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Influence of Climate Change on Formation and Stability of Glacial Lakes in the Himalayas

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Abstract

Aim: This study aimed to analyze the influence of climate change on the formation and stability of glacial lakes in the Himalayas, with a focus on understanding the impacts on local communities, water resources, and regional ecosystems.

Methods: A desktop literature review was used in this study. Relevant journal articles for the study were identified using search engines such as Google Scholar, Google Books, Semantic Scholar, Science.gov and ResearchGate.

Results: The study revealed that climate change has played a significant role in the formation and stability of glacial lakes in the Himalayas. As temperatures continue to rise, the rate of glacial retreat and melting has accelerated, leading to the formation of new glacial lakes and the expansion of existing ones. This has resulted in an increased risk of glacial lake outburst floods (GLOFs), posing threats to downstream communities, infrastructure, and ecosystems.

Conclusion: Changes in precipitation patterns and temperature regimes have altered the hydrological dynamics of glacial lakes in the Himalayas, affecting their volume, water levels, and stability. Variations in the timing and intensity of meltwater inputs, coupled with the destabilization of moraine dams and ice dams, have increased the occurrence of GLOFs.

Recommendation: Further research is needed to better understand the long-term impacts of climate change on glacial lakes and their surrounding ecosystems, as well as to identify best practices for enhancing the resilience of local communities and ecosystems to these changes.

Keywords: *Climate change, glacial lakes, Himalayas, glacial lake outburst floods, adaptation, mitigation, glacial retreat*

INTRODUCTION

The process of glacial retreat is a natural phenomenon that occurs when a glacier loses mass and shrinks in size due to melting and sublimation (Benn et al., 2012). This size reduction often leads to the formation of glacial lakes, which are bodies of water that form as a result of the accumulation of meltwater in depressions on the land surface or within the ice itself. Glacial lakes are important indicators of climate change, as their formation and stability are closely linked to changes in temperature, precipitation, and other climatic factors (Linsbauer et al., 2016). In the Himalayas, the formation and stability of glacial lakes have become increasingly significant as the region continues to experience rapid and dramatic changes in its climate. One of the main drivers of glacial retreat and lake formation in the Himalayas is the increasing temperature, which has been shown to accelerate the rate of glacial melting (Shrestha et al., 2012). As glaciers melt, the water produced often collects in depressions on the land surface, forming glacial lakes.

In addition to temperature and precipitation, other factors can influence the rate of glacial retreat and lake formation in the Himalayas. One such factor is the presence of debris cover on the glacier surface, which can influence the rate of melting by insulating the ice and reducing its exposure to solar radiation (Scherler et al., 2011). However, the presence of debris can also be a double-edged sword, as it can reduce the albedo of the glacier and lead to increased absorption of solar radiation, ultimately accelerating the rate of melting (Scherler et al., 2011). The role of debris cover in glacial retreat and lake formation is therefore complex and can depend on the specific characteristics of the glacier and its surrounding environment. The development of glacial lakes can also be influenced by the topography of the land surface, as lakes are more likely to form in areas with low slope gradients and limited drainage capacity (Linsbauer et al., 2016). In the Himalayas, the complex topography of the region can lead to the formation of a diverse range of glacial lakes, with some forming in large, flat basins, while others develop in narrow, steep-sided valleys (Benn et al., 2012). The topography of the region can also influence the stability of glacial lakes, as lakes formed in steep-sided valleys may be more prone to outburst floods due to the increased likelihood of ice or rock avalanches triggering a breach in the lake's natural dam (Linsbauer et al., 2016).

In recent years, there has been growing interest in the use of numerical models to simulate the behavior of glacial systems and their associated lakes (Linsbauer et al., 2016). These models have helped in improving the understanding of the complex processes that govern glacial retreat and lake formation, as well as the potential impacts of climate change on these systems. For example, Linsbauer et al. (2016) developed a model to simulate the formation and growth of glacial lakes in the Himalayas, finding that future climate change could lead to a significant increase in both the number and size of glacial lakes in the region. Such models have also been used to assess the potential hazards associated with glacial lakes, such as the risk of outburst floods and their potential impacts on downstream communities (Linsbauer et al., 2016). As the climate continues to change, likely, the rates of glacial retreat and lake formation in the Himalayas will likely continue to increase, with potentially significant consequences for the environment and human populations in the region (Rai et al., 2017). For example, the expansion of glacial lakes can lead to the loss of valuable land resources, as well as increased risks of flooding and other natural disasters (Rai et al., 2017). Additionally, the melting of glaciers has far-reaching impacts on the availability of water resources, as many of the major rivers in the region are fed by glacial meltwater (Benn et al., 2012). As the water demand continues to grow, the reduction in glacial mass could lead to increased competition for water resources and heightened tensions between different user groups (Benn et al., 2012).

Effective management of glacial lakes in the Himalayas will require a coordinated and integrated approach, which takes into account the various factors that influence their formation and stability, as well as the potential impacts of climate change on these systems (Rai et al., 2017). This could involve the development of early warning systems to monitor and predict the behavior of glacial lakes, as well as the implementation of appropriate infrastructure and land-use planning strategies to mitigate the potential hazards associated with these lakes (Rai et al., 2017). Additionally, international cooperation and the sharing of scientific knowledge and expertise will be essential for addressing the complex challenges posed by glacial retreat and lake formation in the Himalayas (Benn et al., 2012).

Climate Change and GLOF Risks

Climate change has been a significant factor in increasing the risks associated with glacial lake outburst floods (GLOFs) in the Himalayas. The warming temperatures have led to the melting of glaciers at an accelerated rate, causing the formation and expansion of glacial lakes (Yao et al., 2012). This phenomenon not only threatens the lives and livelihoods of the communities living downstream but also poses a significant risk to the infrastructure and ecosystems in the region (Mool et al., 2011). In this paragraph, we will delve into the factors contributing to the increased GLOF risks, the challenges faced in predicting and mitigating these risks, and the potential consequences of such events. The rapid melting of glaciers has led to the formation of new glacial lakes and the expansion of existing ones (Lutz et al., 2014). As the volume of water in these lakes increases, so does the pressure on the natural barriers holding them back, such as moraines, ice, and rock (Carrivick & Tweed, 2013). This pressure leads to the breaching of these barriers, resulting in catastrophic floods that can wreak havoc on the downstream communities (Watson et al., 2015). Additionally, climate change has been linked to increased precipitation, which further exacerbates the risk of GLOFs by contributing to the rapid filling of glacial lakes (Wang et al., 2015).

One of the challenges in predicting and mitigating GLOF risks is the lack of comprehensive data on glacial lakes in the Himalayas (Racoviteanu et al., 2015). Remote sensing techniques have been employed to monitor the formation and growth of these lakes, but the vast and remote terrain makes it difficult to gather accurate and up-to-date information (Pandey et al., 2021). Furthermore, the complex interactions between the various factors contributing to GLOF risks, such as temperature, precipitation, and glacier dynamics, make it difficult to develop reliable models for predicting future events (Gardelle et al., 2011). In addition to the challenges in predicting GLOF risks, there are also difficulties in implementing effective mitigation measures. Engineering solutions, such as the construction of dams or drainage channels, are expensive and may not be feasible in remote and inaccessible areas (Worni et al., 2012). Moreover, these structures may have negative environmental impacts, such as the disruption of natural ecosystems and habitats (Harrison et al., 2018). As a result, there is a need for more research into the development of sustainable and cost-effective mitigation strategies that can help reduce the risk of GLOFs in the Himalayas.

The consequences of GLOFs may be catastrophic for the communities living downstream, as they may result in the loss of lives, destruction of property, and damage to infrastructure (Bajracharya et al., 2017). In addition to the immediate impact, GLOFs can also have long-term effects on the livelihoods of communities, as they can lead to the loss of agricultural land, disruption of water resources, and the destruction of cultural and historical sites (Rounce et al., 2017). Furthermore, GLOFs exacerbate existing social and economic inequalities, as the most vulnerable populations are often the hardest hit (Shukla, et al., 2018). The impacts of GLOFs are not limited to the communities living downstream; they can also have significant effects on the ecosystems in the region (Ives et al., 2010). The sudden release of large volumes of water, sediment, and debris may lead to the alteration of river channels, the destruction of habitats, and the disruption of ecological processes (Gardelle et al., 2011). In addition, GLOFs contribute to the release of greenhouse gases, such as carbon dioxide and methane, as the floodwaters mobilize organic material stored in the sediments and transport it downstream, where it can be decomposed and released into the atmosphere (Borah et al., 2015).

