10’ rainfall conditions, so as to reconstruct the ’5.10’ debris flow disaster scenario. Numerical simulation results show that the flow speed increased to the maximum after 15-30 minutes since the outburst. The flow lasted for about 3 hours. The speed in the moving section was very high, and decreased sharply at the gully-mouth, then deposits accumulated in the river valley. According to the satellite images and field investigations, the simulation results were compared with the actual situations. The comparison shows the simulation effect is good, the deposition area, the discharge process, and the main damage area were well-reconstructed by FLO-2D simulation. Then, the same method and parameters are used to simulate the accumulation range, depth and velocity of debris flows under the precipitation of 2 % and 0.2 % frequency (fifty and five hundred years rainfall, respectively), and then the risk zoning map is produced using the simulation data. The potentially threatened houses and properties were outlined. The threatened area is 37900m² and 60500m² under 2% and 0.2% rainfall frequencies. There are 22 houses in the highest hazard level. This provides direct reference to the local government to control the debris risk. This work also provides a practical approach for the debris flow hazard assessment.

1. Introduction
Debris flows are generally induced by heavy rainfall and formed in steep terrain, with sharp valleys or slopes, and plenty of loose materials. Debris flows generally have the characteristics of short duration, huge impact force and great destructiveness (Huang, 2009). More and more attention has been paid to the prevention and control of debris flow disasters in mountainous areas, and the risk assessment of debris flow is a key problem (Han et al.,2012). There are many methods for evaluating the risk of debris flow. The traditional methods mainly include analytic hierarchy process, fuzzy comprehensive evaluation, logistic regression model, etc. Among them, the determination of index weight by analytic hierarchy process has great subjectivity, the results are highly influenced by the people conducting the evaluation. The model uses watershed as the basic unit in the debris flow hazard zoning. It cannot
determine the degree of danger at precise locations in the watershed, and cannot accurately describe the movement of the debris flow. The numerical methods focus on the description of the flow process of the debris flow, identifying the flow velocity, spatial distribution of the accumulation thickness and their changes over time, makes them very suitable for the risk assessment of debris flows of population clusters in small watersheds. Song et al.(2018) used the RAMMS model to simulate the movement characteristics of the Baishagou debris flow; Hungr (1995) used the DAN3D model to simulate the flow process of the debris flow; Magirl et al.(2010) used the Laharz model to analyze 7 debris flow valleys in the Santa Catalina Mountains, the movement distance and accumulation range of the shale were simulated and verified with reality; Horton et al.(2019) applied the two-dimensional dynamic debris flow model (Massflow model) to the compilation of the basin-scale disaster map in the epicenter area of the Wenchuan earthquake; Lin et al.(2011) adopted two-dimensional flood and soil-rock flow numerical simulation software FLO-2D to analyze the typhoon-induced debris flow in Songhe area; Chang et al.(2019) used FLO-2D model to evaluate the risk of the debris flow in Bayigou, Dujiangyan under multiple rainfall frequency conditions. The above-mentioned numerical analysis methods have achieved good results in the simulation of debris flow processes, especially the FLO-2D model has great potential in the simulation of debris flow hazards.

The main hazard factor of debris flow disasters is heavy rainfall. Under relatively fragile natural environmental conditions, short-term heavy rainfall can easily cause a lot of debris flows (Shi, 2002). On May 10, 2012, a large-scale hailstorm and heavy rainfall for nearly an hour in Minxian County, Gansu Province caused a large-scale debris flow in the Eryang River catchment, which impacted the villages, roads and transmission equipment on both sides along Eryang River, causing 18 deaths and huge direct losses more than 48 million RMB Yuan (Wang et al., 2013). After comparing with the historical precipitation records of multiple meteorological stations in Minxian County, the precipitation in 1 hour this time was about a 100-year rainfall event.

