Development and distribution of ancient landslides in the northwest corner of the Tibetan Plateau

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Abstract: The periphery of the Tibetan Plateau is a landslide-prone area, yet there is a lack of satisfactory results on the development and distribution of landsides due to low human activity and inconvenient transportation within this area. In this study, taking 38–40°N and 73–76°E as the study region, a detailed distribution map of ancient landslides, including 5378 landslides with a total area of 2705.02 km², is established with the help of Google Earth Engine platform using manual visual interpretation. The numbers and areas of landslides, classified in terms of elevation, slope angle, slope aspect, fault distance, and water system distance, are analyzed. The development of landslides is closely correlated with topographical and geological factors. After comprehensive analysis, we conclude that both the number and total area of landslides in the elevation range of 4–5 km are the greatest; more landslides happen in the slope angle range of 40°–50°; the total area of landslides in the slope angle range of 50°–60° is the largest; both the number and total area of landslides with slope aspects of N, NE, and NW are the greatest; the ancient landslides in this region were weakly impacted by tectonic movement and seismic activity, and more likely caused by reasons like climate change; and the occurrence of ancient landslides in this region is insignificantly correlated with water systems.

Key words: Tibetan Plateau, ancient landslides, manual visual interpretation, development and distribution of landslides

1. Introduction

Landslide hazards are extremely dangerous to human society, causing severe losses and
casualties [1]. Landslides can be divided into several types according to different classification criteria, such as coseismic landslides mainly induced by earthquakes [2, 3] and rainfall landslides triggered by changes in rain and snow patterns [4]. There have been in-depth studies of landslides, including the interpretation [5, 6] and database establishment of coseismic landslides [7], the statistical summary of spatial distribution patterns [8], regional landslide susceptibility assessment [9], calculation of landslide occurrence probability under different triggering conditions [10], and automatic identification of landslides based on machine learning [11]. In addition to such transient landslides, ancient landslides formed by long-term slope movement as well as climatic and tectonic changes, are also the focus of geological hazard prevention [12]. Damage due to the instability and reactivation of ancient landslides is not uncommon [13]. Research on ancient landslides can be highly helpful in hazard prevention [14], in addition to supporting studies on active regional tectonics [15]. Most of the related studies focus on one or more large-scale ancient landslides, such as the Lagangcun giant ancient landslide in Jiacha, Tibet [16], the Xietan landslide [17], the Temi ancient landslide in the upper Jinsha River [18], the Basu giant landslide [19], and the giant ancient landslide in Zhouqu [20].

Although there has been a wealth of research results on landslide hazards, a detailed database of landslides in the northwest corner of the Tibetan Plateau is lacking, hindering a good understanding of the development degree and distribution pattern of regional landslides. To fill this gap, this study aims to investigate multiple densely distributed ancient landslides in the northwest corner of the Tibetan Plateau. Making use of the high-definition remote sensing images of the Google Earth Engine platform, manual visual interpretation of landslides is performed to obtain a detailed landslide inventory. Then, ArcGIS software is used to analyze the distribution pattern of landslides, a database of landslides in the study area is established, and further statistical analysis is conducted to quantify the relationships between landslide traits and multiple influencing factors. This study will be of great significance to the geomorphological analysis and seismic characterization of this region. In addition, it provides scientific and technical support for the early warning, hazard prevention, and mitigation of landslide hazards in this region, and acts as a reference for other ancient landslide studies.