IMPACTS ON LOCAL COMMUNITIES

The Himalayas' local communities rely on the natural resources provided by the glaciers for their livelihoods, including water for drinking, agriculture, and hydroelectric power (Hussain et al., 2020). As the climate continues to change, the stability of these glacial lakes becomes increasingly uncertain, putting these communities at risk of losing their primary resources. The gradual loss of these resources has led to increased competition for water, food, and energy, causing tensions between communities and exacerbating existing social vulnerabilities. The GLOFs cause significant damage to infrastructure, agricultural land, and environmental systems posing a serious threat to human life. For communities living near glaciers, the risk of GLOFs is a constant source of worry and uncertainty.

Another impact on local communities is the alteration of the hydrological cycle, which affects the availability and distribution of water resources (Shrestha et al., 2019). Changes in precipitation patterns and the timing of snowmelt lead to water scarcity during critical periods, such as the growing season. This has serious implications for agriculture and food security, as well as for the livelihoods of those who depend on farming, livestock, and other water-dependent activities. The loss of glacier-fed rivers and streams can lead to the decline of aquatic species, such as fish and invertebrates, which are critical to the functioning of freshwater ecosystems. This can have cascading effects on the food chain, impacting the availability of resources for other species and potentially leading to local extinctions. Furthermore, the loss of glacier cover can also contribute to the decline of terrestrial species, such as plants and animals that are adapted to cold, alpine environments (Scotford & Marshall (2023).

The stability of glacial lakes in the Himalayas also has implications for the cultural heritage and identity of local communities (Kasperson et al., 2015). Glaciers and the surrounding landscapes hold significant cultural, spiritual, and historical value for many indigenous and local populations. As these landscapes change due to the melting of glaciers and the formation of glacial lakes, these communities experience a sense of loss and disconnection from their cultural heritage. The changing landscape and resource availability also affect the patterns of human settlement and migration (Nie et al., 2017). As water resources become scarcer and more unpredictable, communities are forced to relocate to areas with more reliable access to water, leading to the abandonment of traditional settlements and ways of life. This disrupts social networks and connections, further eroding the cultural fabric of these communities.

WATER RESOURCE MANAGEMENT CHALLENGES

As glaciers retreat and melt due to increasing temperatures, glacial lakes are formed, altering the hydrological dynamics of the region (Bajracharya, Maharjan, & Shrestha, 2018). This has had significant implications for water resources, as the region serves as a critical provider of freshwater for millions of people downstream. The first challenge in water resource management is addressing water scarcity. As glacial lakes form and expand, they store and retain more water than traditional glaciers, leading to changes in water availability in the region (Rasul et al., 2017). This results in short-term increases in water availability, but the long-term implications are less certain. With climate change exacerbating the rate of glacier retreat, the ability of these glacial lakes to provide a sustainable source of water becomes questionable, as they are dependent on the continuous input of meltwater from glaciers (Zemp et al., 2019).

The Himalayan region supports diverse ecosystems and human populations that rely on glacial meltwater for agriculture, hydropower generation, and domestic consumption (Panthi, Li, & Dahal, 2016). As the hydrological dynamics shift due to glacial lake formation, water resource managers must make difficult decisions about how to allocate water for these various uses. This can be particularly challenging when the demands of one sector, such as agriculture, may conflict with the needs of another, such as maintaining sufficient water levels for hydropower generation (Mukherji et al., 2015). Transboundary conflicts represent another challenge in water resource management in the context of glacial lake formation in the Himalayas. The region is shared by several countries, including China, India, Nepal, Bhutan, and Pakistan, all of which have vested interests in the water resources provided by the melting glaciers (Wang, Chen, & Yao, 2015). As climate change alters the hydrological dynamics of the region, the potential for disputes over water resources increases.

The unpredictability of glacial lake outburst floods (GLOFs) presents yet another challenge for water resource management in the region. GLOFs occur when the natural barriers containing glacial lakes, such as moraine dams, fail, releasing large volumes of water and causing catastrophic flooding downstream (Carrivick & Tweed, 2013). These events have devastating consequences for downstream communities, infrastructure, and ecosystems, and further strain water resources by causing the loss of stored water and disrupting the flow of rivers (Rounce et al., 2017). In addition to the challenges already discussed, water resource managers must also contend with the potential impacts of glacial lake formation on water quality. As glaciers melt and glacial lakes form, they can release stored pollutants, such as heavy metals and persistent organic pollutants, into the water system (Kumar et al., 2017). These contaminants pose risks to human health and the environment, and their presence in water resources complicates the management of water quality.

