DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Characteristics, driving factors of spatial and temporal variations and tendency of debris flows in the Yunnan section of the Salween River mainstream

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Abstract. Salween River is an important international river in China. The Yunnan section of the Upper Salween Valley (YUSV) has become one of the key energy sources in China due to its vast and unexploited hydropower resource. However, the area experiences the most serious debris flow disasters in Yunnan Province. Many disasters occurred and caused huge loss of life and property. Based on data collection, remote sensing interpretation, field investigation and visits, the authors have obtained more detailed field primary data than previous studies. On this basis, the authors analyzed the developing characteristics of debris flows, and then analyzed the driving factors of spatial and temporal variations of debris flows in the YUSV. And further predicted the future developing trend of debris flows in the YUSV. The results show that: (1) the debris flow is characterized by spatial differentiation with the boundary of Shangjiang Town, Lushui City, which is strong in the north and weak in the south. (2) The main controlling factors for the spatial variation of the debris flow in the north and south are climatic conditions, tectonic faults, topography and geomorphology, and the main controlling factors for the temporal differentiation are rainfall and earthquakes; (3) The debris flows have shown a trend of becoming more and more active, and have shown a cycle of ~3 years since 2000, which is consistent with the overall trend and the active cycle of local precipitation. Extreme rainfall and sudden strong earthquakes, which are on the rise, can trigger concentrated outbreaks of debris flows and require more attention.

Key words: *spatial-temporal variations; driving factors; Tendency; debris flow; the Yunnan section of the Upper Salween Valley*

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Характеристики, движущие факторы пространственных и временных изменений и тенденции развития селевых потоков на Юньнаньском участке главной долины реки Салуин

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Аннотация. Река Салуин — важная международная река в Китае. Юньнаньский участок долины Верхнего Салуина (YUSV) стал одним из ключевых источников энергии в Китае благодаря своим обширным и неразработанным гидроэнергетическим ресурсам. Однако в этом районе происходят самые серьезные селевые катастрофы в провинции Юньнань. Произошло множество стихийных бедствий, которые привели к огромным человеческим жертвам и имущественным потерям. На основе сбора данных, интерпретации данных дистанционного зондирования, полевых исследований и посещений авторы получили более подробные полевые первичные данные, чем предыдущие исследования. На этой основе авторы проанализировали развивающиеся характеристики селевых потоков, а затем проанализировали движущие факторы пространственных и временных изменений селевых потоков в ЮСВ. И далее спрогнозировали будущую тенденцию развития селевых потоков в ЮСВ. Результаты показывают, что: (1) селевой поток характеризуется пространственной дифференциацией с границей городов Шанцзян и Лушуй, которая сильна на севере и слаба на юге. (2) Основными определяющими факторами пространственной изменчивости селевого потока на севере и юге являются климатические условия, тектонические разломы, топография и геоморфология, а главными определяющими факторами временной дифференциации – осадки и землетрясения; (3) Селевые потоки имеют тенденцию становиться все более активными и имеют цикл длительностью ~3 года с 2000 г., что соответствует общей тенденции и активному циклу местных осадков. Чрезвычайные осадки и внезапные сильные землетрясения, число которых растет, могут спровоцировать концентрированные выбросы селевых потоков и требуют большего внимания.

Ключевые слова: *селевой поток; пространственно-временные вариации; движущие факторы; тенденция; Юньнаньский участок долины Верхнего Салуина*

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Introduction

The Yunnan section of the Upper Salween Valley (YUSV for simplification) is one of the areas with the most developed debris flow disasters in Yunnan Province, and is also one of the areas with the most developed debris flow disasters in southwestern China, where debris flow disasters occur frequently (Fig. 1) [*Tang et al., 2003; Yang et al., 2017; Kong et al., 2018; Huang et al., 2020*]. Historical debris flow events, especially major debris flow events with clear disaster losses, can effectively reflect the development patterns, control factors, disaster losses and disaster prevention capabilities of regional debris flow, and provide important data support for the evaluation and prediction of future debris flow [*Simoni et al., 2011; Kirschbaum et al., 2015; Wang et al., 2022; Wan et al., 2023*]. The authors traced the debris flow events in the YUSV for 72 years, according to available event records, a total of 134 debris flow events occurred in the YUSV from 1950 to 2021. The oldest traceable debris flow event was the debris flow occurred in Latu River in the December 1950, during which 2 people were killed. The year with the highest number of outbreaks was 2020, with 14 major debris flow events occurring in one year. Except the two debris flow events, the Dongyueguyima debris flow occurred on August 18, 2010, which killed 96 people and destroyed the Dongyuegu Iron factory in the gully, causing direct economic losses of 140 million yuan [*Su et al., 2012; Zhou et al.,* *2018; Tang et al., 2018*]. On June 28, 2012, a debris flow broke out in the Bibili River in Gongshan County, blocking the Salween River for more than 8 h and forming a 3 km long barrier lake [*Yang et al., 2021*]. On May 10, 2014, a debris flow occurred in the Latudi River in Fugong County, destroying 14 houses [*Guo et al., 2015*]. On May 25, 2020, a group of debris flows broke out along G219 in Gongshan County [*Tie et al., 2021*], causing casualties and property losses, etc.