2. Regional overview and geological background

The study area is located in the northwest corner of the Tibetan Plateau in China, bordering Kyrgyzstan and Kazakhstan, with geographical coordinates of 38°–40°N and 73°–76°E (Figure 1). The largest fault zone in the study area is the Gonggeer tensional fault zone, which strikes in the NW–SE direction and extends 250 km in length. This region has the highest tectonic stress as well as the fastest crustal denudation and uplift rate on the Tibetan Plateau, and its lithology is dominated by Paleozoic gneiss and schist [21]. The temperature in the study area is low with a lot of quaternary glacial cover and abundant water bodies, such as Kangxiwa River and Lake Karakul. Landslides are densely distributed in the study area, often showing a clustered distribution, and there is a giant ancient landslide, the Tahman landslide (Figure 1b). Therefore, we chose this region for the study of ancient landslides in the northwest corner of the Tibetan Plateau.
3. Methods and data
The ancient landslides are identified by manual visual interpretation (Figure 2a). On the ArcGIS platform, the numbers and areas of landslides, classified in terms of elevation, slope angle, slope aspect, fault distance, and water system distance, are analyzed based on the digital elevation model (DEM) and a geological map. The satellite images used in this study are from Google Earth. They have a maximum resolution of 0.5 m. The DEM data from ALOS PALSAR, has an accuracy of 12.5 m. In addition, the national water system data and the structural data of the study area are employed.

4. Results and analysis
4.1. Development degree of landslides
There are a total of 5378 ancient landslides in the study area, covering a total of 2705.02 km$^2$. The areas of single ancient landslides vary widely from 1953 m$^2$ to 25.66 km$^2$. Each landslide is put into one of the six groups by area: $<0.2$ km$^2$, 0.2–0.4 km$^2$, 0.4–0.6 km$^2$, 0.6–0.8 km$^2$, 0.8–1 km$^2$, and $>1$ km$^2$. There are 2485 landslides of $<0.2$ km$^2$ area, which is the most common size and accounts for 46% of the landslides. The total area of landslides in the $>1$ km$^2$ group is 1449 km$^2$, accounting for 53% of the total landslide area.

As the typical ancient landslide, the Tahman landslide (Figure 2(b)) is located at the southeast edge of the study area. It has an overall tongue shape with an area of 5.36 km$^2$, an elevation range of 3255–4706 m, maximum slope angle of 58°, an overall SW trend, more than 2 km from the nearest water system, and a long distance from the fault. The ancient landslide in Figure 2(c) is located in the central part of the study area and is dustpan-shaped, with an area of 4.45 km$^2$, an elevation range of 3306–4348 m, maximum slope angle of 51°, and an overall slope aspect of SE direction. It is situated on the river side with fault structures on its surface.
Figure 2. Distribution of landslides in the study area

4.2. Relationship between landslides and elevation
The elevation of the study area ranges from 1522 to 6820 m. Considering the high terrain, the landslides are grouped in terms of elevation into six groups: ≤2 km, 2–3 km, 3–4 km, 4–5 km, 5–6 km, and ≥6 km. The relationship between the number and area of landslides and their elevation is analyzed, as shown in Figure 3a. There are 2850 landslides within the elevation range of 4–5 km, which is 53% of all the landslides. The number of landslides increases with increasing elevation up to 5 km and decreases with increasing elevation after that. The total area of landslides in the elevation range of 4–5 km is 1336.28 km², which is the largest and accounts for 49.4% of the total landslide area. The area of landslides in the elevation range of 5–6 km is 1044.91 km² and accounts for 38.6% of the total landslide area; the areas of landslides in other elevation ranges are relatively smaller. Overall, both the number and area of landslides in the elevation range of 4–5 km are the greatest.

4.3 Relationship of landslides with slope angle and slope aspect
The slope angles of the study area range from 14.6° to 84.2°. The landslides are grouped into seven groups by slope angle: ≤20°, 20°–30°, 30°–40°, 40°–50°, 50°–60°, 60°–70°, and ≥70°. The relationship between the number and area of landslides and the slope angle is analyzed, as shown in Figure 3b. Slope angles of 40°–50° and 50°–60° are the most common; specifically, there are 1564 and 1466 landslides with a slope angle of 40°–50° and 50°–60°, respectively, accounting for 29.1% and 27.3% of the total. The number of landslides increases with slope angle up to 50° and decreases after that. The total area of landslides with a slope angle between 50° and 60° is 723.48 km², which is the largest and accounts for 26.7% of the total landslide area. The areas of landslides with slope angles of 60°–70° and ≥70° are 688.73 km² and 668.98 km², respectively, and account for 25.5% and 24.7% of the total landslide area. Overall, there are a large number of landslides with a slope angle in the range of 50°–60°, and the corresponding total landslide area is the largest.

