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# **CPEC and BRI Nexus**

## **Perspectives on Economy, Politics, Culture and Environment**

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## **The repercussions of the Glacier Lake Outburst Floods on CEPC in Gilgit-Baltistan, Pakistan**

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### **Abstract**

The China-Pakistan Economic Corridor (CPEC) is a pivotal infrastructure and economic initiative that aims to substantially improve connectivity and regional development. Nonetheless, its execution across the glaciated and mountainous landscape of Gilgit-Baltistan (GB), Pakistan, renders it susceptible to significant environmental threats, especially Glacial Lake Outburst Floods (GLOFs). This chapter examines the escalating threat of Glacial Lake Outburst Floods (GLOFs), their origins, attributes, and significant ramifications for the sustainability of the CPEC. It provides comprehensive accounts of historical GLOF events, their effects on infrastructure and livelihoods, and the escalating risks associated with climate change-induced glacier melt. The study underscores GB's susceptibility owing to its high density of glaciers and glacial lakes, and delineates the potential economic, social, and geopolitical disturbances to CPEC if these risks are not addressed. This chapter highlights the necessity of early warning systems, resilient infrastructure, glacial monitoring, and international collaboration, drawing on global best practices in GLOF risk management, especially from

Bhutan and Switzerland. It culminates with strategic recommendations to enhance CPEC's resilience to future GLOF threats, thereby ensuring regional connectivity and sustainable development in the context of a changing climate.

**Keywords:** Glacial Lake Outburst Floods (GLOFs), Climate Change, Glacier Retreat, Early Warning Systems, Environmental Hazards, Sustainable Development

## **Background**

The economic benefits of CPEC are multifaceted, such as it addresses Pakistan's infrastructure gaps, which have long hindered economic development. It includes the construction of modern highways, railways, and energy infrastructure. A significant portion of the route also focuses on energy projects, including coal, hydro, solar, and wind power. These projects aim to alleviate Pakistan's chronic energy shortages. The development of CPEC projects generates employment opportunities, fostering economic growth and poverty reduction (Arshed et al., 2021). While CPEC offers numerous possibilities, it faces challenges and concerns, including security risks, debt sustainability, and environmental impacts. Balancing the potential benefits with these challenges is a complex task for China and Pakistan.

The project represents a transformative initiative that has the potential to reshape the economic dynamics of the region (Healey, 2004). Its significance extends beyond bilateral relations, encompassing regional and global economic integration. However, realizing its full potential requires addressing challenges and fostering stakeholder cooperation. M. Hussain and Jamali (2019) shared that CPEC is a testament to the evolving nature of international economic partnerships in the 21st century, where connectivity and infrastructure development are central in shaping geopolitical and economic landscapes.

However, the stream of projects in CPEC can be jeopardized if the natural disasters alongside this corridor are not mitigated. For example, Glacial Lake Outburst Floods (GLOFs) are sudden, often catastrophic, floods resulting from the rapid release of water stored in glacial lakes. These events typically occur when a natural dam, consisting of moraine (glacial debris) holding back the lake water, is breached or overtopped (Maskey et al., 2020). GLOFs are natural disasters with devastating potential, particularly in high-mountain regions like Gilgit-Baltistan (Shah et al., 2019). These are primarily triggered by several interrelated factors, such as Glacier melt due to rising temperatures, a consequence of climate change, lead to accelerated glacier melting (Sahade et al., 2015). An inflow of meltwater has the potential to inundate glacial

lakes, leading to heightened water volume and instability. Incidents like avalanches or landslides occurring within glacial lakes can result in the sudden displacement of a substantial amount of water, potentially triggering GLOFs (Glacial Lake Outburst Floods). Volcanic activity in certain regions can lead to the melting of glaciers, consequently causing GLOFs.

