Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 3510944, 11 pages
https://doi.org/10.1155/2022/3510944

Research Article

Effects of Glacier and Geomorphology on the Mechanism Difference of Glacier-Related Debris Flow on the South and North Banks of Parlung Zangbo River, Southeastern Tibetan Plateau

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Received 16 July 2022; Revised 1 September 2022; Accepted 9 September 2022; Published 30 September 2022

Academic Editor: Fadzli Mohamed Nazri

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Alpine glaciers are vulnerable to climate changes, and their recession due to warming has already induced a large number of geohazards closely related to the glacial motion, such as debris flow. Strong coupling of the geology, geomorphology, climate, and glacial action controls the type, size, development, and frequency of debris flow along the Parlung Zangbo River, Southeastern (SE) Tibetan Plateau. Field investigation in recent years indicates that the north bank is prone to much more frequenter debris flows than the south bank. The sharp contrast between the two river banks is due to the different formation conditions of debris flows, especially glaciers and geomorphology. The present paper examines the differences in the glacier and geomorphology conditions for glacier-related debris flows to occur, through a combination of field investigation, interviews with local residents, and geomorphological parameter, and glacier distribution analysis in the ArcGIS platform. The result indicates that, compared to the south bank of the Parlung River, the north bank has more favorable conditions in the glacier and geomorphology south, which is more conducive to the occurrence of debris flow. In conclusion, three kinds of mechanisms due to different formation conditions, especially glacier and geomorphology, are analyzed. The glacier-related debris flows on the south and north banks occur through different mechanisms due to different formation conditions. The debris flows on the north bank primarily occur in modes I and III, while the south bank is dominated by modes II and III debris flows. Based on the result, effective measures are proposed for mitigating damage to roads and railways within this area.

1. Introduction

Glacier-related debris flow is a natural geological phenomenon closely related to the glacial motion, usually triggered by glacial meltwater or intense rainfall. Large glacier-related debris flows could also be caused by icefalls, avalanches, or failure of dams across gullies [1–6]. Glacier-related debris flows are sudden, violent, and difficult to forecast, and tend to travel long distances at high speed. This kind of geohazard, which typically occurs in alpine regions, can cause severe damage to villages, towns, factories, mines, roads, and railways along gullies or at their mouths and thereby terrible loss of life and property [1, 7–10].

Running across the Tibetan Plateau, the Parlung Zangbo River (hereafter "Parlung River") is among the world's rivers with the highest elevation drops and greatest erosive forces. Due to this as well as the frequent earthquakes and abundant precipitation there, this river is located in one of the regions subjected to the largest-scale, most violent, and most hazardous debris flows in the world [11–13]. The Parlung River is home to the largest temperate glaciers in China [14, 15].

The river basin has undergone active endogenic and exogenic geological processes and has an extremely complex tectonic setting and strong neotectonic activity [16]. This, combined with the alpine-gorge terrain, high precipitation, and modern glacial activity, contributes to landslides, debris flow, and other major geohazards, among which glacial debris flow is the most destructive [13, 16, 17].

Many large debris flows have taken place along the Parlung River throughout history. The Sichuan–Tibet Highway, a section of China National Highway 318 (G318) on the north bank of the Parlung River, has been blocked by many debris flows since it was built in the 1950s. For this reason, researchers have conducted a systematic regional survey. Glacier-related debris flows in this area were intensively studied during the comprehensive scientific investigation of the Tibetan Plateau in the 1970s [16, 18]. Recent studies have looked at deglaciation resulting from global warming in detail. Existing research has provided plenty of valuable data and insights into the characteristics of geohazards along the Sichuan–Tibet Highway and the conditions and mechanisms for their occurrence and also proposed preventive measures [17, 19, 20].

Large glacier-related debris flows are considered a serious obstacle to regional economic development and a threat to major construction projects, such as the Sichuan–Tibet Railway (from Chengdu to Lhasa, Figure 1), which is planned to span the Parlung River region. In order to ensure normal traffic along the Sichuan–Tibet Highway and the successful implementation of China's Western Development Program, there is currently an urgent need to address glacier-related debris flows and ensuing environmental problems in the study area in glacier cover and geomorphological settings.

The present paper examines the differences in the Glacier and geomorphology conditions for glacier-related debris flows to occur between the south and north banks of the Parlung River, analyzes the primary mechanisms due to different formation conditions, through a combination of field investigation, and interviews with local residents, geomorphology parameters analysis and glacier distribution analysis in ArcGIS platform. Based on the result, effective measures are proposed for mitigating damages to roads and railways in the study area.

Geohazard history and size scale are from field investigation, interviews with local residents, and previous research. Geomorphology parameters like catchment morphological index, HI which are extracted from ArcGIS software, and high-resolution DEM which is from unmanned aerial vehicle mapping, describe the feature of gullies on both banks. Glacier data from the Second Glacier Inventory Dataset of China [15] are used to analyze the glacier distribution in every gully in GIS.

2. Materials and Methods

2.1. Geological Conditions, Climate, and Precipitation. The Parlung River is located in the northeastern part of the Eastern Himalayan Syntaxis, at the eastern end of the Gangdise–Nyainqentangla fault-fold belt. The area is mainly composed of gneiss of the Nyainqentanglha group and the Gangdise granite and metamorphic Paleozoic rocks (Figure 1; [21, 23–25]). Neotectonics is characterized by fast regional crustal uplift with multiple fault activities. The Tongmai–Zhongkxing fault (TZF) and the Tongmai–Jingzhou (TJF) are two important active faults with an average dextral strike-slip rate of 4 mm/a (Figure 1; [26, 27]). The syntaxis region is highly seismic with 100 earthquakes of M 5.0 or greater from 1950 to 2018, including the Ms 8.6 Assam–Tibet earthquake in 1950 [28].

Located in the southeastern Tibetan Plateau, the Parlung River is more sensitive to climate change than any other parts of Western China. It has a subtropical alpine climate affected by the Indian monsoon. The Indian monsoon carries moisture to the Tibetan Plateau, primarily along the valley of the Yarlung Zangbo River (hereafter "Yarlung River") west of the Parlung River and the Dandong and Chayu Rivers to the south, which all flow southward (Figure 1). This leads to high precipitation on the plateau. For example, the average annual precipitation is as high as 1100–1400 mm/a in Tongmai and Bomi (Figure 1). Due to the humid air and high elevations, the Parlung River has the largest expanses of temperate glaciers in China. A total of 1320 modern temperate glaciers are distributed in the Kangri Karpo Mountains on the river's south bank, covering an area of 2655 km^2 [29–31]. The high precipitation and temperature attributed to the warm moist air from the Bay of Bengal, plus global warming, keep the surface temperatures of the temperate glaciers in this area at around 0°C. Therefore, the glaciers undergo faster ablation than an accumulation of ice and move actively. As a result, deglaciation occurs extensively and provides a lot of materials and water needed for the formation of debris flows.

2.2. Geomorphology. The Parlung River extends to the northeast of the Eastern Himalayan Syntaxis. It is characterized by alpine gorges and deep-incised river valleys with extremely high erosion rates of >5 mm/a [24], and its elevation tends to decrease from east to west. The river flows through wide valleys in its upper reaches and through narrow gorges in its lower reaches. It is bounded to the north by the southeastern branch of the Nyainqentangla Mountains and to the south by the Kangri Karpo Mountains (Figure 2). The extensive development of glaciers and intense tectonic processes has created a wide variety of geomorphic features, such as glacial landforms, alpine gorges, and fluvial depositional landforms (Figure 2).

In the paper, Ke and HI parameters are used to describe the geomorphology features of each gully on the two banks of the Palung River, Ke is the plane shape index of the catchment, and HI is the hypsometric integral. The parameters are calculated in ArcGIS software based on the digital elevation model (DEM), whose resolution is 8 m. The larger the Ke value is, the closer the plane shape of the catchment is to the circle, and the better the catchment capacity is [32]. Ke can be obtained by using equation (1) [33].

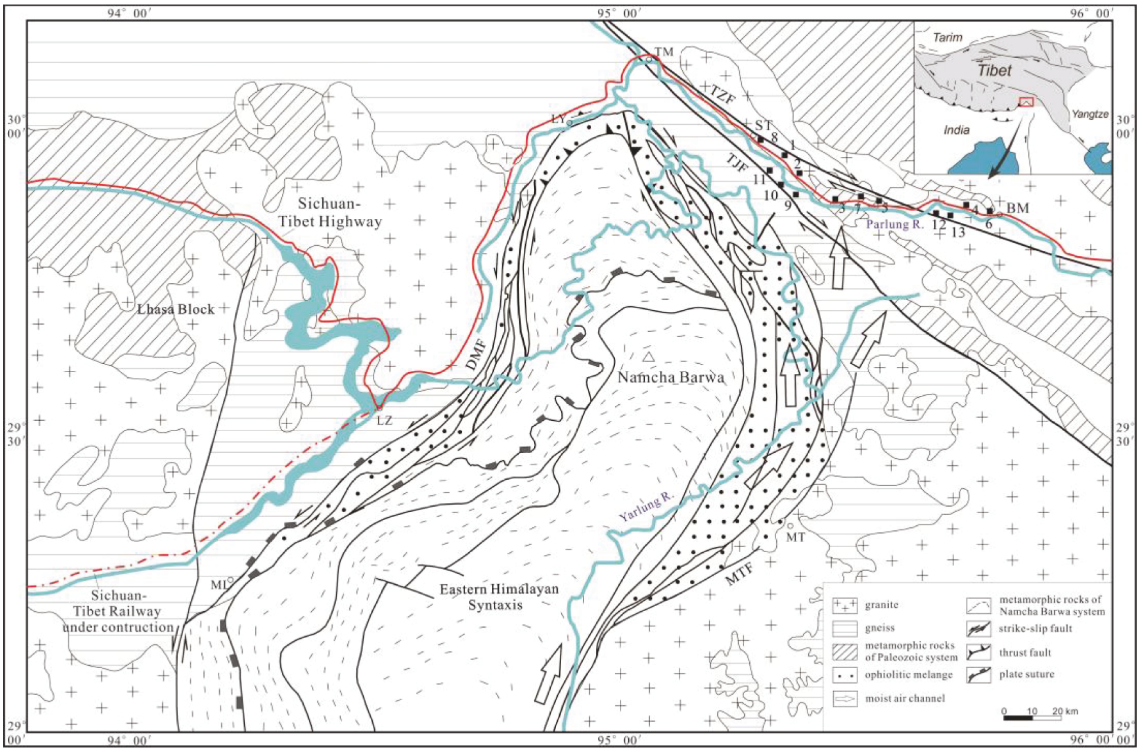

Figure 1: Geological sketch map of the eastern Himalayan syntaxis (after [21, 22]); (Abbrs.: towns, BM-Bomi, ST-Suotong, TM-Tongmai, LY-Layue, LZ-Linzhi, ML-Milin, MT-Motuo. Faults, TZF-Tongmai–Zhongkang fault; TJF-Tongmai–Jinzhula fault; DMF-Dongjiu–Milin fault; MTF-Motuo fault. Numbers: 1-bitong debris flow; 2-dada rock avalanche-debris flow; 3-jiaolong debris flow; 4-cangguo debris flow; 5-zhataduo debris flow; 6-naha debris flow; 7-guxiang rock avalanche-debris flow; 8-suotong debris flow; 9-qiuzhu debris flow; 10-chidan debris flow; 11-songrao debris flow; 12-michong debris flow; 13-danka debris flow).