Another challenge facing water resource managers in the context of glacial lake formation is the integration of climate change adaptation strategies into water management plans. The impacts of climate change on the hydrological dynamics of the region are complex and uncertain, making it difficult to plan for future water resource availability (Lutz, Immerzeel, & Shrestha, 2016). To address this uncertainty, water resource managers must adopt adaptive management approaches, which involve regularly updating management plans based on new information and changing conditions. This requires the development of robust monitoring systems and the incorporation of climate change projections into water resource models and planning tools. The management of water resources in the face of glacial lake formation also requires significant investment in infrastructure and technology. As the hydrological landscape of the region changes, existing water infrastructure, such as dams, reservoirs, and irrigation systems, may need to be modified or replaced to accommodate new water storage and distribution needs (Barnett et al., 2019). Additionally, the development and implementation of early warning systems for GLOFs can help to mitigate the risks associated with these events (Kougkoulos et al., 2018). Investing in new infrastructure and technology is a financial and logistical challenge for water resource managers, particularly in resource-constrained settings.

ECOSYSTEM VULNERABILITY AND ADAPTATION

Climate change has significant implications for the formation and stability of glacial lakes in the Himalayas, as it directly affects the region's ecosystems. Ecosystems in the area face numerous challenges, including loss of biodiversity, shifts in species distribution, and changes in ecosystem services (Shrestha et al., 2012). These alterations lead to an increased vulnerability of the ecosystems, as they struggle to adapt to the rapidly changing environment. In response to these changes, there is a growing need to understand how ecosystems can adapt and become more resilient in the face of climate change (Roux et al., 2011). One important aspect of ecosystem vulnerability in the Himalayas is the shifting patterns of species distribution. As temperatures rise, many species are forced to move to higher elevations in search of more suitable habitats (Parmesan, 2006). This upward migration leads to a loss of species richness, as some species are unable to adapt to the new conditions. Additionally, changes in precipitation patterns exacerbate this issue, as some species are highly sensitive to changes in water availability (Piao et al., 2010). These shifts in species distribution often have cascading effects on the entire ecosystem, as species interactions are disrupted and new ecological communities are formed (Liu et al., 2013).

To adapt to these changes in ecosystem services, human communities must develop strategies to enhance their resilience. This can include adopting more sustainable land use practices, such as agroforestry and conservation agriculture (Lin, 2011), as well as investing in infrastructure to improve water management and reduce the risk of flooding (Kreibich et al., 2017). Additionally, local communities can engage in participatory decision-making processes to ensure that their concerns and knowledge are taken into account in the development of adaptation strategies (Ostrom, 2009). Changes in the formation and stability of glacial lakes in the Himalayas can also have significant implications for the region's biodiversity. As glaciers retreat and new lakes form, these environments can provide new habitats for species to colonize (Borah et al., 2022).

To protect biodiversity in the face of these challenges, conservation efforts must focus on enhancing the resilience of ecosystems and the species that inhabit them. This can be achieved through the establishment of protected areas that encompass a range of habitats and altitudinal gradients, as well as the implementation of habitat restoration projects to improve connectivity and facilitate species movement (Hannah et al., 2007). Additionally, the integration of traditional ecological knowledge into conservation planning may help to ensure that the needs of local communities are taken into account, while also drawing on their expertise in managing ecosystems in a changing climate (Berkes et al., 2000). Another important consideration in understanding ecosystem vulnerability in the Himalayas is the potential for regime shifts, or abrupt changes in ecosystem structure and function (Zhang et al., 2021). These shifts can be triggered by a variety of factors, including climate change, and can lead to the loss of ecosystem services and a decline in biodiversity (Folke et al., 2004). For example, changes in temperature and precipitation patterns can lead to the expansion of woody vegetation into alpine grasslands, which can reduce the availability of grazing resources for livestock and wildlife (Klein et al., 2007). To prevent or mitigate the impacts of these regime shifts, it is crucial to identify the underlying drivers and develop appropriate management strategies (Zhang et al., 2021).

