GIS-based Analysis of Distribution and Development Characteristics of Landslide Hazards in the Bailong River Basin

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Abstract: The Bailong River Basin is one of the most landslide prone areas in China. Based on landslide interpretations from field investigations and high-precision remote sensing images, the influencing factors, distribution rules, and development characteristics of landslides in this region are examined using the powerful spatial analysis capability of the ArcGIS platform. This study identifies the following major influencing factors and provides corresponding conclusions. (1) Fault and tectonic activities: landslides in the study area are distributed mainly in the vicinity of the large and secondary fault zones (< 10 km) and in areas with high peak acceleration and seismic intensity (with a peak motion acceleration of 0.3 g and seismic intensity of a VIII-degree area). (2) Hydrological conditions: the closer to the river (an area of < 200 m), the higher the likelihood of a landslide to occur. Landslide density is highest in areas with substantial short-term rainfall (maximum rainfall amount within 30 min shows the highest correlation with landslides). (3) Topographic parameters of slopes: landslides are distributed mostly on sunny slopes (facing south, southwest, and southeast), gentle slopes (with an incline of approximately 15°–30°), and high mountain areas (with an elevation of approximately 1000–2000 m). (4) Vegetation: areas with low FC coverage (approximately 10%–45%) are prone to landslides, which are distributed mainly in grasslands and cultivated lands. (5) Human engineering activities: densely populated areas (urban areas) and both sides of roads (approximately 0–200 m from a road) are prone to landslides. Overall, landslides are sudden, periodic, synchronous, and occur in groups. The research results have certain reference value for hazard prevention and mitigation in the Bailong River Basin area.

Keywords: Bailong River Basin; Landslide hazards; Distribution law; Developmental characteristics; ArcGIS platform

1. Introduction
Landslide hazards are widely distributed around the world and cause huge losses in life and property yearly, especially in mountainous areas¹. The Bailong River Basin has a complex geological structure, steep mountain terrain, and broken rock masses. In addition, the basin is affected by earthquakes, rainfall, and human engineering activities, thereby making it one of the most landslide prone areas in
China. The residents of the area, who live in the Qinba Mountains and in Sichuan Tibetan gathering areas, suffer from poverty owing to the influence of landslides. Survey results from 2018 show that 1,031 landslides of various types occurred in the area. In terms of disasters in the area, landslides are slightly weaker than debris flows. However, with regard to distribution density and frequency of occurrence, landslides are the most serious types of geological hazards, accounting for more than 40% of the overall disasters that occur in the entire river basin.

Owing to its special geological environment and the wide distribution of various types of landslides, the Bailong River Basin is an important area for landslide research in China. Specifically, the distribution laws and control factors of landslides are among the hotspot issues in this area. Scheidegger et al. believed that the distribution of landslides in the Wudu area of the Bailong River Basin is related to the neotectonic stress field. Li Shuzhen et al. discussed the influence of the Pingding–Huama fault in the Bailong River Basin on the distribution and occurrence of landslides in the area. Pang Maokang and Li Zhiheng et al. analyzed the sensitive aspects of landslide distribution in major factors, such as regional geological background and external environments, and identified the internal mechanisms through which various factors control landslide distribution. A large number of studies unanimously posited that the distribution of landslides in the Bailong River Basin is controlled and influenced by multiple factors, such as slopes, lithology, faults, rivers, vegetation, and human activities. Jia Guiyi et al. assessed the distribution characteristics of geological hazard without a classification in the Bailong River Basin, including landslides, collapses, debris flows, unstable slopes, and so on, and found that the distribution density of geological hazards in the area increases as slope and distance from the river and faults gradually increase. Wu Weijiang et al. studied landslides in Gansu and the tectonic system in Eastern Gansu and believed that the structure controls the development and distribution of landslides to varying degrees. Based on remote sensing interpretations and onsite verification, Meng Xingmin et al. determined that the distribution of four types of landslides in the Bailong River Basin, including loess landslides, loess-bedrock landslides, slope-bedded landslides, and bedrock landslides, is controlled by the distribution of stratigraphic lithology.