There are many debris flow valleys in the Eryang River catchment, the average gully ratio of the main valleys is about 235%, and ditches have serious bank collapse, providing a large amount of loose materials. Cash crops such as Astragalus, Codonopsis and grain crops such as corn and fermented beans are planted in this area. The farming season is from May to June every year. After agricultural ploughing, the soil is loose and the anti-erosion ability becoming poor. Once heavy rainfall occurs, mass debris flow disasters are prone to occur. The threat of debris flow is huge, and it is very important to identify dangerous areas and predict the disaster-causing process. Therefore, in this paper, the authors used the FLO-2D model, took 6 debris flow valleys in the Eryang River catchment as research objects, simulated the debris flow process under the actual rainfall (1% rainfall probability) on May 10, 2012, and conducted a site survey of geological disasters. The results were compared to verify the reliability of the simulation. Furthermore, the same evaluation model was used to simulate the accumulation range, depth, and velocity of the debris flow under the conditions of 2% and 0.2% rainfall frequency, and the risk analysis of debris flow was carried out to provide a basis for the prevention and control of debris flow disasters.

2. General settings of studied area

Min County is located in the southern Gansu Province and belongs to the middle section of the north branch of the West Qinling Mountains. It is close to the boundary between the Yangtze River and the Yellow River. The Tao River flows through it. It is a typical middle-high mountain eroded landform and is one of the active areas of debris flow in Gansu Province (Wang and Xu, 2013).

The study area is located in the Eryang River Basin, a tributary of the Tao River in Min County, Dingxi City, Gansu (Figure 1). It is located at the intersection of the West Qinling Mountains and the Loess Plateau. Neotectonic movement is active, and the topography shows a young structurally eroded mid-mountain landform type. The Eryang River Basin covers an area of about 63 km², the main ditch length is about 15.8 km, the highest elevation in the basin is 3130 m, located at the top of the East Mountain, and the lowest elevation is 2310 m, located at the mouth of the Eryang River into the Nana River. The main ditch and branch ditch of the Eryang River are mostly "V"-shaped valleys, with steep ditch walls, well-developed empty surfaces, and landslides and bank collapses are common. There are many arable
land in the ditch, loose land, and abundant sources. The vegetation coverage in the area is generally poor, with obvious differences in spatial distribution. The rock and soil on both sides of the Eryang River are bare, with only crops and scattered shrubs, and artificially planted forests can be seen in the upper reaches.

The lithology of the strata exposed in the watershed is mainly Devonian, Jurassic slate, shale and sandstone. After tectonic and weathering, the rock mass is fragmented and the stability is poor. Quaternary sediments in the area The main materials are loess, alluvial deposits, debris flow deposits, and residual slope deposits.

The study area is an alpine and humid climate zone. The average annual precipitation is 560.8 mm. The precipitation from June to August accounts for more than 60% of the total precipitation. Affected by the terrain and altitude, the temporal and spatial distribution of rainfall is quite different, showing from the valley to the At the top of the mountain, the rainfall gradually increases with the increase in altitude. The Eryang River belongs to the Yellow River system and is a third-level tributary of the Yellow River: The Eryang River merges into the Nana River in Goumen Village, Chabu Town, then flows about 500 m westward, and merges into the Tao River at Yangpo of Chabu Town. After field investigation, a total of 23 debris flow gullies have developed in the Eryang River Basin, of which 9 are on the left bank and 14 are on the right bank. The linear density of debris flow ditches is 1.45/km. The 6 debris flow gullies selected in this study are symmetrically distributed on both banks of the Eryang River (Table 1). They are all in the active period and present a "V-shaped valley". The longitudinal ratio of the main gully drops to 189.7‰~316.9‰, and the average slope is about 35°~ 50°, the mud-rock flow basin area is 0.54~2.47 km², the loose material types are mainly the residual slope deposits on the slope and cultivated soil, followed by small collapses, landslides and bank collapses on both sides of the channel, and the rest are formed by re-transportation at the bottom of the trench. Loose matter. There is a large area of cultivated land in the 6 valleys, accounting for 51% of the total area of the valley. The farmland in the upper reaches of Yizigou, Jihagou, and Zhalonggou has been converted from farmland, and there are areas in the upstream of Paizuibaoxigou (Paizugou) and Jihagou. Plantation. The conditions at the bottom of the 6 gullies are similar, with debris flow facies gravel, gravel and mud balls. The grain size of the gravel is mostly 2-10 cm, and the maximum visible is 1.3 m. The parent rocks are mainly sandstone, sandy slate, limestone, and limestone. Slate. The length of the replenishment section of the 6 debris flow ditches accounted for 61.8% to 69.2% of the total length of each channel. The Jihagou accumulation fan squeezed the Eryang River channel, causing an oxbow-shaped bend in the Eryang River.
Table 1 Six studied debris flow gullies

