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The nocturnal occurrence of debris flows: evidence from western China

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Debris flow is a major hazard in mountainous areas, with a suspected tendency to occur at night. However, there is a lack of direct evidence supporting the nocturnal occurrence of debris flows. This study confirms the nocturnal occurrence using two independent datasets. Dataset 1 includes 295 post-disaster events across nine provinces in western China, showing 74.9% occurred at night. This supports the general impression that debris flows are more likely to occur at night across China. Dataset 2 consists of 286 debris-flow events from the field observation at Jiangjia Ravine (Yunnan, China) from 1965 to 2023. For the Dataset 2, the frequency of occurrence at night reaches 58.4% and is statistically significant at the 95% confidence interval. This long-term observational record provides direct evidence for the nocturnal occurrence of debris flows. This study provides solid evidence for the nocturnal occurrence of debris flows, aiding risk mitigation strategies.

Debris flows are high-density gravity-driven phenomena characterized by a concentrated amalgamation of water, mud, and solid debris in various proportions^{1,2}. Debris flows can rapidly transport vast quantities of sediment and large boulders over considerable distances, possessing immense destructiveness^{3–5}. Their impact extends beyond destroying infrastructure, such as roads, bridges, and residences, to severe ecological disruptions^{5–8}. Debris flows are instigated by a multitude of factors, including heavy rainfall, earthquakes, volcanic eruptions, rapid snowmelt, and anthropogenic activities^{3,9}. The debris-flow events predominantly occur in mountainous regions characterized by substantial rainfall and intricate terrain, such as the Rocky Mountains, USA¹⁰, the Swiss Alps¹¹, the Pyrenees, Spain¹², the Yakedake, Japan¹³, and mountainous areas in southwest China¹⁴.

The impacts of debris flow on human lives and activities have intensified in recent decades due to climate change and increasing population pressure in mountainous regions⁹. Each year, debris-flow events result in significant loss of lives and properties, especially those occurring at night. Such as the debris flow in Chamoli, India, on February 7, 2021¹⁵, the landslide-debris flow in Shuicheng, China, on July 23, 2019¹⁶, and the debris flow in Mirave, Peru, on February 8, 2019¹⁷. Based on post-event statistics of debris-flow events, there is an impression that debris flow is more likely to occur at night, i.e., the nocturnal occurrence of debris flows. The concentration of rainfall^{14,18,19}, soil temperature variations²⁰, and rising groundwater levels^{21,22} at night are all potential factors contributing to the nocturnal occurrence of debris flows. This nocturnal propensity exacerbates the challenges of early warning and rescue operations, as reduced visibility and increased vulnerability at night often delay emergency responses, thereby amplifying the potential for harm.

A large number of studies on debris flow have been carried out, mainly focusing on identifying the primary factors of debris-flow initiation^{19,23–25}, revealing the dynamic mechanism of high-speed movement of debris flow^{26–28}, establishing physical models reflecting the dynamic behavior of debris flow²⁹, and the monitoring and early warning of debris flow^{11,30}. Rainfall is often considered to be the direct triggering factor for debris-flow initiation, and the rainfall threshold is a key indicator for the early warning of debris flow^{31,32}. The rainfall threshold for triggering debris flow is commonly determined by the power-law relationship between rainfall intensity and rainfall duration, i.e., the *I-D* curve^{10,33,34}. In addition, the maximum rainfall intensity over short durations (usually <1 h) is an important indicator for triggering debris flow^{35,36}. The antecedent soil moisture conditions can also affect debris-flow initiation^{37,38}. However, studies specifically focusing on the debris-flow occurrence are limited due to the scarcity of systematic data, especially over long temporal scales in debris flow-prone areas. Accordingly, there is no specific details or direct evidence to confirm the nocturnal occurrence of debris flows, and the over-generalized understanding of the nocturnal occurrence of debris flows based on sporadic post-event statistics. On the one hand, post-event statistics are often derived from disaster reports involving casualties and economic losses, which indicate that nocturnal debris flows tend to result in more severe casualties than those occurring during the day. This disparity may be attributed to the fact that people are at rest at night and cannot be evacuated in time, thus increasing the likelihood of higher casualties. Consequently, such statistical data may be biased in assessing the nocturnal occurrence of debris flows. Furthermore, although numerous

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debris-flow observation stations exist globally, the episodic and localized nature of debris flows make it challenging to establish a long-term debris-flow dataset. In addition, the limited accessibility and lack of systematic data sharing across monitoring stations constrain the spatial scale of debris-flow dataset at the global scale.

Therefore, more continuous and comprehensive data is needed to verify the nocturnal occurrence hypothesis. To conclusively reveal the nocturnal occurrence of debris flows, it is essential to record the debris-flow events with specific occurrence moments. These debris-flow events must come from debris-flow events monitored by long-term field observation and are independent of disaster reports. Such debris-flow events serve as direct evidences to objectively verify the occurrence of debris flows on a long temporal scale.

This study explains the general impression that debris flows are more likely to occur at night across China, and the key is to directly confirm the nocturnal occurrence of debris flows on a long temporal scale. Two datasets of debris-flow events with specific occurrence moments are collected. The debris flow events in Dataset 1 are collected from post-event reports in western China covering a wide spatial scope, which is used to induce the general impression that debris flows are more likely to occur at night. The debris-flow events in Dataset 2 are from long-term field observation at Jiangjia Ravine (Yunnan, China) from 1965 to 2023. The Dataset 2 is independent of casualties, and can provide direct evidence for the nocturnal occurrence of debris flows on a long temporal scale. Descriptive statistics of frequency distribution is employed, and the 95% confidence interval is used for the significance test of the frequency of nocturnal debris-flow events. Specifically, overall statistical analysis and significance testing are performed on the Dataset 1 and Dataset 2. Additionally, detailed statistical analyses are conducted under different types of sampling conditions. For Dataset 1, debris-flow events are analyzed by province, covering nine provinces in western China. For Dataset 2, debris-flow events recorded at Jiangjia Ravine are analyzed using three stratification schemes: by six ten-year intervals (1965–1974, 1975–1984, 1985–1994, 1995–2004, 2005–2014, and 2015–2023), by month (May to September), and by six debris-flow volume scales (peak discharge $<100 \text{ m}^3/\text{s}$, $100\text{--}500 \text{ m}^3/\text{s}$, $500\text{--}1000 \text{ m}^3/\text{s}$, $1000\text{--}2000 \text{ m}^3/\text{s}$, $2000\text{--}3000 \text{ m}^3/\text{s}$, and $>3000 \text{ m}^3/\text{s}$). Although the timing of debris-flow occurrence varies by region, the presented approach for classifying and quantifying diurnal versus nocturnal occurrence offers a versatile framework for hazard assessment in diverse mountain environments. This study eliminates the ambiguity for the nocturnal occurrence of debris flows, which could be helpful to draw attention to debris flow at night and reduce disaster risk.

Results

The debris-flow events with specific occurrence in this study are considered. There are two sets of debris-flow data, both from western China. One set contains 295 debris-flow events and has a wide spatial scale (Dataset 1), and the other set contains 286 debris-flow events and has a long temporal scale over a specific watershed (Dataset 2). Dataset 1, which contains 295 debris-flow events in western China, was collected from non-technical literature by the Xinhua News Agency. These debris-flow events come from post-event statistics involving the loss of lives and properties. Such a dataset can be used to illustrate the general impression that debris flows are more likely to occur at night. Dataset 2, with 286 debris-flow events, comes from the long-term field observation at Jiangjia Ravine (Yunnan, China) from 1965 to 2023. Specific information on the 286 debris-flow events is available at the National Cryosphere Desert Data Center (<https://doi.org/10.12072/ncdc.ddfors.db6803.2025>). These 286 debris-flow events with specific occurrence moments can be used as direct evidence to reveal the nocturnal occurrence of debris flows. Debris-flow events occurring between 07:00 and 19:00 are classified as diurnal events, whereas those occurring between 19:00 and 07:00 are classified as nocturnal events. The data source and analysis are described in detail in the Methods.

General impression of debris-flow nocturnal occurrence: Based on the Dataset 1, with 295 debris-flow events in western China, the general impression of debris-flow nocturnal occurrence is illustrated. Of the 295 debris-flow events, 221 debris-flow events occurred at night (19:00 to 07:00), accounting for 74.9%, and 74 debris-flow events occurred during the day (07:00 to 19:00), accounting for 25.1% (Fig. 1a). In Fig. 1a, in the nine provinces, the proportion of debris-flow events occurring at night is 57.1% to 100.0%. The frequency distribution of the occurrence moment of 295 debris-flow events is analyzed in Fig. 1b. The frequency distribution of the occurrence moment of 295 debris-flow events follows a Gaussian distribution. The occurrence moment mainly concentrates from 00:00 to 05:00 and 19:00 to 23:00 (Fig. 1b).

Additionally, at the provincial level, the frequency distribution of the occurrence moment of these debris-flow events is analyzed in Fig. 2. For Gansu, the frequency of occurrence moment at night reached 100.0% (Fig. 2a). For Guangxi, the frequency of occurrence moment at night reaches 83.3% (Fig. 2b). For Guizhou, the frequency of occurrence moment at night reaches 71.4% (Fig. 2c). For Shaanxi, the frequency of occurrence moment at night reaches 70.0% (Fig. 2d). For Sichuan, the frequency of occurrence moment at night reaches 62.5% (Fig. 2e). For Tibet, the frequency of occurrence moment at night reaches 71.4% (Fig. 2f). For Xinjiang, the frequency of occurrence moment at night reaches 71.4% (Fig. 2g). For

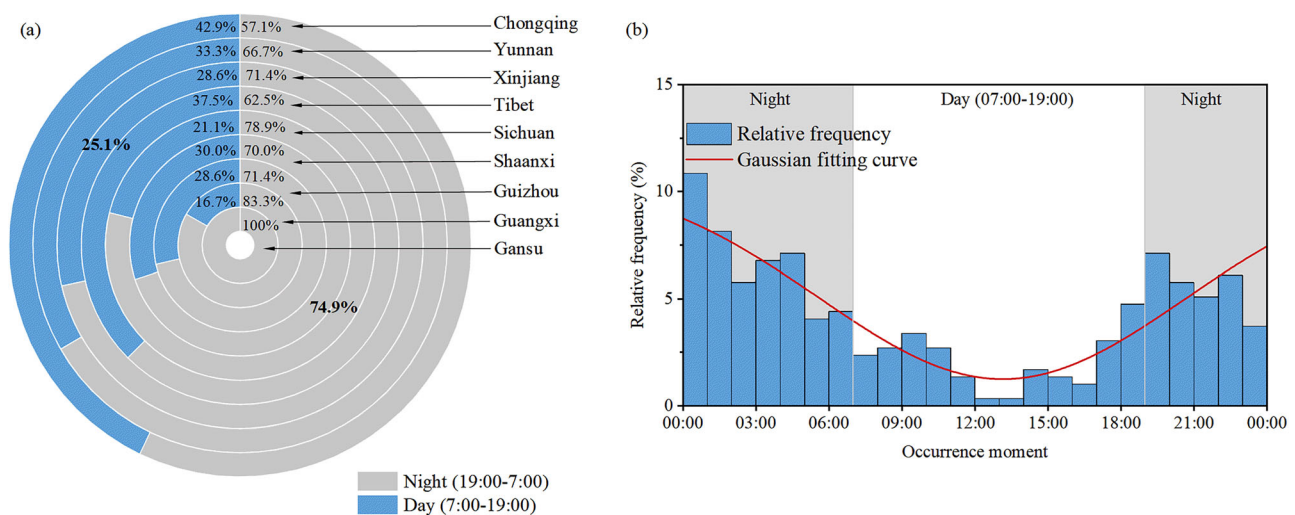


Fig. 1 | Statistics of 295 debris-flow events in nine provinces. **a** The proportion of occurrence moment at night and during the day. **b** Frequency distribution of the occurrence moment within 24 h. Created by the authors using Microsoft Excel.

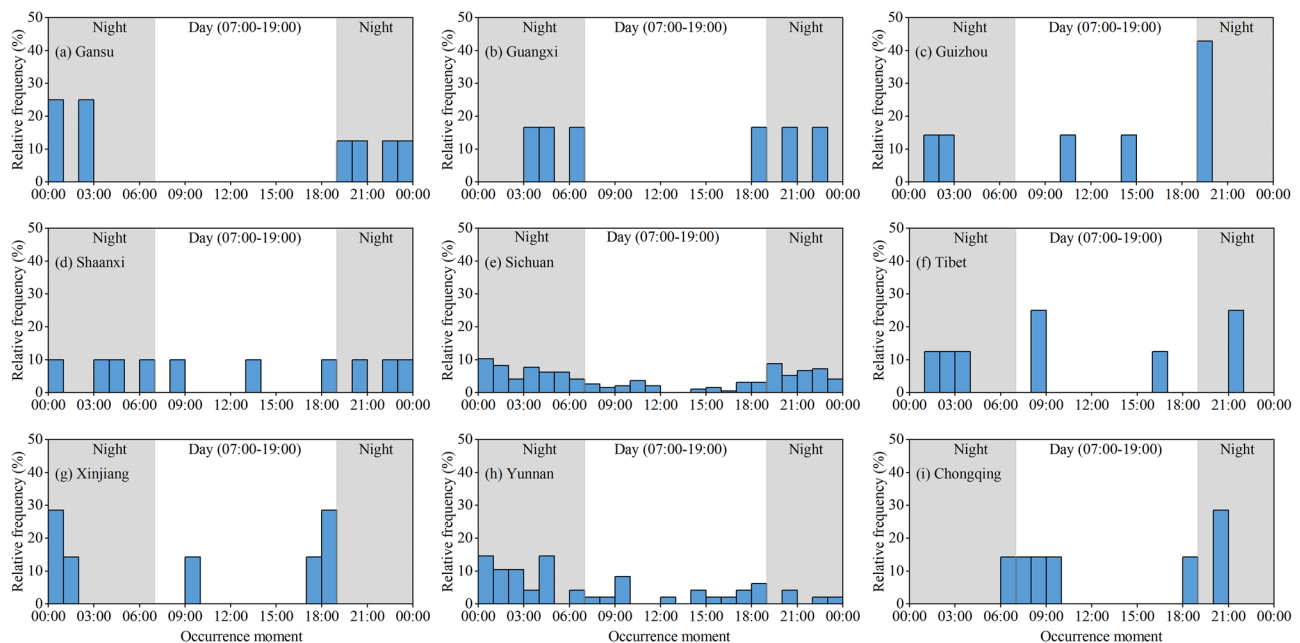


Fig. 2 | Frequency distribution of the occurrence moment of debris-flow events in nine provinces. a Gansu. b Guangxi. c Guizhou. d Shaanxi. e Sichuan. f Tibet. g Xinjiang. h Yunnan. i Chongqing. Created by the authors using Microsoft Excel.

Table 1 | Summary of significance test for all debris-flow events in Dataset 1

Dataset	Total event N	Nocturnal event X	Calculated frequency p	Standard error SE	95% confidence interval	Expected frequency p_0	P -value
Dataset 1	295	221	74.9%	2.5%	[69.7%, 79.8%]	50.0%	3.66×10^{-18}

Yunnan, the frequency of occurrence moment at night reached 66.7% (Fig. 2h). For Chongqing, the frequency of occurrence moment at night reaches 57.1% (Fig. 2i).

On the whole, more than half of debris-flow events occur at night, accounting for 74.9%, and this gives the impression that debris flows are more likely to occur at night. However, the debris-flow events from the nine provinces involve the loss of lives and properties, which may be biased in assessing the nocturnal occurrence of debris flows. Besides, these statistical results indicate that there are regional differences in the occurrence moment of debris-flow events. The number of debris-flow events could affect the distribution frequency of debris-flow occurrence. This is not conducive to explaining the nocturnal occurrence of debris flows, especially for provinces where debris-flow events are rare. Thus, the significance of the debris flow at night needs to be further evaluated.

The significance of the frequency of occurrence moment at night is tested. The overall significance test results for all debris-flow events in Dataset 1 are in Table 1. For the 295 debris-flow events in western China, the 95% confidence interval is [69.7%, 79.8%], and the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval. The calculated P -value of 3.66×10^{-18} is lower than the selected significance level of $\alpha = 0.05$. This indicates that the null hypothesis H_0 can be rejected, and there is a significant difference between the calculated frequency $p = 74.9\%$ and the expected frequency $p_0 = 50.0\%$. The calculated frequency $p = 74.9\%$ is statistically significant. The frequency of debris-flow events at night is significantly higher than 50.0%.

Furthermore, based on provincial sampling, the significance of the nocturnal occurrence of debris flows in nine provinces is tested (Table 2). For the samples of Guangxi, Guizhou, Shaanxi, Tibet, Xinjiang and Chongqing, the significance tests show that the frequency of debris flow occurring at night is statistically insignificant. This is because too few debris-flow events collected in these provinces, and the statistical results may not

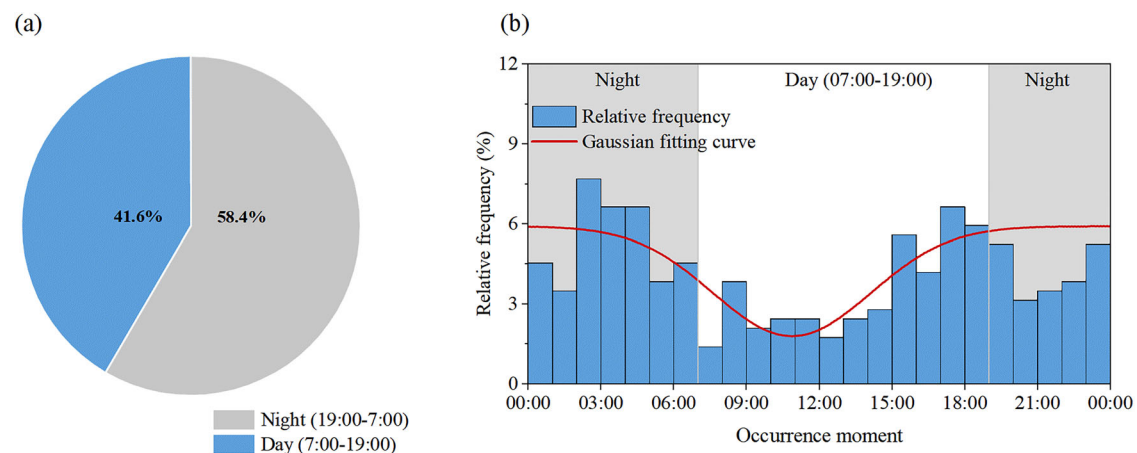
reflect the actual situation. Also, due to the limited number of debris-flow events, the statistical results may be inconsistent with the actual situation in Gansu. The eight collected debris-flow events all occurred at night, and the confidence level of occurring at night reaches 100.0%, which obviously cannot represent the actual situation. For Sichuan, the 95% confidence interval is [72.4%, 84.4%], and the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval. The calculated P -value of 2.10×10^{-16} is lower than the selected significance level of $\alpha = 0.05$. This indicates that there is a significant difference between the calculated frequency $p = 78.9\%$ and the expected frequency $p_0 = 50.0\%$, and the calculated frequency $p = 78.9\%$ is statistically significant. For Yunnan, the 95% confidence interval is [51.6%, 79.6%], and the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval. The calculated P -value of 0.03 is lower than the selected significance level of $\alpha = 0.05$. This indicates that there is a significant difference between the calculated frequency $p = 66.7\%$ and the expected frequency $p_0 = 50.0\%$, and the calculated frequency $p = 66.7\%$ is statistically significant.

Regardless of the statistical discrepancy caused by the insufficient number of debris-flow events in the provincial sampling, the overall significance test indicates that frequency $p = 74.9\%$ at night is statistically significant for the 295 debris-flow events. Although the debris-flow events in the nine provinces are collected from post-event statistics involving the loss of lives and properties, they can at least illustrate the general impression that debris flows are more likely to occur at night.

Direct evidence of debris-flow nocturnal occurrence from Jiangjia Ravine: Based on Dataset 2 with 286 debris-flow events from 1965 to 2023 at Jiangjia Ravine, the occurrence moment of debris-flow events within 24 h is statistically analyzed. Of the 286 debris-flow events, 167 debris-flow events occurred at night, accounting for 58.4%, and 119 debris-flow events occurred during the day, accounting for 41.6% (Fig. 3a). The frequency distribution of the occurrence moment of 286 debris-flow events is analyzed

Table 2 | Summary of significance test for debris-flow events in nine provinces from Dataset 1

Province	Total event N	Nocturnal event X	Calculated frequency p	Standard error SE	95% confidence interval	Expected frequency p_0	P -value
Gansu	8	8	100.0%	0.0%	[68.4%, 100.0%]	50.0%	7.80×10^{-3}
Guangxi	6	5	83.3%	15.0%	[47.8%, 99.1%]		0.21
Guizhou	7	5	71.4%	17.0%	[29.0%, 96.3%]		0.45
Shaanxi	10	7	70.0%	14.0%	[34.8%, 94.3%]		0.34
Sichuan	194	153	78.9%	2.9%	[72.4%, 84.4%]		2.10×10^{-16}
Tibet	8	5	62.5%	17.0%	[24.5%, 91.5%]		0.70
Xinjiang	7	5	71.4%	17.0%	[29.0%, 96.3%]		0.45
Yunnan	48	32	66.7%	6.8%	[51.6%, 79.6%]		0.03
Chongqing	7	4	57.1%	18.7%	[18.4%, 90.1%]		1.00

**Fig. 3 | Statistics of 286 debris-flow events at Jiangjia Ravine from 1965 to 2023. a** The proportion of occurrence moment at night and during the day. **b** Frequency distribution of the occurrence moment within 24 h. Created by the authors using Microsoft Excel.**Table 3 | Summary of significance test for all debris-flow events in Dataset 2**

Dataset	Total event N	Nocturnal event X	Calculated frequency p	Standard error SE	95% confidence interval	Expected frequency p_0	P -value
Dataset 2	286	167	58.4%	2.9%	[52.4%, 64.2%]	50.0%	5.30×10^{-3}

in Fig. 3b. The frequency distribution of the occurrence moment of 286 debris-flow events follows a Gaussian distribution. Within 24 h, the occurrence moment is concentrated at 2:00 to 5:00 and 17:00 to 20:00, with the frequencies being 21.0% and 17.8% respectively.