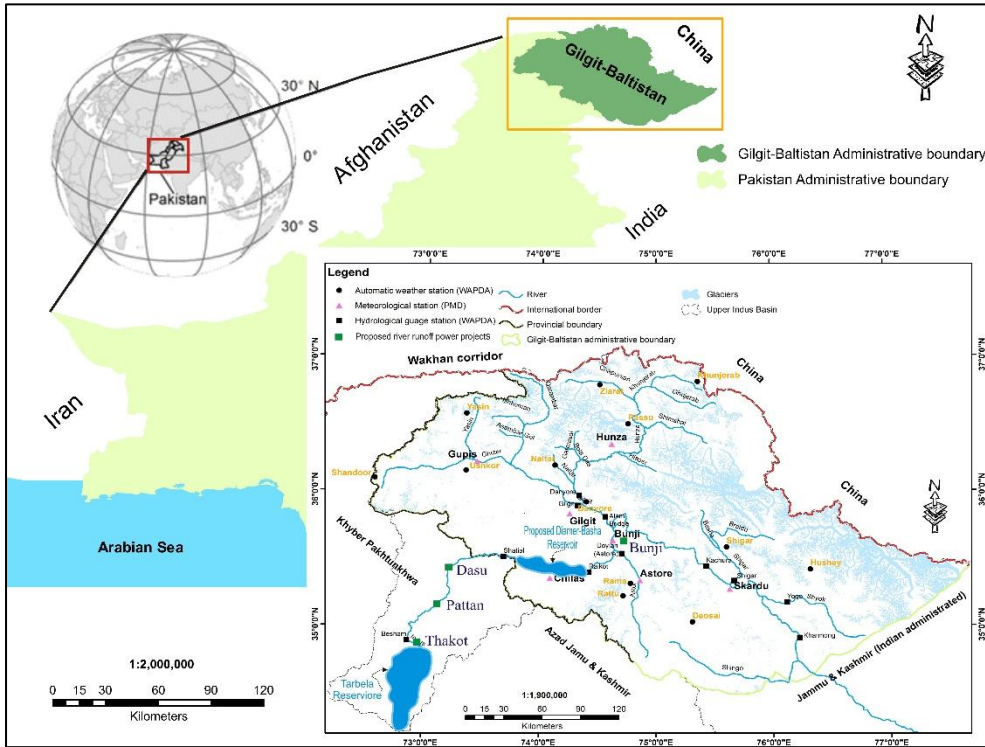


Figure 5. Map of Gilgit-Baltistan

According to several key features, GLOFs are characterized by *Sudden Onset*: GLOFs often occur with little warning, making early detection and evacuation challenging. *High Velocity*: These floods can move at astonishing speeds, carrying debris, rocks, and sediment, leading to significant erosional and destructive power. *Enormous Volumes*: GLOFs can release vast volumes of water, posing a substantial threat to downstream areas (Huggel et al., 2020). Gilgit-Baltistan (GB) is a mountainous region located in northern Pakistan (Figure 1), home to some of the world's highest peaks and largest glaciers, such as the Karakoram Range and Siachen Glacier, Baraldu, Biafo-Hisper, Batura, Chogolugma and many more glaciers (Qureshi et al., 2021). Geographically, It shares borders with China, Afghanistan, and Indian-administered Jammu and Kashmir (Maqpoon et al., 2013). Its geography makes it highly susceptible to GLOFs. The region has many glacial lakes, potentially hazardous due to their unstable moraine dams (Ashraf et al., 2012).

Climate change has amplified the risk of GLOFs in Gilgit-Baltistan due to rising temperatures, which have led to the rapid retreat of glaciers. As glaciers shrink, the volume of meltwater feeding into glacial lakes increases (Rehman, 2015). Due to these changes, the region has witnessed a heightened frequency of GLOF events.

Gilgit-Baltistan is home to numerous villages, towns, and crucial infrastructure, including parts of the China-Pakistan Economic Corridor (CPEC) and the Karakoram Highway (KKH) (Waheed et al., 2023). These settlements and infrastructure are often located in vulnerable downstream areas, making them susceptible to GLOF impact. GLOFs can have profound consequences for the people of Gilgit-Baltistan in terms of casualties, damage to homes, and destruction of agricultural land. Subsistence agriculture, a primary source of livelihood and critical infrastructure, including roads and bridges, can be washed away or severely damaged, hindering transportation and connectivity. In Gilgit-Baltistan, GLOFs are not just geological events but a matter of life, safety, and sustainable development. Understanding the causes and characteristics of GLOFs is crucial for assessing the risks they pose to this vulnerable region. Mitigation and adaptation strategies are essential to reduce the impact of these floods on the communities, infrastructure, and environment of Gilgit-Baltistan.

In light of the raised issues concerning environmental calamities, the primary purpose of this chapter is to establish the importance of GLOFs as a significant natural hazard in the Gilgit-Baltistan region. We will elucidate why GLOFs are relevant and highly interested in the context of China-Pakistan Economic Corridor (CPEC). It will explore how the vulnerability of CPEC to GLOFs can impact economic development, safety, and regional connectivity in the region.

### **Causes and Characteristics of GLOFs**

GLOFs, or Glacial Lake Outburst Floods, are sudden and often devastating



Figure 6. Impact of GLOF on livelihood (left Badswat, Ghizer and right Attaabad Hunza)

events when a glacial lake's dam or moraine (a mound or ridge of unsorted sediment deposited by a glacier) fails, releasing a large volume of water downstream. These events are typically associated with glaciers in mountainous regions and can have severe consequences for downstream mountain communities and ecosystems (Figure 2 & 3.) Here are some of the causes and characteristics of GLOFs:

***Causes of GLOFs are associated with Glacial Retreat:*** One of the primary causes of GLOFs is the retreat of glaciers due to climate change. As glaciers melt and recede, they leave behind depressions or basins that can fill with meltwater, rainwater, or a combination of both. ***Glacial Lake Formation:*** Meltwater from glaciers collects in these depressions, forming glacial lakes. The rapid accumulation of water can lead to the expansion of these lakes, which can pose a risk if the dam or natural barrier holding the water back is not stable. ***Mechanical and Thermal Erosion:*** Glacial ice can melt and erode the dam or moraine that holds back the lake, weakening its structural integrity. The combination of mechanical erosion (ice movement) and thermal erosion (melting due to temperature changes) can lead to dam failure. ***Earthquakes and Landslides:*** Seismic activity or landslides in mountainous regions are other factors that can trigger lake outburst floods by causing the dam or moraine to rupture or collapse. These events can also displace ice and debris into the lake, increasing the flood's destructive potential (Figure 3).



Figure 7. Impact of GLOF on CPEC (GLOF 2022 of Shishper, Hunza)

Glacier Lake outburst floods typically occur with little to no warning. The release of water from a glacial lake can be remarkably rapid, leading to a sudden surge of floodwater downstream (Wang & Zhou, 2017). It is characterized by high flow velocities due to the steep terrain of mountainous regions. The water can carry debris, rocks, and sediment, which increases the flood's destructive power. Church and Jakob (2020) state that the volume of water released during a GLOF can be enormous, ranging from thousands to

millions of cubic meters. This can result in widespread flooding in downstream areas (Church & Jakob, 2020). GLOFs often carry large amounts of debris and sediment eroded from the glacier, lakebed, and surrounding terrain. This sediment can further exacerbate the destructive impact of the flood. It can have catastrophic consequences for downstream communities, infrastructure, and ecosystems. They can lead to loss of life, damage to property, and disruption of critical infrastructure such as roads and bridges. The floodwaters from a GLOF can travel long distances downstream, affecting communities and ecosystems far from the source (Maurer et al., 2020). Climate change contributes to the increasing frequency and severity of GLOFs as glaciers retreat and glacial lakes expand. This makes GLOFs a critical issue to address in the context of climate change adaptation and mitigation. Efforts to mitigate the risks associated with GLOFs include monitoring and early warning systems, engineering interventions to stabilize glacial lake dams, and improved land-use planning in vulnerable areas. Understanding the causes and characteristics of GLOFs is crucial for reducing the potential impact of these hazardous events.

### Assessing the Risks and Challenges

Gilgit-Baltistan (GB) is a northern Pakistan region located in the northwestern part of the Indian subcontinent. It is a strategically important area known for its stunning landscapes, including rugged mountains, deep valleys, glaciers, and pristine lakes (S. Hussain, 2015). It shares borders with India-administered Jammu and Kashmir to the east, Afghanistan's Wakhan Corridor to the west, the Chinese region of Xinjiang to the north, and Pakistan's Khyber Pakhtunkhwa province to the south. The region is characterized by some of the world's highest mountain ranges, including the Karakoram Range, the western Himalayas, and the Hindu Kush (Padukone, 2014).



Figure 8. Mean Temperature and Precipitation trend of Gilgit-Baltistan (Source: Data source Pakistan Metrological Department (1984-2013))

Gilgit-Baltistan, a region nestled within the grandeur of the Karakoram Range in northern Pakistan, is renowned for its breathtaking prevalence of glaciers

and glacial lakes. GB has several of the world's highest peaks, including K2 (the second-highest peak on Earth), Gasherbrum I, and Broad Peak. The region is known for its numerous glaciers, including the Siachen Glacier, one of the world's longest glaciers crisscrossed by deep river valleys, with the Indus River being the most significant. The Hunza, Shyok, and Gilgit Rivers also flow through the region. This rugged terrain boasts thousands of glaciers, many of which are the most extensive in the world. These glaciers, formed over centuries, have carved the dramatic landscapes of steep peaks, deep valleys, and pristine lakes that define the region's natural beauty. However, the impact of climate change is significant as rising temperatures accelerate the retreat of these glaciers (Figure 4), contributing to the formation of glacial lakes, which leave behind depressions and basins filled with meltwater. While these lakes enhance the picturesque scenery, they also pose significant risks, as their natural or manufactured dams can fail, leading to catastrophic glacial lake outburst floods (GLOFs). Thus, the prevalence of glaciers and glacial lakes in Gilgit-Baltistan (Figure 5) is evidence of its awe-inspiring landscapes and a reminder of the delicate balance between nature's grandeur and the challenges a changing climate poses.

GB experiences diverse climates, from alpine and subarctic in the high mountains to arid and semi-arid in the valleys. Winters are cold and harsh, with heavy snowfall in the high-altitude areas. Summers are relatively milder, making it a popular destination for trekkers and mountaineers. The region is renowned for its breathtaking natural beauty, scenic landscapes, crystal-clear lakes like Attaabad and Sheosar Lake, and lush green valleys. The Karakoram Highway, which passes through Gilgit-Baltistan, offers stunning views of the surrounding mountains. Gilgit-Baltistan has diverse ethnic groups, including the Balti, Shina, Burusho, Wakhi, and Domki people, each with distinct cultures and languages. The region has a rich cultural heritage, with influences from Tibetan, Central Asian, and South Asian traditions. It is known for its traditional music, dance, and festivals, which reflect the unique cultural mix of the area.

The economy of GB is primarily based on agropastoral life, with crops like wheat, barley, potato and fruits being grown in the valleys (Kolář et al., 2022). Tourism is a growing sector, attracting visitors to the region's natural beauty, trekking and mountaineering opportunities, and cultural experiences. The region is also strategically important due to its proximity to China and its role in the China-Pakistan Economic Corridor (CPEC).

Gilgit-Baltistan has a unique political status within Pakistan. It is self-governing to some extent but lacks full provincial status (Uddin). It has its

legislative assembly and governor, but ultimate authority rests with the federal government of Pakistan. Overall, Gilgit-Baltistan is a region of immense natural beauty and cultural diversity, making it a significant tourist destination and an area of strategic importance due to its proximity to China and its role in regional connectivity projects (Nigar, 2018).

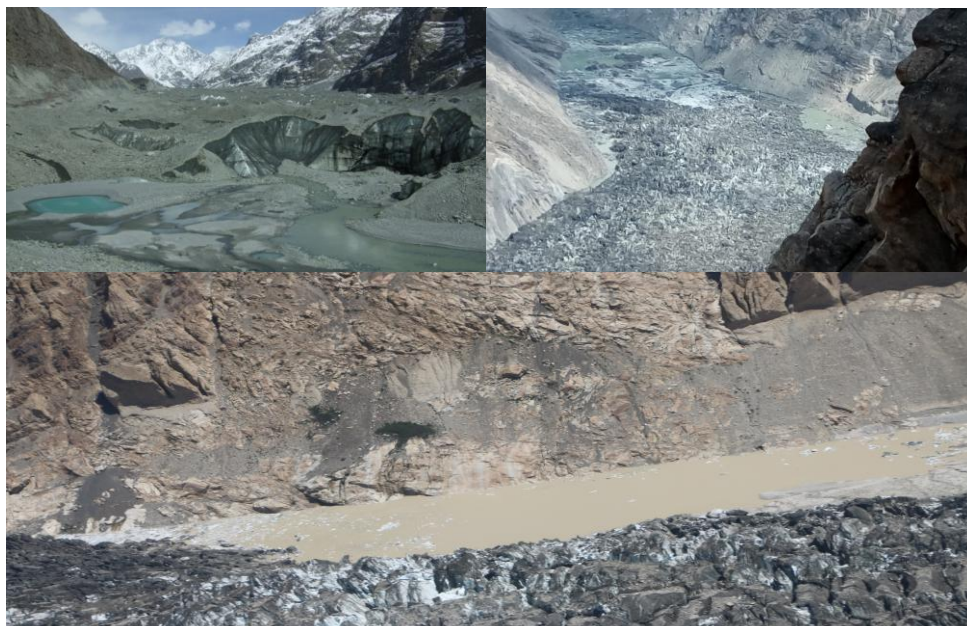


Figure 9. Selected Glaciers of Karakoram with Glacier Lakes (Hinerchi left, Shishper Glacier right and Bottom Khurdopin Glacier)