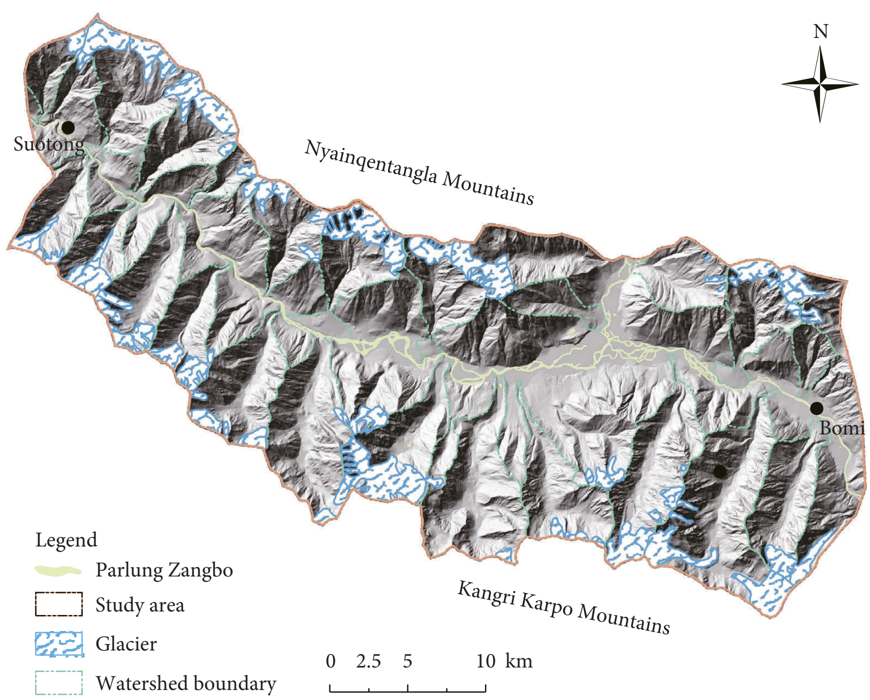

Figure 2: Glacier distribution and overall form of gullies along two banks between Bomi and Suotong in Figure 1 (glacier data are from [15]).

$$Ke = \frac{W}{L}. \quad (1)$$

where W is the largest width of the catchment and L is the length of the valley.

HI is widely used to quantitatively determine the evolution stage of landforms. The smaller the value is, the more mature the landform is, and the higher the erosion degree is. HI can be obtained by equation (2) [34].

$$E = \frac{H_{\text{mean}} - H_{\text{min}}}{H_{\text{max}} - H_{\text{min}}} = HI. \quad (2)$$

H_{mean}, H_{max}, and H_{min} are mean value, maximum value, and minimum value of elevation in one catchment.

2.3. Geohazard History. Strong coupling of the above geology, climate, geomorphology, and glacial actions control the type, size, development, and frequency of debris flows in the Parlung River region. Since the 1950s, the study area has been frequently hit by debris flows of different sizes, resulting in huge loss of life and properties (e.g. 1–13 in Figure 1; [16]) and has a tendency for concentrated outbreaks (Figure 3). In particular, some debris flows were extremely disastrous, such as that occurring in the Gu Xiang area on September 29, 1953 [14].

According to the size classification, which is based on the total volume, peak discharge, and flooded area in the field, the size classes of the debris flows are given in Table 1, coinciding with the debris flow frequency based on interviews with locals and previous studies. The result shows that in the region between Bomi and Suotong (Figure 2), the south and north banks of the Parlung River differ greatly in terms of the occurrence of debris flows. Compared to the north bank, the south bank shows much smaller sizes and a lower frequency of debris flows (Table 1).

3. Analysis of the Glacier and Geomorphology Conditions of Debris Flow

Due to its unique geographic location and climate, debris flows along the Parlung River are closely associated with moisture distribution and glacial movement. Zheng et al., [35] found that they are a direct consequence of glacier's recession.

3.1. Comparison of Hydrology and Glacier Distribution between the Two River Banks. The data from field investigation and the Second Glacier Inventory Dataset of China [15] suggest significant differences in glacier distribution between the north and south banks of the Parlung River. In terms of the glacier type, valley glaciers are distributed only along the south bank, while the north bank is covered primarily by cirque glaciers and hanging glaciers. The snow line is generally higher in the east than in the west (Table 2).

In the region between Bomi and Suotong, the north bank of the river has 28 glaciers, which account for 32.56% of the region's total number of glaciers, 34.56% of glacier coverage, and 35.62% of ice reserves. The south bank has 58 glaciers, which make up 67.44% of the region's total number of glaciers, 65.44% of glacier coverage, and 64.39% of ice reserves (Table 2). It is clear that the south bank has more glaciers than the north bank.

It is clear that glaciers are more developed along the south bank of the Parlung River than along its north bank. The north bank shows a snow line higher than that along the south bank and has no valley glacier, indicating that snow and ice along the north bank are more lacking. Numerous large glaciers have formed on the Kangri Karpo Mountains because the mountains just stand in the way of the warm moist air brought by the southwest monsoon blowing from the great bend of the Yarlung River (Figure 1) and thus become the wettest part of the Tibetan Plateau. After the moist air climbs over the Kangri Karpo Mountains and passes the Parlung River, it decreases in moisture content and thus supplies less moisture to the river's north bank (the Nyainqentangla Mountains). Therefore, the north bank is dominated by cirques and hanging glaciers.

Moreover, glaciers along the south bank (ubac) melt at slow rates as they have lower surface temperatures due to low solar irradiation received. After a certain amount of snow has accumulated on a glacier, the glacier tends to move down the valley under gravity or pressure. This contributes to the higher probability of the formation of valley glaciers along this bank. In contrast, glaciers along the north bank (adret) show higher surface temperatures due to greater solar irradiation and thus melt faster. For this reason, glaciers are unlikely to fill valleys, and the dominant glacier types are cirque glaciers and hanging glaciers. Due to their differences in moisture supply and solar insolation, the north bank has a snow line higher than that of the south bank. The more active glacial motions and faster rate of melting along the north bank are regarded as preconditions for the formation of glacial debris flow. Glacier melting provides enough water and glacier transforms into solid matter in the glacial debris flow.

3.2. Differences in Geomorphology between North and South Banks. Ke and HI values of every valley are obtained to analyze the difference of geomorphology between north and south banks. Figure 4 just shows that Ke and HI values of valleys along the north bank are both larger than valleys along the south bank, especially the Ke index, which means closer the plane shape of catchment is to the circle, and higher the erosion degree is.

Therefore, under the effect of long-term structural erosion and glacier erosion, valleys along the two banks of Parlung Zangbo reflect sharply different geomorphological features (Figure 4), see Table S1 in the Supplementary Material for comprehensive analysis. As shown in Figure 5, a generalized model is used to describe the geomorphological differences of the valleys between the two banks. The overall form of the valley along the north bank is prone to taking the shape of a funnel and the cross section takes *V*-shape. While for most valleys along the south bank, its overall form is prone to take the shape of oak leaf and cross section takes *U*-shape. The probable reason may be that due to intense sun

(a) (b) (c) (d) (e) (f)

Figure 3: Debris flow events from investigation in the field. (a) Bitong debris flow in 2016; (b) Dada debris flow in 2017. (c) Guxiang debris flow in 2020. (d) Jiaolong debris flow in 2016; (e) Chidan debris flow in 2016. (f) Songrao debris flow in 2018).

Table 1: Typical debris flows along the Parlung River from Bomi to Suotong (e.g. 1–13 in Figure 1).

No.	Name	Date	Size class	Data source	Location
1	Bitong gully	5 Sep. 2007	Middle	Interviews with local residents	
		5 Sep. 2016	Large	Field investigation	
2	Dada gully	4 Aug. 2013	Small	Interviews with local residents	
		20 Jul. 2017	Middle	Field investigation	
3	Jiaolong gully	Sep. 1988	Middle	[14]	
		15 Aug. 1989	Large	[14]	
		5 Sep. 2016	Middle	Field investigation	
4	Cangguo gully	1975	Large	[14]	
		1996	Large	[14]	
5	Zhataduo gully	Jul. 1987	Large	[14]	North bank
6	Naha gully	1968	Super-large	Interviews with local residents	
		1978	Large	[14]	
		Sep. 2018	Middle	Field investigation	
7	Guxiang gully	29 Sep. 1953	Super-large	[28]	
		1954	Large	[14]	
		1963	Large	[14]	
		30 Jul. 2005	Large	Interviews with local residents	
		Jul. 2020	Large	Field investigation	
8	Suotong gully	26 Jul. 1991	Middle	[14]	

Table 1: Continued.

No.	Name	Date	Size class	Data source	Location
9	Qiuzhu gully	2014	Middle	Interviews with local residents	South bank
		28 Aug. 2016	Middle	Field investigation	
10	Chidan gully	5 Sep. 2016	Middle	Field investigation	
11	Songrao gully	4 Sep. 2007	Large	[32]	
		25 Jul. 2010	Large	[32]	
		11 Jul. 2018	Large	Field investigation	
12	Michong gully	Aug. 2015	Small	Interviews with local residents	
13	Danka gully	Aug. 2015	Small	Interviews with local residents	

Table 2: Glaciers along the Parlung river from Bomi to Suotong.

Location	Types of glacier	*Number of glaciers and percentage*		*Area of glaciers (km^2) and percentage*		*Volume of glaciers ($10^6 \times m^3$) and percentage*		Average snow line (m)
North bank	Hanging glacier	18	20.93%	41.12	30.84%	2867.45	33.93	4040
	Cirque glacier	10	11.63%	4.96	3.72%	142.57	1.69%	
	Valley glacier	0	0%	0	0%	0	0%	
South bank	Hanging glacier	23	26.74%	31.18	23.38%	2058.01	24.35%	3429
	Cirque glacier	15	17.44%	5.82	4.36%	194.73	2.30%	
	Valley glacier	20	23.26%	50.27	37.70%	3188.54	37.73%	
Sum total	—	86	100%	133.35	100%	8451.3	100%	—

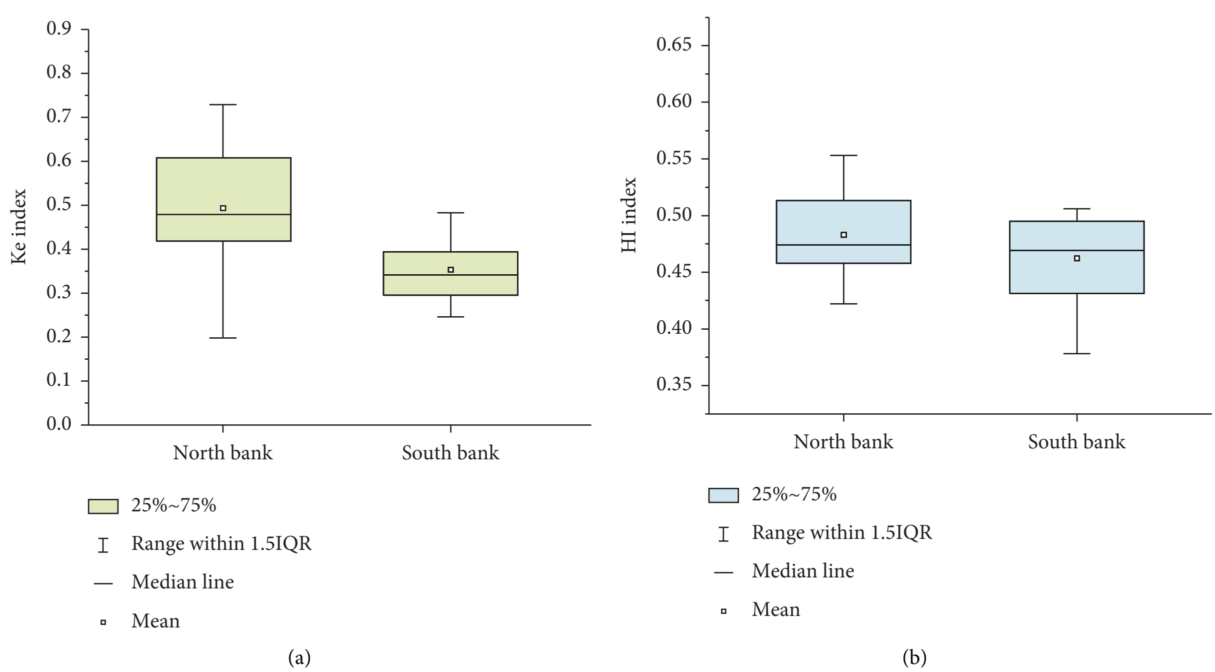

Figure 4: Comparison of Ke index and HI between valleys along two banks ((a) Ke index; (b) HI index).

exposure, it is hard to form a large-scale glacier running through the whole valley along the north bank, and the glacier remains mostly at the edge of the valley at high altitude. Under the effect of freeze-thaw weathering and glacier erosion over the years, only mountains at high altitudes suffer repeated erosion, thus forming wide tops and narrow bottoms. Its overall form takes the shape of a funnel, and its cross section takes the shape of "v" at the lower part, which is favorable for debris flow events (Figure 5).