The significance of the frequency of occurrence moment at night is tested. The results of the overall significance test for all debris-flow events from 1965 to 2023 are in Table 3. For the 286 debris-flow events at Jiangjia Ravine, the 95% confidence interval is [52.4%, 64.2%], and the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval. The calculated P -value of 5.30×10^{-3} is lower than the selected significance level of $\alpha = 0.05$. This indicates that the null hypothesis H_0 can be rejected, and there is a significant difference between the calculated frequency $p = 58.4\%$ and the expected frequency $p_0 = 50.0\%$, and the calculated frequency $p = 58.4\%$ is statistically significant. The frequency of the 286 debris-flow events at night is higher than 50.0%. Therefore, it is credible that debris flows are more likely to occur at night.

Further, the period from 1965 to 2023 is divided into six ten-year intervals, and the occurrence moment of the debris-flow events in the six ten-year intervals are statistically analyzed. During the six ten-year intervals, the proportion of debris-flow events occurring during the day is 0.0% to 48.6%. The proportion of debris-flow events occurring at night is

51.4% to 100.0% (Fig. 4a). Figure 5a illustrates the frequency of the nocturnal debris-flow events in the six ten-year intervals. The frequency of the nocturnal debris-flow events almost exhibits an upward trend in the six ten-year intervals from 1965 to 2023. Additionally, the frequency of debris-flow events at night in each year is calculated, ranging from 16.7% to 100.0%, with an average of 66.8%. Figure 5b illustrates the frequency fluctuation of the nocturnal debris-flow events in each year from 1965 to 2023. Taking 50% as the basement, the frequency of nocturnal debris-flow events in most years exceeds 50%, and the frequency is lower than 50% in a few years. From 1965 to 2023, the frequency of nocturnal debris-flow events exhibits an inter-annual fluctuation (Fig. 5b), this may be affected by uneven rainfall.

The frequency distribution of the occurrence moment of these debris-flow events in the six ten-year intervals is analyzed (Fig. 6a–f). The frequency distribution of occurrence at night and during the day is uneven. Overall, the occurrence moment of debris-flow events mainly concentrates from 00:00 to 4:00 and from 18:00 to 22:00 for the six ten-year intervals. There is an extreme statistical situation from 2015 to 2023, the total frequency of debris-flow occurrence at night is 100.0% (Fig. 6f). From 2015 to 2023, only three debris-flow events were observed, and they all occurred at night. Obviously, this cannot infer the nocturnal occurrence of debris flows. This may be

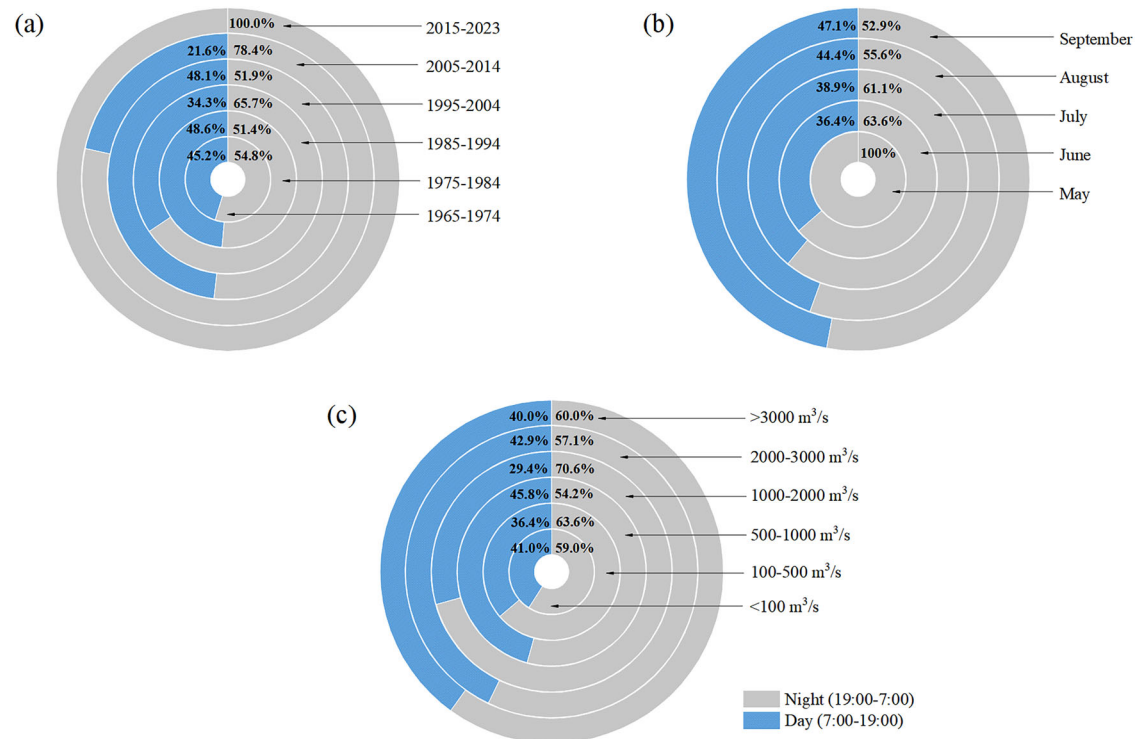


Fig. 4 | Statistics of occurrence moment at night and during the day for 286 debris-flow events at Jiangjia Ravine from 1965 to 2023. a Ten-year interval from 1965 to 2023. **b** May to September from 1965 to 2023. **c** Different peak discharge ranges from 1965 to 2023. Created by the authors using Microsoft Excel.

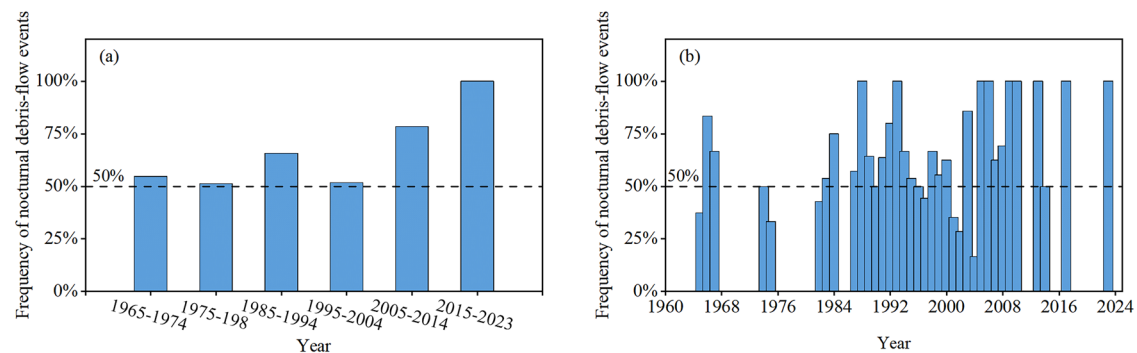


Fig. 5 | Frequency of nocturnal debris-flow events at Jiangjia Ravine from 1965 to 2023. a Frequency of nocturnal debris-flow events in six ten-year intervals. **b** Frequency of nocturnal debris-flow events in each year. Created by the authors using Microsoft Excel.

because the statistical bias is caused by the insufficient number of debris-flow events and does not necessarily reflect the actual situation.

The significance of the frequency of occurrence moment at night is tested. The results of the significance test for debris-flow events in six ten-year intervals are in Table 4. For 1965–1974, 1975–1984, and 1995–2004, the expected frequency $p_0 = 50.0\%$ falls within the 95% confidence intervals. This indicates that there is no significant difference between the calculated frequency p (54.8%, 51.4%, and 51.9%) and the expected frequency $p_0 = 50.0\%$, and these calculated frequencies may be caused by random fluctuations. For 1985–1994 and 2005–2014, the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence intervals. The calculated P -values (0.01 and 7.53×10^{-4}) are lower than the selected significance level of $\alpha = 0.05$. This indicates that there is a significant difference between the calculated frequency p (65.7% and 78.4%) and the expected frequency $p_0 = 50.0\%$, and the calculated frequencies are statistically significant. The frequency of debris-flow events at night is significantly higher than 50.0%. For 2015–2023, there are only three debris-flow events. Although the confidence level reaches 100.0%, it is not statistically representative.

Regarding the intra-annual variation in the occurrence moment of debris-flow events, the occurrence moment of debris-flow events at Jiangjia Ravine within 12 months is investigated. Figure 7 illustrates the frequency distribution of 286 debris-flow events each month from 1965 to 2023. The distribution follows a Gaussian distribution. Statistics indicate that debris-flow events occur from May to September at Jiangjia Ravine (Table 5). In these 286 debris-flow events, two debris-flow events occurred in May, accounting for 0.7%. In June, 55 debris-flow events occurred, accounting for 19.2%. In July, 113 debris-flow events occurred, accounting for 39.5%. In August, 99 debris-flow events occurred, accounting for 34.6%. In September, 17 debris-flow events occurred, accounting for 6.0%. In terms of intra-annual variation, from May to September, the number of debris-flow events is the least in May and the most in July. July and August are the main periods for debris-flow outbreaks at Jiangjia Ravine, indicating a significant temporal concentration of debris-flow events. In addition, the monthly rainfall averages at Jiangjia Ravine from 1965 to 2023 are plotted in Fig. 7. At Jiangjia Ravine, the rainfall is concentrated from May to September. The concentration period of monthly rainfall almost coincides with the concentration period of debris-flow events. This indicates that rainfall may be

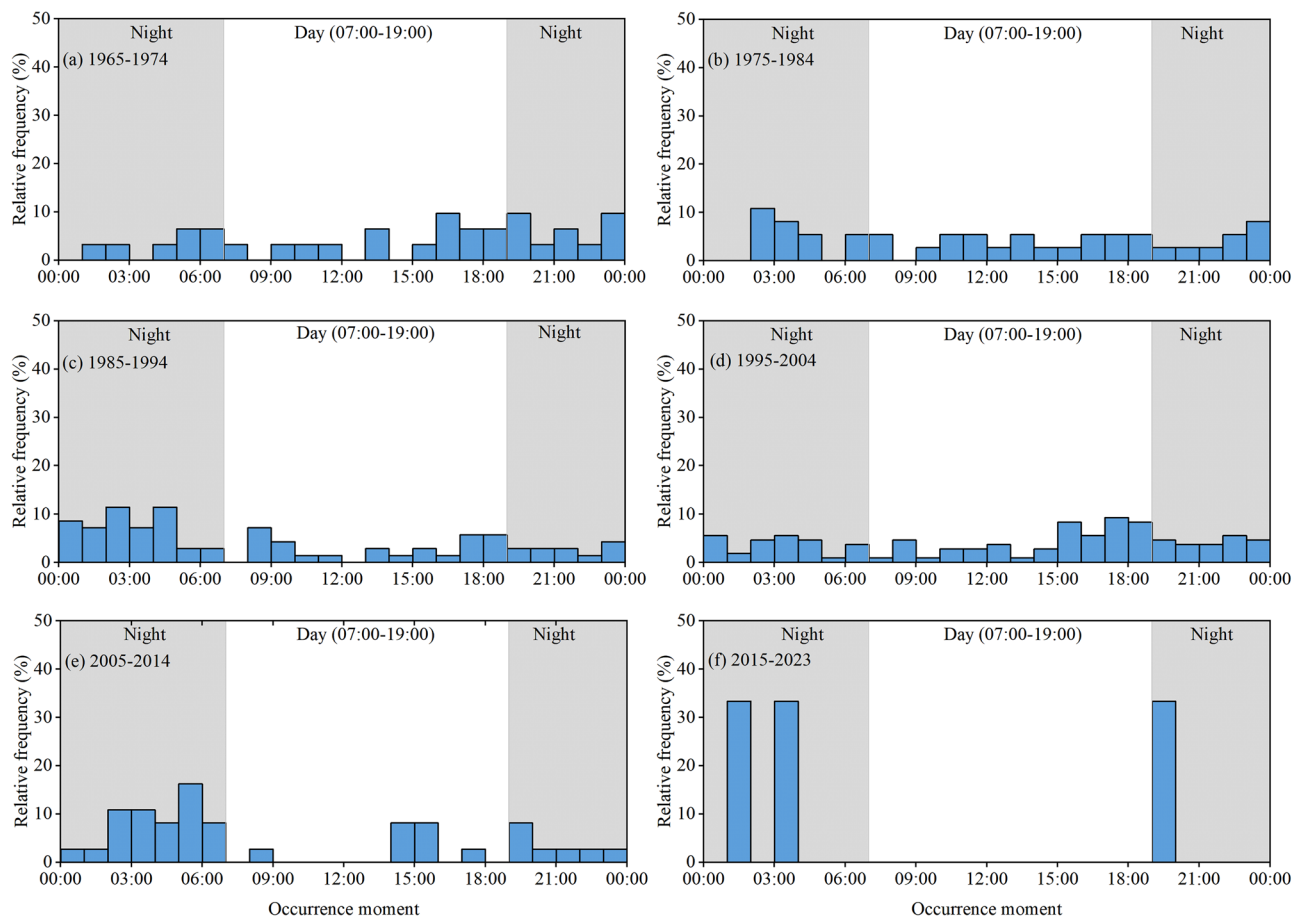


Fig. 6 | Frequency distribution of the occurrence moment of debris-flow events in six ten-year intervals from 1965 to 2023 at Jiangjia Ravine. **a** 1965–1974. **b** 1975–1984. **c** 1985–1994. **d** 1995–2004. **e** 2005–2014. **f** 2015–2023. Created by the authors using Microsoft Excel.

Table 4 | Summary of significance test for debris-flow events in six ten-year intervals

Ten-year interval	Total event <i>N</i>	Nocturnal event <i>X</i>	Calculated frequency <i>p</i>	Standard error <i>SE</i>	95% confidence interval	Expected frequency <i>p</i> ₀	<i>P</i> -value
1965–1974	31	17	54.8%	8.9%	[36.0%, 72.7%]	50.0%	0.72
1975–1984	37	19	51.4%	8.2%	[34.4%, 68.1%]		1.00
1985–1994	70	46	65.7%	5.6%	[53.4%, 76.7%]		0.01
1995–2004	108	56	51.9%	4.8%	[42.0%, 61.6%]		0.77
2005–2014	37	29	78.4%	6.7%	[61.8%, 90.2%]		7.53×10^{-4}
2015–2023	3	3	100.0%	0.0%	[29.2%, 100.0%]		0.25

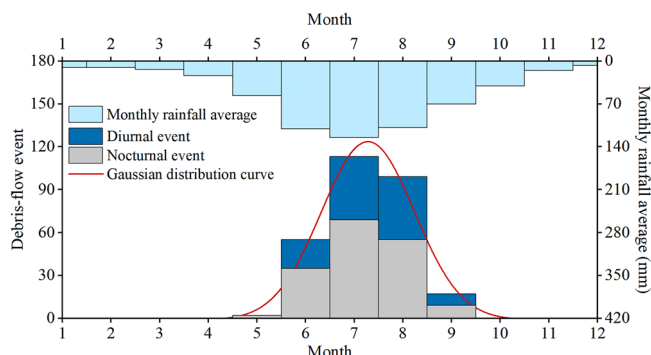


Fig. 7 | Frequency distribution of debris-flow occurrence per month, and monthly average rainfall from 1965 to 2023 at Jiangjia Ravine. Created by the authors using Microsoft Excel.

the key factor affecting intra-annual debris-flow outbreaks. There is a time lag in the response of debris flow to rainfall. The short-duration intensity of rainfall is important for runoff-generated debris flows^{39,40}.

Debris flows at Jiangjia Ravine occur from May to September, and the occurrence moments of debris-flow events from May to September from 1965 to 2023 is statistically analyzed. From May to September, the proportion of debris-flow events occurring during the day is 0.0% to 47.1%, and the proportion of debris-flow events occurring at night is 52.9% to 100.0% (Fig. 4b). The frequency distribution of the occurrence moments of these debris-flow events from May to September is analyzed (Fig. 8a–e). The frequency distribution of occurrence moments at night and during the day is uneven, with the frequency of occurrence moments at night exceeding 50.0%. The frequency of occurrence moments during the day ranges from 0.0% to 47.1%, and the frequency of occurrence moment at night ranges from 52.9% to 100.0% from May to September. Overall, the occurrence moment of debris-flow events mainly concentrates from 00:00 to 3:00 and

from 18:00 to 23:00. There are only two debris-flow events observed in May. Due to the insufficient number of debris-flow events, the statistical results of the occurrence moment in May are not representative (Fig. 8a).

The significance of the frequency of occurrence moment at night is tested. The significance test for debris-flow events in five months is in Table 6. For May, there are only two debris-flow events, and the confidence level reaches 100.0%. Because there are too few debris-flow events, it is not statistically representative. For June and July, the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval, and the calculated P -values (0.04 and 0.02) are lower than the selected significance level of $\alpha = 0.05$. This indicates that there is a significant difference between the calculated frequency p (63.6% and 61.1%) and the expected frequency $p_0 = 50.0\%$, and the calculated frequencies are statistically significant. The frequency of debris-flow events at night is significantly higher than 50.0%. For August and September, the expected frequency $p_0 = 50.0\%$ falls within

the 95% confidence interval. This indicates that there is no significant difference between the calculated frequency p (55.6% and 52.9%) and the expected frequency $p_0 = 50.0\%$, and both calculated frequencies may be caused by random fluctuations.

In these 286 debris-flow events, there are differences in the scale of debris flows. The maximum peak discharge is 5280.0 m³/s, the minimum peak discharge is 2.4 m³/s, and the average peak discharge is 698.7 m/s. The frequency distribution of peak discharge is shown in Fig. 9a. The peak discharge follows an exponential distribution and exhibits a long-tail effect. As the peak discharge increases, the number of debris-flow events decreases (red curve). The cumulative distribution of peak discharge is fitted by the Boltzmann function (black dashed curve). The cumulative frequency of peak discharge less than 500 m/s is 44.8%. The cumulative frequency of peak discharge greater than 500 m/s can reach 55.2%. A debris-flow event consists of multiple surge flows and lasts for a considerable period of time. In these 286 debris-flow events, the maximum duration reaches 16.4 h, the minimum duration is 0.4 h, and the average duration is 4.0 h. The frequency distribution of the duration is shown in Fig. 9b. The duration of debris-flow events follows a lognormal distribution, exhibiting a long-tail effect. When the duration is higher than 3 h, the number of debris-flow events is gradually decreasing (red curve). The cumulative distribution of duration is fitted by the Boltzmann function (black dashed curve). The durations of debris-flow events are concentrated between 2 and 5 h, with a cumulative frequency as high as 63.6%. The cumulative frequency of duration less than 2 h is only 15.4%. Debris-flow events with such high peak discharges and long durations can pose a serious threat to downstream. This gives rise to the necessity of analyzing the occurrence moment of debris-flow events at different scales.

