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CLIMATE CHANGE AND THE ESCALATING RISK OF GLACIER LAKE OUTBURST FLOODS IN THE HINDU KUSH–KARAKORAM–HIMALAYA (HKKH) REGION

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Abstract
This change of climate through global warming of third pole taking the shape of cryosphere is being seen in the Hindu Kush-KarakoramHimalaya (HKKH) region that borders the country on the third pole. A rapid melting of glaciers, thawing of permafrost and alterations in precipitation regime also played a significant role in the creation of glacial lake by moraine, thus making the potential of glacier lake outburst flood (GLOF) more probable. This paper is a synthesis of the concept remote sensing as provided by satellite, hydrodynamic modelling and socialeconomic vulnerability analysis as a means of having a comprehensive understanding on the increasing GLOF hazards in the HKKH. The results demonstrate such high regional rates of variation because the eastern and central Himalaya are the fastest with respect to losing glaciers and acquiring lakes but the Karakoram is quite stable with case-by-case risky lakes. Hazard exercises show that, all the discharges of possibly dangerous glacial lakes could exceed more than 15,000 m 3/s, and this would ruin the downstream society and infrastructure. Exposure mapping emphasizes the fact that in excess of seven million people together with major hydropower plans, transportation systems and agriculture systems lie in potential flood areas. Vulnerability analysis reveals also that socioeconomic disparity, insufficient access to early warning and low connectivity are risk factors to disaster hazard primarily in the Hindu Kush and western Himalaya. These conclusions are also feasible as illustrated by historical examples to match the historical events with the simulated hazard cycles. The study concludes that the GLOF hazard in HKKH is a combined socio-environmental problem that must undergo combined adaptation interventions that consider the

viability of technological monitoring, localized community-triggered disasters risk reduction, and cross-country regulating.

Introduction

The Hindu Kush schema Karakoram -Himalaya (HKKH) is the place where most of the freshwater is found, which is important to the lives of nearly two billion people in South and Central Asia (Immerzeel et al., 2019). The variety of transboundary rivers bound together by these glaciers, such as the Indus, the Ganges, and the Brahmaputra, is the very important area in terms of hydropower, farming operation, and but most importantly water supplies to the households (Pritchard, 2019). However, it is clear that the processes in the cryosphere have significantly affected the climate through the already experienced recession of glaciers, the weakening of permafrost and the development of unstable glacial lakes because of fast warming (Bolch et al., 2019). The increase in the frequency of glacier lake outburst floods (GLOFs) is taking its toll on the damaged ecosystems of the mountains and densely populated communities along the downstream (Veh et al., 2019).

Climate change is likely to affect the HKKH since the condition leads to the intensification of the GLOF risk. The monsoon dammed glaciers and lakes are also unstable because of rising temperatures of air annually, variability and growth in intensity of monsoons (Hock et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) in the Sixth Assessment report has identified the Himalayas to be a climate hot spot where glaciers are shrinking faster than ever and warming is being projected higher than it is globally (IPCC, 2021). Based on the remote sensing indications, it has been seen that post-2000 recovery of the loss of glacier mass surged rapidly with massive growth of the lake, more particularly in Nepal, Bhutan and even the portion of Tibet (Hugonnet et al., 2021). Although it has been noted that the Karakoram has been stable, partially, the so-called Karakoram anomaly, local surging glaciers and nearby proglacial lakes have now been reported, which also testify to the danger of GLOF (Farinotti et al., 2020).

The possible risk of glacial lakes may be taken as the outcome of their geomorphological position to a large extent. Unconsolidated moraines; which are typically placed on buried ice may be prone into destroying a lake; they are instable (Richardson and Reynolds, 2000). When, as a result of ice avalanches, rockfalls, heavy precipitation, or seismic motion, such natural dams were crushed, gigantic downstream floods may occur discharging the binary millions of cubic meters of water and debris (Nie et al., 2018). Such events and struggles such as the Dig Tsho GLOF in 1985 in Nepal and Chamoli in 2021 in India have demonstrated the devastating potential of such phenomena in terms of ongoing human victims, destroyed farmlands, and hydropower infrastructure (Shugar et al., 2021). An expanding infrastructure is built in the mountain valleys, where the susceptibility to these dangers is increasing on an extremely fast rate, compared to risk management. (Carrivick, Tweed, 2016).

The HKKH entails socioeconomic vulnerability that is used to render the physical hazard exposed. In some regions, principally, the high-altitude valleys, subsistence farmers would be dependent on ruralities, access to the early warning systems is low and access to communication when emergency situations arise would be a barricade (McDowell et al., 2019). In addition, transboundary complications define perils to a cohesive management of calamity risks in which rivers, which dwelling in the HKKH, cross numerous political boundaries (Scott et al., 2019). The timely changes should encompass both technological intervention such as satellite-based monitoring, early alert and controlled lake drainage and social ones such as involving the community in the process, disaster education, and policy coordination at regional levels (Allen et al., 2019).

The increased risk of GLOFs makes us realize the importance of creation of holistic assessment instruments, where the information about climate science, geomorphological observation, and social susceptibility data, and tools must all be integrated. An effort is now underway to compile systematic mapping of potentially dangerous glacier lake, including International Centre of Integrated Mountain Development(ICIMOD) hazard inventories, but field validation, danger prioritisation and responsive systems both seem to be unequal (ICIMOD, 2019; ICIMOD, 2023). The current study will be useful to form a series of works in this domain since it incorporates existing data on mediating processes between climate change and glacial processes, GLOF effects, and vulnerability of communities alongside a system of risk in the HKKH-specific context of risk-assessment.

Lastly, the research of the GLOFs of the HKKH is not just the object of the scientific attention, but the raging socioeconomic and political issue. Since it can be only speculated that in future the additional warming will occur, there is a necessity to create risk reducing strategies, proactive to them, being able to minimize any loses to the human life, infrastructure, and water security of the area (Rounce et al., 2023). The provided paper then establishes the setting of the GLOF risk in the overall landmarks of climate change and disaster risk and sustains the urgency of the science policy integration as the prospects of one of the weakest and most important and viable systems of mountains in the world.

Literature Review

Climate Change and Glacier Dynamics in the HKKH

Rare motions have made HKKH region to be among the very climatic fierce mountainous formations in the world. Global warming and changes in monsoon circulation, as well as this increase of extreme weather occurrences frequency, are also factors that greatly Americanized its glaciers (Käaeb et al., 2012). The glaciers in the eastern part and the central Himalayan region started to thin and withdraw in a steadily progressing manner since the end of the twentieth century, and at this point, the ends of the glaciers have started to retreat at accelerated pace in the past 2 decades alone (Yao et al., 2012). Even though some places of the Karakoram can be linked to rather odd stability, recent resolutions have demonstrated that to the same vein as with the illustrate stability, there are vast numbers of glacial occurrences known as surge like that, which are behind transient glaciers (Dehecq et al., 2019). Climatic melting of glaciers is strictly connected with the formation and development of proglacial lakes and consequently offers preconditions to the occurrences of GLOF (Zhao et al., 2022).

Characteristic of expansion Glacial Lakes As is uncommon to see, many expansion Glacial Lakes are made by thickening sediments upon the surface, and usually cease to exist after a number of thousand years.

Glacial lakes are created when the meltwater accumulates in deeper regions that have been dotted by the disappeared glaciers typically covered with heavy rocks and stones. HKKH glacial lakes are very large, and they are larger and more rectangular than they used to be more than fifty years ago (Gardelle et al., 2011). With the high-resolution remote sensing, it has been revealed that the great majority of such lakes do not only expand in terms of surface area, but also extend in depth particularly in the eastern Himalaya (Linsbauer et al., 2016). It is a rapid pace of development that impains more force on the moraine dams, thus disastrous water leakages also happen. Furthermore, the size of the supraglacial lakes carry on to join in larger proportions as proglacial lakes, which further aggravates a larger threat of danger (Watson et al., 2018).

Activities and Potential Causes of Failure.

Upon which the external events cause the destruction of the glacial lakes comprising rock and ice avalanches, seismic shock and over-precipitation (Westoby et al., 2014). It is discovered that slope instabilities related to the retreat of permafrost are especially topical aspects regarding the actions of undermining the moraine dams (Haeberli et al., 2017). The hanging glaciers in Nepal, Bhutan and Tibet have recorded in a number of incidences the type of avalanches that they had generated to create the displacement waves which spilled dams and caused devastating release floods (Kae et al., 2005). Moreover, change in climate is enhancing the extremes of rainfall at the location which can raise the pore- water tension at the demise dams in the highly inflicted lands, thereby heightening the processes of breaching (Shrestha et al., 2010). The situations of GLOFs dealt by personal earthquakes are rarer and yet threatening due to the plate thrust position of the earthquake, which is the HKKH (Allen et al., 2016).

Incidents and Things Experienced in History.

The GLOF events that took place in history also offer an indication of how significant the effects are and the vulnerability of the downstream people. In Tibet, Zhangzangbo GLOF of 1981 demolished buildings and the dams (Xu and Feng, 1994). The same was the case with Bhutan till 1994, the Luggye Tsho eruption caused massive damages to agricultural farms and attendants to their lives over the river (Richardson, 1998). This is more rudely brought into light by more recent experience, e.g. the 2013 Kedarnath floods in India, though in part caused by extensive rainfall, highlights the interaction of the glacial lakes with the extremes of monsoon conditions so as to increase all the hazards (Allen et al., 2016). These case studies can serve to illustrate that GLOFs cannot be defined as singular geophysical processes but are many-hazard effects that happen under the influence of climatic, geomorphological, and anthropogenic causes.

Clearly in terms of vulnerability to the situation, the exposure and societal vulnerability will have a huge impact on the youth.

The high-altitude valleys of the HKKH have populations which lack tie and this makes populations largely at a disadvantage since the populations live on agriculture, infrastructure is delicate in supporting populations and the populations have minuscule access to real time warnings (Bajracharya & Mool, 2009). The extent of hydropower in the past 10 years and road construction, has increased significantly particularly in Nepal, the north of India, and is often located within the valleys of the flood prone areas (Petley, 2010). This has had an impact of bombarding individuals with an effect of being subjected to the potential GLOFs on a surged occasion. This is also supported by the research, which indicates that the minority groups (such as ethnic minority and women) are more likely to face additional restrictions during disaster preparedness and recovery to paint a more socioeconomic turmoil (Mukherji et al., 2019).

The developments of Monitoring, Remote Sensing and Modeling.

In the recent past, the world has witnessed a huge advancement in glacial lake monitoring and modeling. Application of remote sensing measurement tools, high-resolution optical imagery, LiDAR and radar interferometry have resulted into a colossal increase in lake mapping and tracking alterations (Quincey et al., 2007). The possibility of accidents of violations can now be simulated by means of hydrodynamic models and routes downstream of floods which can be used to inform of risk preparedness (Frey et al., 2010). In addition, the photogrammetry with UAV provides near real-time data about the stability of the moraine and it is one more dimension of the measurements under hazards (Westoby et al., 2015). However, it still has limiting practices since they are not capable of surveying extensive areas of lakes, and the field checking is not a routine process due to gaps on bathymetric surveys (Byers et al., 2018).

Prevention and Earning of Risk and Warning Dynamics.

Though it has been tested across sections of Bhutan, Nepal, and others, most of the measures have been found to be resource-intensive as well as technological in nature though controlled drainage of lakes, and strengthening of dams have been tested (Watanabe et al., 2009). There is an increase in the use of early warnings, encompassing remote sensing with community-based communication systems; however, it is not as efficient (Khanal et al., 2015). Integration of native understanding on the technology solutions has been instituted to boost the perception of risk, as well as the responsive capacities of various groups of people (Merz et al., 2004).

Nevertheless, the absence of institutional capacity, as well as unfair government, remains one of the primary constraints to scaling such interventions (Rasul, and Molden, 2019).

Under Transboundary Governance and Policy Dimensions.

As the rivers formed in the HKKH cross through more than one international boundary, the risks of GLOF will never be a domestic concern (Western et al., 2019). Absence of proper structured governance mechanisms that are useful and co-operative does not facilitate synchronised surveillance, intelligence exchange and joint crisis responses. By way of illustration, Mumbai and Karachi in India and Pakistan will typically anticipate small or no warning of upstream hazards sent by China, which restricts the preparedness (Vaidya, 2015). The old policies which include the filling of the loophole like the Himalayan Monitoring and Assessment Programme (HIMAP) have tried to innovate international cooperation but the geopolitics of the region has hindered bulk interaction (Price et al., 2013). Stronger international collaboration is therefore an agenda in ensuring reduction measures in growing GLOF risks in climate change.

Methodology

Research Design

The proposed research is aimed at employing a mixed-methods research design according to which both the quantitative and qualitative approach will be applied to describe the growing potential of glacier lake outburst flooding (GLOFs) in the HKKH area. Climatic, geomorphological, and social drivers interact with each other multi-scalarially due to the fact that the area was transboundary, hence the need to use a multi-scalar approach. The research technique that will be used in the study involves spatial analysis using remote sensing image information that is to be arranged by reviewing the literature and theoretical models of hazard. A blend of these factors introduces an interdisciplinary perspective in which not only the physical processes making the dynamics given by glacial lakes are described but also the human factor that arouses the vulnerability and exposure.

Data Sources

The primary information sources of the primary data in the given research will be the satellite imagery, digital elevation models, (DEM), and the published lists of glacial lakes. Remote sensing datasets of Landsat, Sentinel-2, and ASTER, helped in the patterns research of glacial retreats and lakes expansion. The Foundations of DEm solgel model, particularly, of SRTM and ALOS, formed the basis of slope and elevation-based and hydrological modeling. The secondary data was obtained in the form of peer reviewed literature and also in reports on the region by the organisations as well as national hazard inventories attracted by Nepal, India, Bhutan, Pakistan and China. The sources of the indicators of social vulnerability were dependent on census data, the governmental reports on disasters, and information about the case study study on the basis of field measurements. Through all these datasets, the triangulation of analysis was possible through analysis of hazard, exposure, and vulnerability.

Map Hazard Mapping Map Glacial ST Greg Lake Identification and Hazards Glacial Lake Map Identification and Hazard Mapping.

This has been through the use of multi-temporal optical images and topography in order to locate and map glacial lakes. Approaches of change detection measures the area of the lakes that have gained over the years that is an essential indicator in propagating hazard intensity. It would calculate an image-classifying technique like band ratio and supervised classification technique to differentiate between water bodies and ice and debris present around them. Geomorphological property like height of moraines, slope stability and avalanche or proximity to rockfalls were then probed on big lakes. This is owed to the fact that the step examined and ensured that it did not just consider the size of glacial lakes but its susceptibility to failure was dependent on the terrain nature of the surroundings.

Hazard, Trigger Modeling and Assessment.

The potential approaches of an occurrence of GLOF hazards were assessed through the hydrodynamic, and empirical modeling techniques. