Recent Variations of Batura and Other Glaciers and Their Impacts on the Karakoram Highway (Postprint)

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Abstract

The Karakoram Highway serves as a crucial corridor for the opening-up of China's Xinjiang region and has long been impacted by glacier hazards, with the Battura section along the middle Hunza River being the most severely affected. Based on field investigations, remote sensing imagery, and other data, this study analyzes the century-scale variations, their driving factors, and impacts on the highway for the Battura, Pasu, and Gulkin glaciers. The results indicate: (1) Over the past century, particularly since 2000, the Battura, Pasu, and Gulkin glaciers have generally experienced slight retreat, with the direct threat to the highway tending to diminish. (2) Intensified glacier melting and ice tongue fluctuations have caused frequent shifts in meltwater runoff, and secondary disasters such as glacier meltwater floods, glacial lake outburst floods, and glacier debris flows are increasingly affecting the safe operation of the highway. (3) The most direct threat of glacier change in the Battura section to the highway is the new river channel shift of the Battura River in June–July 2021, which will cause water flow to directly impact and erode the roadbed, compromising highway safety. The findings of this study can provide valuable reference for glacier hazard monitoring and prevention along the China-Pakistan Highway and other land corridors connecting western China with Central and South Asia.

Full Text

Recent Variations of the Batura, Pasu, and Ghulkin Glaciers and Their Impact on the China-Pakistan Karakoram Highway

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Abstract

The Karakoram Highway (KKH) serves as a critical corridor promoting the opening-up of Xinjiang, China, and has long been affected by glacier hazards, particularly the Batura section in the middle reaches of the Hunza River. Based on field investigations and remote sensing data, this study analyzes the variations, causes, and highway impacts of the Batura, Pasu, and Ghulkin glaciers over the past century. The results indicate that: (1) Over the past century, especially since the 1970s, the three glaciers have generally experienced weak retreat, with their direct threat to the highway tending to diminish. (2) Glacier ablation intensification and ice tongue fluctuations have caused frequent meltwater runoff migration, and secondary disasters such as glacial meltwater floods, glacial lake outburst floods, and glacial debris flows are increasingly affecting highway safety operations. (3) The most direct threat to the highway from glacier variations in the Batura section is the new diversion of the Batura River in June-July 2021, after which water flow will directly impact and erode the roadbed, affecting highway safety. These findings provide reference for glacier hazard monitoring and prevention along the China-Pakistan Highway and other land corridors connecting western China with Central and South Asia.

Keywords: Karakoram Highway; Batura Glacier; meltwater runoff; glacier hazards

Introduction

The Karakoram Highway (KKH), stretching from Kashgar in Xinjiang to Thakot in Pakistan, is a strategic corridor for China-Pakistan connectivity and the construction of the China-Pakistan Economic Corridor. The highway traverses the eastern Pamir Plateau and Karakoram Mountains, one of the most concentrated glacier distribution areas in High Mountain Asia, where glacier hazards have repeatedly threatened and interrupted traffic, causing significant losses. The Batura section in the middle reaches of the Hunza River in northern Pakistan is the closest to glaciers and most concentrated in glacier hazards along the entire highway, with the Batura, Pasu, and Ghulkin glaciers posing the greatest and most direct threats.

In 1973, the main drainage channel of the Batura Glacier (the Batura River) changed course, triggering a glacial flood that destroyed the under-construction highway and bridges. In 1974-1975, a Chinese research team conducted comprehensive scientific investigations of the Batura Glacier, including terminus advance/retreat, flow velocity, thickness, and meltwater runoff, providing scientific recommendations for repair along the original route and ensuring long-term stable traffic. Subsequent investigations in 1978 and 1980 accumulated rich scientific data on geology, geomorphology, glacial physics, hydrology, and meteorology. These studies revealed the advance-retreat variations of the Batura, Pasu, and Ghulkin glaciers over the past century and predicted that the Batura Glacier would advance again around the 2010s.

Since the 1990s, these glaciers have undergone many new changes that pose fresh threats to normal highway operation. For example, the main drainage outlet of the Batura Glacier has continuously shifted northward, eventually causing the meltwater channel to be squeezed and cut off by the ice tongue, triggering another major river diversion after nearly 50 years. The moraine-dammed lake at the Pasu Glacier terminus has frequently burst, causing outburst floods that interrupted traffic. The frequent fluctuations of the Ghulkin Glacier terminus have caused continuous migration of drainage channels beneath the ice cliff, triggering debris flows that severely silted highway bridge bottoms in 2018 alone. Given the increasingly prominent disaster risks and the irreplaceable status of the highway, it is necessary to reveal and analyze the historical and recent changes of these three glaciers to provide reference for highway safety operation and disaster prevention.