GB, a mountainous region in northern Pakistan, boasts a remarkable prevalence of glaciers and glacial lakes. Nestled within the Karakoram Range, it houses thousands of glaciers, including some of the world's largest and most extensive ice formations, contributing significantly to its "Third Pole" status (Bahadur, 2004). As these glaciers retreat due to climate change, they often give rise to glacial lakes within the region, such as Attaabad Lake and Sheosar Lake, enhancing the area's breathtaking natural beauty. However, this abundance of glacial lakes also presents a potential hazard, as the dams holding them back can fail, triggering glacial lake outburst floods (GLOFs) with devastating consequences downstream (Figure 6). Consequently, Gilgit-Baltistan's glacial landscape has scientific intrigue and environmental challenges, highlighting the delicate balance between natural beauty and environmental risks (Farrukh, 2019).

Climate change has profoundly impacted glacial melt in regions like Gilgit-Baltistan. Rising global temperatures have accelerated the retreat of glaciers, causing them to lose ice mass at an alarming rate (D. Karim et al., 2020;

Mazhar et al., 2020). This increased meltwater flows into the region's rivers and contributes to the formation of glacial lakes, raising concerns about glacial lake outburst floods (GLOFs). Moreover, the reduction in glacier size threatens the reliable water supply that downstream communities depend on, particularly for agriculture and hydropower. The consequences of glacial melt due to climate change are far-reaching, affecting not only local ecosystems and water resources but also posing long-term challenges for adaptation and sustainable development in these high-mountain areas.



Figure 10. Impact of Climate Change on Agriculture Land/Crops

### **China-Pakistan Economic Corridor is Transformative Project**

The China-Pakistan Economic Corridor (CPEC) is widely recognized as a transformative project with the potential to reshape not only the economic landscape of China and Pakistan but also the broader geopolitical dynamics of the region (Garlick, 2020). Stretching over 2,000 kilometres, CPEC (Figure 7) is a monumental undertaking aimed at creating a robust network of infrastructure and economic connectivity between China's western region, particularly Xinjiang, and Pakistan's Gwadar Port on the Arabian Sea (Hanif, 2021; Khattak & Khan, 2021).

At its core, CPEC is designed to significantly reduce the transportation time and costs for Chinese goods transferring to and from the Middle East, Africa, and Europe. By providing a shorter and more efficient trade route compared to the traditional sea route through the South China Sea and the Strait of Malacca, CPEC holds immense strategic value for China. It helps diversify its trade routes, enhances energy security, and strengthens its economic ties with Pakistan (Alam et al., 2023; F. Hussain & Hussain, 2017).

One of the flagship components of CPEC is the Gwadar Port, strategically

located in Pakistan's Baluchistan province (Asif, 2018; Shah et al., 2019). Gwadar Port's deep-sea facilities have the potential to become a crucial trade and logistics hub for the region, offering access to the Arabian Sea and facilitating trade between China and its trading partners. China has invested significantly in upgrading and expanding Gwadar Port, which is expected to be pivotal in CPEC's success (Asif, 2018).

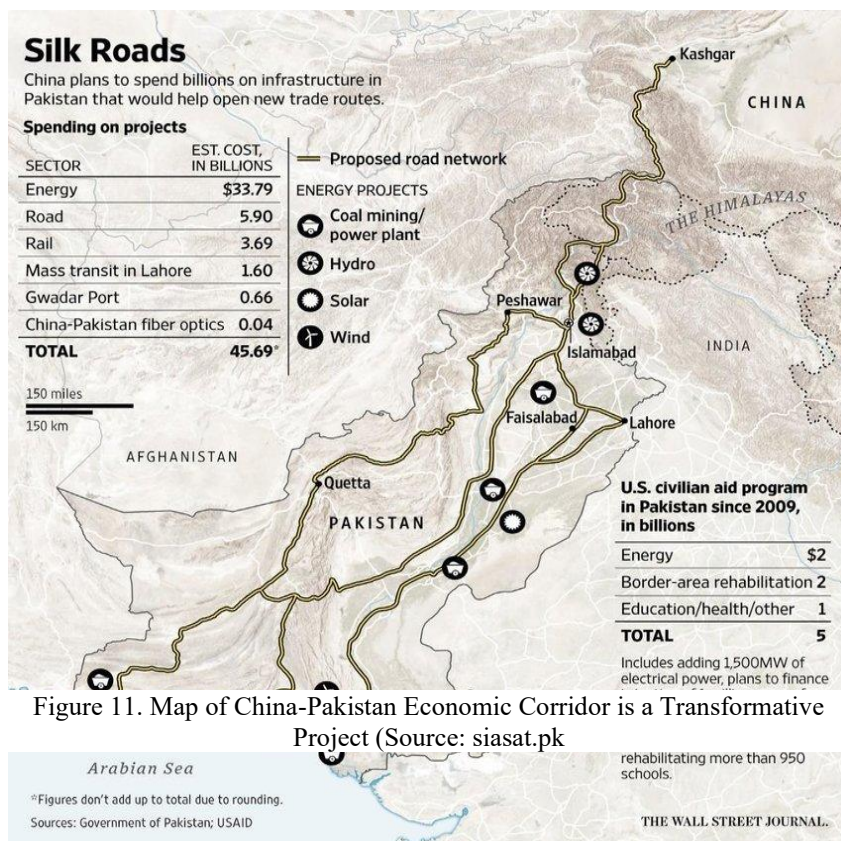


Figure 11. Map of China-Pakistan Economic Corridor is a Transformative Project (Source: [siasat.pk](http://siasat.pk))