Table 5 | Statistics of 286 debris-flow events from May to September from 1965 to 2023 at Jiangjia Ravine

Month	Debris-flow event	Proportion of total events (%)
May	2	0.7%
June	55	19.2%
July	113	39.5%
August	99	34.6%
September	17	6.0%

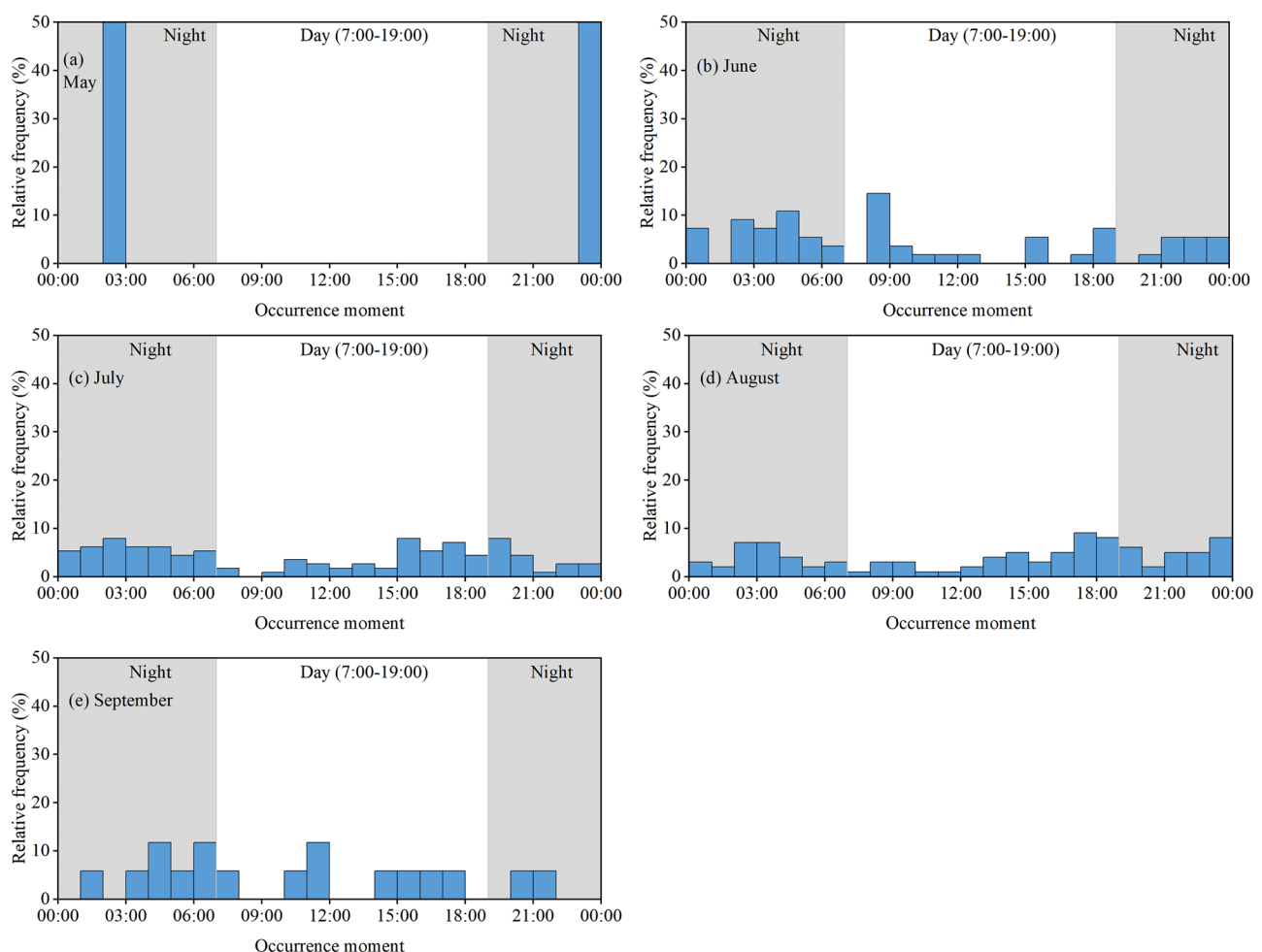
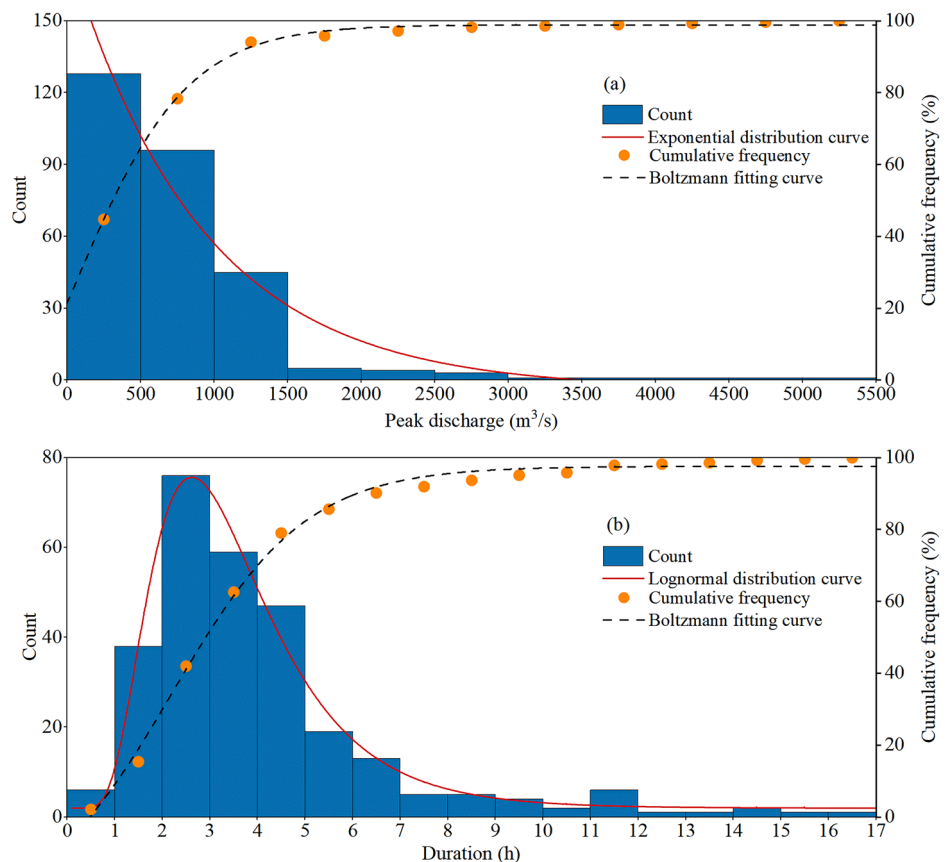


Fig. 8 | Frequency distribution of the occurrence moment of debris-flow events from May to September from 1965 to 2023. a May. b June. c July. d August. e September. Created by the authors using Microsoft Excel.

Table 6 | Summary of significance test for debris-flow events in five months

Month	Total event N	Nocturnal event X	Calculated frequency p	Standard error SE	95% confidence interval	Expected frequency p_0	P -value
May	2	2	100.0%	0.0%	[15.8%, 100.0%]	50.0%	0.50
June	55	35	63.6%	6.4%	[51.1%, 76.2%]		0.04
July	113	69	61.1%	4.5%	[51.4%, 70.1%]		0.02
August	99	55	55.6%	4.9%	[45.2%, 65.5%]		0.31
September	17	9	52.9%	12.0%	[27.8%, 77.0%]		1.00

Fig. 9 | Frequency distribution of 286 debris-flow events at Jiangjia Ravine from 1965 to 2023. a Peak discharge. b Duration. Created by the authors using Microsoft Excel.

The occurrence moment at different debris-flow volume scales is statistically analyzed. The scales of debris-flow events are characterized by peak discharges. The peak discharges of the 286 debris-flow events range from 2.4 to 5280.0 m/s. The peak discharges of the 286 debris-flow events are divided into six ranges (< 100 m/s, 100–500 m/s, 500–1000 m/s, 1000–2000 m/s, 2000–3000 m/s, and > 3000 m/s). The statistics of the occurrence moment within the six peak discharge ranges are shown in Fig. 4c. Within these six peak discharge ranges, the proportion of debris-flow events occurring during the day is 29.4% to 45.8%, and the proportion of debris-flow events occurring at night is 54.2% to 70.6%. The frequency distribution of occurrence moments of these debris-flow events for the six peak discharge ranges is analyzed (Fig. 10a–f). Within each peak discharge range, the frequency distribution of occurrence moments at night and during the day is uneven, and the total frequency of occurrence moments at night is always higher than the total frequency of occurrence moments during the day. In the six peak discharge ranges, the frequency of occurrence moment during the day ranges from 29.4% to 45.8%, and the frequency of occurrence moment at night ranges from 54.2% to 70.6%. With a peak discharge of 2000–3000 m/s, there were seven debris-flow events observed. With peak discharge higher than 3000 m/s, there were five debris-flow events observed. Due to the insufficient number of debris-flow events, the frequency

distribution of the occurrence moment may not be statistically representative for both peak discharge ranges (Fig. 10e, f). Overall, for significantly destructive debris-flow events (peak discharge > 100 m/s), the frequency of occurrence moment at night is higher than 50.0%. Such large-scale debris flows with high frequency at night are quite dangerous in mountainous areas with dense population.

The significance of the frequency of occurrence moment at night is tested. The significance test for debris-flow events in six peak discharge ranges is in Table 7. For peak discharges of < 100 m/s and 500–1000 m/s, the expected frequency $p_0 = 50.0\%$ falls within the 95% confidence intervals. This indicates that there is no significant difference between the calculated frequency p (59.0% and 54.2%) and the expected frequency $p_0 = 50.0\%$, and both calculated frequencies may be caused by random fluctuations. Peak discharges of 2000–3000 m/s and higher than 3000 m/s are not statistically representative, because there are too few debris-flow events. For peak discharges of 100–500 m/s and 1000–2000 m/s, the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence intervals, and the calculated P -values (0.01 and 4.60×10^{-3}) are lower than the selected significance level of $\alpha = 0.05$. This indicates that there is a significant difference between the calculated frequency p (63.6% and 70.6%) and the expected frequency $p_0 = 50.0\%$, and the calculated frequencies are statistically