However, landslides in the Bailong River Basin are widely distributed, with various types, thereby generating serious hazards. Although the landslides in this river basin have been investigated extensively, weak links remain. For example, landslide data are limited, thereby resulting in insufficient investigation depth, and area data on hazard spatial and temporal distributions are lacking. Meanwhile, previous studies generally target the Gansu section of the river basin, and research on the entire area is scarce. Thus, holistic understanding on the distribution and development characteristics of landslides is limited. Currently, no unified understanding exists on the relationship between the influencing factors and spatial and temporal patterns of landslides. Moreover, most previous studies focus on the relationship between geological hazards and various factors, and research on landslides as separate types of hazards has yet to be conducted. In this study, landslides are assessed separately, and the distribution and development characteristics of landslides in the Bailong River Basin are summarized. This study will considerably enrich the scientific understanding of landslides and provide a reliable geological basis for hazard prevention and mitigation in this area.

2. Study area
The Bailong River is a tributary of the Yangtze River, which lies between 102°57′~105°26′ east longitude and 32°36′~34°23′ north latitude. The Bailong River flows through Diebu, Zhouqu, Tanchang, Wudu, and Wenxian in Gansu Province, covering 23 ethnic groups, including the Han, Hui, Tibetan, and Manchu. The river basin covers an area of approximately 31,800 km² and has a population of more than 2 million. The study area belongs to the western section of the Qinling Mountains and is located at the confluence of the Qinghai–Tibet Plateau, the Loess Plateau, and the Sichuan Basin. The terrain in the area is high in the northwest and low in the southeast, with steep slopes with an incline of approximately 60°. High mountainous areas account for approximately 14% of the entire area, middle mountainous areas account for approximately 84%, and valley lowlands account for only 1.6%. Structurally, the area is located at the eastern boundary of the Cenozoic Indian–Asian plate collision zone. The deformation effect is obvious in the area, and neotectonic activities are
strong; thus, a large number of faults and folds are developed, and rock masses are substantially broken. The Pre-Sinian to the Quaternary strata are exposed, and the widely distributed strata are the Devonian, Silurian, Carboniferous, and Jurassic, with the Devonian and Silurian as the most common. The lithology strength of the area is relatively low and mainly from weak rock formations. Moreover, the main lithology is phyllite, shale, slate, and limestone. The area is covered with Malan loess and susceptible to structural damage, rainfall erosion, and weathering erosion. The study area is located in the famous north–south seismic zone of China and affected by the Songpan–Pingwu seismic zone of neighboring areas. In addition, the area is in an VIII-intensity region, and ground motion peak acceleration is approximately 0.1–0.4g[17-19]. Historically, numerous destructive earthquakes occurred in the area. Strong earthquakes in neighboring locations also affected the area, including 15 earthquakes with serious casualties.

The interannual variation of precipitation in the Bailong River Basin is large. According to data from a weather station, the minimum annual precipitation is only approximately 253.0–494.6 mm, and the maximum annual precipitation is approximately 560.6–1162.2 mm, which is approximately 1.74–2.35 times the amount of the former. Meanwhile, average annual rainfall is approximately 436–778 mm[20-22]. According to the statistics, rainfall demonstrates a certain periodic variation characteristic, with a long period of 25 years and a short period of approximately 5 years. The spatial and temporal distributions of precipitation in the study area vary substantially in a year. Rainfall is mostly concentrated from May to September, accounting for 70% of the total annual rainfall. In terms of space, rainfall is relatively high in the east and north and low in the west and south. Vegetation coverage in different areas is between 25% and 55%, with an average of approximately 40%. The soil layer exhibits high elasticity and is typically very thin, loose, and poor in terms of erosion resistance; thus, maintaining water and soil is difficult.

3. Dataset
The data were interpreted by the French Pleiades high-resolution satellite (with a panchromatic resolution of 0.5 m + multispectral imagery of 2 m), and Landsat8 data (with a panchromatic resolution of 15 + multispectral imagery of 30 m) were used to assist in interpreting the geological environment information. Landslide distribution and scale were identified, and areas where landslides were relatively prevalent were determined. At the same time, geographical and geological environments were assessed at the regional scale, including topography, rock mass type, geological structure, vegetation coverage, land use type, and so on. Meanwhile, appropriate ground surveys were conducted to verify the results of the remote sensing interpretation and provide basic data for landslide ground surveys to identify comprehensively the development characteristics and distribution rules of the landslides in the area.

Rainfall data were obtained from the records of 52 meteorological stations, which were nearly uniformly distributed across the study area. The temporal distribution and spatial extent of rainfall showed a significant correlation with landslide occurrences in the Bailong River Basin. Furthermore, the statistical analysis demonstrated that average precipitation in the study area in the past 15 years was unevenly distributed, with rainfall relatively concentrated in certain areas.

4. Results

4.1 Landslide overview
A landslide is a phenomenon in which the rock and soil body of a slope is affected by rainfall erosion, river erosion, seismic activity, human disturbances, and/or other factors and slides down the slope along the weak surface (belt) under the action of gravity. Landslides are the second most prevalent geological hazards in the Bailong River Basin after debris flows.

A total of 1,031 landslides occurred in the area, including 75 in Tangchang County, accounting for 7% of the total number of occurrences; 55 in Diebu County, accounting for 5%; 149 in Kang County, accounting for 15%; 260 in Wen County, accounting for 25%; 435 in Wudu District, accounting for 42%; and 57 in Zhouqu County, accounting for 6% (Fig. 1).
Figure 1. Distribution of landslides in six counties in the Bailong River Basin in Gansu Province

According to their material composition, the landslides are mainly accumulation layer landslides, rock landslides, and loess landslides. Among the different types, accumulation layer landslides are the most common, with 769 occurring in different sites, accounting for 74.59%, and 262 occurring in rock sites, accounting for 25.41%. Based on the thickness of the landslide body, most of the landslides in the area are medium and shallow landslides, with a number of 526 and 400, respectively. In addition, 84 deep landslides and 21 ultradepth landslides occurred in the area. According to their movement pattern, push-type landslides account for 59.51% (614 landslides), and traction landslides account for 40.49% (417 landslides; Table 1).

### Table 1. Landslide types and characteristics

| Classification basis | Type of landslide | Main features | Number | Percentage (%) |
|----------------------|------------------|---------------|--------|----------------|
| Material composition | Loess landslide  | Sliding body is composed mainly of loess | 84 | 8.15 |
|                      | Accumulation layer landslide | Landslide body is composed of loose accumulated bodies from various sources | 789 | 76.53 |
|                      | Bedrock landslide | Landslide body is composed of bedrock | 158 | 15.32 |
| Landslide body thickness | Ultradeep landslide | Landslide thickness > 50 m | 21 | 2.03 |
|                      | Deep landslide | Landslide thickness 25~50 m | 84 | 8.15 |
|                      | Midlevel landslide | Landslide thickness 10~25 m | 526 | 51.02 |
|                      | Shallow landslide | Landslide thickness < 10m | 400 | 38.80 |
| Form of exercise     | Slumping landslide | Upper rock layer slides, squeezing the lower part, thereby producing deformations | 614 | 59.51 |
|                      | Retrogressive landslide | Lower part slides first; thus, the upper part loses support, deforms, and slides | 417 | 40.49 |

4.2 Influencing factors and distribution law of landslides

Owing to the combined influence of various factors, such as geological structures, slope topography parameters, vegetation, rivers, rainfall, and human engineering activities, the development and distribution of landslides in the Bailong River Basin demonstrate certain patterns. On the ArcGIS
platform, the 1:50,000 digital elevation model is used as the base map to integrate the landslides identified through field investigation and remote sensing interpretation. Meanwhile, the distribution law of the landslides in the study area is obtained with a combined surface rupture map and fault distribution map provided by the earthquake department.

4.2.1 Influence of faults and tectonic activities
The Bailong River Basin is located at the junction of two plates, where neotectonic activities (crustal uplifts, fault activities, and seismic activities) are active and have dominant control over the evolution of the topography in the area. Thus, a series of thrust nappe structures, deep faults, and rock folds developed in the basin, thereby providing favorable conditions for landslide occurrences.

(1) Distributed mostly near large and secondary fault zones
A buffer analysis of the fault distance of the landslides in the study area reveals that the landslides surrounding the fault are densely developed. As the distance between the buffer zone and fault increases, the number of landslides decreases (Fig. 2). In addition, the landslides are concentrated mainly in areas less than 10 km from the fault, which account for 67.57% of the total number of occurrences. A total of 684 landslides occurred within this range, accounting for 66.34% of the total number of landslides in the area (Fig. 3).

These findings are observed mainly owing to the following reasons. (1) Regional fractures break rock mass structures and weaken their stability, thereby resulting in large amounts of loose deposits. (2) The groundwater around the broken rock soil is active, thereby forming a water-rich stratum, which serves as a favorable foundation for the development of landslides\[23\]. (3) The main and secondary fault planes provide a natural boundary for the development of landslides, where the stress concentration phenomenon is obvious, thereby causing damage easily\[24\]. (4) The stratum has been continuously active since the Holocene, thereby exerting a significant impact on the development of landslides and their slow changes\[25\].

