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Analysis of Quantified Hillslope Erosion by Excess Topography in the Hengduan Mountain

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Abstract

Hillslope erosion, as an important Earth surface process, also plays an irreplaceable role in the formation and evolution of the landscape. Especially in the deep canyon area, the erosion process, dominated by landslides, controls the direction and process of landscape evolution. In this study, we analyzed the relationship between excess topography and slope erosion based on the threshold hillslope theory. The findings of our study show that the average slope of the six major rivers in the Hengduan mountain area is between 25° and 30°. Additionally, the area with a slope of 30 ± 5° near the river valley accounts for up to 82%. Taking 30° as an example threshold hillslope, the average thickness of the excess topography in the Hengduan mountain area reaches 32.2m. Based on the maximum average erosion rate of 0.48 mm/s, the excess topography thickness can supply the erosion amount for 67,000 years. Meanwhile, about 71% of the 4,430 landslides in the Hengduan mountain area are located in areas with excess topography, and more than 48% are situated in areas with excess topography exceeding 50m in height. Moreover, the excessive topography volume in the six rivers of the Hengduan mountain area exhibited a strong linear correlation with the erosion rate, suggesting that the distribution of excessive topography can serve as an indicator of spatial variations in erosion capacity. Quantification of hillslope erosion through excess topography can be a breakthrough in understanding the plateau uplift mechanism and hillslope erosion process.

Keywords

Excess topography, threshold hillslope, hillslope erosion, Landslide, Hengduan mountain

1. Introduction

In recent years, studies on the evolution of the orogenic belt have focused on the coupling of glaciers, river erosion, and structural uplift [1-4]. However, hillslope erosion as an important earth surface process also plays an irreplaceable role in the formation and evolution of the landscape [5, 6]. Especially in the deep canyon area, the erosion process dominated by landslides controls the direction and process of landscape evolution [7]. The hillslope angle is an important indicator of hillslope stability. When the stable threshold hillslope is exceeded, the erosion rate of the hillslope will increase significantly and quickly adjust itself in the form of landslides [5, 7]. In active orogenic, the landslide is the dominant process of surface erosion response to rapid rock uplift in the Himalayan eastern tectonic syntaxes [8].

However, the current research on hillslope erosion is mainly based on the field of geological engineering and natural disasters, and a lot of work has been carried out in erosion mechanism [9], disaster mode [10], remote sensing image characteristics of landslide, landslide database construction, and numerical simulation [11]. There are few studies on the impact of hilslope erosion

on landslide in Hengduan mountain, mainly because the amount of hillslope erosion is difficult to quantify by landform parameters, and the traditional method of nuclide measurement of erosion rate is difficult to be applied in a large range due to the high cost [12]. In recent years, as the application field of DEM has been broadened and deepened with the improvement of data accuracy, the study of landscape evolution has moved from a qualitative to a semi-quantitative-quantitative stage [13, 14]. Based on the threshold hillslope theory, the topography index of excess topography was first proposed by Blothe et al. [15]. Excess topography refers to potentially unstable mountains with slopes greater than the threshold hillslope, and their study suggests that more than 75% of the Karakoram landslides are located in these excess topography. So in the high-relief Hengduan mountain area, is there a similar phenomenon. Through the statistical analysis of slope, we obtained the threshold hillslope of the region, and then based on the threshold hillslope theory, extracted the Excess topography of the area. Meanwhile, the excess topograpy volume was also calculated and associated with the erosion rate data in Hengduan mountain area of the six major river basins, then compare the spatial relationship between the excess topograpy and the landslides in the area, can reveals the important role of landslide dominant hillslope erosion in the landscpe evolution of Hengduan mountain area, and provides new ideas for the study of landscape evolution in this region and even more areas. At the same time, the unstable mountains in the Hengduan Mountain area can also be quantified by extracting the excess topograpy, so as to serve the engineering construction and disaster prevention and mitigation in the region.

2. Study area

The study area is limited to the traditionally defined Hengduan Mountain area. There are six mountains and six rivers, from the western Gaoligong mountain to the eastern Min River (Figure 1). The region spans 24°40′–34°00′ N, 96°20′–104°30′ E, and covers 360,000 km^3 [16], most of which are mountainous. High mountains and extremely high mountains above 3,500 meters account for 73% of the total area. Gongga Mountain, Meili Mountain, Siguniang Mountain and Yulong Mountain embrace. This area is typically a high-elevation, low-relief landscape dissected by river gorges that are broadly distributed along the plateau margin [17]. Hengduan mountain area spans many fault zones, broken rock mass, and steep and slippery slopes, landslide is the most common and most efficient hillslope erosion event often occurs, and large landslides frequently inundate these rivers [18, 19]. The southeastern Tibetan Plateau has been separated into several blocks by a series of large strike-slip and thrust faults formed by the convergence of India and Eurasia [20]. The lithology of the strata in Hengduan Mountain is very complex, and a large number of magmatic rocks, metamorphic rocks, and sedimentary rocks in different historical periods from the Triassic and Palexia to the west are distributed and the change of sedimentary thickness is very obvious.

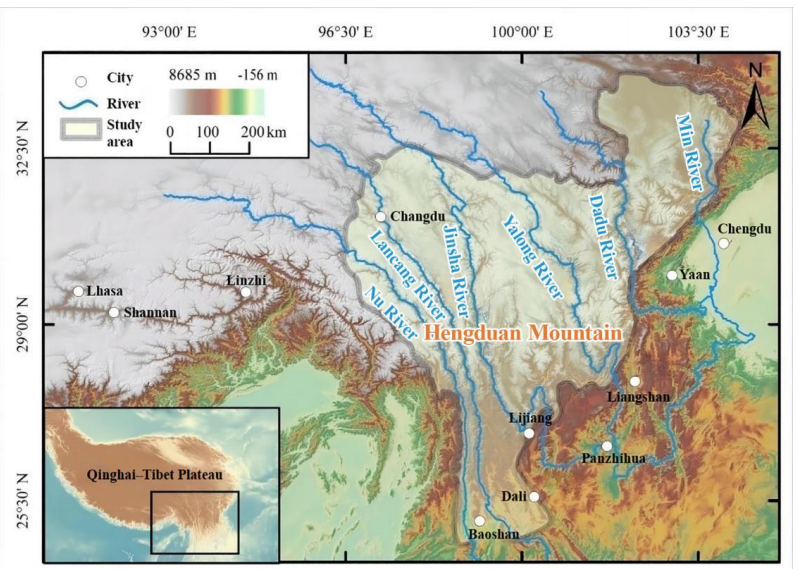

Figure 1. Research area overview.

3. Method

The SRTM DEM data at the 30m spatial resolution used in this paper are all obtained from the US Geological Survey United States Geological Survey (USGS) data-sharing platform (https://earthexplorer.usgs.gov/). At the same time, this paper mainly uses Google Earth to establish a preliminary understanding of the macroscopic landform of the Hengduan Mountain area and to identify some landslides in the research area combined with the field investigation work.

3.1 Value of the threshold hillslope

The threshold hillslope is the internal friction angle that controls the stability of the slope (one of the shear strength indicators of the soil or rock, reflecting the size of the internal friction between the particles inside the soil or rock. The greater the internal friction angle, the higher the strength) of the average [21]. The value of the threshold hillslope is a prerequisite for calculating the extraction of excess topography, and many studies have shown that the threshold hillslope of hillslope erosion is between 30°- 35° [15, 22-24]. In order to obtain the reasonable threshold hillslope value of the Hengduan mountain area, the slope of the six basins was divided into statistics, and the areas far from the river and flat terrain without the slope movement were removed. The area with a slope range of 30 ± 5 is widely distributed in the Hengduan mountain area, accounting for about 82%, and the hillslope range may be the reasonable value range of the threshold hillslope of the Hengduan mountain area.

3.2 Extraction of the excess topography

Excess topography refers to a potentially unstable hillslope with a slope greater than the threshold hillslope. Assuming that the threshold hillslope always exists, the excess topography can be used to represent all the large bedrock landslides within the region. The site-specific threshold hillslope surface extraction excess topograph process is performed as follows [25],

$$\dot{z}(x,y) = \min_{(s,t)\in(-\infty,\infty)} \left\{ z(x+s, y+t) + s_t \sqrt{s^2 + t^2} \right\} \tag{1}$$

where z is the real elevation of the topography, x, y are coordinates, and s, t is the filter coefficient, which refers to the distance from the center of the filter to the point (x, y).

The elevation of excess topography z_E can then be obtained by subtracting the elevation of the threshold hillslope surface from the real surface elevation as follows:

$$z_E(x,y) = z(x,y) - \dot{z}(x,y) \tag{2}$$

3.3 Landslide and erosion rate data

Most hillslope erosion studies follow the same conditions in the future as those that have occurred in the past [27]. This paper collected and sorted out the data of 4430 landslide points in the six rivers of Hengduan Mountain area, and most of the landslide information came from the address cloud platform of the China Geological Survey (http://geocloudsso.cgs.gov.cn/), Some of the landslide data was

obtained through field investigation combined with high-resolution remote sensing image (www.google.com/earth). Discrimination standards of landslide are as follows, (1) obvious landslide rear wall, (2) floodplain terrace and mound shape and asymmetric sediment, (3) obvious river shape changes, and (4) obvious basin density changes. A typical landslide is shown in the following Figure 2.

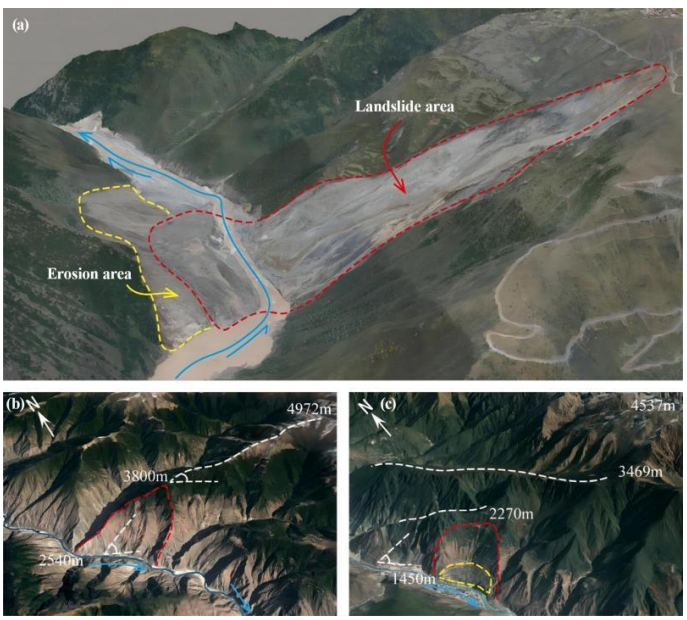

Figure 2. Schematic diagram of typical landslide.

In this paper, 62 erosion rates measured by nuclide ^{10}Be in six major basins were collected from the open erosion rate database OCTOPUS [28]. The distribution of sampling point locations and size is shown in Figure 3.

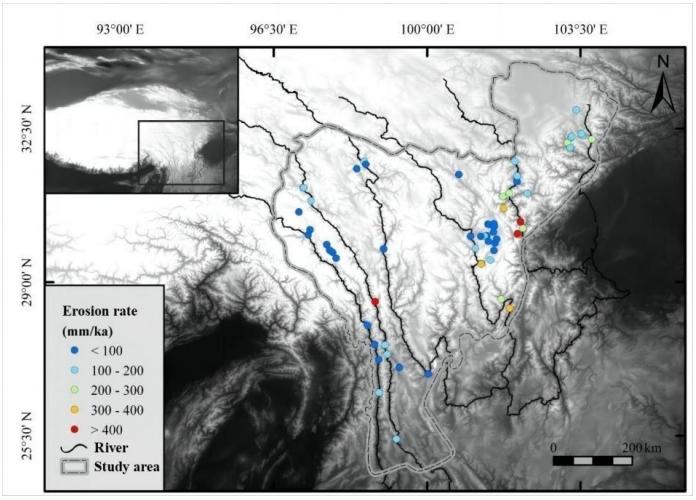

Figure 3. Distribution of erosion rate sampling points in the six Rivers of Hengduan Mountain area.

4. Result

4.1 Distribution of excess topography

Using the surface volume tool of ArcGIS10.2, the threshold hillslope of 30, the excess topography volume is 11.6103km^3, and the average thickness of the excess topography is respectively 32.2m. Based on the maximum average erosion rate of 0.48 mm/s measured by nucleoside ^{10}Be, the excess topography thickness can supply the erosion amount of 67,000 years. The average thickness of excess topography is calculated considering a large number of non-slope areas and the average erosion rate is the maximum in the area. Therefore, the results of the hillslope erosion time scale calculation may be somewhat underestimated, and the sustained erosion time provided by the hillslope is far beyond the calculated value. There are obvious differences in the excess topography of different basins in the Hengduan Mountain area. As shown in Figure 4, when the threshold hillslope is 30, the excess topography of the middle and lower reaches of the Min River, Dadu River, Lancang River, and Nu River are widely distributed, while the excess topography of the Yalong River and Jinsha River is less distributed. Among them, the excess topography in the Min River is mainly distributed in the north of Li County in Sichuan Province, while the excess topography in the Dadu River is mainly distributed on both sides of the river between Danba County and Shimian County, while the excess topography in the Lancang River and Nu Rivers is concentrated in the two rivers.