| Gullies    | Area (km²) | Length (km) | Gradient (‰) | Elevation difference (m) |
|------------|------------|-------------|--------------|--------------------------|
| Lalonggou  | 1.47       | 1.31        | 205.9        | 350                      |
| Zhalonggou | 1.36       | 1.66        | 217.4        | 400                      |
| Yizigou    | 2.12       | 2.48        | 189.7        | 550                      |
| Jiehagou   | 2.47       | 1.67        | 250          | 650                      |
| Lalugou    | 0.90       | 1.19        | 316.9        | 450                      |
| Paizuigou  | 0.54       | 1.31        | 246          | 400                      |

After the "5.10" torrential flood and debris flow occurred in 2012, 10 blocking dams were built in Paizuigou. An on-site investigation in September 2019 found that the first 6 blocking dams had been filled up and buried by debris flow deposits and landslide deposits on both sides, and the last 4 blocking dams still had a blocking effect. At the mouth of Zhalonggou, a drainage canal with a length of about 400 m was built, with a width of 10-15 m and a depth of 3 m.

3. Debris flow dangerous evaluation

The FLO-2D model was proposed by O’Brien (2009) and O’Brien et al. (1993). It uses finite differences to calculate the vertical depth and flow velocity, and reasonably predicts the flow and accumulation range of debris flow. It can be used for processes such as debris flow, flood, dam break, and urban inundation. Simulation and can be used for disaster risk assessment.

In the process of simulating the movement of debris flow, the FLO-2D software divides the terrain into several grids of equal size. In each grid, its Manning coefficient and elevation value are unique. Through the equation of motion and the continuous equation, each grid can be calculated. The fluid depth and fluid flow rate in each grid, and then the movement range of the fluid is known, and the velocity change of the fluid between adjacent grids is calculated through the momentum equation. And the continuity equation controls the conservation of mass in each grid when the debris flow moves. The rheological equation considers the impact of the collision between particles on the flow resistance of the debris flow.

3.1 Date preparation

3.1.1 Topographic data processing. The terrain data comes from a 1:50,000 Digital Elevation Model (DEM). Transform the elevation data into ASCII format, import it into FLO-2D, divide it into 10 m × 10 m units, determine the elevation of each evaluation unit through interpolation calculation, and complete the terrain data processing.

Use ARCGIS to vectorize the main terrain elements of the study area, such as watershed boundaries, water outlet points, and barrier dams, and import them into FLO-2D.

3.1.2 Parameter selection. According to on-site investigations and the engineering geology analogy method, it is judged that the debris flow in the study area is a viscous debris flow, and the average weight of debris flow deposits is 2.5 g/cm³. Guo et al. (2014) measured the fluid gravity of the debris flow in the Eryang River Basin, which was about 17.0~17.6 kN/m³. In this paper, the fluid gravity measurement result of the debris flow in the literature (Guo et al., 2014) was used, and combined with the average weight of the deposits, the debris flow mud was calculated. The sand volume concentration is about 46.67%~50.67%, the median value is 48.67%.

High-concentration debris flow appears laminar flow characteristics under the action of yield stress. The friction between laminar flows can be expressed by laminar flow retardation coefficient K. This article refers to previous research examples and uses engineering geology analogy method. The value of K is 2.250.

According to the debris flow deposits, the bulk density of the fluid and the material composition, the debris flow in the study area is judged to be viscous and moderately resistive, and the sediment ratio
Rns is 0.75. According to Wang et al. (2003), the unified relationship between sediment ratio-volume concentration-rheological parameters. The Manning coefficients of Lalonggou, Zhalonggou, Lalugou, Jihagou, Yizigou, Paizuigou, are 0.0193, 0.0224, 0.0045, 0, 0, 0.0224, respectively.