Some debris flow events may not have been recorded due to their long history, but the existing records of debris flow events and the sensitivity evaluation results of debris flow in the YUSV are sufficient to show that it is a highly prone and high-risk area for debris flow disasters [*Tang, 2005; Liu et al., 2012; Kong et al., 2019; Xu et al., 2022; Liu et al., 2024*], which requires great attention. On the one hand, due to the landforms of many mountains and canyons in YUSV, the contradiction between man and land is prominent. Inhabited areas such as counties, towns, and villages are mostly directly distributed in the flat dam areas of river valleys on both sides of the main stream, and are often located directly at the mouth of debris flow ravines. On the other hand, most human-related engineering facilities are also distributed in the main stream valley and its branch ditches on both sides, such as national highway G219 and tourism-related facilities, state grid transmission lines, bridges, factories and mines, etc. In recent years, with the economic development, the infrastructure construction of the YUSV has made very significant progress, which has also put forward greater demand for risk prevention of debris flow disasters.

Relying on the the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), the authors have carried out debris flow investigation and research work in the YUSV for three years. Based on data collection, remote sensing interpretation, on-site surveys, and visits, we obtained more detailed first-hand field data than previous studies, especially the updated database of debris flow events in the main stream of the Nu River. On this basis, the patterns and differentiation characteristics of debris flows in the main stream of the upper Salween River at the temporal and spatial levels are analyzed, and then the influence mechanism of different driving factors on the spatial and temporal distribution of debris flows is analyzed, so as to determine the future development trend of debris flows in the YUSV. It should be pointed out that previous research is the basis for the relevant work of this article [*Tang et al., 2003; Xu, 2016; Feng, 2020; Huang et al., 2020*]. Different from previous research, the progress of this article not only further enriches the database of debris flow outbreaks, but also extracts the main influencing factors of debris flow through quantitative methods, especially analyzing the impact of earthquakes and active faults on the spatiotemporal differentiation of debris flows in the YUSV, and extracted the activity cycle of debris flow outbreaks since 2000, and predicted the future evolution trend of debris flows. Relevant results will deepen the research on debris flow in the YUSV, with a view to benefiting the risk prevention of debris flow disasters in towns, settlements and important traffic arteries along the river.

Regional background

The study area locates in the southern section of the Sanjiang tectonic belt. Neotectonic movements are active in the area [*Li et al., 2019*]. Faults are developed, the Nujiang Fault zone runs through the north and south of the study area. There are also Longling-Ruili fault zone, Puladi-Caojian fault which is the secondary fault (Fig. 1*a*). Among them, the Nujiang fault zone is the main active fault, which is right-lateral strike-slip with a thrust component, and the average annual slip rate is 0.42 mm [*Wang et al., 2008*]. The fault zone trends nearly north-south and dips steeply to the west, and the damage zone is several kilometers wide. The rock in the damage zone is strongly fractured, and fault breccia, mylonitization, and schistification zones are developed [*Li, 2008*]. The strata in the area are mostly distributed in a nearly north-south direction, which is consistent with the regional tectonic trend. In terms of stratigraphic lithology, the right bank of the YUSV is dominated by Proterozoic gneiss and Mesozoic basic and ultrabasic rocks, while the left bank is dominated by Paleozoic limestone and Mesozoic sand and mudstone. In terms of topography, the YUSV belongs to the longitudinal valley zone in the southern section of the Hengduan Mountains. The elevation of the study area is high in the north and low in the south. The landform is generally controlled by the north-south tectonics. It is an alpine canyon landform with two mountains sandwiched by a river. The main stream of the upper Salween runs through the entire area from north to south, with east and west sides are Gaoligong Mountain and Biluo Snow Mountain respectively. Valleys grow vertically on both sides of the YUSV, providing favorable topographic and geomorphological conditions for the occurrence of debris flows. In terms of climate, the study area belongs to the southwest monsoon climate type. Bounded by Liuku, the northern section of the study area is dominated by temperate monsoon climate, while the southern section has a subtropical monsoon climate. Due to the large span from north to south, the climate is greatly affected by topography and atmospheric circulation, and the three-dimensional climate characteristics are obvious. Most areas in the region do not have severe cold in winter, and the average annual temperature is 15.1°. Affected by the warm and humid airflow of the Indian Ocean, water and heat appear at the same time. The rainfall in the rainy season accounts for more than 80% of the total annual precipitation [*Zhang et al., 2007*]. The rainfall in the upper Salween valley in the region is more in the north and less in the south. The annual total in the northern section is 1,000–1600 mm, 750–1000 mm in the southern section, and the rainfall increases sharply towards the watersheds on both sides of the main stream. The vegetation coverage rate in the study area is relatively high, which is similar to the climate segmentation. With Liuku as the boundary, the vegetation in the study area also shows obvious north-south differences. Obvious vertical zoning can be seen in the northern section, transitioning from shrubs, broad-leaved forests, coniferous forests to alpine meadows from low to high elevation. The vertical distribution of vegetation in the southern section is not obvious, and the main vegetation types are broad-leaved forests, shrubs, and grassy slopes. Mountains with higher altitudes are covered by coniferous forests, with a smaller proportion. The intermountain basin is mainly cultivated land, mostly paddy fields, and is the main crop area in the YUSV.

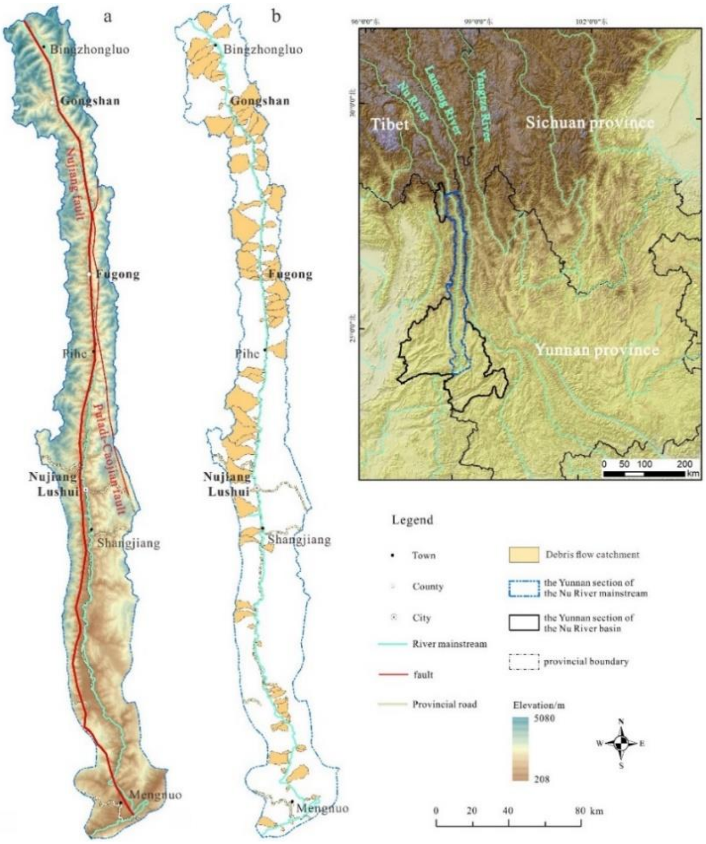

Fig. 1. Location of the study area and distribution of debris flows: a – main faults and terrain; b – distribution of major debris flows

Data and method

Data

Debris flow inventory comes from reference, on-site visits, field surveys and remote sensing interpretation. The remote sensing images involved mainly include Keyhole, Spot, Planet, and Google Earth from 1965 to 1976. DEM comes from NASA's SRTM DEM, which is used for delineating debris flow basin boundaries and extracting topographic parameters of debris flow influencing factors. NDVI (normalized vegetation index) and land use type data are extracted based on Landsat8 satellite images. Average annual rainfall data are based on the national monitoring stations published by the Meteorological Bureau, and are interpolated by the Kriging method using ArcGIS software. The strata and fault data are derived from the 1:50 0000 regional geological map, and are calculated according to the main faults, secondary faults of main fault and other small faults, which are assigned to the impact weight of the faults, and then ArcGIS software is used to generate a fault density distribution map (Fig. 2).

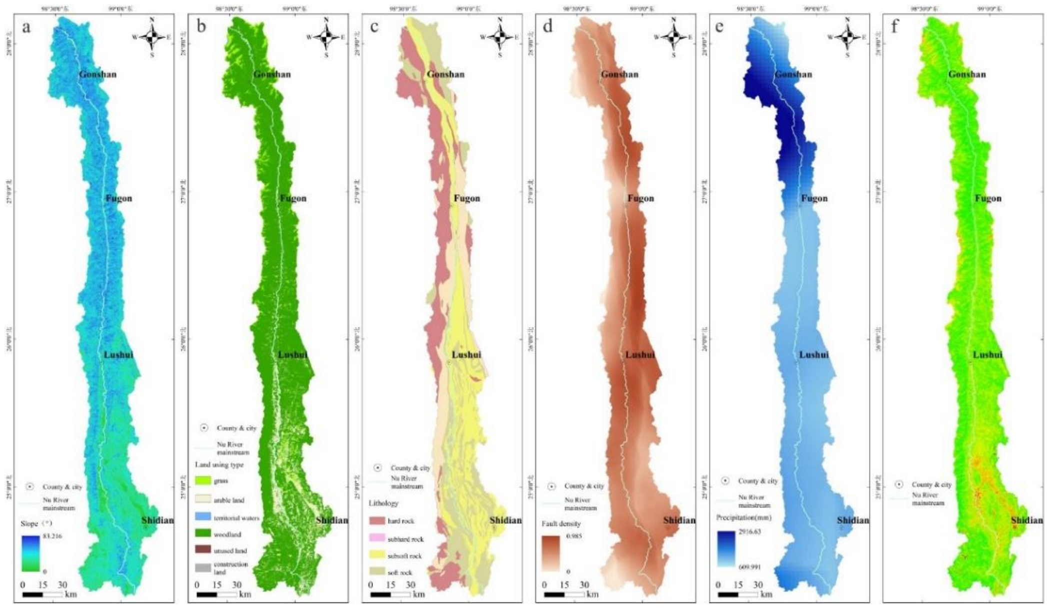

Fig. 2. The influencing factors of debris flow in YUSV: a – slope; b – land using type; c – lithology; d – fault density; e – precipitation; f – NDVI

Method

Field surveys used traditional geological survey methods, and remote sensing interpretation was based on visual interpretation before and after the debris flow event. Based on statistical methods, the temporal differentiation and spatial differentiation characteristics of debris flow are analyzed. The weight analysis of driving factors is completed on the ArcGIS platform using Geodetector.

Geodetector is a set of statistical methods that detect spatial differentiation and reveal the driving force behind it. The basic idea is: assuming that the research area is divided into several sub-regions, if the sum of the variances of the sub-regions is less than the total regional variance, then there is space differentiation [*Wang et al., 2017*]. Assuming that the spatial distribution of a set of independent variables. This paper takes each debris flow basin as the analysis unit and uses a Geodetector model to detect the degree of influence of various influencing factors on the development of debris flows. The Geodetector formula is expressed as follows:

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h \, \sigma_{h^2}.$$

In Formula 1: h is the classification of debris flow influencing factors, $h \in [1, L]$; N_h is the number of analysis units corresponding to a certain classification h, and N is the analysis unit of all debris flows in the study area; σ_h^2 and σ^2 are the influencing factors of a certain variance of h at one level and the variance of the whole region. $q \in [0, 1]$, the larger the q value, the more obvious the stratification heterogeneity is. Since the development of debris flow is the result of the joint action of various factors, the larger the q value, the stronger the explanatory power of the influencing factors on the development of debris flow, on the contrary the weaker it is; when $q = 1$, it indicates that the influencing factor completely controls the development of debris flow; when $q = 0$, it indicates that the development of debris flow is not affected by this factor.

In order to more accurately characterize the development degree of different debris flows and reflect the differences, the frequency of debris flow outbreaks in the study area in the past 50 years was selected as the dependent variable Y. The data came from on-site surveys, interviews and reference analysis. The influencing factor is the independent variable X, in order to highlight the role of the dominant factors in the formation of debris flows in this study area, six influencing factors including slope, NDVI index, precipitation, fault density, lithology, and land use type were finally selected to analyze the main controlling factors of debris flows in the YUSV (Fig. 2).

Inventory of debris flow

Distribution of debris flow

In order to obtain an accurate inventory of debris flows, reference analysis, on-site visits, field surveys, and remote sensing interpretation methods are used to supplement each other for verification. Previous reference has recorded some debris flow outbreaks in the YUSV, especially typical events with direct economic losses, as part of this debris flow inventory; because debris flows have a time dimension, the oldest debris flow that can be accessed on site is 1950, so the record of debris flow events is limited to 1950–2021, mainly interviewing residents near the debris flow ravine, so as to ensure the accuracy of the interview results to the greatest extent; on-site investigation is an important method for debris flow research, which can directly obtain the detailed debris flow information such as volume, scale, stage, source distribution, blockage situation, etc.; remote sensing interpretation can intuitively identify two-dimensional debris flow accumulation fans, source distribution, blockage situation, etc. Based on the multi-stage remote sensing image interpretation, the topographic and geomorphological characteristics before and after the debris flow can also be compared and analyzed to identify the debris flow. On-site surveys and remote sensing interpretation can verify the results of reference and on-site visits. Combining the debris flow activity level, outflow volume, material source distribution, and disaster and danger information obtained through the above methods, the inventory of 103 major debris flows in the YUSV was finally formed, and the basin boundaries of the debris flows were delineated based on DEM data, remote sensing images, and GIS platforms, the spatial distribution data of debris flows in the main stream of the upper Salween River was obtained finally (Fig. 1*b*).

Debris flow events

On the basis of referring to existing reference [*Tang et al., 2003; Xu, 2016; Feng, 2020; Huang et al., 2020*], in order to fully obtain records of major debris flow events in the YUSV in addition to on-site surveys and interviews, Multi-period remote sensing image data including Keyhole, RapidEye, Planet, and Google Earth were used to interpret and analyze debris flow events (Fig. 3), and finally the number of debris flow events was reduced from 86 in the original reference [*Huang et al., 2020*] to 134 times. But even so, because the debris flow events that can be recalled or recorded are often large-scale or major debris flow with serious disasters, the actual debris flow events should be larger than the statistical results of this time.

09/11/2009 21/09/2010

Fig. 3. Comparison of remote sensing interpretation before and after a typical debris flow outbreaking based on RapidEye imagery (Dongyueguyima gully)

Spatial and temporal variations of debris flows along the YUSV

Spatial variations of debris flows

Debris flows in the YUSV generally show spatial differentiation characteristics of strong in the north and weak in the south, with Shangjiang Town, Lushui City as the boundary, and the junction of Yunnan and Tibet in Bingzhongluo, Gongshan county in the north as the debris flow-prone section (Fig. 1). The overall development level of debris flow on the China-Myanmar border from the south of Shangjiang town to Mengpeng town, Zhenkang County, Lincang city is relatively low. Subdivided into local sections, from north to south, from Bingzhongluo town in Gongshan to Fugong County, a relatively equal number of debris flows develop on both sides of the main stream of the upper Salween River. Debris flow from Fugong County to the south to Pihe town is concentrated on the right bank of the main stream of the Salween River, while debris flow from Pihe town to the south to Shangjiang town, Lushui City is mainly distributed on the left bank of the main stream of the Salween River. There is no obvious difference in the number of debris flows on both sides of the Salween main stream south of Shangjiang Town.

In terms of debris flow scale and frequency, there were 11 small-scale debris flows, 86 medium-scale debris flows, and 6 large-scale debris flows in the entire section (Fig. 4*a*); there were 58 low-frequency debris flows, 24 medium-frequency debris flows, and 21 high-frequency debris flows. (Fig. 4*b*). Generally speaking, the debris flows in the Yunnan section of the main stream of the Nu River are mainly medium-sized and medium to low frequency debris flows, among which large-scale and high-frequency debris flows are mainly distributed in the section north of Shangjiang town, Lushui city (Fig. 4).

Temporal variations of debris flows

(1) Multi-year time scale

According to the statistical results of the frequency of major annual debris flow events in the YUSV that can be traced from 1950 to 2021 (Fig. 5), a total of 6 debris flows occurred in the study area in the 1950s, of which 5 occurred in 1952. A total of 4 debris flows occurred in the 1960s. A total of 13 mudslides occurred in the 1970s, including 9 in 1979. A total of 7 debris flows occurred in the 1980s. A total of 7 debris flows occurred in the 1990s. A total of 26 debris flows occurred in the 2000s. A total of 55 debris flows occurred in the 2010s, including 10 in 2010. In 2020, 14 debris flows occurred in the study area, and in 2021, 1 debris flow occurred. From 1950 to 2021, there have been a total of 134 major debris flow events.

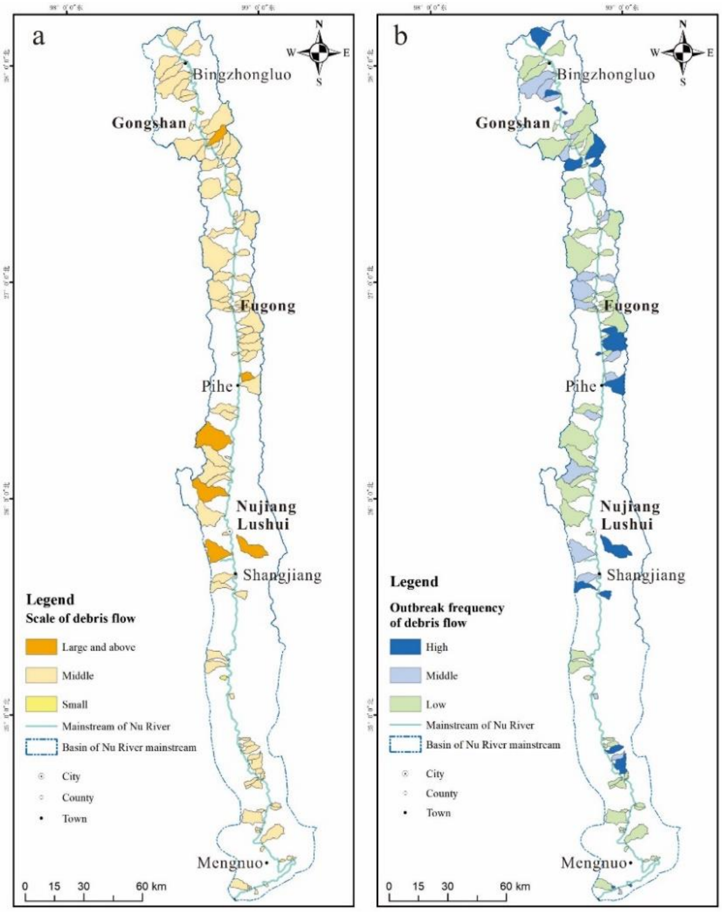

Fig. 4. Spatial distribution feature of debris flows' scale and outbreaking frequency in YUSV: a – scale of debris flow; b – outbreak frequency of debris flow

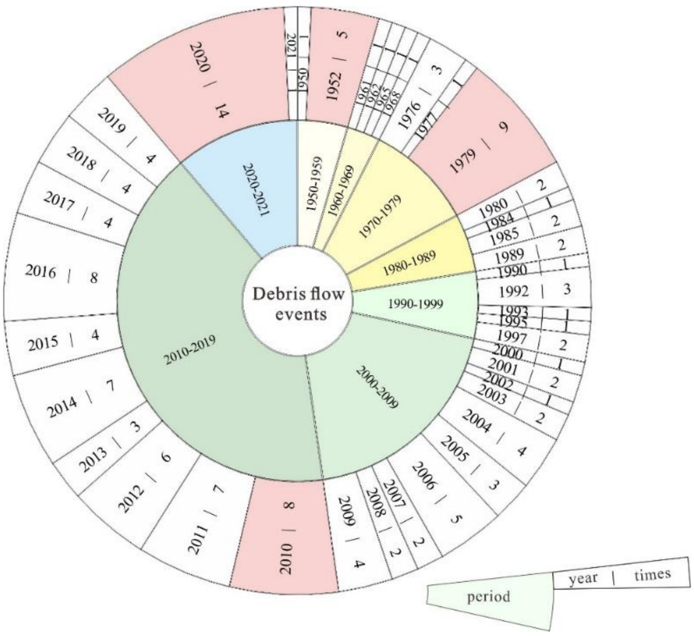

Fig. 5. Statistical results on the annual frequency of debris flows in YUSV from 1950 to 2021

(2) Monthly time scale

Based on the historical debris flow outbreak month information obtained through surveys, interviews, and reference analysis, it can be concluded that debris flows in the study area mainly occur from March to October, and March to May and July to October are two concentrated outbreak periods, with the highest number in August. This result is consistent with previous research [*Huang et al., 2020*] (Fig. 6). It shows significant differentiation characteristics between different months, which is obviously closely related to the climatic conditions of the study area.

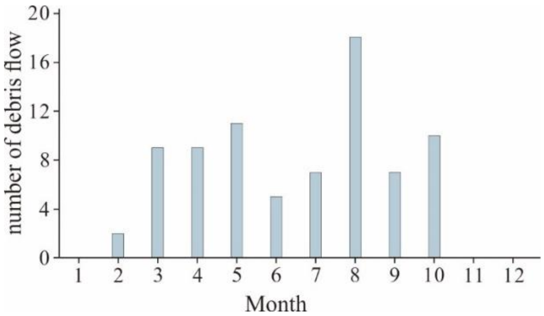

Fig. 6. Statistical results on the monthly frequency of debris flows in YUSV from 1950 to 2021

Driving factors of spatial variations of debris flows

Weight result of driving factors

Using Geodetector, the geodetector is generally classified into six categories: topography, lithology, fault, meteorological conditions, vegetation and land use, based on the aforementioned six characteristic variables related to debris flows (Fig. 2). Analyze the contribution of different driving factors to the spatial distribution of debris flows. The results show that precipitation, fault density and slope are the three factors with the largest q values (Table 1). These three factors also correspond to climate conditions, fault, and topography respectively.

Table 1. Impact factor *q*-values based on the Geodetector

Independent variable	Slop	NDVI	Precipitation	Fault density	Land using type	Lithology
q-value	0.026	0.020	0.058	0.036	0.019	0.010

Analysis of main driving factors

(1) Climate

As mentioned before, the debris flows in the YUSV generally show spatial differentiation characteristics of strong in the north and weak in the south. The occurrence of rainfall-type debris flows is closely related to climatic conditions. In fact, the multi-year average rainfall values in the study area also show very significant north-south differentiation characteristics (Fig. 2*e*). Taking Liuku as the boundary, the precipitation in the north of Liuku is significantly greater than that in the south of Liuku. The trend is increasing from the north of Liuku to Gongshan. Gongshan has the highest average annual rainfall, reaching 1800 mm/a. The trend is generally decreasing from the south of Liuku to Zhenkang, Lincang city, and in Zhenkang county, Lincang City reached the lowest value, about 700 mm/a (Fig. 2*e*). Therefore, as the factor with the largest influence, the climatic conditions in the YUSV largely determine the spatial differentiation characteristics of debris flow distribution.

(2) Fault

There are a large number of faults developed in the Salween Basin, including the Nujiang fault and other secondary faults (Fig. 1). Due to the significant differences in fault scale and activity, the Nujiang fault has a significant impact on the rock strength and topography of the fault zone and surrounding areas. The degree of influence is much greater than that of other faults, and this feature can also be clearly seen in the fault density map formed after fault classification (Fig. 2*d*). The overall trend of the Nujiang fault is nearly north-south, and it has different spatial intersection relationships with the valleys on both sides of the Salween main stream, which also affects the contribution of the fault to the occurrence of debris flows to a certain extent. From the junction of Yunnan and Tibet southward to Pihe, the Nujiang fault basically extends along the main stream valley, and the number, scale, and frequency of debris flows on both sides are relatively even (Fig. 1). Debris flows from Pihe to the south to Shangjiang are mainly distributed on the left bank of the main stream of the Upper Salween River. This spatial differentiation feature may be largely controlled by the Nujiang fault (Fig. 7).

(3) Topography

Due to differences in regional uplift rates and climate, the topographic and geomorphological characteristics of the valleys on both sides of the YUSV are significantly different from north to south. In fact, not only the slope factor (Fig. 2*a*), but also factors such as relative height difference show similar north-south differences, which results in different topographic and geomorphological conditions of debris flows in the north and south of the main stream of the upper Salween River. It is obvious that the average slope of the debris flow gully basin is higher. The larger the relative height difference, the more favorable it is for the occurrence of debris flows. Based on the comparative analysis of statistical data, the topography of the 103 debris flows in the study area is very different. The results show that the average slope and relative height difference of the 73 debris flows in the northern area are significantly larger than those in the southern area (Fig. 8), which is roughly bounded by Shangjiang town. The spatial differentiation of debris flows in the Yunnan section of the YUSV is closely related to topographic and geomorphological conditions.

The open circles represent the relative height difference, and the open triangles represent the average slope.

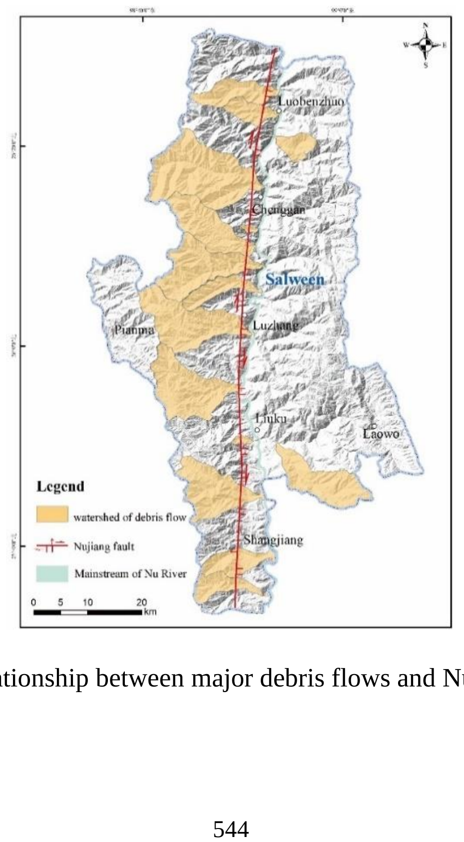

Fig. 7. Spatial distribution relationship between major debris flows and Nujiang fault zone