Ecosystem-based adaptation (EbA) is an emerging approach that aims to promote the resilience of both ecosystems and human communities in the face of climate change (Haritashya et al., 2018). This approach involves the implementation of various practices, such as reforestation, habitat restoration, and sustainable land use planning, to enhance the capacity of ecosystems to provide essential services and support human well-being (Salerno et al., 2016). By focusing on the interdependence between ecosystems and human communities, EbA helps to address the challenges posed by climate change in a holistic and integrated manner (Munang et al., 2013). A key aspect of EbA in the context of glacial lake formation and stability in the Himalayas is the management of upstream linkages.

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Another important component of EbA is the integration of traditional and scientific knowledge. Local communities in the Himalayas have developed a wealth of knowledge and practices related to the management of natural resources and ecosystems, which can provide valuable insights for the development of adaptation strategies (King et al., 2019). One of the challenges in implementing EbA in the Himalayas is the need for enhanced collaboration and coordination among various stakeholders, such as governments, NGOs, and local communities (Jiang, 2018). This can be facilitated through the establishment of multi-stakeholder platforms and networks, which can provide a forum for the sharing of knowledge, resources, and expertise (Veettil et al., 2016).

Monitoring and Early Warning Systems

Monitoring and early warning systems play a crucial role in assessing the formation and stability of glacial lakes in the Himalayas, particularly in the context of climate change. The implementation of these systems has become essential for detecting potential risks associated with glacial lake outburst floods (GLOFs) and initiating appropriate disaster mitigation measures (Bhattacharya & Bolch, 2020). One key aspect of such monitoring systems is the use of remote sensing technologies, which have significantly improved our ability to collect extensive and accurate data on glacial lakes in the region. Satellite imagery, for example, allows scientists to track changes in lake size, depth, and ice cover, as well as to identify potentially hazardous lakes (Nie et al., 2017). This comprehensive information is useful in developing predictive models that assess the likelihood of GLOFs and inform early warning systems. In addition, these systems can help identify changes in glacial lake morphology and dynamics over time.

Furthermore, monitoring and early warning systems can be used to assess the potential consequences of GLOFs on downstream communities and infrastructure. Through the integration of hydrological and hydraulic models with remote sensing data, these systems can evaluate the potential inundation extent and flood magnitude of GLOFs, which informs risk assessment and mitigation strategies (Carrivick & Tweed, 2013). This information is essential for minimizing the human and economic impacts of these devastating events. Another important aspect of monitoring and early warning systems is their ability to facilitate international collaboration and data sharing. Given the transboundary nature of the Himalayas, the development and implementation of these systems can promote cooperation among countries in the region, which is essential for addressing the challenges posed by climate change (Shrestha et al., 2019). This collaborative approach can lead to more effective and efficient management of glacial lake resources and associated risks. Moreover, the use of monitoring and early warning systems can also help to inform local communities and stakeholders about the potential risks associated with glacial lakes. Through raising awareness about these issues, these systems can promote more sustainable land-use practices and support the development of community-based disaster risk reduction strategies (Dimri et al., 2021). This engagement with local communities is vital for ensuring the long-term success of these systems and the overall resilience of the region.

To maintain the effectiveness of monitoring and early warning systems, continuous improvements in the underlying technologies and methodologies are necessary. For example, advances in satellite remote sensing technology, such as the development of higher-resolution imagery and increased revisit times, can enable more accurate and timely monitoring of glacial lakes (Bajracharya et al., 2018). Similarly, improvements in modeling techniques may enhance the reliability and accuracy of GLOF risk assessments and early warning systems. Importantly, the implementation of monitoring and early warning systems should be accompanied by capacity-building efforts aimed at enhancing the ability of local institutions and communities to manage glacial lake risks. This includes training programs focused on remote sensing, data analysis, and modeling techniques, as well as the development of local expertise in these areas (Westoby et al., 2014).