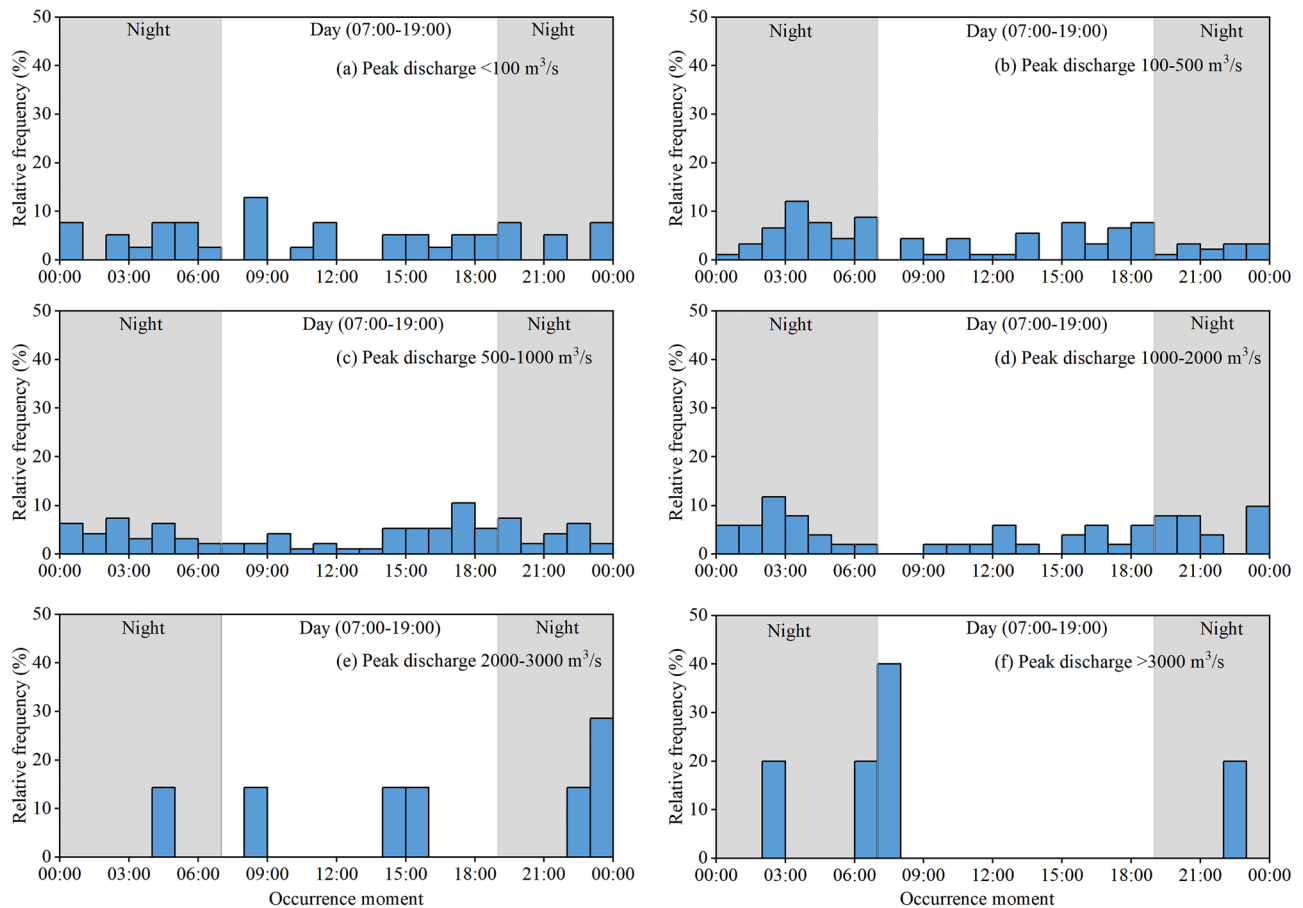


Fig. 10 | Frequency distribution of the occurrence moment of debris-flow events at six peak discharge ranges from 1965 to 2023. a Peak discharge <100 m³/s. **b** Peak discharge 100–500 m³/s. **c** Peak discharge 500–1000 m³/s. **d** Peak discharge

1000–2000 m³/s. **e** Peak discharge 2000–3000 m³/s. **f** Peak discharge >3000 m³/s. Created by the authors using Microsoft Excel.

Table 7 | Summary of significance test for debris-flow events in six peak discharge ranges

Peak discharge (m ³ /s)	Total event <i>N</i>	Nocturnal event <i>X</i>	Calculated frequency <i>p</i>	Standard error <i>SE</i>	95% confidence interval	Expected frequency <i>p</i> ₀	<i>P</i> -value
<100	39	23	59.0%	7.8%	[42.1%, 74.4%]	50.0%	0.34
100–500	88	56	63.6%	5.1%	[52.7%, 73.6%]		0.01
500–1000	96	52	54.2%	5.1%	[43.7%, 64.4%]		0.48
1000–2000	51	36	70.6%	4.6%	[56.2%, 82.5%]		4.60 × 10 ^{−3}
2000–3000	7	4	57.1%	18.7%	[18.4%, 90.1%]		1.00
>3000	5	3	60.0%	21.9%	[14.7%, 94.7%]		1.00

significant. The frequency of debris-flow events at night is significantly higher than 50.0%.

Based on the above statistical analysis, the results of the overall significance test indicate that the frequency of occurrence moment at night is statistically significant for the 286 debris-flow events. This provides direct evidence for the nocturnal occurrence of debris flows. However, for specific significance tests based on different sampling types, the frequency of occurrence moment at night does not consistently exhibit statistical significance. Even though the frequency of occurrence moments at night is higher than 50.0%, the statistical significance is limited in certain cases. For example, during the periods 1965–1974, 1975–1984, and 1995–2004 in the ten-year interval sampling, as well as in August and September in the monthly sampling, and

for debris-flow events with peak discharges of <100 m³/s, 500–1000 m³/s, and 2000–3000 m³/s in the debris-flow volume scale sampling, the significance is notably poor. Conversely, the confidence levels for the frequency of occurrence moment at night are exceptionally high, reaching 100.0% in specific samples, such as 2015–2023 in the ten-year interval sampling and May in the monthly sampling. It is clear that this does not imply that debris flows exclusively occur at night. The aforementioned statistical discrepancies may stem from the limited number of debris-flow events within certain sampling types. Nevertheless, these biases do not undermine the statistical significance of the frequency of occurrence moment at night in the overall significance test because the overall significance test encompasses 286 debris-flow events, which is substantially higher than those within the various sampling types.

Discussion

Overall, for the 295 debris-flow events from post-event statistics (Dataset 1), the frequency of nocturnal debris-flow events is 74.9%, which is statistically significant at the 95% confidence interval. This illustrates the general impression that debris flows are more likely to occur at night. For 286 debris-flow events from long-term field observation (Dataset 2), the frequency of nocturnal debris-flow events is 58.4%, which is statistically significant at the 95% confidence interval. This provides direct evidence for the nocturnal occurrence of debris flows. Nevertheless, in detailed sampling statistics, the frequency of nocturnal debris-flow events may need to be treated dialectically. On the one hand, based on detailed sampling statistics, the frequency of nocturnal debris-flow events is not always statistically significant at the 95% confidence interval, especially for cases where debris-flow events are limited. For example, among the provinces sampled in Dataset 1, Guizhou, Shaanxi, Tibet, Xinjiang, and Chongqing have fewer debris-flow events. In Dataset 2, based on ten-year interval sampling, there are fewer debris-flow events in the 1965–1974. Based on monthly sampling, there are fewer debris-flow events in September. Based on debris-flow volume scale sampling, there are fewer debris-flow events with peak discharge higher than 2000 m³/s. On the other hand, in some sampling statistics, although the significance level in the frequency of nocturnal debris-flow events is as high as 100%, these may not be statistically representative due to the limited debris-flow events. For example, among the provinces sampled in Dataset 1, Gansu has fewer debris-flow events. In Dataset 2, based on ten-year interval sampling, there are fewer debris-flow events in the 2015–2023, and based on monthly sampling, there are fewer debris-flow events in May.

In addition, for Yunnan Province, the frequency of nocturnal debris-flow events is statistically significant for both the 48 events in Dataset 1 or the 295 debris-flow events in Dataset 2. However, in Dataset 1, the 48 debris-flow events in Yunnan are collected in post-event statistics with casualties, which may introduce statistical bias and reduce representativeness. For the Dataset 2, these debris-flow events observed at Jiangjia Ravine in Yunnan from 1965 to 2023, the frequency of nocturnal debris-flow events exhibits an inter-annual fluctuation (Fig. 5b), which may be affected by the uneven rainfall. Although the extensive temporal span is nearly 60 years, the field observation data is confined to Jiangjia Ravine, thus limiting the spatial scope of the field observation data for debris flows. This may lead to insufficient analysis in the nocturnal occurrence of debris flows. To strengthen the understanding of the nocturnal occurrence of debris flows, future efforts should focus on collecting more field observation data from other debris-flow-prone basins.

To capture the broad period during which residents are likely indoors or asleep in this study region for the purposes of hazard management and emergency response, the nighttime was defined as 19:00–07:00. However, the definition of nighttime can affect the frequency of debris flow at night, which in turn affects the monitoring strategies and emergency responses. For debris-flow monitoring purposes, using local sunrise and sunset times may be more appropriate, as camera-installation strategies should indeed consider seasonal daylight variation. In summer, the typical sunrise and sunset times at Jiangjia Ravine are 06:20 and 19:50, respectively. Based on this, the nighttime period would be 19:50–06:20, which is shorter than the nighttime 19:00–07:00. Under the nighttime 19:50–06:20, the frequency of debris-flow events at Jiangjia Ravine occurring at night is 51.0%, which is lower than 58.4%, the frequency of debris-flow events occurring at night under the nighttime 19:00–07:00. This suggests the importance of night-vision cameras in debris flow monitoring may not be as high as expected based on the nighttime 19:00–07:00.

Alternatively, defining nighttime based on residential sleep periods may be more relevant for emergency response. Following the typical residential 8-hour sleep pattern, the nighttime is defined as 22:30–06:30, which is shorter than the nighttime 19:00–07:00. Under the nighttime 22:30–06:30, the frequency of debris-flow events at Jiangjia Ravine occurring at night is

42.3%, which is lower than 58.4% under the nighttime 19:00–07:00. Although the apparent nocturnality of debris flows diminishes under a sleep-based definition, this does not imply that nighttime emergency preparedness can be relaxed. On the contrary, debris flows that occur during sleep hours often result in more severe casualties due to slower human response.

In addition, the frequency of nighttime events using alternative nighttime definitions (e.g., 19:50–06:20 and 22:30–06:30) decreased to 51.0% and 42.3%, respectively, confirming that the classification of debris-flow events as diurnal or nocturnal does have a degree of sensitivity to the time thresholds selected. Nonetheless, the nighttime 19:00–07:00 covers wide periods when residents may be indoors or sleeping during the active debris-flow season in this study region. This definition is particularly important for hazard management and emergency response, as daytime and nighttime operational conditions (e.g., staffing levels, visibility, and evacuation feasibility) are key considerations. Grouping events based on broad daytime and nighttime periods provides a practical framework for risk communication and management.

The high frequency of debris flows at night may be related to low temperatures and concentrated rainfall at night, which is regulated by topographic effects. Due to the large temperature difference between day and night in mountainous areas, the lower temperature makes it easier for water vapor to condense and form rainfall at night, which results in greater intensity of rainfall at night⁴¹. High intensity and long duration of rainfall at night often lead to rapid saturation of the soil, causing soil instability, thereby increasing the possibility of debris flows^{42,43}. Especially in the mountainous areas of western China, the abundant water vapor from the Indian Ocean and Pacific Ocean forms concentrated rainfall areas when it reaches the high mountains of western China. The enlarged temperature difference at night makes it much easier for water vapor to condense into raindrops. Combined with the geological conditions such as large terrain height difference and strong tectonic activity, debris flows frequently occur at night in mountainous areas.

