Characteristics of Rainfall-Induced Landslide Disasters and Analysis of Disaster-Causing Rainfall in Eastern Qinghai (Postprint)

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Abstract

Rainfall-induced landslides are the most frequent and impactful geological hazards in Qinghai Province, yet research on the rainfall characteristics that trigger such landslides remains insufficient. By analyzing the precipitation conditions on the day of occurrence and 1~10 d prior for 339 rainfall-induced landslide events that occurred from 2016 to 2023, this study aims to clarify the disaster characteristics of rainfall-induced landslides and the precipitation conditions that cause them. The research indicates: (1) Rainfall-induced landslides exhibit an east-west distribution pattern with higher frequency in the east; Xining City and Haidong City recorded the highest number of events, with the districts of Xining City, Huangzhong District, Minhe County, and Ledu District being high-incidence counties. (2) The frequency of rainfall-induced landslides shows good consistency with flood season precipitation and is closely related to antecedent cumulative precipitation. (3) Landslide occurrence exhibits a lag effect; effective precipitation for landslides within a 10 d period features two effective precipitation periods at 3 d and 7 d, and the probability of landslide occurrence is relatively high when the 10 d cumulative precipitation exceeds 40 mm. (4) During the process of landslide occurrence, light rain and moderate rain serve as the foundation, while heavy rain and precipitation exceeding the heavy rain threshold act as the triggering factors.

Full Text

Characteristics of Rainfall-Induced Landslide Disasters in Eastern Qinghai and Analysis of Their Triggering Rainfall

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Abstract

Rainfall-induced landslides are the most frequent and impactful geological disasters in Qinghai Province, yet research on the rainfall characteristics that trigger such landslides remains limited. By analyzing precipitation conditions for rainfall-induced landslides over 1–10 days prior to occurrence, this study aims to clarify the disaster characteristics and triggering precipitation conditions. The research indicates: (1) The spatial distribution shows more occurrences in the east and fewer in the west, with Xining City and Haidong City having the highest frequency; the districts of Xining City proper, Huangzhong District, Minhe County, and Ledu District are identified as high-incidence counties. (2) Landslide frequency correlates strongly with precipitation distribution—years with higher rainfall experience more landslides, with August being the peak month. (3) Light to moderate rainfall serves as the foundational condition for landslides, while heavy rainfall or greater acts as the triggering factor. When cumulative rainfall over 10 days exceeds 40 mm, the probability of landslide occurrence increases significantly. (4) Rainfall-induced landslides exhibit a lag effect relative to rainfall. The probability of occurrence is highest on the day following two consecutive days of heavy rainfall or greater, as well as on the third day after rainfall ends. Additionally, landslide probability increases again approximately five days after rainfall ceases. These findings provide a scientific basis for understanding landslide mechanisms and developing forecasting and early warning models.

Key words: rainfall-induced landslides; disaster-causing rainfall; pre-effective rainfall; eastern Qinghai

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Landslides are common geological hazards characterized by wide distribution, high incidence frequency, and significant danger [**?**], with distribution patterns closely related to slope morphology, topographic features, and vegetation factors [**?**]. Global economic losses from landslide disasters reach nearly ten billion dollars annually, causing thousands of casualties and posing severe threats to human life [**?**]. Various factors trigger landslides, including rainfall, earthquakes, and human activities, among which rainfall-induced landslides account for approximately 72.8% of the total [**?**]. The majority of these events are dominated by antecedent effective precipitation [**?**] and are closely related to rainfall duration, precipitation amount, and rainfall type. However, different types of rainfall-induced landslides exhibit distinct triggering mechanisms [**?**]. Conse-

quently, studying the characteristics, processes, mechanisms, and thresholds of rainfall-induced landslides has become a major research focus and challenge [**?**].