(2) Distributed mostly in areas with high seismic peak acceleration and high seismic intensity
The Bailong River Basin is located at the intersection of the Central Orogenic Belt and the North–South Seismic Tectonic Belt. Numerous devastating earthquakes occurred in the past, and the area is affected by moderate-to-strong earthquakes in neighboring areas. The seismic intensity map (Fig. 4) and peak acceleration map (Fig. 5) are used to analyze the distribution of the landslide hazards. In terms of distribution density, the seismic intensity VIII area exhibits the highest density at 0.2 points/km², which is much higher than that in the VI-degree area (0.09 places/km²) and VII-degree area (0.08 places/km²). With regard to landslide scale, giant and large landslides are distributed in the intensity VIII area, and medium and small landslides are scattered in the VI-degree area, with most concentrated in the seismic intensity VII and VIII areas (Fig. 6). The largest number of landslides is
distributed in the area with a peak acceleration of 0.3 g, where the point density is also the largest (0.11 places/km²). The number of landslides in this area is greater than that in the area with accelerations of 0.2 g (0.07 places/km²) and 0.15 g (0.09 places/km²; Fig. 7). This finding is basically consistent with the results of the seismic intensity analysis. The results of the two analyses well illustrate the impact of earthquakes on landslides.

The strong impact of earthquakes on the geological environment caused slope rock and soil bodies to become loose or to break and the slope structure to become fragile within a certain range. Various types of loose accumulations developed, with thickness reaching hundreds of meters. Therefore, landslides demonstrate an increasing number or advancing development trend after a strong earthquake.

**Figure 4.** Distribution of seismic intensity  **Figure 5.** Distribution of peak motion acceleration and landslides and landslides

**Figure 6.** Landslide density at different earthquake intensities  **Figure 7.** Landslide density at different earthquake peak accelerations

### 4.2.2 Effect of hydrological conditions

1. **Distributed mostly in areas near both sides of the river**

Rivers are among the main factors affecting the occurrence and distribution of landslides. After investigation, this study determines that the landslides in the area are densely distributed along the trunk and tributaries of the Bailong River, Baishui River, Minjiang River, and Gongba River, with their number exceeding 60% of the total occurrences in the region (Fig. 8). The statistics show that the number of landslides in the area is the largest, totaling 709 within less than 200 m from the river and accounting for 68.7% of the total. Moreover, the closer to the river, the larger the number of landslides (Fig. 9).

These findings are observed mainly owing to the following reasons. (1) Rivers erode bank slopes by undercutting and side cutting valleys, thereby changing the shape and gradient of slopes, making slopes on both banks steep, increasing the specific drop of a river bed, and breaking slope rocks.
(2) The Bailong River immerses the lower part of the slope, and seasonal water levels fluctuate, thereby resulting in changes in pore water pressure at the foot of the slope and reducing the stability of the slope rock and soil body\cite{30,31}. (3) Areas near rivers often have abundant Quaternary loose deposits, which are easily disturbed, thereby inducing landslides\cite{32}. (4) Generally, residents gather in riverbank areas, and frequent human activities exert a certain impact on the stability of bank slopes.

Figure 8. Distribution of water system buffer  Figure 9. Areas with different distances and landslides from rivers and landslides

(2) Distributed mostly in areas with abundant short-term rainfall
The total annual rainfall in the Bailong River Basin is small, but rainfall distribution is concentrated, and torrential rains often occur. Correlation analysis is performed between average annual rainfall and maximum rainfall in 24 h and 30 min and the number of landslides (Fig. 10). In terms of time, a vast majority of landslides occur during the rainy season. Moreover, landslides occur frequently in areas with an average annual rainfall of approximately 0–600 mm, a maximum amount of rainfall of approximately 35–45 mm in 24 h, and a maximum amount of rainfall of approximately 15–20 mm in 30 min (Fig. 11). According to the observations, rainfall is closely related to the occurrence and distribution of landslides, and a maximum amount of rainfall in 30 min has a high correlation with the distribution of landslides\cite{33}.

Its development mechanism is mainly manifested in the following aspects. (1) Abundant rainfall penetrates the loose accumulation covered by the slope surface. Debris and clay mixtures increase in weight after absorbing moisture and move along slopes or valleys, thereby causing landslides easily \cite{34}. (2) Rainfall penetrates into the deep parts of a slope, and the matrix suction of unsaturated soil is reduced or eliminated, thereby weakening the structural strength of rocks and soil\cite{35}. (3) In heavy rainfall, torrents will form in slope sections, scouring and eroding the slope body and foot. A new free surface will appear on the slope body, thereby facilitating conditions for the occurrence of landslides. (4) Water pressure is often formed inside a slope during short-duration heavy or continuous rain. The water pressure direction points to the free surface, which promotes the destruction of the slope body and reduces the stability of the slope.