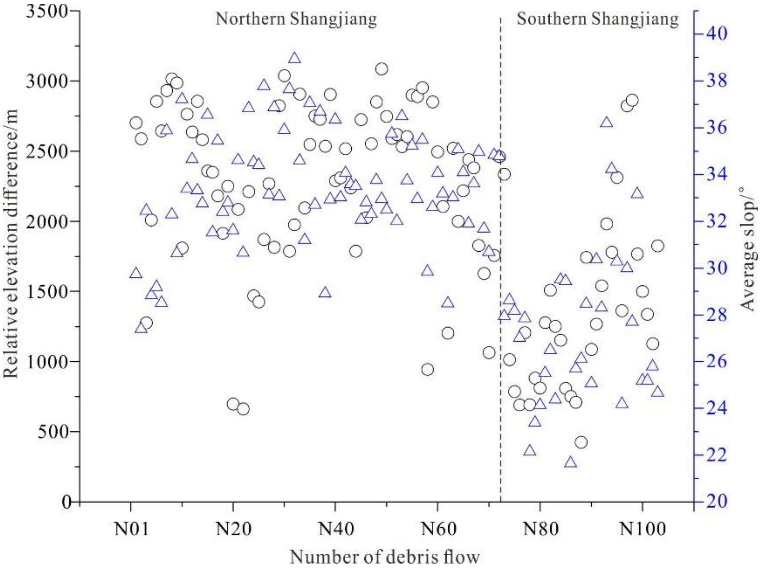

Fig. 8. Comparison of geomorphologic parameters of northern and southern debris flows in YUSV

Driving factors of temporal variations of debris flows

Precipitation

The study area is dominated by rainfall-type debris flows, and the occurrence of debris flows in the area is closely related to changes in climatic conditions. Based on the statistical results of the annual frequency of major debris flow events from 1950 to 2021, it can be concluded that before 1980, except for the frequent debris flow events in 1952 and 1979, interannual debris flow outbreaks in the study area were relatively rare. After 1980, the frequency of debris flow disaster outbreaks in the study area was low in the 1980s and 1990s. After 2000, the outbreak period ushered in, and the frequency of outbreaks was significantly higher than in previous years. From 2001 to 2003, the frequency of debris flow outbreaks was low. In the three years from 2004 to 2006, the frequency of debris flow disasters was high. From 2007 to 2009, the activity of debris flow was low. From 2010 to 2012, the frequency of debris flow disasters in the study area was the most frequent. During the period of frequent disasters, especially in 2010, the frequency of debris flow disasters was the highest, causing heavy casualties and property losses; in 2013, the frequency of debris flow disasters was relatively low, and then increased significantly from 2014 to 2016, and from 2017 to 2019, the frequency of debris flow disasters increased again. There was a relative lull, but an outbreak occurred again in 2020, with 14 debris flow gullies recorded in a single year. It can be concluded that the overall trend of debris flow disasters in the high-mountain canyons in the YUSV is becoming more active, although the average annual rainfall in this region has no significant increasing trend [*Fan et al., 2012; Liu et al., 2017; Yang et al., 2021*], but extreme rainfall events show a clear upward trend (Fig. 9). The occurrence of debris flows since 2000 has a certain periodicity, and the cycle is roughly three years. This cycle is also consistent with the rainfall cycle of the main stream of the upper Salween River obtained based on the Daojieba site [*Liu et al., 2017*].

In terms of the seasonal pattern of debris flow outbreaks, the climate in the study area is a warm temperate plateau monsoon climate. Affected by the warm and humid air flow from the Indian Ocean, water and heat appear at the same time. The rainy season in the study area can last up to 9 months, but rainfall characteristics are inconsistent in different regions. Taking Liuku, Fugong and Gongshan, where debris flows are most common in the study area, as examples, the monthly rainfall in Liuku is unimodal, with the rainy season from May to October, while Fugong and Gongshan are bimodal, with rainfall begins to increase significantly from mid-February every year, reaches the maximum value around late March, and then gradually decreases. There is another peak period from June to September, which provides good meteorological conditions for the development of geological disasters. Monthly rainfall trend is basically consistent with the monthly time scale outbreak frequency trend of debris flow calculated in this article (Figs. 6, 10). Therefore, the time pattern of debris flow occurrence in the study area is consistent with the pattern of concentrated rainfall and has obvious seasonality. It generally occurs in the rainy season from March to October. Debris flow disasters account for more than 80% of all debris flow disasters in the area (Fig. 6).