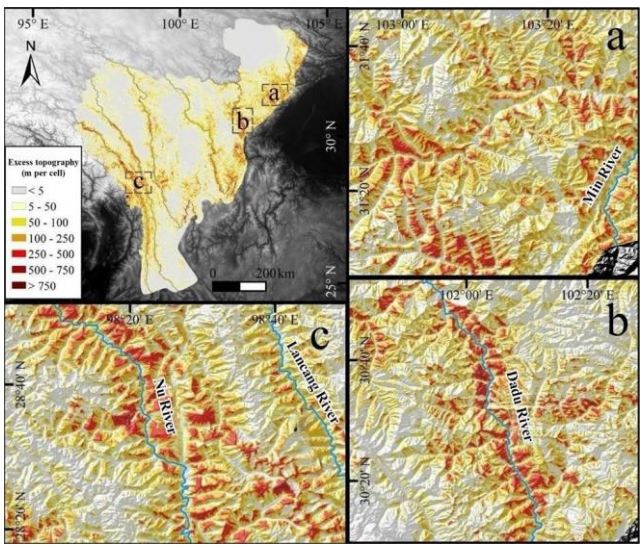

Figure 4. Distribution of excess topography.

4.2 Relationship of the excess topography to the erosion rate

Based on the above research, this paper wrote the Arcpy script to generate 62 circular buffers for a radius of 5km and calculated the excess topography volume falling in the 62 circular regions to analyze the correlation between excess topography and erosion rate. The correlation of erosion rates and the excess topography in six basins was analyzed separately using the linear fitting tool in Origin software, and the results are shown in Figure 5. The goodness of fit of Min, Dadu, Yalong, Jinsha, Lancang, and Nu rivers R^2 is 0.86,0.83,0.84,0.75,0.83 and 0.89 respectively. The correlation coefficient R is greater than 0.75, and the excess topography and erosion rate showed a strong positive correlation in the six basins. Among them, the erosion rate sampling point spacing in the Nu River is relatively average, and the erosion rate has the strongest correlation with the Among them, the erosion rate sampling point spacing in the Nu River is relatively average, and the erosion rate has the strongest correlation with the excess topography. The erosion rate in the Jinsha River, may be the result of the sparse effect of erosion rate sampling points. The erosion rate in the Jinsha River, which may be the result of the sparse effect of erosion rate sampling points.