1. Study Area Overview

The Batura, Pasu, and Ghulkin glaciers originate from the main ridge of the western Karakoram Mountains—the north slope of the Hunza Karakoram Mountains [Figure 1: see original paper]. The Hunza Karakoram Mountains have an average elevation exceeding 6000 m, with the highest peak Batura at 7795 m, providing extremely favorable topographic conditions for glacier development and making the Batura Glacier group one of the largest, lowest-terminus, and most frequently advancing/retreating glacier groups along the highway. The upper accumulation basins of these glaciers are broad with sufficient material supply, while the middle and lower reaches extend into dry and hot valleys with intense ablation, making them typical polythermal glaciers with high mass balance levels. Our interpretation shows that the Batura Glacier is about 56.5 km long with a terminus elevation of about 2540 m; the Pasu Glacier is about 26.4 km long with a terminus elevation of about 2700 m; and the Ghulkin Glacier is about 28.26$±$0.47 km long with a terminus elevation of about 2620 m.

2. Data and Methods

2.1 Data Sources

2.1.1 Landsat Imagery This study used Landsat series imagery acquired from 1972-2021 to reveal glacier changes . All images were obtained from the United States Geological Survey (https://earthexplorer.usgs.gov/) and underwent systematic radiometric and geometric correction. To improve interpretation accuracy of glacier boundaries, drainage outlets, and meltwater channels, we selected images from late ablation seasons with cloud-free conditions over the glacier area and minimal mountain shadow coverage.

2.1.2 Ice Surface Elevation Change Dataset Based on geodetic methods, the High Mountain Asia ice surface elevation change dataset was generated through spatial matching and error correction of SRTM DEM and ASTER stereo image pairs, providing surface elevation changes and mass balance of High Mountain Asia glaciers. The dataset' s errors mainly come from generation accuracy and spatial matching bias of the DEMs, which were corrected and evaluated using elevation residuals in stable non-glacier areas. The dataset has a spatial resolution of 30 m and is available from PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.876545).

2.1.3 Ice Surface Velocity Dataset The ITS_{LIVE} (Inter-mission Time Series of Land Ice Velocity and Elevation) product contains glacier velocity data for High Mountain Asia from 1985-2018. Based on Landsat imagery and using the automated feature-tracking processing chain method, the product extracts glacier velocities through local normalization, oversampling, and feature tracking. Although spatial matching bias of Landsat images was corrected using stable bedrock terrain, it cannot be completely eliminated. Therefore, we used Landsat imagery to directly estimate glacier velocity uncertainties, which exceed 10 $\mathrm{m\cdot a^{-1}}$ for Landsat 7 images and about 0.5 $\mathrm{m\cdot a^{-1}}$ for Landsat 8 images. This study selected annual average velocity composite data from 2013-2018 with 120 m spatial resolution (https://its-live.jpl.nasa.gov/).

2.2 Methods

2.2.1 Glacier Boundary Interpretation Due to extensive debris cover and frequent terminus fluctuations, we used visual interpretation to extract glacier boundaries. In the bare ice area of the upper and middle reaches, boundaries were digitized directly based on significant color differences in false-color composites (thermal infrared, red, and green bands). In debris-covered lower reaches, boundaries were identified based on combinations of terminal ice cliffs, drainage outlets, and topographic/hydrological features. False-color imagery significantly enhances color differences between bare ice and debris-covered areas, debris-covered areas and bedrock, and between ice cliffs and water flow, enabling accurate identification of ice tongue and drainage outlet positions. Field investigations show that strong ablation at glacier tongues makes the combination of terminal ice cliffs and outlets represent the glacier' s foremost position. We first completed boundary extraction for 2021, then modified changing parts like the ice tongue using multi-temporal imagery to obtain boundaries for other years.

2.2.2 Interpretation Accuracy Assessment The accuracy of glacier boundary interpretation from optical imagery is mainly affected by spatial resolution. We evaluated uncertainty using the method of counting pixels crossed by the glacier outline:

$$E = N \times \lambda$$

where E is glacier area uncertainty, N is the number of pixels crossed by the glacier boundary, and λ is pixel area.