4. Formation Mechanism of Debris Flow along the Parlung River

The occurrence of landslides, debris flows, and other geohazards depends on a combination of internal and external conditions, including active tectonics, topography, climate, and hydrology. Field investigation and the abovementioned analysis show that glacier-related debris flows vary between the south and north banks despite their overall wide

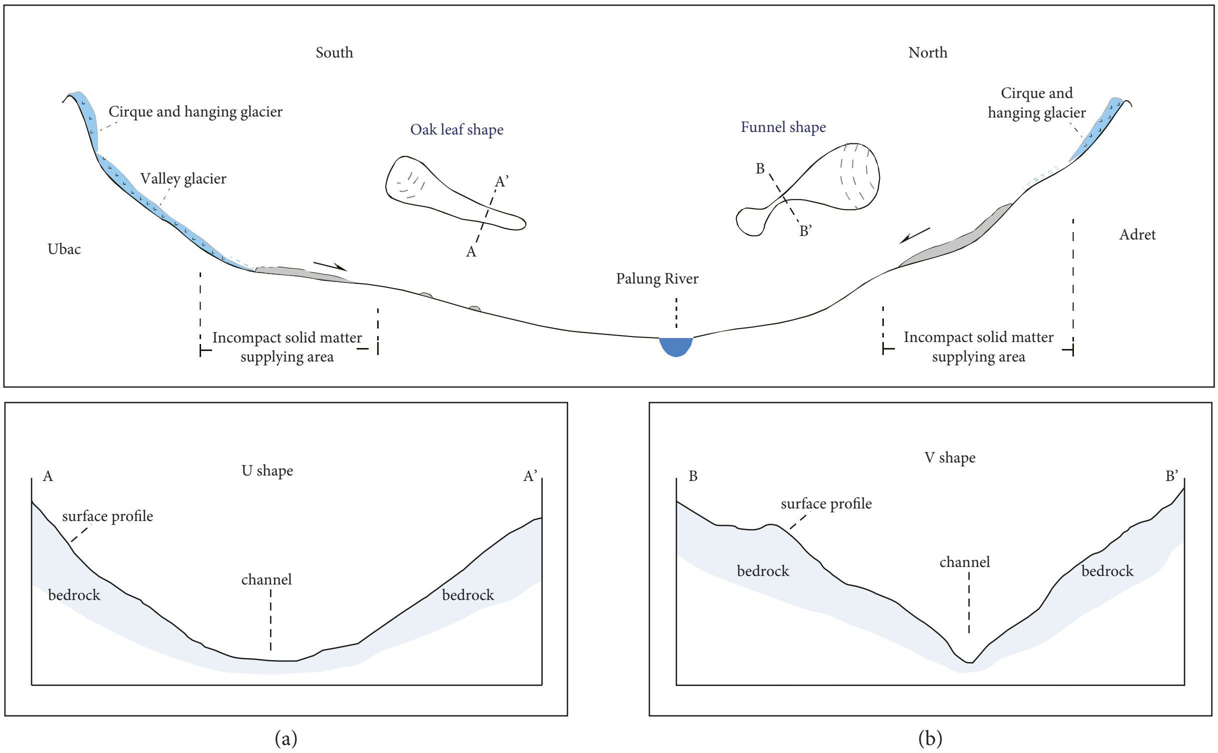

FIGURE 5: The generalized model to describe the comparison of gully geography along the two banks ((a) cross section of most gullies in the south bank; (b) cross section of most gullies in the north bank).

distribution across the region. According to field investigation and previous research [14, 16, 22, 36], the formation of debris flows on the south and north banks of the Parlung River can be explained by three modes:

Mode I: During movement, a glacier tends to fracture during intense melt at its snout. The glacial meltwater then moves into the glacial body along the resulting fractures and accumulates into runoff at the glacier base. Cavities form at the glacier snout due to erosion by runoff. As the fractures continue to grow the glacial till deposited by the glacier tends to collapse, motivating the slow-moving glacier to move downward faster. During fall and breakage, ice will melt and the huge amounts of energy contained in meltwater runoff will destabilize the loose gully deposits, which then develop into a debris flow (Figure 6(a)).

Mode II: In the early stage, the small quantities of glacial meltwater and surface runoff generated by rainfall also provide solid materials for the formation of a debris flow. When the ablation of a glacier accelerates or heavy rainfall occurs, the resulting water forms runoff, which will erode the glacial till and debris from landslides previously deposited in the gully and entrain the underlying sediments. The sediments will then be fluidized and move, forming a debris flow (Figure 6(b)).

In mode III, upstream rainfall and glacial meltwater will be blocked by the dam formed by a landslide in the narrow part and moraine in the gully. After the dam breaks the water will be discharged rapidly. The discharged water then entrains the underlying sediments, resulting in a glacial debris flow (Figure 6(c)).

5. Discussion

As mentioned above, the north bank has more favorable conditions in glacier and geomorphology than the south bank, which is more conducive to the occurrence of debris flows and this is consistent with the present situation of debris flow events. The dominance of cirque and hanging glaciers on the upper part of gullies in the north bank indicates greater potential energy carried by icefalls and avalanches. As the north bank is the adret, the glaciers there are more active and melt more intensely, increasing the probability of icefalls, avalanches, and rockfalls. Therefore, the mode of debris flow changes to mode I. The Guxiang debris flow on September 29, 1953, is the typical event [14]. Active glaciers will produce more meltwater and modern glacial till. The unique funnel shape of gullies not only facilitates the confluence of water from different sources but also increases the likelihood of blockage and dam breakage at the narrow part of a gully. Then, mode III debris flow will occur. The Bitong debris flow in 2016 (Figure 3(a)) and Dada debris flow in 2017 (Figure 3(b)) are the typical events on the north bank. On the south bank (ubac), the gullies are oak leaf-shaped and typically covered with valley glaciers. As the speeds of glacier motion and water catchment are slow, it will take a longer time for the materials produced by repeated freezing and thawing in the early stages and from a gully to develop into a debris flow. In this situation, a mode II debris flow is more likely to occur. In fact, as the statistics in Table 1, most of the debris flows along the south bank are Mode II. However, in extreme conditions, there is also the possibility

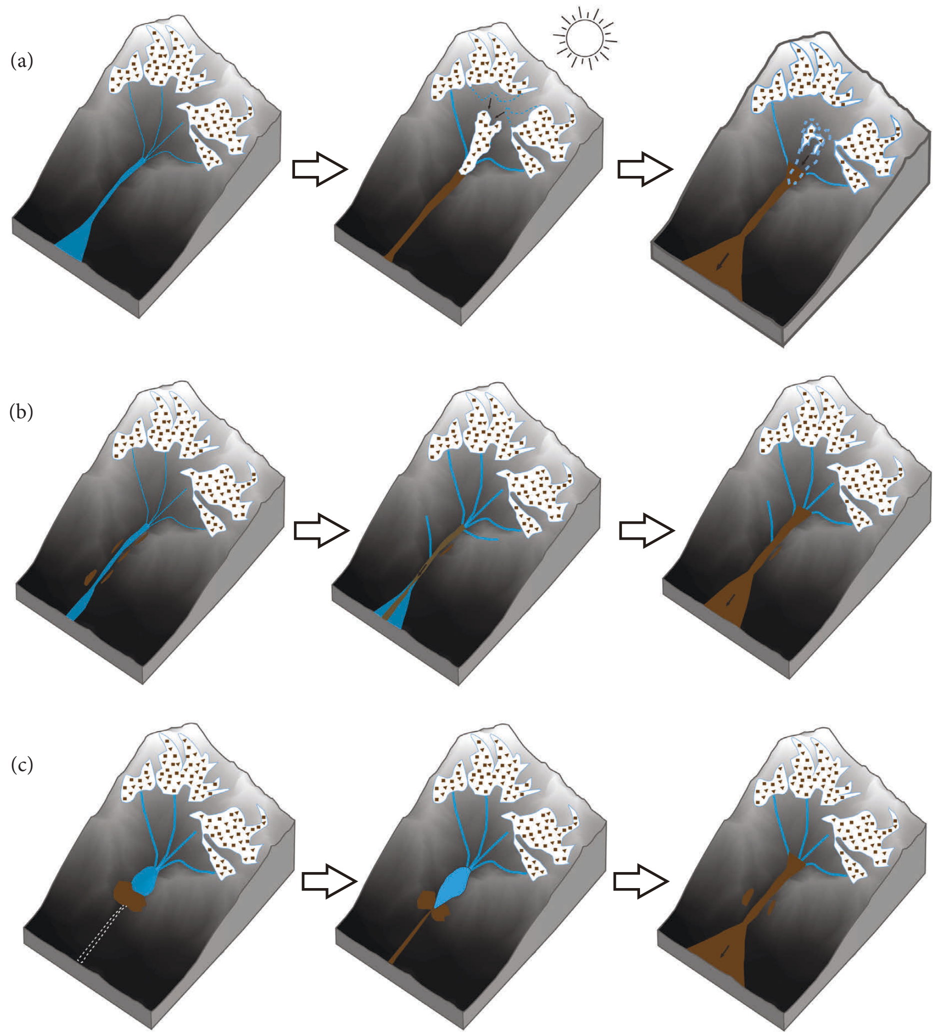

Figure 6: Formation mechanisms of debris flow along the Parlung River. (a) Mode I, (b) mode II, and (c) mode III.

of a model I or III debris flow. The debris flow event in 2018 in Songrao gully is just the typical one which outbreak for the reason of rockfall/moraine-initiating (Figure 3(f)) and dam-breaking debris flow in 2010, respectively [22, 36]. For the reason that the initiating course is hard to observe, the formation mechanisms of several debris flows could not be obtained; however, according to the field investigation in recent years, the result is clear that the debris flows on the north banks primarily occur in modes I and III, while the south banks are dominated by mode II debris flows (Table 3).

The Parlung glacier is the controlling dynamic factor of debris flow in the Parlung River. Warming is the main cause of glacial recession. Mass meteorological data show that climate warming has been significant in the Parlung River since the 1970s, the warming rate in Bomi is 0.23°C/10 years [36, 37]. It is speculated that the melting rate of glaciers will accelerate in the future, and that the north bank will be more affected than the south bank, for smaller glaciers are more sensitive than larger ones and are easier to lose material.

The disappearance and recession of glaciers brings enough water and impact solid matter for glacier-related debris flows. No doubt, debris flows in the region will increase gradually in the future [16, 17, 22, 38, 39]. Strong earthquakes are bound to be the center of the centralized breaking out of glacier-related debris flows. In addition, the melting of the glacier will form moraine lakes, which pose a hidden danger from the subsequent debris flows caused by glacial-lake outburst floods.

The paper suggests that the major transport projects to be built on the Parlung River, such as the Sichuan–Tibet Expressway and the Sichuan–Tibet Railway, should be located on its southern bank, in order to mitigate the influence of debris flows. To spare gullies prone to debris flows, bridges and tunnels are proper solutions.

Table 3: Formation mechanisms of debris flows along the Parlung River from Bomi to Suotong (e.g., 1–13 in Figure 1).

NO.	1	2	3	4	5	6	7	8	9	10	11	12	13
Name	Bitong gully	Dada gully	Jiaolong gully	Cangguo gully	Zhataduo gully	Naha gully	Guxiang gully	Suotong gully	Qiuzhu gully	Chidan gully	Songrao gully	Michong gully	Danka gully
Formation mechanism	Modes I and III	Mode III	Mode III	Mode II	—	Modes I and III	Modes I and III	Mode III	Mode II	Mode II	Modes I and III	Mode II	Mode II
Data source	This study	This study	[16]	This study	—	This study	[16]	[16]	This study	This study	[22]	This study	This study
Location					North bank						South bank		

6. Conclusion

The present paper indicates that compared to the south bank of the Parlung River, the north bank shows much larger and higher frequency debris flows in recent years. In fact, the north bank has more favorable conditions in glacier and geomorphology than the south bank, which is more conducive to the occurrence of debris flow. There are more active and distributed glaciers on the north bank of the Parlung River than on the south bank, which means enough water and material for the debris flow. The Ke index and HI show that valleys along the north bank reflect higher circle and erosion degree, the overall shape of gullies in the north bank is mainly funnel shaped and the cross section shows the shape of "*v*" at the lower part, which is favorable for debris flow formation. Relevant results provide a way to study the relationship between environmental conditions and the glacier-related debris flow, not just in SE Tibet Plateau but also in the marine alpine area.

Three formation mechanisms are concluded: mode I: icefalls, avalanches, and rockfalls mix with water in a gully and transform into a debris flow; mode II: gully bed deposits are destabilized by surface runoff and then develop into a debris flow; and mode III: the break of a debris dam suddenly causes a debris flow. The glacier-related debris flows on the south and north banks occur through different mechanisms due to different formation conditions, the debris flows on the north banks primarily occur in modes I and III, while the south banks are dominated by modes II debris flows. The understanding of the regional debris flow could be promoted in the initiation mechanism.

The disappearance and recession of glaciers bring enough water and impact solid matter for glacier debris flows, no doubt debris flow in the region will increase gradually in the future, and the north bank is more prone than the south bank. This paper suggests that the major transport projects to be built on the Parlung River should be located on its south bank, in order to mitigate the influence of debris flows. To spare gullies prone to debris flows, bridges and tunnels are proper solutions.

Data Availability

The glacier dataset used in this study were provided by the National Cryosphere Desert Data Center (https://www.ncdc.ac.cn).

Disclosure

This study has previously been presented at a conference [40].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work was supported by the Second Tibetan Plateau Scientific Expedition and Research (STEP) Program (Grant no. 2019QZKK0902), "Geo-Hazard Survey and Risk Management in Southeast Margin and Transition Zone of the Tibetan Plateau (DD20221741)" which was funded by the China Geological Survey and Key laboratory of Deep-Earth Dynamics of Ministry of Natural Resources Open Project (no. J1901). The authors convey their sincere thanks to Dr. Dongxu Yang and Eng. Dong Yang for providing valuable discussions in the field.

Supplementary Materials

Table S1 shows that the mean and max Ke index of the north bank is 0.49 and 0.73, much larger than the south bank. For HI index, there is not much large difference between the north and south banks, while the north bank is generally larger than the south bank. (*Supplementary Materials*)

References

[1] O. Korup and J. J. Clague, "Natural hazards, extreme events, and mountain topography," *Quaternary Science Reviews*, vol. 28, no. 11-12, pp. 977–990, 2009.

[2] S. T. McColl, "Paraglacial rock-slope stability," *Geomorphology*, vol. 153, pp. 1–16, 2012.

[3] L. Fischer, R. S. Purves, C. Huggel, J. Noetzli, and W. Haeberli, "On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas," *Natural Hazards and Earth System Sciences*, vol. 12, no. 1, pp. 241–254, 2012.

[4] J. Gao, T. Yao, V. Masson-Delmotte, H. C. Steen-Larsen, and W. Wang, "Collapsing glaciers threaten Asia's water supplies," *Nature*, vol. 565, no. 7737, pp. 19–21, 2019.

[5] A. Kääb, M. Jacquemart, A. Gilbert et al., "Sudden large-volume detachments of low-angle mountain glaciers - more frequent than thought," *The Cryosphere*, vol. 15, pp. 1751–1785, 2021.

[6] B. An, W. Wang, W. Yang et al., "Process, mechanisms, and early warning of glacier collapse-induced river blocking disasters in the Yarlung Tsangpo Grand Canyon, southeastern Tibetan Plateau," *Science of the Total Environment*, vol. 816, Article ID 151652, 2022 Apr 10.

[7] T. Takahashi, *Debris Flow Mechanics, Prediction and Countermeasures*, pp. 103–168, Taylor & Francis, London, 2014.

[8] N. Chen, Q. Zou, F. Su, P. Cui, and Y. Zhang, "Risk assessment and disaster reduction strategies for mountainous and meteorological hazards in Tibetan Plateau," *Chinese Science Bulletin*, vol. 60, no. 32, pp. 3067–3077, 2015.

[9] A. Kääb, S. Leinss, A. Gilbert et al., "Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability," *Nature Geoscience*, vol. 11, no. 2, pp. 114–120, 2018.

[10] S. Luo, J. Xiong, S. Liu et al., "New insights into ice avalanche-induced debris flows in southeastern Tibet using SAR technology," *Remote Sensing*, vol. 14, no. 11, p. 2603, 2022.

[11] Y. J. Shang, Z. Yang, L. Li, D. Liu, Q. Liao, and Y. Wang, "A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin," *Geomorphology*, vol. 54, no. 3-4, pp. 225–243, 2003.

[12] Y. G. Ge, P. Cui, Fh Su, Jq Zhang, and Xz Chen, "Case history of the disastrous debris flows of Tianmo watershed in Bomi County, Tibet, China: some mitigation suggestions," *Journal of Mountain Science*, vol. 11, no. 5, pp. 1253–1265, 2014.

[13] W. Tang, Ht. Ding, Ns. Chen et al., "Artificial neural network-based prediction of glacial debris flows in the Parlung Zangbo

basin, southeastern Tibetan plateau, China," *Journal of Mountain Science*, vol. 18, no. 1, pp. 51–67, 2021.

[14] Y. F. Shi and S. Yang, "The glacial debris flow in Guxiang, Tibet," *Chinese Science Bulletin*, vol. 6, pp. 542–544, 1964.

[15] S. Y. Liu, W. Q. Guo, J. L. Xu et al., "The Second Glacier inventory dataset of China (version 1.0)," *Cold and Arid Regions Science Data Center at Lanzhou*, vol. 61, 2013.

[16] I. T. S. Imhe, "A study of typical mountain hazards along sichuan-tibet Highway," in *The Chinese Academy of Sciences and Water Conservancy Ministry of China and ITS (Institute of the Traffic Science, the Tibet Autonomous Region)*, pp. 158–184, IMHE (Institute of Mountain Hazards and Environment), Chengdu, 1999.

[17] Y. J. Shang, H. D. Park, Z. Yang, and J. Yang, "Distribution of landslides adjacent to the northern side of the yarlu tsangpo grand canyon in Tibet, China," *Environmental Geology*, vol. 48, no. 6, pp. 721–741, 2005.

[18] R. Du, H. Li, L. Wang, Y. L. Wang, and Z. L. Qian, "Formation and development of glacial debris flow in the Guxiang gully, Xizang," in *Proceedings of the Lanzhou Institute of Glacier and Permafrost, CAS, Special Issue on China Debris Flow. Science Press*, p. 1, Beijing, 1985.

[19] Q. L. Zeng, *Formation of Huge-Thick Loose Accumulations in Southeast Tibet with Associated Hazards Modes and Mitigations: A Case Study in Ranwu to Lulang Section of Sichuan-Tibet Highway*, pp. 87–95, Thesis of University of Chinese Academy of Science, 2007.

[20] J. J. Zhang, J. K. Liu, B. Gao et al., "Characteristics of material sources of Galongqu glacial debris flow and the influence to Zhamo Road," *Journal of Geomechanics*, vol. 24, no. 1, pp. 106–114, 2018a.

[21] Z. Q. Xu, Z. H. Cai, Z. M. Zhang, L. Huaqi, C. Fangyuan, and T. Zhemin, "Tectonic and fabric kinematics of the namche barwa terrane, eastern himalayan syntaxis," *Acta Petrologica Sinica*, vol. 24, no. 7, pp. 1463–1476, 2008.

[22] R. Q. Wei, Q. L. Zeng, T. Davies et al., "Geohazard cascade and mechanism of large debris flows in Tianmo gully, SE Tibetan Plateau and implications to hazard monitoring," *Engineering Geology*, vol. 233, pp. 172–182, 2018.

[23] L. Ding and Zhong, "Fission track evidence for the Neocene rapid uplifting of the eastern Himalayan syntaxis," *Chinese Science Bulletin*, vol. 40, no. 16, pp. 1497–1500, 1995.

[24] P. K. Zeitler, A. S. Meltzer, L. Brown, W. S. Kidd, C. Lim, and E. Enkelmann, "Tectonics and topographic evolution of namche barwa and the easternmost Lhasa block, Tibet," *GSA Bull. Spec*, vol. 507, pp. 23–58, 2014.

[25] J. J. Zhang, J. C. Wang, and L. Chen, "Distribution of the Quaternary accumulation along Zhamu-Suotong section of the Sichuan-Tibet high way and their occurrence characteristics," *Science Technology and Engineering*, vol. 17, no. 32, pp. 37–43, 2016.

[26] R. Jinwei, S. Jun, C. Zhongquan, and W. Yipeng, "Quaternary faulting of Jiali fault, southeastern Tibetan plateau," *Seismology and Geology*, vol. 22, no. 4, p. 344, 2000.

[27] F. . t. Tang, J. Song, Z. Q. Cao et al., "The movement Characters of main faults around Eastern Himalayan Syntaxis revealed by the latest GPS data," *Chinese Journal of Geophysics*, vol. 53, no. 9, pp. 2119–2128, 2010.

[28] Ceic, "Earthquake Catalogue from China Earthquake Network Center," 2018, http://www.csndmc.ac.cn/newweb/data.htm.

[29] J. J. Li and Zheng, *Tibet Glacier. 1-36*, pp. 217–228, Science Press, Beijing, 1986.

[30] D. S. Mi and Xie, *Glacier Inventory of China, XI, the Ganga Drainage Basin*, pp. 9–437, Xi′an Cartographic Press, Xi′an, 2002.

[31] W. Yang, T. Yao, B. Xu, G. Wu, L. Ma, and X. Xin, "Quick ice mass loss and abrupt retreat of the maritime glaciers in the Kangri Karpo mountains, southeast Tibetan Plateau," *Science Bulletin*, vol. 53, no. 16, pp. 2547–2551, 2008.

[32] A. Faghih, B. Samani, T. Kusky, S. Khabazi, and R. Roshanak, "Geomorphologic assessment of relative tectonic activity in the m lake basin, zagros mountains of Iran," *Geological Journal*, vol. 47, no. 1, pp. 30–40, 2012.

[33] M. T. Ramirez-Herrera, "Geomorphic assessment of active tectonics in the Acambay graben, Mexican Volcanic Belt," *Earth Surface Processes and Landforms*, vol. 23, no. 4, pp. 317–332, 1998.

[34] R. J. Pike and S. E. Wilson, "Elevation-relief ratio, hypsometric i and geomorphic area-altitude analysis," *The Geological Society of America Bulletin*, vol. 82, no. 4, pp. 1079–1084, 1971.

[35] B. X. Zheng and Q. H. Ma, "Relationship between the glacier variation and the debris flow development of the holocene in the GongGa mountainous region," *Lanzhou institute of Gliacolgoy and Geocryolog, Chinese Academy of Sciences*, vol. 12, no. l, pp. l–8, 1994.

[36] M. F. Deng, N. Chen, and M. Liu, "Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo valley, south-eastern Tibetan Plateau," *Natural Hazards and Earth System Sciences*, vol. 17, no. 3, pp. 345–356, 2017.

[37] W. Yang, T. Yao, B. Xu, L. Ma, Z. Wang, and M. Wan, "Characteristics of recent temperate glacier fluctuations in the Parlung Zangbo River basin, southeast Tibetan Plateau," *Chinese Science Bulletin*, vol. 55, no. 20, pp. 2097–2102, 2010.

[38] C. U. Peng, C. H. Rong, X. Lingzhi, and S. Fenghuan, "Risk analysis of mountain hazards in Tibetan Plateau under global warming," *Progressus Inquisitiones de Mutatione Climatis*, vol. 10, no. 2, pp. 103–109, 2014.

[39] S. L. Gariano and F. Guzzetti, "Landslides in a changing climate," *Earth-Science Reviews*, vol. 162, pp. 227–252, 2016.

[40] J. J. Zhang, J. K. Liu, Y. L. Li, J. C. Wang, L. Chen, and B. Gao, "Conditions and mechanism for formation of glacial debris flows in Parlung Zangbo, SE Tibetan Plateau," in *Proceedings of the 5th International Conference Debris Flows: Disasters, Risk, forecast, protection*, p. 671p, Tbilisi, Georgia, 2018b.