3.2 numerical assimilation of “5.10” debris flow
According to field investigations and interviews, the debris flow in the Eryang River Basin began to erupt at about 17:50 on May 10, 2012, reached its peak at about 18:00, and gradually decreased at 21:00. The debris flow process lasted about 3 hours. The rainfall data uses the rainfall observation data from the Mazichuan automatic station in Min County, as shown in Figure 2 (Cheng et al., 2018). The calculation of the flow process curve uses the hydrological model of the western Sichuan region in the "Manual for the Calculation of Heavy Rain and Flood in Small and Medium-sized River Basins in Sichuan Province". The study area is located in the southern part of Gansu Province and is relatively close to the western Sichuan region. The geology, geomorphology and climate are similar. The parameters in above-mentioned manual have good applicability in rainfall-runoff analysis in this area. Use the inference formula method to generalize the flow process curve of the clear water flow in each debris flow ditch, and multiply it by the amplification factor BF (BF=1/(1-cv)=2.10) to obtain the flow process curve of the debris flow (Figure 3).

![Figure 2](image)
**Figure 2** Rainfall curve of Mazichuan monitoring station (May 10th, 2012)

![Figure 3](image)
**Figure 3** The flow process curve of clear water (left) and debris flow (right)

It can be seen from Figure 3 that each debris flow ditch reaches its peak 15-30 minutes after the eruption, and the flow gradually drops after about 3 hours; this is basically consistent with the situation at the time of "5.10" learned from the site investigation and interview. The simulation results show that the debris flow fluid moves faster in the circulation area, with a maximum speed of up to 7 m/s; near the mouth of the ditch, the velocity drops rapidly, most of the debris flow merges into the turbulent Eryang River, and the accumulation depth in some areas is large. Through FLO-2D simulation, the accumulation fan area and the average thickness of debris flow accumulation of 6 debris flow ditches are obtained, as shown in Table 2. The area and thickness obtained from the field survey are listed in Table 2 at the same time, and the simulation result is compared with the actual area. It can be seen that, except for Lalonggou and Lalugou, the error rate of the accumulation fan area of other ditch is between -6.2%~28.5%, and the error rate of accumulation fan thickness is
between -7.5%~23.3%. Most of the simulated accumulation thickness is lower than the actual thickness. The main reason is that since the "5.10" debris flow broke out, a small amount of loose material has been rushed out of the ditch every year. The thickness of the accumulation fan increases year by year, and the measured thickness is larger than the actual accumulation thickness of the "5.10" debris flow. The error rate of the accumulation area of Lalonggou and Lalugou reached 189.8% and 2827.5%, respectively. The area of the simulated accumulation fan was much larger than the actual area. The main reason was that the villagers built houses and reclaimed land near the mouth of the ditch, and carried out artificial manipulation of the debris flow accumulation fan.

| Gully       | Deposition area/m² | Deposition depth/m | Gully       | Deposition area/m² | Deposition depth/m |
|-------------|--------------------|--------------------|-------------|--------------------|--------------------|
| Actual      | Simulated          | Diff/%             | Actual      | Simulated          | Diff/%             |
| Lalonggou   | 3968               | 11500              | 189.8       | 1.50               | 1.12               | -25.3               |
| Zhalonggou  | 9826               | 11600              | 18.1        | 1.60               | 1.31               | -18.1               |
| Lalugou     | 731                | 21400              | 2827.5      | 1.10               | 0.31               | -71.8               |
| Paizugou    | 9218               | 10500              | 13.9        | 0.58               | 0.57               | -1.7                |
| Yizigou     | 15956              | 20500              | 28.5        | 0.60               | 0.74               | 23.3                |
| Jiehagou    | 21971              | 20600              | -6.2        | 1.60               | 1.48               | -7.5                |

3.3 "5.10" Debris Flow Risk Assessment
The current risk classification indicators of debris flow mainly include flow velocity and mud depth (Chang et al., 2014), impact force and accumulation thickness (Cong et al., 2019), frequency and intensity (Yang et al., 2018; Erena et al., 2018) The hazards of debris flow in the Eryang River Basin are mainly due to the solid matter carried by the debris flow. Silted farmland and houses, as well as the impact and erosion of medium and high-speed viscous torrents on the valley banks. Therefore, in this study, indicators such as flow velocity and deposition depth are used for risk classification.