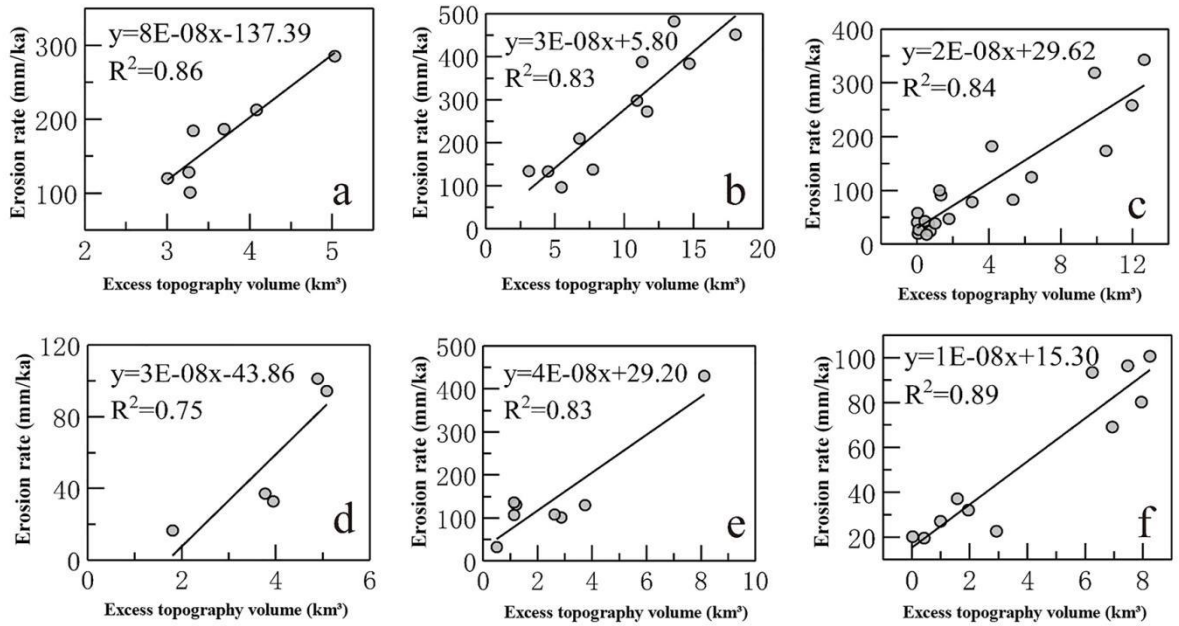

Figure 5. The erosion rates of the six Rivers in Hengduan Mountain are correlated with the excess topography (a, b, c, d, and e represent the Min River, Dadu River, Yalong River, Jinsha River, Lancang River, and Nu Rivers respectively).

4.3 Relationship between excess topography and landslide

Based on the assumption that threshold hillslope always exists, excess topography is such an indicator that can quantify the amount of long-term hillslope erosion in an area. Blothe More than 75% of the 492 landslides of different sizes found in the Himalayan-Karakoram Mountains are located in excess topography with slopes greater than 30° [22]. Hengduan Mountain area belongs to a typical high mountain canyon type landform, and landslides also develop in large numbers in this area. Based on the above studies, in order to verify that the excess topography is also applicable as a topographic index to quantify hillslope erosion in the Hengduan mountain area, the distribution pattern of the excess topography and its spatial association with landslides in the area should be investigated. As shown in Figure 6, among the 4430 landslides collected in the Hengduan Mountains, more than 71% of the landslides are in excess topography with a threshold hillslope of 30°, and the spatial correlation between the two is strong. Among them, the Min River is located in excess topography as high as 75%, while the Dadu River, Yalong River, Jinsha River, Lancang River, and Nu Rivers are 73%, 69%, 71%, 63%, and 70% respectively. Large landslides are concentrated in the Min River, the middle and lower reaches of the Dadu River, and the parallel flow area of the three rivers, which are also the places where the excess topography is widely distributed. The excess topography is classified according to the value of a single grid in the grid, and the grid value determines the height of the excess topography. There are 1518 landslides in the excess topography over 50m, accounting for 48% of the total landslide; over 5m, only 17% of the total landslide, and most of them are located in Dali and Baoshan in Yunnan in Lancang River. Small and medium-sized earthquakes are frequent in the Indian Ocean, which increases the frequency of landslides.

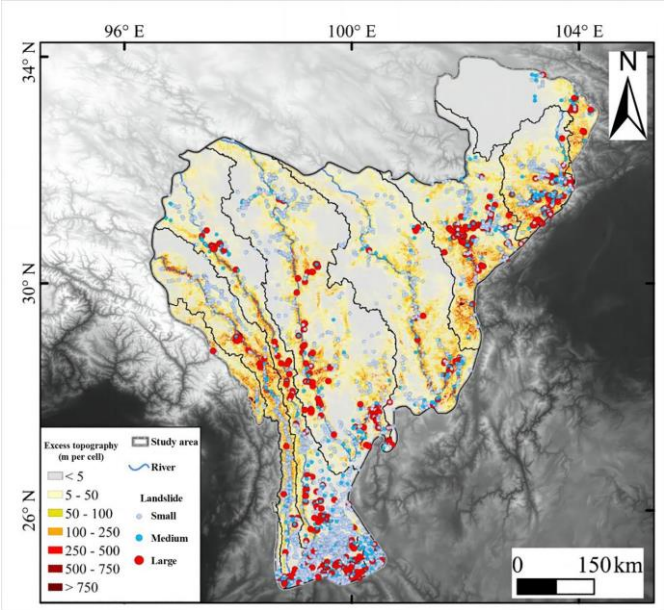

Figure 6. Excess topography and landslide in the Hengduan Mountains.