The eastern region of Qinghai belongs to the loess hilly area, representing a significant portion of the province' s territory with highly concentrated population and economy in valley alluvial-proluvial plains where geological disasters frequently occur [**?**]. Landslide disasters pose serious threats to life, property, and engineering construction in this region [**?**]. On [date], a landslide on the northwest side of Hongya Village, Weiyuan Town, Huzhu County, Haidong City, caused fatalities. With rising temperatures and increasing precipitation, rainfall-induced landslides in eastern Qinghai are becoming more severe. This region is expected to experience the most significant population and economic growth in Qinghai, as well as the greatest impacts from precipitation-induced disasters [**?**].

Although numerous scholars have analyzed rainfall characteristics of landslide disasters worldwide, research on disaster-causing rainfall and thresholds specifically for Qinghai, particularly eastern Qinghai, remains lacking. Such studies are essential for enhancing the province' s capability to prevent and mitigate rainfall-induced geological disaster risks. This paper analyzes landslide cases and meteorological station precipitation data in disaster-affected areas of eastern Qinghai to clarify occurrence characteristics, disaster-causing rainfall, and threshold features. The results provide a scientific basis for understanding landslide mechanisms and constructing forecasting and early warning models, thereby improving provincial capabilities for rainfall-induced landslide prediction and early warning.

1.1 Study Area Overview

Eastern Qinghai Province is located on the northeastern edge of the Tibetan Plateau, with elevations ranging between 1667–5153 m. It is the most densely populated and economically developed region in the province, administratively comprising Xining City, Haidong City, Haibei Prefecture, Hainan Prefecture, and Huangnan Prefecture, accounting for [missing percentage] of the province' s total area. The region features well-developed mountains, valleys, and hills with complex geological environmental conditions, fragile ecology, widespread high and steep slopes, and well-developed free faces. Overall slope stability is generally poor, and due to natural conditions and geological environment, slope geological hazards are quite prominent, making this the area with the most frequent geological disasters in the province. Eastern Qinghai has a plateau continental climate, with precipitation concentrated in [missing months] each year, accounting for [missing percentage] of annual total precipitation.

1.2 Data and Methods

This study selects meteorological data from [missing number] national-level meteorological stations and [missing number] regional meteorological stations in

eastern Qinghai Province from [missing year] to [missing year]. Precipitation data are sourced from the Meteorological Big Data Cloud Platform · Tianqing. After quality control by the meteorological department, ArcGIS software performs linear regression interpolation on missing precipitation data and landslide points without precipitation data to calculate daily precipitation for each point. According to the *Technical Specification for Meteorological Disaster Risk Assessment: Rainstorm* (DB63/T 2186-2023) [**?**], daily precipitation is classified into levels (Table). Geological disaster case data are obtained from the Qinghai Provincial Natural Resources Administration, with a temporal scale of [missing].

1.3 Basic Characteristics of Geological Hazards

Qinghai Province has recorded [missing number] geological disasters, with [missing number] occurring in eastern Qinghai. Among geological disasters in eastern Qinghai (Fig. [Figure 2: see original paper]), landslides are most frequent with [missing number] occurrences, accounting for 90.9%; collapses account for 61.3%; and debris flows account for [missing percentage]. Based on landslide triggering factors, [missing number] rainfall-induced landslide events were selected, representing 74.0% of total landslides. Therefore, this paper focuses on the occurrence characteristics and disaster-causing rainfall of rainfall-induced landslides in eastern Qinghai.

2.1.1 Spatial Distribution Characteristics

Rainfall-induced landslide disasters in eastern Qinghai generally show a distribution pattern of more occurrences in the east and fewer in the west (Fig. [Figure 3: see original paper]). Xining City accounts for 34.8% of occurrences, Haidong City for 45.4%, [missing region] for [missing percentage], and [missing region] for [missing percentage]. At the county level, high-incidence counties include [missing number] counties, representing 56.9% of total occurrences in eastern Qinghai: Ledu District with [missing number] occurrences, Huangzhong District with [missing number], Xining City proper with [missing number], and Minhe County with [missing number].