CPEC encompasses many projects, including developing road and rail networks, energy infrastructure, and special economic zones. These projects aim to boost Pakistan's infrastructure, address energy shortages, promote industrialization, and create job opportunities. Moreover, CPEC's potential to stimulate economic growth in Pakistan aligns with the country's development goals (M. Z. U. Khan & Khan, 2019).

While CPEC holds immense promise, it is not without its challenges and controversies. Security concerns have been persistent, particularly in Baluchistan, where insurgent groups have targeted CPEC-related projects. Critics have also raised questions about transparency, environmental impact, and the extent to which local communities benefit from the initiative (Wilburn

& Wilburn, 2014). Addressing these challenges will be crucial to fully realizing CPEC's transformative potential.

In conclusion, CPEC represents a transformative project that has already begun to reshape the economic and geopolitical dynamics of the region. Its success will depend on effective management, addressing security concerns, and ensuring that its benefits are equitably distributed among the people of Pakistan. CPEC underscores China's strategic interests and Pakistan's aspirations for economic development, making it a project of significant global significance and scrutiny.

### **Historical GLOF Events Along the CPEC Route**

Historically, the China-Pakistan Economic Corridor (CPEC) route, which traverses through the mountainous regions of northern Pakistan, has been susceptible to Glacial Lake Outburst Floods (GLOFs). These events occur when the natural or man-made dams that hold back glacial lakes fail, releasing massive amounts of water, debris, and ice downstream. Here are some notable historical GLOF events along the CPEC route as below:

***Khurdopin Glacier GLOF:*** The Khurdopin Glacier, located in the Shimshal Valley of the Hunza district, has exhibited a historical pattern of surging, retreating, and bursting approximately every 20 years. The glacier's bursting in 1905 and 1964 significantly affected both public and private infrastructure downstream, extending beyond Gilgit city. The most recent surge occurred around 1998-99. After a prolonged period of minimal movement, the glacier rapidly advanced in October 2016. As ice and sediment accumulated in the river, a substantial lake formed by December 2017. According to expert reports, the glacier's behavior has been unusually pronounced, resulting in the Shimshal River's complete blockage and a glacial lake's formation.

***Shishper Glacier GLOF (2020-2022):*** In 2020 and 2021, a GLOF event originating from the Shishper Glacier in the Hunza Valley threatened downstream communities and infrastructure (G. Khan et al., 2021; I. Rashid et al., 2020; Saifullah et al., 2020; Singh et al., 2023). The surge of glacial meltwater and debris posed significant risks, and authorities had to evacuate vulnerable areas and take preventive measures. While the situation was managed without severe damage, it highlighted the ongoing threat of GLOFs in the region (G. Khan et al., 2021).

***Barpu GLOF (2017):*** In 2017, another GLOF event occurred in the Barpu Glacier area, leading to heightened concerns about the vulnerability of the CPEC route to such natural disasters (Gao et al., 2021). The Barpu GLOF

resulted from a glacial lake dam bursting, sending a surge of water and debris downstream. Fortunately, there were no reported casualties, but the incident underscored the importance of monitoring and managing glacial lakes in the region (Sivalingam et al., 2023).

These historical GLOF events serve as reminders of the challenges and risks associated with the rugged and glaciated terrain along the CPEC route. Climate change has accelerated glacial melt in the region, increasing the potential for such events. Consequently, infrastructure development under the CPEC initiative must consider the impact of GLOFs on transportation routes, energy projects, and local communities and incorporate measures to mitigate these risks. Monitoring, early warning systems, and disaster preparedness are crucial components in addressing the threat of GLOFs along this vital economic corridor. The impact of Glacial Lake Outburst Floods (GLOFs) along the China-Pakistan Economic Corridor (CPEC) route can be significant and multifaceted, affecting infrastructure, communities, and the economy in various ways:

GLOFs can damage or destroy critical transportation infrastructure, such as roads and bridges, disrupting the flow of goods and people along the CPEC route. In particular, the Karakoram Highway (KKH) has been vulnerable to such events as it traverses through mountainous terrain. *It* can also impact energy infrastructure, including hydropower projects. Damage to power generation facilities can lead to regional electricity shortages and disruptions, affecting industries and households. Floodwaters and landslides resulting from GLOFs can damage communication networks, making it difficult for authorities to coordinate rescue and relief efforts in affected areas. It can lead to the loss of human lives, destruction of homes, and displacement of communities. People living near glacial lakes are particularly vulnerable to such events, and their livelihoods, including agriculture and tourism, may be severely affected. The trauma and psychological impact on affected communities can be long-lasting. Displacement and loss of homes and livelihoods can lead to social and economic challenges for these communities. GLOFs can disrupt trade along the CPEC route, affecting the flow of goods between China and Pakistan. Delays in transportation and damage to infrastructure can lead to increased costs for businesses. Rebuilding and repairing infrastructure damaged by GLOFs can be costly. Governments and international agencies must often allocate significant resources to restore roads, bridges, and other critical facilities. GLOFs can impact the energy supply, affecting industries and businesses dependent on a stable power supply. Energy shortages can lead to production delays and reduced economic activity. Many areas along the CPEC route are popular tourist destinations.