2.2.3 Identification of Drainage Outlets and Meltwater Channels Drainage outlets are the discharge points of englacial and subglacial water systems at glacier termini. We identified migration changes of drainage outlets and meltwater channels by combining field investigation records with remote sensing imagery. As shown in [Figure 2: see original paper], in late ablation season Landsat images, the accurate positions of drainage outlets and channels can be effectively identified due to the Batura Glacier' s large discharge. Additionally, during the two major diversion periods, the Batura River' s lower reaches remained stable while the upper reaches extended with ice tongue fluctuations, allowing accurate identification of drainage system changes through multi-temporal imagery.

3. Results and Analysis

3.1 Glacier Terminus Variations

Over the past 150 years, the Batura Glacier has experienced multiple advance-retreat fluctuations. It advanced in the 1930s, remained relatively stable until the 1960s, then began retreating. From the 1960s to 1970s, the ice tongue retreated about 827 m, then advanced again in the 1980s, accumulating about 410 m of advance by 1990 before declining again in the early 1990s. By 2021, it had retreated about 150-200 m. Overall, the Batura ice tongue has experienced a cycle of advance every 50-60 years over the past 150 years, but each advance generally lasts only 20-30 years, with retreat being the dominant trend.

The Pasu Glacier, despite a major surge in 1978 that advanced the ice tongue about 1200 m, has been in long-term retreat, with only one minor advance around 1990. From 1978 to 2021, the Pasu ice tongue retreated about 1200 m, showing accelerated retreat over the past century.

The Ghulkin Glacier has been one of the most active glaciers along the highway, with frequent fluctuations over the past century. The southern ice tongue retreated 260 m from 1972-1995, advanced 180 m from 1995-2000, then slowed its advance rate, retreating about 100 m by 2021. The northern ice tongue has been even more active, retreating 390 m from 1972-1995, advancing 200 m from 1995-2000, then fluctuating within a small range.

3.2 Meltwater Channel Changes

In June-July 2021, after the Batura River diversion, the glacier' s main drainage outlet shifted from near the medial moraine to the south side of the ice tongue.

Before 2015, the migration rate was slow and remained stable on the south side. After 2015, the migration rate accelerated significantly, gradually crossing the medial moraine to the north side of the ice tongue. By July 2021, the main outlet was on the northwest side, with the drainage channel extending completely across the ice tongue front [Figure 4: see original paper]. In July 2021, the ice tongue' s sudden advance squeezed and cut off the main drainage channel, triggering another major Batura River diversion. Due to ice dam blockage, meltwater was forced to erode a new path through moraine hills, directly causing the river' s diversion.

Affected by terrain, the Pasu Glacier' s drainage channel is very stable. After 1978, a small moraine-dammed lake formed near the ice tongue, with a measured area of about 0.12 km^2 in 1994. The lake burst multiple times in 2008, 2010, and 2016, causing outburst floods [6,10-11]. However, after several bursts and long-term erosion by meltwater, the moraine dam' s integrity has been damaged, greatly limiting recent lake development scale.

The Ghulkin section is the most affected by glacial meltwater along the highway. With the ice tongue divided into north and south branches and extremely short meltwater flow paths (<2 km), the meltwater radiates unstably and frequently changes course. The Ghulkin Glacier has about 2 main drainage channels and countless small ones [4]. The north ice tongue' s Channel 1 and the south ice tongue' s Channel 2 have been basically abandoned, with Channel 3 temporarily becoming the main channel before water volume rapidly decreased again. Therefore, the south ice tongue' s meltwater channels have been unstable in recent years.

3.3 Ice Surface Elevation and Velocity

The "Karakoram Anomaly" has attracted much attention in recent years, but for the Batura region on the northwestern edge of the Karakoram, studies have found that glacier mass loss has accelerated since 2000 [20,25]. Research based on SRTM DEM shows that from 2000-2016, the mass balances of the Batura and Pasu glaciers were -0.05\$$\pm0.11mw.e.a$^{-1}\$ and -0.00\$$\pm0.10mw.e.a$^{-1}\$ respectively, indicating near-equilibrium before 2000 but accelerated mass loss afterward. All three glaciers show surface elevation decline, especially near termini, with rates of -0.09\$$\pm0.29m\cdot a^{\{\text{-1}\},-0.15\pm0.17m\cdot a}\{\text{-1}\}, and-0.08\pm0.26m\cdot a$^{-1}\$ respectively [Figure 5: see original paper], demonstrating that the Batura region glaciers have experienced mass loss.