Differences in rainfall during the day and at night may affect the occurrence of debris flows. Rainfall at night reaches more than 70% in the mountainous areas of western China, and there are many torrential rains⁴⁰. At Jiangjia Ravine, debris flow is a typical rainstorm type, and the rainy season (from May to September) is the outbreak period of the debris flow every year. Studies on rainfall-triggered individual debris-flow events have shown that the response (time lag) of debris flow to heavy rainfall is within a few hours^{39,44}, delaying the timing of debris flows to late night or early morning. Figure 11a illustrates the annual debris-flow events and annual rainfall at Jiangjia Ravine from 1965 to 2023. High annual rainfall is often accompanied by more debris-flow events, such as in 1965, 1991 and 1997 (Fig. 11a). The annual debris-flow events show a positive correlation with annual rainfall (P -value < 0.005, Fig. 11a). The higher the annual rainfall, the more debris-flow events. Therefore, as a key trigger of hazards, rainfall could be a crucial aspect of monitoring. High-precision rainfall data can help with early warning of debris flows and reduce the risks caused by debris flows at night.

Studies have shown that half-day (daytime and nighttime) rainfall patterns show significant regional differences^{45,46}, which may affect the occurrence of debris flows. Although rainfall has been identified as the main trigger for debris flows in this study region, the lack of half-day rainfall statistics limits the quantitative assessment of the changes in the occurrence of debris flows under the difference in rainfall during the day and at night in local regions. It should be emphasized that the temporal patterns and triggering mechanisms of debris flows identified in this study are specific to the geomorphological and climatic context of Western China, and may not be directly transferable to other mountain environments. In regions such as Northwest America and the European Alps, local convective cells driven by solar heating tend to produce concentrated rainfall, which can rapidly trigger debris flows during the daytime^{31,47}. Such local convective regimes can skew the debris-flow occurrence distribution toward daytime, a pattern that differs from the broader, rainfall-driven processes dominant in Western

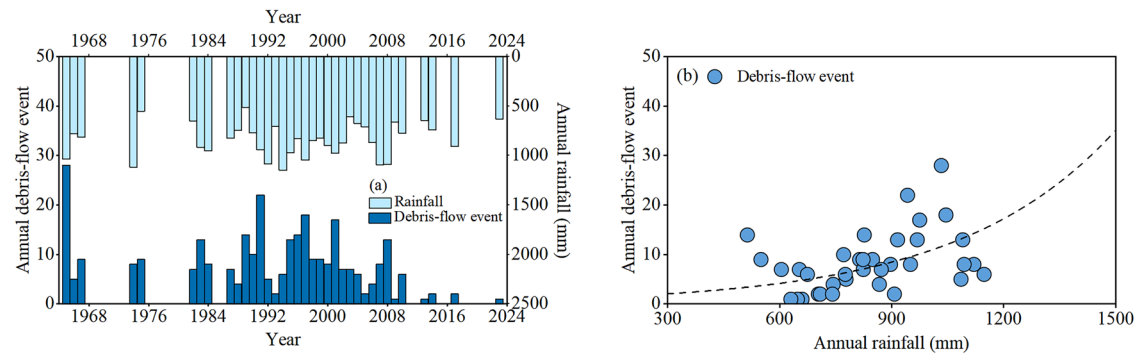


Fig. 11 | Debris-flow events and rainfall at Jiangjia Ravine. a Annual debris-flow events and annual rainfall at Jiangjia Ravine from 1965 to 2023. **b** The relationship between annual debris-flow events and annual rainfall. Created by the authors using Microsoft Excel.

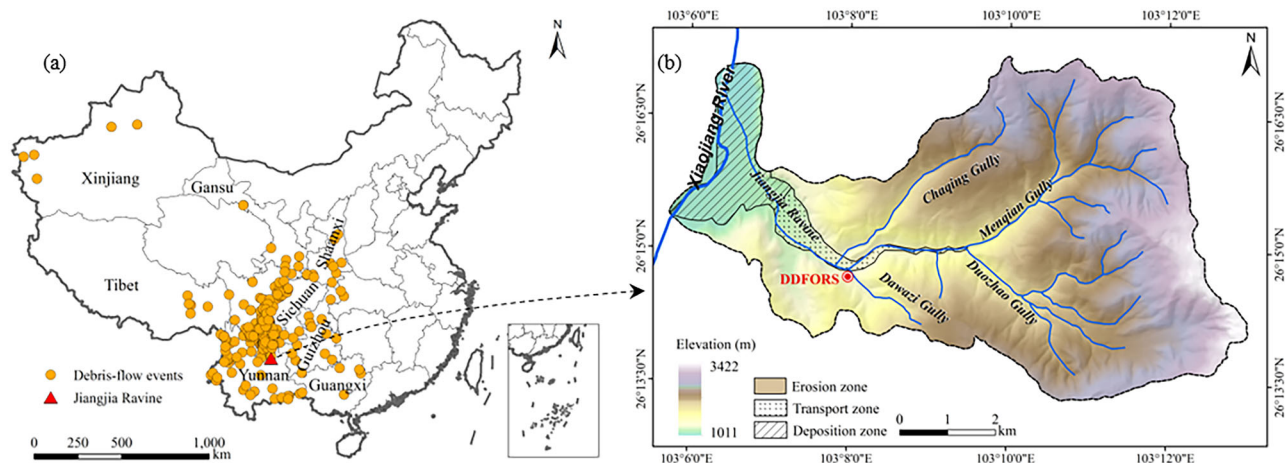


Fig. 12 | Debris flows in western China. a The distribution of 295 debris-flow events in China from Dataset 1. **b** Jiangjia Ravine (Yunnan Province, China). Created by the authors using ArcGIS.

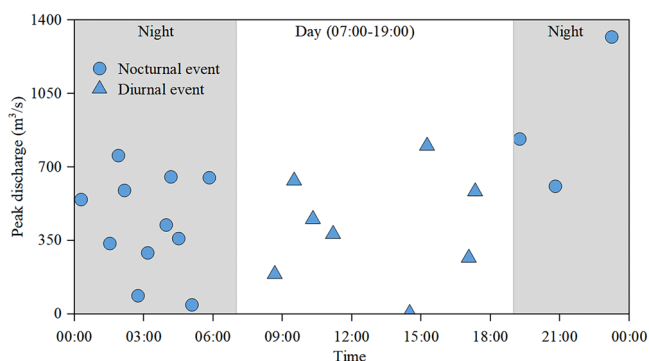


Fig. 13 | The definition of diurnal and nocturnal debris-flow event. Data points represent the 22 debris-flow events in 1991. Created by the authors using Microsoft Excel.

China. Therefore, we urge caution when extrapolating our debris-flow occurrence statistics to regions characterized by these highly localized convective storm regimes.

Methods

Data source

Dataset 1 containing 295 debris-flow events in western China: There are 295 debris-flow events with specific occurrence moment collected from western China (Fig. 12a). The specific information on the 295 debris-flow events is

recorded in the supplementary material (Supplementary Data 1). These debris-flow events are primarily distributed across the marginal mountainous regions of several plateaus in western China, including the Qinghai-Tibet Plateau, the Loess Plateau, and the Yunnan-Kweichow Plateau. Geologically, these areas are characterized by significant altitude variations, the presence of active tectonic faults, and a high concentration of seismic zones. The presence of deep, extensive fault zones increases seismic activity, which can lead to surface rock fracturing and generate large quantities of loose debris, making these regions prone to debris flows⁴⁸. For example, Xiaojiang Fault Zone⁴⁹, Anning River Fault Zone⁵⁰, Longmenshan Fault Zone⁵¹, and Bailongjiang Fault Zone⁵² are typical debris-flow activity zones. In addition, the marginal mountainous areas of the Qinghai-Tibet Plateau are characterized by abundant ice and snow meltwater⁵³, and concentrated rainfall is mainly found in the marginal mountainous regions of the Loess Plateau and the Yunnan-Kweichow Plateau⁵⁴. These mountainous regions, with their significant altitude variations, vast debris reserves, and plentiful water sources, create favorable conditions for debris-flow occurrences. Debris flows in these areas are predominantly triggered by snowmelt and intense rainfall events.

These debris-flow events with a wide spatial scope beyond a specific watershed distributed in nine provinces in western China, the detailed locations of these debris-flow events are shown in Fig. 12a. At the provincial level, these debris-flow events are distributed in Gansu, Guangxi, Guizhou, Shaanxi, Sichuan, Tibet, Xinjiang, Yunnan, and Chongqing in China. These debris-flow events are listed in Table 8, and the highest quantity of debris-flow events occurred in Sichuan Province (194 events), followed by Yunnan Province (48 events). The debris-flow events in Yunnan Province in Dataset

Table 8 | 295 debris-flow events from nine provinces in China

Province	Gansu	Guangxi	Guizhou	Shaanxi	Sichuan	Tibet	Xinjiang	Yunnan	Chongqing
Number of debris-flow events	8	6	7	10	194	8	7	48	7

1 do not include the debris-flow events recorded from the debris-flow field observation at Jiangjia Ravine (Yunnan, China) in Dataset 2. Due to the difficulty in collecting debris-flow events with specific occurrence moment across China, this debris-flow data comes from post-event statistics. These events with loss of lives and properties may not be used directly to prove the nocturnal occurrence of debris flows, but can be used as a supplement to the spatial scope limitations of field observation data at a specific watershed, so as to confirm the general impression that debris flows are more likely to occur at night on a wide spatial scope.

Dataset 2 containing 286 debris-flow events at Jiangjia Ravine: Jiangjia Ravine is located in Yunnan Province, China (Fig. 12b). It is a tributary of the Xiaojiang River in the upper reaches of the Yangtze River. In Fig. 12b, the specific geographical location is between N26°13' ~ N26°17' and E103°06' ~ E103°13'. The main channel is 13.9 km long with a drainage area of 48.6 km² and extends from the drainage divide at 3269 m altitude west to the junction with the Xiaojiang River at 1042 m^{14,27}. Slopes steeper than 25° comprise 55% of the watershed area with a typical local relief of 500 m. The main channel can be divided into three sections with different morphologic characteristics: the erosion zone, debris-flow transport zone, and the deposition zone (Fig. 12b). The erosion zone with an average slope of 17° and a length of 10 km, there are frequent collapses and landslides, resulting in an abundant supply of loose materials. Debris-flow transport zone has an average slope of 5° and a length of 1.3 km. The deposition zone has an average slope of 3.7° and a length of 2.6 km. In this zone, large amounts of sediment carried by debris flows are retained.