GLOFs can deter tourists, leading to declining tourism-related revenue and employment opportunities.

To mitigate the impact of GLOFs on infrastructure, communities, and the economy along the CPEC route, various measures can be taken:

- *Early Warning Systems:* Implementing early warning systems that detect potential GLOFs and provide timely alerts to communities downstream is crucial for saving lives and minimizing damage.
- *Infrastructure Resilience:* Designing and constructing infrastructure, including roads and bridges, to be more resilient to GLOFs can reduce the extent of damage and shorten recovery times.
- *Community Preparedness:* Communities in vulnerable areas should be educated and prepared to respond to GLOF threats. Evacuation plans and emergency shelters can help protect lives.
- *Climate Change Adaptation:* Addressing the root cause of glacial melt and GLOFs by taking measures to mitigate climate change and reduce greenhouse gas emissions is essential for long-term resilience.
- *International Collaboration:* Given the transboundary nature of GLOF risks, international cooperation between China, Pakistan, and neighbouring countries is crucial for monitoring and managing these hazards effectively.

Glacier Lake Outburst Floods along the CPEC route pose significant risks to infrastructure, communities, and the economy. Addressing these risks requires a combination of infrastructure improvements, early warning systems, community preparedness, and climate change mitigation efforts to ensure the safety and sustainability of the region's development and economic activities.

### **Assessing the Vulnerability of CPEC to GLOFs**

Assessing the vulnerability of the China-Pakistan Economic Corridor (CPEC) to Glacial Lake Outburst Floods (GLOFs) involves evaluating several vital factors, including the proximity of CPEC to glacial lakes and vulnerable areas, the implications of climate change, and the resilience and vulnerability of infrastructure:

***Geographical Location:*** Much of the CPEC route traverses through mountainous regions of northern Pakistan, where numerous glacial lakes are found. The melting glaciers often form these lakes, and their proximity to the infrastructure can pose a significant risk.

***Potential GLOF Sources:*** Identifying the specific glacial lakes that pose a GLOF risk to the CPEC route is essential. Lakes located upstream of critical

infrastructure, such as roads, railways, and power plants, are of particular concern.

***Local Communities:*** Evaluating the presence of local communities in vulnerable areas is crucial. GLOFs can severely impact these communities, leading to loss of lives, displacement, and disruption of livelihoods.

***Glacial Retreat:*** The accelerated melting of glaciers due to climate change contributes to the formation of glacial lakes and increases the risk of GLOFs. Assessing the region's glacial retreat rate is essential to understanding the evolving threat.

***Changing Precipitation Patterns:*** Climate change can also alter precipitation patterns, potentially leading to increased rainfall or snowmelt in the mountains. This can further exacerbate GLOF risks.

***Temperature Increases:*** Rising temperatures can affect the stability of glacial moraines and dams, potentially increasing the likelihood of GLOF events.

***Design and Construction:*** Evaluating the design and construction standards of infrastructure along the CPEC route is critical. Infrastructure built to withstand GLOF impacts, such as stronger bridges and embankments, can reduce vulnerability.

***Early Warning Systems:*** The availability of early warning systems that can detect GLOF threats and provide timely alerts to authorities and communities is crucial for reducing vulnerability.

***Emergency Response and Preparedness:*** Assessing the preparedness of local authorities and communities to respond to GLOF events can help mitigate the impact. Evacuation plans, emergency shelters, and disaster response capabilities are essential.

***Risk Mitigation Measures:*** Identifying and implementing risk mitigation measures, such as relocating vulnerable infrastructure or implementing engineering solutions to stabilize glacial lakes, can enhance resilience.

The vulnerability of CPEC to GLOFs is a complex issue that involves assessing the proximity of critical infrastructure to glacial lakes, understanding the implications of climate change on glacial dynamics, and evaluating the resilience and vulnerability of the infrastructure itself. A comprehensive risk assessment, early warning systems, and proactive measures are essential to mitigate the potential impact of GLOFs on the CPEC route and ensure the safety and sustainability of this vital economic corridor.

## **Impact on CPEC and Economic Implications**

The potential impact of Glacial Lake Outburst Floods (GLOFs) on the China-Pakistan Economic Corridor (CPEC) and its economic implications is a matter of significant concern. GLOFs can have far-reaching financial consequences, particularly in CPEC, a vital trade and infrastructure project connecting China and Pakistan (Khayyam & Tariq, 2022).

Firstly, the economic consequences of GLOF-related disruptions are substantial. GLOFs can destroy critical transportation routes, such as roads and railways, which are the lifelines of CPEC. This disruption can impede the smooth flow of goods and services, affecting trade between China and Pakistan and potentially causing economic losses for both countries.

Secondly, the costs associated with infrastructure damage and repair are a significant concern. GLOFs can destroy bridges, tunnels, and other infrastructure components along the CPEC route. The financial burden of repairing and rebuilding this infrastructure falls on China and Pakistan, straining their budgets and potentially delaying the completion of CPEC projects (Hameed, 2018).

Furthermore, safety concerns for workers and local communities cannot be understated. GLOFs can pose severe risks to the safety of construction workers and the residents of nearby areas. Ensuring the safety of these individuals requires additional investments in disaster preparedness and response measures, which can further add to the project's overall costs.

In conclusion, GLOFs can have substantial economic implications for CPEC, affecting trade, infrastructure, and safety. As such, both China and Pakistan must incorporate robust risk mitigation strategies into the planning and execution of CPEC projects, with a particular focus on addressing the challenges posed by GLOFs to safeguard their long-term economic interests.