Spatially, Xining City shows a decreasing distribution from the main urban area outward, with Chengbei District having the most occurrences at [missing number], followed by Chenzhong District with [missing number]; Huangyuan County has no recorded rainfall-induced landslides. In Haidong City, rainfall-induced landslides mainly occur in Zhongba Township and Qutan Town of Ledu District, with [missing number] occurrences each. In Haibei Prefecture, landslides are concentrated in the western Qilian Mountains, with Babao Town in Qilian County having the most at [missing number] occurrences. In Hainan Prefecture, the distribution shows more in the east and fewer in the west, mainly in Xiuma Township and Hebei Township of Tongde County, with [missing number] occurrences each; Gonghe County has no recorded rainfall-induced landslides. In Huangnan Prefecture, landslides are concentrated in the north, with no recorded

disasters in the south; Cuozhou Township in Jianzha County has the most at [missing number], followed by [missing location].

High-incidence areas feature widespread loess layers with relatively loose rock and soil layers, low vegetation coverage, and poor stratigraphic stability due to weathering and lateral water erosion. This indicates that rainfall-induced landslides in eastern Qinghai are primarily related to precipitation and geological layer properties.

2.1.2 Temporal Variation Characteristics

Monthly variation analysis (Fig. [Figure 4: see original paper]) shows rainfall-induced landslides are concentrated in [missing month], accounting for 94.9% of total occurrences, as the flood season in Qinghai occurs from [missing month] to [missing month], with 83.8% of annual precipitation concentrated in this period. Landslide frequency shows good consistency with precipitation variation trends, with more landslides in months with higher precipitation. However, landslide disasters are also influenced by human activities and local disaster-pregnant environments besides precipitation. For example, maximum monthly precipitation occurs in [missing month], but the highest monthly landslide frequency occurs in [missing month].

Interannual variation shows that annual landslide frequency varies by year but maintains high consistency with precipitation trends, particularly during the flood season. When flood season precipitation is equal to or below normal, landslide occurrences are significantly lower. The year with the most landslides was [missing year] with [missing number] occurrences, also the year with highest annual precipitation. In [missing year], landslide occurrences were relatively high, corresponding to above-normal flood season precipitation.

2.2 Relationship between Landslides and Precipitation

Previous studies indicate that rainfall-induced landslide events exhibit a lag effect, with rainfall within [missing number] days before the geological disaster exerting varying degrees of influence on its development [**?**]. This corresponds to weather forecasting primarily focusing on [missing number]-day forecasts. Therefore, this study analyzes disaster-causing rainfall characteristics by combining actual forecasting and early warning timeliness and comprehensively considering the combined effects of rainfall on the day of occurrence and antecedent rainfall.

2.2.1 Relationship with Total Precipitation on Landslide Day and Previous 10 Days Generally, landslides are more likely to develop in areas with greater rainfall, and landslide occurrence is basically positively correlated with precipitation amount. From [missing number] precipitation-induced landslide events in eastern Qinghai, [missing number] events with valid rainfall data were selected. Analysis of the proportion of landslide occurrences corresponding

to accumulated precipitation (Fig. [Figure 6: see original paper]) reveals that [missing analysis]. Typically, as accumulated precipitation increases, landslide probability also increases. However, the analysis found that when precipitation is in the 20–40 mm range, landslide occurrence proportion is highest; when precipitation is in the 60–100 mm range, the proportion decreases; and when precipitation exceeds 100 mm, the landslide proportion increases again. This is mainly related to frequent continuous rainfall or sudden heavy precipitation in eastern Qinghai. Continuous rainfall reduces friction on weak surfaces in rock and soil, increases hydrostatic pressure on structural planes, and causes structural planes to evolve into sliding surfaces. Sudden heavy precipitation increases landslide mass weight, ultimately causing failure of slope soil or bedrock. Therefore, landslide early warning must consider not only daily precipitation but also accumulated precipitation effects.

2.2.2 Relationship with Daily Precipitation on Landslide Day and Previous 10 Days According to the standards in Table , daily precipitation data were analyzed for [missing number] rainfall-induced landslide events on the day of occurrence and the previous 1–10 days. Among these, [missing percentage] of landslides occurred on days with no rainfall, [missing percentage] on days with light rain, [missing percentage] with moderate rain, [missing percentage] with heavy rain, and [missing percentage] with torrential rain or above. This shows that on landslide occurrence days in eastern Qinghai, light rain or no rainfall predominates, accounting for [missing percentage], which reduces local residents' vigilance and increases disaster probability.

From day 1 to day 10 before landslide occurrence, the proportion of no-rain days gradually increases, peaking on day [missing] at 54.6%. The proportion of light rain remains relatively stable at around [missing percentage]. Moderate rain is concentrated around days [missing], with other periods maintaining a stable proportion between [missing percentage]. Heavy rain shows a wave-like distribution within days [missing], with proportions ranging from 5.6% to 9.9%, peaking on day [missing]. Torrential rain and above-level precipitation on day [missing] before landslide occurrence accounts for [missing percentage], reaching up to 11.6%. This shows that within [missing number] days before landslide occurrence, the proportions of light and moderate rain remain relatively stable, while heavy rain and above-level precipitation on the day of occurrence and preceding days [missing analysis].

When heavy rain or above-level precipitation occurs [missing number] times within 10 days before landslide occurrence (Table), [missing analysis]. When heavy rain or above-level precipitation occurs on [missing number] consecutive days, [missing analysis]. When heavy rain or above-level precipitation occurs with a [missing number]-day interval, [missing analysis]. This indicates that consecutive heavy rain or above-level precipitation events, as well as events with [missing number]-day intervals, are prone to trigger landslides.

2.2.3 Relationship with Heavy Rain and Above-Level Precipitation
Statistics show that among [missing number] landslide events, [missing number] landslides experienced [missing number] instances of heavy rain or above-level precipitation before occurrence, among which [missing percentage] had heavy rain or above-level precipitation accounting for [missing percentage], [missing percentage] had [missing number] instances, [missing percentage] had [missing number] instances, and [missing percentage] had [missing number] instances. This indicates that heavy rain or above-level precipitation easily triggers landslides.

Heavy rain or above-level precipitation occurred on the day of landslide occurrence in [missing percentage] of cases, [missing number] days before in [missing percentage], [missing number] days before in [missing percentage], and [missing number] days before in [missing percentage]. After [missing number] instances of heavy rain or above-level precipitation, landslides are likely to occur on the same day or day [missing number].

When heavy rain or above-level precipitation occurs [missing number] times within the day of landslide occurrence and previous 10 days (table omitted), [missing percentage] of landslides occur after continuous precipitation, among which [missing percentage] occur when heavy rain or above-level precipitation appears on the day of landslide occurrence and [missing number] days prior, and [missing percentage] occur when heavy rain or above-level precipitation appears [missing number] days before landslide occurrence.

3 Conclusions

Based on [missing number] rainfall-induced landslide disaster events and daily precipitation observation data from 1–10 days before landslide occurrence, this study investigates the occurrence characteristics and disaster-causing rainfall of rainfall-induced landslides in eastern Qinghai Province, yielding the following conclusions:

(1) Rainfall-induced landslides show an east-west distribution pattern, with Xining City and Haidong City having the highest occurrence frequency. Among them, Xining City proper, Huangzhong District, Minhe County, and Ledu District in Haidong City are high-incidence counties, mainly influenced by precipitation and geological layer properties.

(2) The frequency of rainfall-induced landslides shows good consistency with flood season precipitation and is closely related to antecedent precipitation accumulation. Landslides are mainly caused by precipitation amounts of [missing range]; when cumulative precipitation reaches above 100 mm, the probability of landslide occurrence [missing text]; when cumulative precipitation exceeds 50 mm, [missing text].

(3) Landslide occurrence exhibits a lag effect, with effective precipitation for landslides occurring within [missing number] effective precipitation peri-

ods. The precipitation impact is most significant when cumulative precipitation exceeds 40 mm, resulting in a higher probability of landslide occurrence.

(4) During landslide occurrence processes, light and moderate rain serve as the foundation, while heavy rain and above-level precipitation act as triggering factors. Continuous [missing number] instances of heavy rain or above-level precipitation and [missing number]-day intervals between heavy rain or above-level precipitation events are prone to trigger landslides.

References

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Note: Figure translations are in progress. See original paper for figures.