(a) Average annual rainfall (b) Maximum amount of rainfall in 24 h (c) Maximum amount of rainfall in 30 min
4.2.3 Influence of slope terrain parameters

(1) Distributed mostly on sunny slopes
Slope aspect is also one of the factors affecting landslide distribution. Slopes of every orientation exist in the study area, and landslides occur on slopes with different aspects. The survey results show that the landslides on the sunny slopes of the Bailong River Basin are more developed than those on the shaded slopes (Fig. 12). In terms of quantity, the landslides are mainly concentrated on the slopes facing south, southwest, and southeast, accounting for 46.07% of the total number of occurrences. Among these landslides, the number of those that developed on the south-facing slope is the largest, at 185, accounting for 17.94% of the total number. The southwest slope totals 162 landslides, accounting for 15.71%, and the southeast slope totals 138 landslides, accounting for 13.39%. Landslides on the northern slope number at least 100, thereby accounting for only 9.70%. The other slopes are basically flat. From the perspective of disaster distribution density, the south and southwest slopes have the highest distribution density, followed by the southeast slope (Fig. 13).

These findings are observed mainly owing to the following reasons. (1) In addition to the influence of topography and landforms, the spatial distribution of landslides has a certain directional effect[36]. As an important factor reflecting the terrain, the aspect of a slope affects the microclimate of the slope and is closely related to the formation and development of landslides[37]. In the northern hemisphere, south-facing slopes are typically defined as standard sunny slopes, whereas north-facing slopes are defined as standard shaded slopes. Compared with shaded slopes, sunny slopes experience longer periods of sunshine, stronger solar radiation, and more changes in temperature and humidity; thus, their weathering effects are more intense[38, 39]. (2) Human activities are conducted more on sunny slopes than on shaded slopes, and human disturbances directly affect the stability of a slope.
Distributed mostly on gentle slopes

The gradient of a slope is closely related to the development of landslides\textsuperscript{[40, 41]} (Fig. 14). According to the statistics, the slope gradient in the Bailong River Basin most prone to landslides is approximately 15°–45°. Slopes with a gradient between 15° and 30° have the highest susceptibility to landslides, with the highest number and distribution density, followed by slopes with a gradient between 30° and 45°. Slopes with a gradient steeper than 45° experience the fewest number of landslides, with the smallest density (Fig. 15).

These findings are observed mainly because of the following reasons. (1) Areas with a gradient between approximately 15° to 45° are major places of human activities, such as river beds, low terraces, and valleys; thus, the slopes in these areas are greatly disturbed. Engineering activities, such as road construction and repair, can change the terrain of a local area, reduce the stability of a slope, and generate large amounts of accumulations, such as abandoned slag and stone, and engineering waste, which can become major causes of landslides\textsuperscript{[42]}. (2) The steeper the slope, the higher the maximum shear stress concentration in the leading-edge slope body, and the more obvious the tensile stress concentration in the trailing edge. The stress concentration and differentiation of the slope body are not conducive to maintaining its stability, thereby inducing landslides easily\textsuperscript{[43, 44]}. (3) A slope affects stress distribution and controls the thickness of loose deposits on the slope surface. In the study area, the surface of slopes with an incline of less than 45° is covered with substantial amounts of weathered residual soil. However, the surface of slopes with an incline of more than 45° is mainly exposed, with relatively complete bedrock or cemented conglomerate. Thus, retaining the residual slope soil is difficult, and the stability of the slope is relatively high. Slopes with a gradient of less than 15° are relatively gentle and demonstrate overall satisfactory stability; thus, landslides do not form easily on such slopes\textsuperscript{[45, 46]}. (4) An increasing gradient provides substantial potential energy for surface deposits, thereby increasing the possibility of landslide occurrences\textsuperscript{[47, 48]}.
(3) Distributed mostly in middle and low mountain areas

The elevation of the Bailong River Basin is approximately 600–4,800 m. According to the survey, 762 landslides occurred within the elevation range of 1,000–2,000 m, with the largest number of developments and the highest point density (Fig. 16). A total of 12 sites are within elevations higher than 3,000 m, with the least number of developments and the lowest point density (Fig. 17). These findings are observed because of the following reasons. (1) The northwest high mountainous area, with an elevation within the range of approximately 2000–3000 m, is dominated by relatively complete bedrock and covered mostly by alpine tundra. The slope gradient in this area is relatively large; thus, residual surface soil is minimal, and landslides are unlikely to occur. The areas with an elevation of approximately 1,000–2,000 m are the middle and low mountain areas on both sides of the river valley. These areas are strongly affected by river erosion, and rock and soil bodies in these locations are broken. Moreover, these areas are highly prone to landslides. (2) The area with an elevation of approximately 1000–2000 m is densely populated, with abundant cultivated land. The transformation of the geological environment by human activities is a major cause of landslides. (3) Rainfall amounts at different elevations differ, and varying rainfall amounts facilitate the occurrence of landslides differently.