The three glaciers maintain high surface velocities, with 2013-2018 average velocities of 59.60\$$\pm0.28m\cdot a^{\{\text{-1}\},106.44\pm0.44m\cdot a}\{\text{-1}\}, and 19.50\pm0.35m\cdot a$^{-1}\$ respectively. Spatially [Figure 5: see original paper], high-velocity zones appear near the equilibrium line in upper glacier regions. The Batura Glacier' s maximum velocity occurs at the firn basin outlet where the first and second ice flows form an icefall, approaching 1200 $m\cdot a^{-1}$. The Pasu Glacier' s maximum velocity is about 940 $m\cdot a^{-1}$ at the same location. The Ghulkin Glacier has relatively gentle velocities, with maximum velocity also near the icefall. Compared to the Batura and Ghulkin glaciers, the Pasu Glacier’ s faster velocity indicates higher mass balance levels, which is the main reason for its stronger ablation.

4. Discussion

4.1 Factors Influencing Glacier Variations

Mountain glaciers are products of climate and topography interaction, but on decadal to centennial scales, glacier changes are primarily controlled by climate conditions. Glacier mass balance is directly determined by annual climate states, while terminus fluctuations are more influenced by long-term climate cycles due to the lag between climate change and ice tongue response. The lag period mainly relates to glacier scale—3-30 years for small glaciers and longer for large ones. For large compound mountain glaciers like Batura, Pasu, and Ghulkin, long-term temperature fluctuations are key factors affecting terminus fluctuations. Since the 1970s, the glacier accumulation zones have remained basically stable while ablation zones show elevation decline, indicating that warming in the Hunza Valley has directly accelerated glacier mass loss. The simultaneous thinning and fluctuation of the three ice tongues fully demonstrate the lag in glacier response to climate and the influence of glacier scale on this lag. Studies show that over the past 150 years, the Batura ice tongue’ s fluctuations have a lag of about 10-20 years relative to temperature cycles, with several advances corresponding well to staged temperature changes [4,7-8]. Based on this relationship, researchers successfully predicted the ice tongue’ s fluctuations in the 1970s-2000s and its latest round of advance in the 2010s.

Surge-type glaciers experience periodic rapid movement at speeds several to hundreds of times normal [24]. Some studies consider the high velocities, large crevasses, and arcuate structures in the Batura Glacier’ s first and second ice flows as surge manifestations [4,6], but this is not uncommon for large mountain glaciers. For giant glaciers like Batura, tributary surges have limited impact on terminus fluctuations—surges of tributaries in glaciers like Karayaylak and Fedchenko did not change overall retreat trends [30]. The Pasu Glacier surged in 1978 and the Ghulkin Glacier in 1994 [11], but since their accumulation zones did not significantly thicken, the possibility of large-scale surges in the near future is low.

4.2 Factors Influencing Meltwater Runoff

Higher mass balance levels result in significantly greater meltwater discharge from these three glaciers compared to similarly-sized glaciers elsewhere—the Batura Glacier even exceeds the Fedchenko Glacier near 2 km^2 [29]. The Batura River’ s multi-year average discharge is 40.1 $m^3 \cdot s^{-1}$, with instantaneous maximum exceeding 600 $m^3 \cdot s^{-1}$, of which nearly 80% is concentrated in June-September [28]. The Batura River’ s water source is glacier meltwater, so discharge is mainly controlled by temperature, increasing with warming and sometimes decreasing with temperature drops during summer precipitation [27]. Even in July, the Batura River' s discharge fluctuates dramatically with extreme heat events [28]. The Pasu and Ghulkin glaciers' meltwater runoff shows similar intra-annual variation but far less dramatically.

The Batura River' s inter-annual variation is relatively 平缓 because: (1) In dry years, less precipitation but more meltwater, while in wet years, more precipitation but less meltwater, creating natural regulation [28]; (2) The ice tongue area' s annual average temperature is close to 0°C, causing intense ablation and thermokarst phenomena, so englacial fractures, cavities, and moraine water retention also regulate runoff [4]; (3) Since the 1970s, glaciers in the Batura basin have remained basically stable, and even increased mass loss since 2000 has limited impact on meltwater runoff. In fact, not only the Batura River but the entire Hunza River basin' s annual runoff shows no significant change [20].