## **Mitigation and Adaptation Efforts**

Mitigation and adaptation efforts for Glacial Lake Outburst Floods (GLOFs) are crucial in addressing the risks associated with these potentially devastating events. Several key strategies can be employed to reduce the impact of GLOFs on communities and infrastructure.

***Early Warning Systems for GLOF Detection:*** Implementing effective early warning systems is paramount. These systems involve deploying sensors near glacial lakes to monitor water levels, temperature, and seismic activity. When abnormal changes or signs of an impending GLOF are detected, automated

alerts are sent to relevant authorities and communities. Public awareness campaigns play a vital role in ensuring that people are informed about how to respond to these warnings promptly. By providing advance notice, early warning systems can save lives and minimize property damage in GLOF-prone regions.

***Infrastructure Upgrades and Retrofitting:*** Proactive measures are essential to enhance resilience against GLOFs. Existing infrastructure, such as bridges, roads, and buildings, can be retrofitted to withstand potential flood events. Engineers can design structures with flood resilience in mind, ensuring they can withstand the force of a GLOF. Furthermore, when planning new infrastructure projects, careful consideration should be given to elevating critical facilities and avoiding construction in high-risk areas. These measures can significantly reduce infrastructure vulnerability to GLOFs (Figure 8).



Figure 12. Mitigation and Adaptation measurement along KKH (Photo source: DDMA Hunza)

***Glacial Lake Monitoring and Risk Assessment:*** Regular monitoring and risk assessment of glacial lakes are crucial for identifying potential hazards. Advanced remote sensing technologies, including satellite imagery and drones, can be employed to track changes in the size and volume of glacial lakes. Risk assessments help determine which lakes are most likely to pose a

threat in the future. Based on these assessments, targeted mitigation strategies can be developed. It may include controlled drainage of glacial lakes to reduce the risk of sudden outbursts or reinforcing unstable moraine dams to prevent catastrophic failures.

***International Collaboration on Climate Change Mitigation:*** GLOFs are closely linked to climate change, as rising temperatures contribute to glacier melt and the formation of unstable glacial lakes. Addressing the root causes of GLOFs requires international cooperation to combat climate change. Nations must work together to reduce greenhouse gas emissions and limit global warming. Participation in international agreements like the Paris Agreement is essential to mitigate the long-term impacts of climate change, including the increased likelihood of GLOFs. By reducing the rate of glacier melt, climate change mitigation efforts indirectly contribute to GLOF risk reduction.

A comprehensive approach to GLOF mitigation and adaptation includes establishing early warning systems, infrastructure improvements, ongoing monitoring of glacial lakes, and international efforts to combat climate change. These measures collectively aim to reduce the risk of GLOFs, enhance the safety of communities in vulnerable areas, and protect critical infrastructure from the potentially devastating consequences of glacial lake outburst floods.

### **Case Studies and Best Practices**

***Bhutan's Glacial Lake Management:*** Bhutan has proactively managed GLOF risks in its mountainous regions. The country has identified and prioritized high-risk glacial lakes and implemented measures such as controlled drainage to reduce water levels in these lakes during the monsoon season (Gurung et al., 2017). Additionally, Bhutan has established early warning systems and conducted extensive public awareness campaigns (Shrestha et al., 2016). These measures have significantly reduced the vulnerability of local communities to GLOFs.

***Swiss Alps GLOF Mitigation:*** Switzerland, known for its mountainous terrain, has effectively implemented various strategies to manage GLOF risks. The Swiss have employed advanced monitoring systems to track glacier dynamics and assess the stability of glacial lakes (Vilimek et al., 2014). When necessary, they conduct controlled drainage to prevent catastrophic outbursts. Switzerland's comprehensive approach to GLOF risk management includes infrastructure resilience measures, such as reinforcing bridges and roads in vulnerable areas (Khanal et al., 2015). These case studies offer valuable lessons that can be applied to the China-Pakistan Economic Corridor (CPEC) to mitigate GLOF risks.

***Early Warning Systems and Public Awareness:*** Bhutan's successful approach underscores the importance of early warning systems and public awareness campaigns. Implementing similar systems along the CPEC route and educating local communities about GLOF risks can help save lives and reduce the impact of floods (Tsering et al., 2021).

***Prioritization of High-Risk Areas:*** Like Bhutan, CPEC planners should prioritize high-risk areas along the corridor for comprehensive risk assessment and mitigation. Identifying and addressing vulnerabilities in critical infrastructure, such as bridges and tunnels, is essential to ensure the corridor's resilience (Ruta et al., 2019).

***Infrastructure Resilience:*** Switzerland's experience highlights the importance of infrastructure resilience. Retrofitting and reinforcing critical infrastructure components can enhance their ability to withstand GLOF-related disruptions (I. Karim & Ahmad). CPEC projects should incorporate such resilience measures to minimize damage and downtime.

***Advanced Monitoring Technologies:*** Advanced monitoring technologies, including remote sensing, can provide valuable data for risk assessment and early warning (Casagli et al., 2023). It can benefit from similar monitoring systems to track the region's glacial lakes and glacier dynamics.

**International Collaboration:** Given the transboundary nature of GLOF risks in mountainous regions, collaboration between China and Pakistan is crucial. These countries should also collaborate with neighbouring nations and international organizations to share data, expertise, and best practices in GLOF risk management.

As demonstrated by Bhutan and Switzerland, successful GLOF risk management in mountainous regions offers valuable insights for mitigating GLOF risks along the CPEC route. Implementing early warning systems, prioritizing high-risk areas, enhancing infrastructure resilience, utilizing advanced monitoring technologies, and fostering international collaboration are key components of an effective strategy to protect the CPEC project and the safety of those living in the region.