4.2.4 Effect of vegetation

(1) Distributed mostly in areas with low vegetation coverage

Vegetation coverage (FC) can be divided into five levels, that is, FC < 10% represents low vegetation coverage, 10% ≤ FC < 30% denotes low vegetation coverage, 30% ≤ FC < 45% signifies moderate
vegetation coverage, 45% ≤ FC < 60% is high vegetation coverage, and FC > 60% is likewise high vegetation coverage. The analysis shows that as vegetation coverage increases, the density of landslide hazards tends to decrease (Fig. 18). The hazard density of landslides in the study area reaches the maximum value, with the FC ranging from 10% to 30%, and the minimum value, with the FC in the range over 60% (Fig. 19).

The impact of vegetation on landslides is reflected mainly in three aspects. (1) The hydrogeological effect: vegetation is a form of water storage and slope soil regulator, thereby affecting the hydrological function of the soil[51, 52]. When the FC is low, the amount of rainfall infiltration in the soil is large. As rainfall continues, the water absorption capacity of the slope soil becomes saturated, cohesion decreases, and self-weight increases. Therefore, the ability of a slope is weakened by external interference, and its stability is reduced, thereby facilitating the occurrence of landslides. When the FC is high, a part of the rainfall infiltration process is suppressed. The stability of the rock and soil body is enhanced, which reduces the possibility of landslides[53]. (2) The mechanical effect: the vegetation root system is embedded in the bedrock or the deep part of the soil, thereby strengthening it and improving the overall shear strength of the slope soil. (3) The slope protection effect: areas with high FC can protect and fix slopes; thus, soil erosion does not occur easily. Moreover, in such areas, the terrain is eroded and cut at slow and weak levels, and the degree of slope deformation and damage is low. By contrast, in areas with low FC, soil erosion is substantial, terrain cutting is strong, slope deformation and damage are high, and landslides are likely to occur[54].

![Landslide density at different FC levels](image)

**Figure 18.** Distribution of FC and landslides

**Figure 19.** Landslide density at different FC levels

(2) Distributed mostly in cultivated lands and grasslands

Land types in the Bailong River Basin can be mainly classified as cultivated lands, forest lands, grasslands, unused lands, and urban and rural residential lands (Fig. 20). In terms of number, the landslides in the study area are mainly concentrated in the cultivated lands, comprising 553 sites, thereby accounting for 53.6% of the total number, followed by the grasslands, with 362 sites, accounting for 35.1%. The number of landslides distributed in the grasslands and cultivated lands accounts for 88.7% of the total, which is far more than the number of landslides in the other land types (Fig. 21).

The reasons why landslides are highly likely to occur in grasslands and cultivated lands are described briefly. (1) Grasslands, especially the superficial layer; litter; and ground cover that accumulates on surfaces decay easily, thereby creating a loose and porous soil structure. Therefore, the bulk density of surface soil is relatively small[55], which is prone to deformation and destruction. (2) Grasslands and cultivated lands are highly disturbed by people; thus, their surface is relatively loose. After rains, such lands are conducive to rainwater retention and infiltration. Moisture absorbed by the soil accumulates on the water barrier, and the root layer gradually absorbs water and becomes saturated. As the “saturated shell” softens, it becomes prone to damage[56, 57]. (3) Grasslands and cultivated lands host herbaceous plants with small root systems and shallow burial depths, which have a poor stabilizing effect on slopes. By contrast, the vegetation root system in woodlands is highly developed, and the
thick root system is interspersed and intertwined in the soil body, which substantially enhances the soil’s resistance to erosion and plays a role in stabilizing a slope\cite{58, 59}.