Climate Modelling and Projections

Climate modeling is an essential tool for understanding and projecting the impacts of climate change on various aspects of the Earth's systems (Rounce et al., 2017). Climate models are complex mathematical representations of the Earth's climate system, which can be used to simulate and predict future climate states based on various greenhouse gas emissions scenarios. These models incorporate processes related to atmospheric circulation, ocean currents, land surface processes, and the interaction between the atmosphere, oceans, and land surface (Flato et al., 2013). One of the primary applications of climate modeling in relation to glacial lakes in the Himalayas is the projection of future temperature and precipitation patterns, which may have significant implications for glacial mass balance and the subsequent formation of glacial lakes (Gardelle et al., 2011). Climate models project an overall increase in temperature across the Himalayas, with greater warming at higher elevations (Lutz et al., 2014). This increase in temperature has led to enhanced glacial melt and the formation of new glacial lakes, as well as the expansion of existing glacial lakes (Fujita, 2017). In addition to temperature, climate models also project changes in precipitation patterns across the Himalayas. Some studies suggest that the region will experience an increase in precipitation, particularly during the monsoon season, which could further contribute to glacial mass loss and the formation of glacial lakes (Kumar et al., 2014). However, other studies have indicated a decrease in precipitation in certain parts of the Himalayas, which could lead to a reduction in glacial melt and a slower rate of glacial lake formation (Immerzeel et al., 2020).

The accuracy and reliability of climate models is an ongoing area of research, and improvements in modelling techniques and computational resources continue to contribute to a better understanding of the potential impacts of climate change on glacial lakes in the Himalayas (Shukla, et al., 2018). Ensemble modelling, which combines multiple climate model outputs to provide a more robust projection of future climate conditions, is a common approach used to account for uncertainties in individual models (Tebaldi & Knutti, 2007). Another important aspect of climate modelling concerning glacial lakes in the Himalayas is the representation of regional-scale climate processes, which can have a significant influence on local climate conditions and glacial lake formation (Mölg et al., 2012). High-resolution regional climate models (RCMs) are often used to provide more detailed information on regional climate variability and change, which can be critical for understanding the impacts of climate change on glacial lakes in the Himalayas (Dimri et al., 2019). The use of climate modelling and projections can also help inform the assessment of potential hazards associated with glacial lake outburst floods (GLOFs), which can occur when the natural barriers holding back glacial lakes fail, releasing large volumes of water and debris downstream (Carrivick & Tweed, 2016). Through the combination of climate model outputs with information on glacial lake morphology and stability, researchers can estimate the likelihood of GLOF events under different climate change scenarios, and identify areas at increased risk of GLOFs in the future (Lutz et al., 2014).

Despite the advances in climate modelling and the increasing availability of high-resolution climate data, there are still some limitations and uncertainties associated with projecting the impacts of climate change on glacial lakes in the Himalayas (Rounce et al., 2017). These uncertainties stem from the choice of climate model, the quality and availability of observational data, and the representation of complex processes related to glacier dynamics and glacial lake formation (Mölg et al., 2012). To address these uncertainties and improve the reliability of climate projections for glacial lakes in the Himalayas, ongoing research efforts are focused on the development of more sophisticated climate models (Shukla, et al., 2018). These efforts will be critical for informing decision-making and guiding adaptation strategies to minimize the potential impacts of climate change on glacial lakes in the Himalayas and the communities that depend on them (Pritchard, 2019).

CONCLUSION

Changes in precipitation patterns and temperature regimes have altered the hydrological dynamics of glacial lakes in the Himalayas, affecting their volume, water levels, and stability. Variations in the timing and intensity of meltwater inputs, coupled with the destabilization of moraine dams and ice dams, have increased the likelihood of GLOFs.

RECOMMENDATIONS

Effective adaptation strategies are essential for managing the impacts of climate change on glacial lakes in the Himalayas. This includes measures such as early warning systems, community-based risk management, infrastructure improvements, and land-use planning to reduce vulnerability to GLOFs. Additionally, long-term strategies for mitigating climate change and reducing greenhouse gas emissions are crucial for addressing the underlying drivers of glacial melt and ensuring the resilience of Himalayan communities and ecosystems in the face of a changing climate.

Land use planners and infrastructure developers should consider the potential hazards associated with glacial lakes and the effects of climate change. It is crucial to avoid constructing infrastructure in high-risk areas, such as downstream of potentially unstable glacial lakes, to minimize exposure and vulnerability to GLOFs. Rigorous risk assessments should be conducted for infrastructure projects, including hydropower plants or roads, to ensure they do not exacerbate the instability of glacial lakes or increase the susceptibility to GLOFs.

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