The 2021 Batura River diversion shares similarities with the 1973 event: both occurred during June-July when meltwater discharge rose rapidly, both followed long-term slow migration of the main drainage outlet, and both were associated with sudden ice tongue advances. Therefore, the causes are basically the same. As shown in [Figure 7: see original paper], the Batura Glacier' s material supply is extremely asymmetric: the north side consists of the Yoksugoz, North, and West ice flows, while the south side consists mainly of the first and second ice flows. The south side has greater elevation differences and broader firn basins, resulting in larger material supply that directly causes greater thickness and velocity on the south side [4]. In the middle-lower reaches, the south side' s arcuate structures and bare ice extent are significantly larger than the north side, visually demonstrating this velocity difference. Under long-term action of this velocity difference, the main drainage outlet is slowly pushed northward, extending the drainage channel across the ice tongue front until being cut off by sudden ice tongue advance, forcing diversion. Therefore, the difference in material supply between the south and north sides is the root cause of Batura River diversion, while sudden ice tongue advance is the direct trigger [4,6].

4.3 Impact on the Highway

We selected three stable reference points along the highway (Batura Bridge, Pasu Bridge, and Ghulkin Bridge) and measured the shortest distance between reference points and ice tongues to assess highway-glacier proximity [Figure 6: see original paper]. Since 1972, the distance between the Batura ice tongue and highway has generally increased, currently exceeding 500 m, posing no direct threat in the short term. The Pasu ice tongue has accelerated retreat since 1972, continuously increasing its distance from the highway, thus also posing no short-term direct threat. Although the Ghulkin north and south ice tongues fluctuate within small ranges, their extreme proximity (the north tongue is only about 170 m away) means the direct threat will persist long-term, with surge potential cannot be excluded.

For the Batura Glacier, the more realistic threat is the new major diversion of the Batura River in June-July 2021. After diversion, the river' s flow path shortened, gradient increased, and erosion capacity strengthened, significantly widening and deepening the new channel within one year [Figure 7: see original paper]. More critically, the new channel flows southward downstream, running parallel to the highway, so water flow will directly impact the roadbed at the bend. One could even speculate that only the sturdy roadbed forces the water southward back to the old channel. The Batura River features large discharge, highly concentrated runoff, and rapid rise/fall [28], so in future intense ablation seasons, water flow exceeding 600 $m^3 \cdot s^{-1}$ carrying ice and sediment will cause strong roadbed erosion, posing a major threat.

The Pasu Glacier' s strong recent ablation has increased meltwater runoff, but limited lake development scale has reduced the threat of large-scale outburst floods to downstream highway. The Ghulkin Glacier' s meltwater causes minor issues like road surface icing and major problems like roadbed erosion, bridge siltation, and even debris flow floods. However, after engineering measures in 2018, meltwater disasters in the Ghulkin section have been effectively controlled [11]. Nevertheless, the migration and swing of the Ghulkin Glacier' s meltwater channels cannot be ignored, as they may render water discharge structures obsolete and potentially exceed single-channel capacity, triggering new disasters.

5. Conclusion

The Batura section of the China-Pakistan Karakoram Highway faces the most severe glacier hazard threats, representing a critical section affecting highway operation. Based on field investigations and remote sensing data, we analyzed the century-scale variations, causes, and highway impacts of the Batura, Pasu, and Ghulkin glaciers. The main conclusions are:

1) Over the past century, especially since the 1970s, the Batura, Pasu, and Ghulkin glaciers have generally been in weak retreat, with ice tongues retreating, thinning, or remaining basically stable, and their direct threat to the highway tending to diminish.
2) Under the combined influence of intensified glacier ablation and ice tongue fluctuations, meltwater runoff in the Batura section frequently migrates and changes course, and secondary disasters such as glacial meltwater floods, glacial lake outburst floods, and glacial debris flows increasingly threaten highway safety.
3) The most direct threat to the highway from glacier variations in the Batura section is the new diversion of the Batura River in June-July 2021, after which water flow will directly impact and erode the roadbed, affecting highway safety.

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