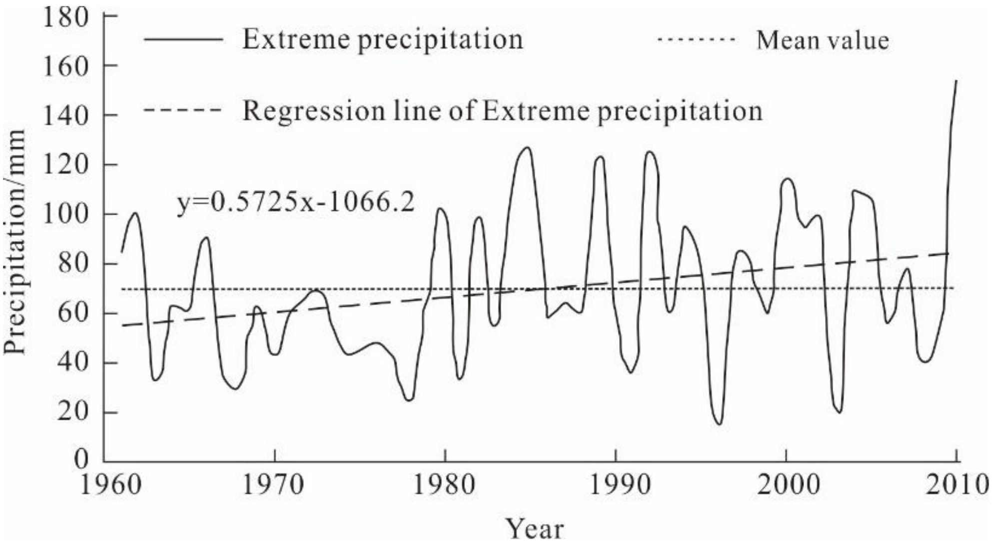

Fig. 9. Trend in rainstorm in the Yunnan section of Nu River Basin [*Liu et al., 2019*]

It should be pointed out that although the occurrence pattern of debris flow in the study area is consistent with the monthly rainfall pattern, occasional extreme rainfall often triggers concentrated outbreaks of debris flow events. For example, extreme rainfall in October 1989 caused a large number of debris flows, destroying 1,397 houses, killing 17 people, and causing direct economic losses of 36 million yuan [*Tang et al., 2003*]. The rainfall for four consecutive days from May 24 to 27, 2020 reached 348.2 mm, which was the largest continuous heavy rainfall weather process in Gongshan since meteorological records were recorded. The concentrated heavy rainfall caused 208 new geological disasters in Gongshan. Among them, 65 were new debris flows [*Tie et al., 2021*].

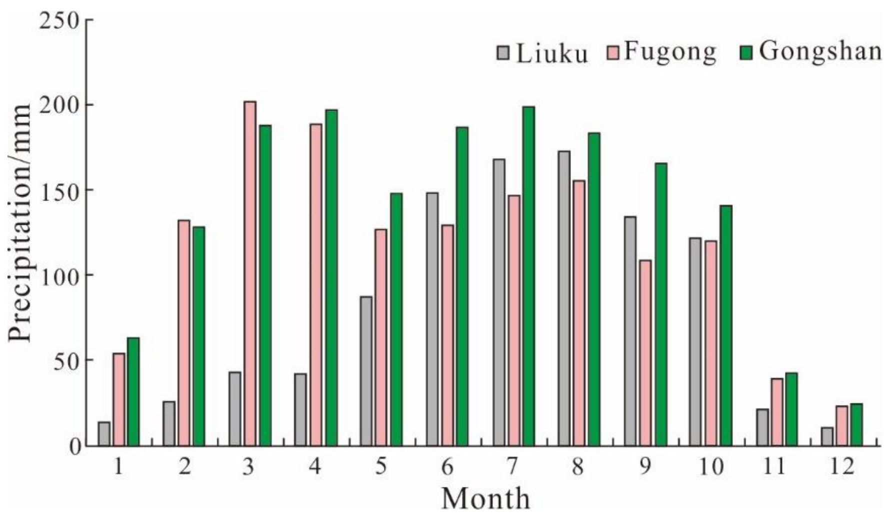

Fig. 10. Comparison of average monthly rainfall in typical towns in YUSV

Earthquake

In areas where rainfall-type debris flows are prone to occur, an outbreak period of debris flows often following some exact earthquakes [*Tang, 2008; Cui et al., 2013; Zhang et al., 2023*]. The YUSV is generally located in the Tengchong-Longling seismic zone in western Yunnan. The two earthquake events that have had the greatest impact on the study area since 1950 are the Motuo earthquake in 1950 and the Tengchong, Luxi earthquakes in Yunnan in 1976. After the earthquake, the study areas all ushered in a period of debris flow outbreaks. Two years after the 1950 Motuo earthquake, in 1952, there was a concentrated outbreak period of debris flows in the study area, and they were all located in areas closer to the epicenter such as Fugong and Gongshan. From May to July 1976, five earthquakes of magnitude 6 or above occurred in Tengchong and Luxi, Yunnan, with the maximum magnitude Ms6.6 [*China Seismological Network, 2023*]. Three years after the earthquake, in 1979, the debris flow in the YUSV ushered in an explosive period, there were 9 major debris flow events recorded in a single year, causing a large number of casualties and property losses (Fig. 5, Table 1). Therefore, earthquakes are a very important indirect triggering factor for debris flows in the study area. After the earthquake, the study area will usher in a concentrated outbreak period of debris flows.

Conclusion

(1) Debris flows in the YUSV generally show spatial differentiation characteristics of strong in the north and weak in the south. The debris flow-prone section is bounded by Shangjiang town, Lushui city, and the section from Shangjiang to Bingzhongluo is a section prone to large-scale and high-frequency debris flows. The main controlling factors of spatial variation are climate conditions, fault structures, and topography.

(2) Since 1950, debris flow disasters in the high-mountain canyons of the YUSV have generally shown an increasingly active trend, but there has been a surge in debris flow outbreaks in some years. March to October in every year is the period of concentrated debris flow outbreaks. Rainfall and earthquakes are the main factors controlling the temporal variation of debris flows.

(3) Debris flow activity has shown an activity cycle of about 3 years since 2000, which is generally consistent with the precipitation activity cycle. Rising extreme rainfall and sudden strong earthquakes will trigger concentrated outbreaks of debris flows and require much attention.

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