5. Discussion

hillslope erosion can dominate the geomorphic characteristics of the basin to some extent, and the reverse slope formed by a large base landslide area can reach the order of 10 km^2, with landslides extending over thousands of kilometers driving the rapid expansion of the river network in the basin, which controls the local morphology of the watershed by reshaping the low-level runoff system [29]. Landslides in some areas are characterized by small scale but high frequency, which have the ability to change the runoff density and watershed area to control the spatial distribution of the watershed. Some studies believe that the reduction of basin area caused by hillslope erosion is low undulating surface formation an important way [30, 31]. As shown in Figure 7, in the Yalong River and Jinsha River, Jinsha river upstream and Lancang River upstream between the small basin area, low runoff density, river erosion, and cut the transformation ability is weak, the plane in the process of crust uplift local residual formed high altitude low fluctuation of negative terrain, these areas excess topography is less, and the three rivers and current area is the typical deep valley area, excess topography is large distribution. Ouimet research on the hillslope and erosion rate of the eastern edge of the Qinghai-Tibet Plateau found that the stability of the hillslope is controlled by the slope [7]. When the slope exceeds the threshold hillslope, the erosion rate nonlinearly increases to 0.6 mm/y. The Qinghai-Tibet plateau continuously uplift, river response uplift rapid cut, increasing slope, hillslope stability gradually reduced, increasing valley hillslope slope, at the same time, the plateau climate, high degree of weathering, deterioration, rock mass collapse, eventually instability catastrophic hillslope erosion events prompted landslide approach to reach stable threshold hillslope. Excess topography can not only characterize historical landslides that have already occurred but can also indicate future places prone to landslides.

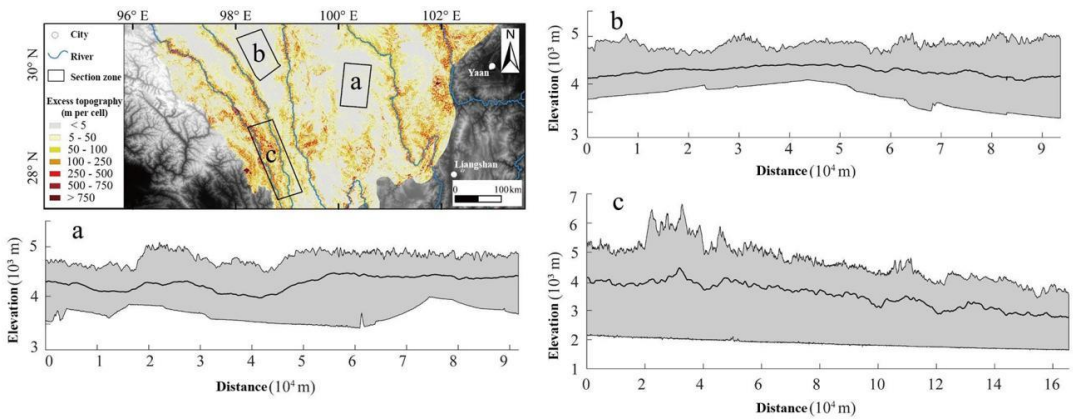

Figure 7. The topographic relief of the Hengduan Mountain area.

6. Conclusion

Erosion events such as landslides are extreme geological hazards. By adjusting the shape of hillslopes, basins, and longitudinal profile of rivers, impacting river sediment flux, hillslope erosion rapidly destroys the equilibrium state of the landscape and profoundly changes the evolution direction and process of landscapes in the Hengduan mountain area. The main conclusions and understandings are as follows: (1) The average slope of the six major Rivers in the Hengduan mountain area is between 25° and 30°, and the area with a slope of 30 ± 5° near the river valley accounts for up to 82%. Taking 30° as an example threshold hillslope, the average thickness of the excess topography in the Hengduan mountain area reaches 32.2m, which can supply at least 67,000 years of erosion materials. (2)About 71% of the 4,430 landslides in the Hengduan mountain area are located where the excess topography is distributed, and more than 48% are located in the excess topography with a height of more than 50m. (3) The amount of excess topography in the six basin of the Hengduan mountain area showed a strong linear correlation with the erosion rate measured by the cosmogenic nuclides burial 10Be, indicating that the erosion in the Hengduan mountain area is largely provided by the hillslope materials and the distribution of the excess topography can be used to reflect the spatial differences in erosion capacity.

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