The risk assessment results are shown in Figure 4. The total area of "5.10" debris flow danger zone is 57 900 m², accounting for 60.2% of the total area. Among them, the high-risk zone area accounts for the higher proportion of the total dangerous zone area is Jihagou and Zhalonggou, which are 34.23% and 38.60%, respectively.

Due to the re-planning of houses after the "5.10" debris flow, most of the buildings along the Eryang River are relatively safe under the condition of 1% rainfall frequency, but there are still parts along Zhalonggou, Jiehagou and Yizigou. Housing construction is susceptible to the threat of mudslides, and about 21 houses are involved (see the partial enlargement in Figure 4).

![Figure 4 Hazard zoning map of “5.10” debris flow](image)

3.4 Numerical simulation and risk assessment of different rainfall frequency conditions
By simulating the "5.10" process and comparing it with the actual situation, the reliability of the model and parameters is verified. The FLO-2D model can reproduce the debris flow process and simulate the
temporal and spatial distributions of debris flow velocity and deposition depth. We used the same parameters and methods to simulate the debris flow conditions under the conditions of P=2% and P=0.2% rainfall frequency, and carried out the debris flow risk assessments for the above two conditions (P=2% and P=0.2%).

Through simulation, the debris flow discharge curve with P=2% and P=0.2% rainfall probability and the zoning map of debris flow risk are obtained. The simulation results show that under the condition of 2% rainfall frequency, the total dangerous area of debris flow is about 37,900 m$^2$, and Paizuigou, Lalugou, and Yizigou have no high-risk areas. In addition, Paizuigou has built a series of barrier dams after 2012 outburst, which is not dangerous now. Low-risk areas accounted for 72.2% of the total dangerous areas. Zhalonggou has the highest proportion of high-risk areas at 13.95%. It is mainly distributed at the mouth of the ditch and is about 30 m away from residential buildings on the left bank. The threat is relatively small. However, there are still 4 households in the middle-risk zone along Yizigou, and 5 households in the middle-risk zone at the mouth of Jihagou. Under the condition of 0.2% rainfall frequency, the total area of the debris flow risk area is 60,500 m$^2$. Compared with the once-in-a-century condition, the total area of the risk area has increased by only 4.5% (2,600 m$^2$); however, the area of the medium-high risk area accounts for The high-risk area of Jihagou deposition area is about 4,000 m$^2$, accounting for 34.78% of the total area; the second is Yizigou and Zhalonggou, the areas of high-risk area are 3,100 m$^2$ and 2,500 m$^2$, respectively, accounting for 12.82% and 35.82% of the total area. A blocking dam has been build in Paizuigou, and there is no high-risk area Paizuigou. Except for Lalugou, residents in other ditch mouths and channels are threatened. There are about 38 households in total, of which about 22 households are in the middle and high risk area.

4. Conclusions

(1) Using the rainfall observation data, the FLO-2D simulation was used to reproduce the movement and accumulation characteristics of the debris flow on "5.10", and obtain the accumulation range, accumulation depth, and development process of the debris flow. Compared with the field conditions obtained from the field survey, the error of the simulation result of the accumulation fan thickness is between -7.5%~23.3%, and the error of the simulation result of the accumulation fan area is between -6.2%~28.5%, excluding the effect of large-scale artificial reconstruction, the numerical simulation results are well fit with the actual situation, and the simulation effect is good.

(2) Through simulation, the debris flow dangerous zone under different rainfall frequency scenarios is divided based on the debris flow accumulation depth and impact speed; then, potential threatened objects such as houses and properties are delineated. This provides good reference of prevention, control and governance of debris flow risk.

(3) The FLO-2D model can describe the debris flow process and partition the hazard degree. Through numerical simulation under different rainfall frequencies, the spatial distribution and change process of the depth and velocity of the debris flow can also be obtained, which can affect the process and impact of the debris flow. The scene is expressed intuitively.

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