**Figure 20.** Distribution of landslides and land types  **Figure 21.** Landslides in different land types

### 4.2.5 Influence of human engineering activities

1. **Distributed mostly in densely populated areas**
   A statistical comparison between the population density of 132 towns and villages in the Bailong River Basin and the landslide hazard density reveals that the number of landslides in the study area demonstrates a satisfactory correlation with population density (Figs. 22 and 23). It is highly developed in counties and densely populated areas, and the towns with the highest population density are also the areas with the most developed landslides (Fig. 24). For example, Chengguan Town in the Wudu District has an area of 40.76 km$^2$, a population density of 1,498.27 people/km$^2$, and a density of up to 1,104.14 points/10$^3$ km$^2$.

   These findings are observed mainly because of the following reasons. (1) The larger the population density, the higher the degree of transformation of the geological environment. Unreasonable human activities, such as slope foot excavation, hillside farming, sand and coal mining, drainage and diversion, bridge and road construction, and so on, exacerbate environmental geological problems and are major factors that induce landslides\cite{60, 61}. (2) Frequent human engineering activities destroy the original stable state of slopes. During the investigation, this study determines that slope excavation causes stress release and obvious unloading effects. Unloading cracks at the rear of a slope body extend and penetrate, and rock masses tend to be broken and loose. Slopes with a gentle incline are prone to landslide formation and unstable slopes, whereas slopes with a steep incline are prone to dangerous rock formation and collapse. (3) A large-scale filling and excavation project is being conducted at the study area, and the slope was in a stable state under natural conditions before filling and excavation. When the ridge was excavated and filled in the side ditch on both sides, it remained basically stable through rolling and tamping. When eroded and scoured by rainfall and water flow at the bottom of the slope, loose soil will appear in the fill area, and tension cracks will appear on the ground surface, specifically, near the edge of the slope top of the fill platform. Owing to the anisotropy of the soil, the crack will extend, open, and move. With the expansion and penetration of tensile cracks, partial collapse and slip will gradually occur at the edges, thereby forming small stepped platforms. These platforms will eventually break and become unstable, and landslides will form during heavy or continuous rainfall\cite{62-64}.
(2) Distributed mostly along both sides of the road

The interpretation and survey results of the study area show that the landslides are concentrated near traffic routes (Fig. 25). A buffer zone analysis of the roads in the study area indicates that the number of landslides gradually decreases as the distance from the road increases. The largest range is from 0 m to 200 m, with the number of landslides reaching 536. When distance is 800–1000 m, the number of landslides is reduced to 72 (Fig. 26).

This phenomenon occurs owing to the following reasons. (1) The construction of roads enhances convenience, but a large number of excavation slope foot during construction produces high and steep free surfaces, which changes the slope’s shape and balance state. When the stress field of the slope body is adjusted, local stress concentration occurs, thereby decreasing the stability of the rock and soil body. In the absence of supporting facilities, instability is likely, thereby inducing landslides\cite{65}. For example, the construction of the Lianghekou–Yuhe Highway can induce 15 small landslides, which can develop every 3 km. (2) Waste residue after slope excavation is piled along the highway, thereby providing loose solid materials for landslides. For example, the Jiang–Wu (Jianluo–Wudu) Highway generated 1.5 million m$^3$ of accumulated waste soil\cite{66}. (3) The effect of vehicle loads (including vehicle weight and vehicle impact dynamic load) reduces the slope stability coefficient by approximately 5.8%–12.1% and can also induce the occurrence of landslides\cite{67}. 

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Figure 22. Density map of landslides

Figure 23. Population density

Figure 24. Correlation diagram between landslide density and population density
4.3 General development characteristics of landslides
After the investigation, this study determines that the development characteristics of the landslides in the Bailong River Basin are closely related to topography, geological conditions, rock and soil bodies, hydrogeological conditions, and human activities. Generally, landslides demonstrate the following rules.

4.3.1 Suddenness
Suddenness has two meanings. First, landslides can form and develop rapidly. The process is extremely strong, and signs before the hazard are not obvious or lacking. Second, heavy rains can induce landslides. In areas with complex topography and geomorphology, the local microclimate changes considerably. Thus, forecasting the occurrence and intensity of heavy rains and predicting landslides induced by heavy rains are difficult. In addition, the residents of the area are unprepared, because heavy rains occur mostly in the evenings or at midnight, which increases the suddenness of landslides, thereby making prevention difficult.

4.3.2 Periodicity
Periodicity is mainly manifested in two aspects. First, the frequent occurrence of landslides is basically consistent with interannual changes in rainfall. Landslide occurrence periods may exhibit certain differences in different regions, but the general trend closely resembles periodic changes in rainfall. For example, Huama Ditch in Tanchang County experienced a large number of landslides in 1976, 1991, 2000, and 2010, with heavy rainfall. Second, landslides are likely to occur in months with the highest concentration of rainfall in the year. Precipitation in the Bailong River Basin is concentrated mostly from May to September. Precipitation during these five months is more than two thirds the total annual amount, and more than 80% of the landslides in the area occur during this period. For example, large-scale landslides occur in Renjia Ditch, Tangchang County from May to September in one year, which erode the China National Highway 212 and farmland, causing varying levels of property damage in the local area. In addition, landslides in Zhouqu, Sanyanyu, and other places occur during the rainy month of August. July to September is the period of heavy rains in Kang County, which is also the period with high landslide incidences. However, landslides occur less frequently at other times of the year.

4.3.3 Group occurrence
Group occurrence manifests in time and space. In terms of time, landslides occur frequently during rainy years or rainy seasons. For example, during the “7.17” heavy rains in Kang County in 2009, 138 mm of rain fell continuously for seven days, causing the river to rise rapidly and eventually landslides. This phenomenon caused one death, traffic interruptions for more than a month, and direct economic losses of approximately 2 billion yuan. With regard to space, landslides are concentrated and prevalent
in areas with concentrated populations and high-intensity human engineering activities. Landslides are distributed in clusters in slippery formations, near fractured and broken zones, and in Quaternary gully accumulation areas. For example, along the Diebu–Bailong River fault and branch faults, namely, the Dayu–Pingya fault and Guanggai–Die mountain south foot fault, landslides occur in specific zones.

4.3.4 Synchronization

In terms of time, continuous or heavy rainfall typically triggers rapid flooding, which induces continuous and multiple landslides within a short period of time or in the same location or in groups. For example, Sun’er Ditch in the Xinzhai Township of Tanchang County experienced two landslides in the span of one week. In terms of space, in areas with poor geological conditions or concentrated populations, landslides and other hazards induce one another in the event of heavy rainfall or earthquakes, which can occur simultaneously. They demonstrate the characteristic of “superposition-magnification” in terms of degree of damage, which should not be underestimated. For example, the six counties in the Bailong River Basin were severely damaged during the 2008 Wenchuan earthquake. The earthquake caused the resurgence of common geological hazards as well as the occurrence of new ones, and landslides developed in groups in the area. According to the survey, the total number of landslides in the six counties in the Bailong River Basin caused and aggravated by the earthquake is 585[68].

5. Conclusion

Based on the research, this study presents the following conclusions on the influencing factors, distribution laws, and overall development characteristics of the landslides in the Bailong River Basin.

(1) According to the investigation in 2018, landslides occurred frequently in the Bailong River Basin, and their number totaled 1,031.

(2) Numerous landslides occur within 10 km from faults. In areas with high peak ground acceleration, the number of landslides is large and density is high. Moreover, frequent landslides occur in areas that experience high seismic intensity, where scales are relatively large.

(3) In terms of hydrological conditions, landslide distribution is mainly affected by rivers and rainfall. The closer to the river, the higher the likelihood of landslides to occur. The number of landslides is largest in the areas less than 200 m from the river. The number of landslides is highest in the areas with an average annual rainfall of approximately 0–600 mm, a maximum amount of rainfall of approximately 35–45 mm within 24 h, or a maximum amount of rainfall of approximately 15–20 mm in 30 min. Based on the analysis of the statistical data, a maximum amount of rainfall in 30 min has a direct effect on the occurrence and distribution of landslides.

(4) The terrain parameters of a slope also exert a certain influence on the distribution of landslides. The specific mechanism is as follows. Landslides are mostly developed on sunny slopes facing the south, southwest, and southeast. A slope incline of approximately 15°–45° is the most suitable for the development of landslides. Areas with an elevation in the range of 1000 m to 2000 m are highly prone to landslides.

(5) Landslides are affected by vegetation and are likely to develop in areas with low vegetation coverage. Areas with a vegetation coverage of 10% < FC < 45% have the highest landslide density. Grasslands and cultivated lands are highly sensitive and prone to landslides compared with other land types.

(6) Disturbances to the geological environment from human engineering activities can induce landslides. Densely populated towns and both sides of roads, especially areas within 200 m, are highly susceptible and prone to landslide hazards.

(7) Rainfall distribution in the Bailong River Basin is uneven, and heavy or long-term rain is common. The geological environment in this area is relatively fragile, and a large number of landslides develop owing to the long-term and multi-period activities of active faults and the impact of earthquakes. Overall, landslides appear to be sudden, periodic, synchronous, and group occurring.

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