The bedrocks of Jiangjia Ravine are Proterozoic shallow metamorphic slate and phyllite, which are poor in strength and easy to weather. The slate and phyllite are widely distributed upstream of the channel and are strongly affected by tectonic activities. As a result, there are huge amounts of loose materials stored in the valley, up to $1.2 \times 10^9 \text{ m}^3$ ^{14,33}. The Jiangjia Ravine experiences substantial rainfall, with annual rainfall ranging from 700 to 1200 mm, showing significant seasonality⁵⁵. About 85% of total annual rainfall is concentrated from May to September, and about 40% of the rainfall occurs between altitudes of 2500 m and 3000 m^{14,33,44}. Abundant loose materials and concentrated rainfall have created favorable conditions for the occurrence of debris flows. Debris flows usually occur during summer rainstorms when runoff concentrates in channels and mobilizes sediment¹⁴. The debris flows at Jiangjia Ravine are typically rainstorm-type. These debris flows exhibit a variety of patterns and comprehensive processes, rendering Jiangjia Ravine an exemplary site for the observation and study of natural debris flows.

In 1961, the Dongchuan Debris Flow Observation and Research Station (DDFORS) was established at Jiangjia Ravine. Long-term observation and research on the initiation, transportation, and accumulation of debris flows have been carried out¹⁴. The monitoring network Jiangjia Ravine primarily encompasses meteorological monitoring in the upstream material source area and debris-flow dynamics observation in the downstream transport area. Based on field observation, each debris-flow event has comprised more than a dozen surge flows and several continuous flows. A surge flow is identified when there is a noticeable interval between two debris flows. In contrast, a continuous flow is characterized by either a large continuous discharge or an extended duration of a single debris flow^{56,57}.

Importantly, the occurrence moment, ending moment, and duration of debris-flow events are meticulously recorded. At Jiangjia Ravine, a typical debris-flow event exhibits an intermittent nature, lasting from three to four hours and sometimes extending to tens of hours^{57,58}. Notably, from 1965 to 2023, these debris-flow events at Jiangjia Ravine have not caused any casualties. Therefore, field observation of debris-flow events at Jiangjia Ravine is a good choice for verifying the occurrence of debris flows. From

1965 to 2023, 286 debris-flow events with specific occurrence moments at Jiangjia Ravine were used to reveal the nocturnal occurrence of debris flows. Taking the debris-flow events in 2001 as an example, the information of debris-flow events at Jiangjia Ravine are listed in Table 9.

Data analysis

Definition of diurnal and nocturnal debris-flow event: Before statistical analysis, the diurnal and nocturnal debris-flow events are defined. Descriptive statistics are used to analyze the occurrence moments of debris-flow events. On the one hand, overall statistical analysis and significance testing are performed on the Dataset 1 and Dataset 2. On the other hand, detailed analyses under different sampling conditions are presented. For Dataset 1, based on provincial sampling, statistical analysis is conducted on the debris-flow events in nine provinces. For Dataset 2, based on ten-year interval sampling, monthly sampling, and debris-flow volume scale sampling, statistical analyses are performed on the debris-flow events at Jiangjia Ravine. Whether it is an overall statistical analysis or the detailed sampling analysis, the 95% confidence interval is used for the significance test of the frequency of nocturnal debris-flow events.

The occurrence moment of debris-flow events is utilized to investigate the nocturnal occurrence of debris flows. Based on the 24 h daily routine of the residents in western China, the period from 07:00 to 19:00 is defined as daytime, while the period from 19:00 to 07:00 of the next day is defined as nighttime. The 19:00–07:00 window is chosen to represent the extended period during which local residents are generally indoors or asleep, thereby providing a practical basis for emergency resource allocation and public warning strategies. This fixed time window is not intended as a proxy for darkness and simplifies comparisons across seasons and years. Debris-flow events occurring between 07:00 and 19:00 are classified as diurnal events, whereas those occurring between 19:00 and 07:00 are classified as nocturnal events. Taking the debris-flow events in 1991 at Jiangjia Ravine as an example, the definitions of diurnal and nocturnal debris-flow events are explained. As illustrated in Fig. 13, the data points located within the white region represent debris-flow events occurring during the day (circles), while the data points located within the gray region represent debris-flow events occurring at night (triangles).

Statistical analysis of the data: It is assumed that the probability of debris-flow events occurring within 24 h is uniform. Descriptive statistics for the both datasets are calculated to evaluate the nocturnal occurrence of debris flows. On the one hand, the general impression that debris flows are more likely to occur at night is explained on a spatial scale. Based on the Dataset 1, which has 295 debris-flow events across China, the frequency distribution of occurrence moment at night and during the day within 24 h are analyzed. On the other hand, the nocturnal occurrence of debris flows is directly proven on a temporal scale. Firstly, based on Dataset 2 with 286 debris-flow events from the long-term field observation at Jiangjia Ravine (Yunnan, China), the frequency distributions of occurrence moment at night and during the day within 24 h are analyzed from both inter-annual and intra-annual perspectives. In terms of the inter-annual variation of debris-flow occurrence moment, the frequency distribution of occurrence moment within 24 h is analyzed at temporal scales of a 59-year interval (1965–2023) and six ten-year intervals (1965–1974, 1975–1984, 1985–1994, 1995–2004, 2005–2014, and 2015–2023). For the intra-annual variation of debris-flow occurrence moment, the frequency distribution of occurrence moment within 24 h is analyzed in twelve months (from January to December). Furthermore, the frequency distribution of occurrence moment within 24 h is analyzed at six peak discharge ranges ($< 100 \text{ m}^3/\text{s}$, $100\text{--}500 \text{ m}^3/\text{s}$, $500\text{--}1000 \text{ m}^3/\text{s}$, $1000\text{--}2000 \text{ m}^3/\text{s}$, $2000\text{--}3000 \text{ m}^3/\text{s}$, and $> 3000 \text{ m}^3/\text{s}$).

Table 9 | Information on the debris-flow events in 1991 at Jiangjia Ravine

No.	Event	Occurrence moment (h:min:s)	Ending moment (h:min:s)	Duration (h)	Peak discharge (m ³ /s)	Number of surge and continuous flows
1	1991-06-15	03:58:00	10:41:00	6.72	423.8	78
2	1991-06-21	08:40:00	14:30:00	5.83	189.1	45
3	1991-06-24	05:05:00	06:55:00	1.83	43.5	30
4	1991-07-06	14:30:00	18:00:00	3.50	3.5	9
5	1991-07-08	01:54:00	12:42:00	10.80	754	201
6	1991-07-09	04:10:00	19:30:00	15.33	653.6	427
7	1991-07-11	02:45:00	05:30:00	2.75	87.3	33
8	1991-07-12	05:50:00	11:30:00	5.67	648.7	220
9	1991-07-15	17:20:00	20:30:00	3.17	583.2	114
10	1991-07-16	23:14:00	03:00:00	3.77	1319.4	107
11	1991-07-17	19:15:00	22:30:00	3.25	833.5	79
12	1991-07-18	17:03:00	19:40:00	2.62	267.1	51
13	1991-08-13	01:32:00	06:00:00	4.47	335.5	82
14	1991-08-13	10:19:00	14:30:00	4.18	452.2	112
15	1991-08-13	15:15:00	19:20:00	4.08	801.4	156
16	1991-08-14	00:17:00	05:10:00	4.88	545.5	181
17	1991-08-15	09:30:00	19:30:00	10.00	634.4	224
18	1991-08-16	02:10:00	06:30:00	4.33	589	97
19	1991-08-28	03:10:00	05:27:00	2.28	290.9	67
20	1991-09-03	04:30:00	07:30:00	3.00	359.6	61
21	1991-09-06	20:48:00	23:00:00	2.20	609	34
22	1991-09-09	11:11:00	13:40:00	2.48	380.5	49

The significance of the frequency of occurrence moment at night is further tested. There are two types of significance tests for Dataset 1 and Dataset 2, corresponding to the above statistical frequency analyses. One is the overall significance test; all debris-flow events in Dataset 1 and Dataset 2 are treated as two samples respectively, to test the significance of the nocturnal occurrence of debris flows on the whole. The other is the specific significance test based on different sampling types. For Dataset 1, based on provincial sampling, the significance of the nocturnal occurrence of debris flows in nine provinces is tested. For Dataset 2, based on ten-year interval sampling, monthly sampling, and debris-flow volume scale sampling, the significance of the nocturnal occurrence of debris flows is tested.

The 95% confidence interval is used to analyze the significance of the debris-flow nocturnal occurrence. More specifically, the 95% confidence interval evaluates the credibility of a null hypothesis (H_0) and an alternate hypothesis (H_1). The null hypothesis H_0 : the probability of debris flow occurring during the day and at night is equal, i.e., the expected frequency p_0 of debris-flow occurrence moment at night is 50.0%. The alternate hypothesis H_1 : the frequency of debris-flow occurrence moment at night is calculated based on the statistics of debris-flow events. This frequency is termed the calculated frequency p . The calculated frequency p is equal to the number of debris-flow events X occurring at night divided by the total number of debris-flow events N in a sample, i.e., $p = X/N$ (%). The calculated frequency p includes the frequency of debris-flow events occurring at night in Dataset 1 and Dataset 2, as well as the frequency of debris-flow events occurring at night under different sampling types, such as province sampling, ten-year interval sampling, monthly sampling, and debris-flow volume scale sampling.

The upper and lower limits of the 95% confidence intervals are calculated using an exact data-driven method, the Clopper-Pearson method. The Clopper-Pearson method inverts the cumulative binomial distribution to yield exact lower and upper bounds at the designated confidence level, which does not rely on normal approximations. To test whether the frequency p of debris-flow events occurring at night is different from the

expected frequency p_0 , a two-sided exact binomial test is used with a significance level of $\alpha = 0.05$. If the expected frequency $p_0 = 50.0\%$ falls within the 95% confidence interval, and at the same time, the calculated P -value is higher than the selected significance level of $\alpha = 0.05$, the null hypothesis H_0 cannot be rejected, indicating that the calculated frequency p is not significantly different from the expected frequency p_0 , and the calculated frequency p is statistically insignificant. On the contrary, if the expected frequency $p_0 = 50.0\%$ falls outside the 95% confidence interval, and at the same time, the calculated P -value is lower than the selected significance level of $\alpha = 0.05$, the null hypothesis H_0 can be rejected, indicating that there is a significant difference between the calculated frequency p and the expected frequency p_0 , and the calculated frequency p is statistically significant. These analyses are performed in Python using the *statsmodels* and *scipy* libraries to ensure reproducibility and robustness of statistical inference.

Data availability

The Dataset 1 with 295 debris-flow events in western China is presented as supplementary material (Supplementary Data 1). The Dataset 2 with 286 debris-flow events at Jiangjia Ravine comes from the Dongchuan Debris Flow Observation and Research Station (DDFORS), Chinese Academy of Sciences. It can be available at National Cryosphere Desert Data Center via <https://doi.org/10.12072/ncdc.ddfors.db6803.2025>.

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Author contributions

D.S. designed the study and obtained the funding. Q.C. conducted the study, collected and analyzed the data and wrote the first draft of the paper. L. W., H. J., H. T., and Y. W. contributed to the interpretation of results. All authors were involved in the writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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