## **Conclusion**

In examining the impact of Glacier Lake Outburst Floods (GLOFs) hazards on the China-Pakistan Economic Corridor (CPEC) in Gilgit-Baltistan, it becomes evident that the intersection of rapid climate change and ambitious infrastructure development presents a complex and pressing challenge. This investigation has unveiled several key insights: First and foremost, GLOFs are

a growing threat in mountainous regions, exacerbated by the effects of climate change. The rapid melting of glaciers and the formation of potentially unstable glacial lakes underscore the urgency of proactive GLOF risk management. The China-Pakistan Economic Corridor, a linchpin of regional trade and development, traverses this vulnerable terrain, making it susceptible to GLOF-related disruptions. These disruptions can have far-reaching consequences, affecting trade routes, infrastructure, and the safety of local communities. However, there is hope. The case studies of successful GLOF risk management in Bhutan and Switzerland provide valuable lessons. Early warning systems, infrastructure resilience, and international cooperation have effectively mitigated GLOF risks. Looking ahead, it is clear that proactive GLOF risk management is not just a necessity but a strategic imperative for the success of CPEC in Gilgit-Baltistan. It describes comprehensive strategies, including early warning systems, resilient infrastructure, and policies prioritising safety and sustainability.

In conclusion, the confluence of GLOF hazards and the China-Pakistan Economic Corridor underscores the need for foresight, collaboration, and adaptive measures. By addressing these challenges head-on, CPEC can thrive and set an example for sustainable, resilient development in the face of climate-related risks. In doing so, it will contribute to economic growth, the well-being of the region's people, and the preservation of its natural environment.

### **Future Challenges and Recommendations**

*Anticipating Future GLOF Risks in the Context of Climate Change:* The impact of climate change on glacial dynamics and the frequency of GLOFs is a significant challenge. To address this, comprehensive research and modelling efforts should be undertaken to anticipate how climate change will affect glacial lakes and GLOF risks along the CPEC route. It includes monitoring glacier retreats, lake expansion, and changing precipitation patterns.

*Strategies to Enhance CPEC's Resilience to GLOFs:* Enhancing the resilience of the CPEC infrastructure to GLOFs is imperative. Recommendations include designing critical infrastructure, such as bridges and tunnels, to be flood-resistant, elevating key facilities above potential flood levels, and developing emergency response plans. Additionally, building redundancy into the transportation network to allow for alternative routes during disruptions can be crucial.

**Policy Recommendations and International Cooperation:** Policymakers should consider the following recommendations:

**Legislation and Regulation:** Develop and enforce regulations that require infrastructure projects in GLOF-prone areas to adhere to strict safety and resilience standards. It includes regular inspections and maintenance.

**Insurance and Risk Assessment:** Encourage private sector involvement in risk assessment and insurance solutions for GLOF-related risks, which can help cover damages and recovery costs.

**International Cooperation:** Collaborate with neighbouring countries, particularly China, to share data, expertise, and resources for GLOF risk management. Joint research and monitoring efforts can provide a comprehensive view of the GLOF risk landscape in the region.

**Capacity Building:** Invest in training programs and capacity building for local communities, government agencies, and first responders to improve preparedness and response to GLOFs.

**Climate Change Mitigation:** Continue efforts to mitigate climate change through international agreements like the Paris Agreement. Reducing greenhouse gas emissions can help slow the pace of glacier melt and mitigate the formation of unstable glacial lakes.

**Public Awareness:** Implement public awareness campaigns to educate local communities about GLOF risks and the importance of preparedness and response.

**Research and Monitoring:** Invest in ongoing research and monitoring of glacial lakes and the surrounding environment. This includes using remote sensing technologies, drones, and satellite imagery to track glacial lakes and glacier changes. Regular risk assessments should inform adaptive strategies.

**Early Warning Systems:** Strengthen and expand early warning systems along the CPEC route, ensuring they are equipped with real-time data and effective communication channels. Regular testing and drills are essential to ensure their readiness.

**Ecosystem-based Approaches:** Consider ecosystem-based approaches to GLOF risk reduction, such as afforestation and reforestation in vulnerable areas, which can stabilize slopes and reduce the risk of landslides contributing to GLOFs.

Addressing future challenges related to GLOFs along the CPEC route necessitates proactive measures. Anticipating climate change impacts, enhancing infrastructure resilience, formulating effective policies, and

promoting international cooperation are critical steps toward mitigating GLOF risks and ensuring the CPEC project's long-term sustainability and the surrounding communities' safety.

### **Suggested Citation**

Khan, G., Baig, S.S., Bano, I. (2025). The repercussions of the Glacier Lake Outburst Floods on CEPC in Gilgit-Baltistan, Pakistan. In *CPEC and BRI Nexus: Perspectives on Economy, Politics, Culture and Environment* (pp 137-161). CSC-KIU.

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The China Study Centre (CSC) at Karakoram International University (KIU) is funded by the Higher Education Commission (HEC), Government of Pakistan. HEC frames the core objectives of the establishment of this Centre with special reference to the benefits that will achieve from creating a space that facilitates study and research on diverse arts, culture, history and polity of China, Pakistan, Gilgit-Baltistan and surrounding mountainous regions. The establishment of CSC aims to provide a base to learn Chinese society. The Centre provides an opportunity to develop research collaborations with counterparts in Xinjiang and mainland China. It is expected that these collaborations will play a key role in conducting research that has high relevance to Gilgit-Baltistan. There exist many commonalities between the two regions that provide important opportunities for collaboration between KIU, Chinese universities and beyond.



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