The slope aspects are divided into nine directions, namely Flat, N, NE, E, SE, S, SW, W, and NW, to analyze the relationships between the number and area of landslides and the angle aspect (Figure 3c). There are 899, 903, and 847 landslides with slope aspects of N, NE, and
NW, respectively, and the corresponding total areas are each above 450 km$^2$, showing a clear dominance.

4.4 Relationship between landslides and fault distance

The study area is large with many concentrated faults. As a result, the impact of faults on the distribution of landslides usually weakens with distance, so the regions too far away from the faults are negligibly affected. With this in mind, the landslides are grouped in terms of their distance from faults at 1km intervals, except those with a distance greater than 10 km, are combined into one group. The relationships between the number and area of landslides and the fault distance are shown in Figure 3d. There are 832 landslides with a fault distance of up to 1 km, covering a total area of 667 km$^2$. However, there are also many landslides with a fault distance greater than 10 km, indicating that the ancient landslides in this region are weakly impacted by tectonic movement and seismic activity. Rather, they are more likely caused by climate change and other factors.

4.5 Relationship between landslides and water system distance

Water systems are widely distributed in the study area. Here the landslides are grouped in terms of their distance to water systems at 200 m intervals, and those with a distance greater than 2 km are combined into one group. The analysis results are shown in Figure 3e. There are 910 landslides with a distance of 0–0.2 km (higher than any other distance), and their corresponding area is 631.3 km$^2$, while the numbers and areas of landslides with distance to water systems in the range of 0.2–1 km are largely identical but with minor differences.

The closer a region is to a water system, the greater the development of ancient landslides in that region. Nevertheless, there is also a trend similar to the analysis above in terms of fault distance, i.e., many ancient landslides happened in regions beyond 2 km from any river, indicating that the occurrence of these ancient landslides was relatively insignificantly correlated with water systems.
Figure 3. Relationships between landslide number and area and different factors: (a) elevation, (b) slope angle, (c) slope aspect, (d) fault distance, and (e) water system distance

5. Conclusion

There are as many as 5378 ancient landslides in the northwest corner of the Tibetan Plateau (38°–40°N and 73°–76°E) with a total area of 2705.02 km². There are 2485 landslides of <0.2 km², the most common size and accounts for 46% of the landslides. The total area of landslides in the > 1 km² group is 1449 km², accounting for 53% of the total landslide area. The development of landslides is closely correlated with topographical and geological factors. After comprehensive analysis, we conclude that both the number and total area of landslides in the elevation range of 4–5 km are the greatest; more landslides happen in the slope angle range of 40°–50°; the total area of landslides in the slope angle range of 50°–60° is the largest; both the number and total area of landslides with slope aspects of N, NE, and NW are the greatest. There are 832 landslides with a fault distance of up to 1 km, covering a total area of 667 km². However, there are also many landslides with a fault distance greater than 10 km, indicating that the
ancient landslides in this region are weakly impacted by tectonic movement and seismic activity. Rather, they are more likely caused by climate change and other factors. The closer a region is to a water system, the greater the development of ancient landslides in that region. Nevertheless, there is also a trend similar to the above analysis in terms of fault distance. That is, many ancient landslides happened in regions beyond 2 km from any river, indicating that the occurrence of these ancient landslides was relatively insignificantly correlated with water systems. In this study, a database of ancient landslides in the region of $38^\circ$–$40^\circ$N and $73^\circ$–$76^\circ$E, is established to preliminarily analyze the development degree and distribution pattern of ancient landslides in the northwest corner of the Tibetan Plateau. The ancient landslides in the surrounding regions will be investigated in the follow-up studies.

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7. References
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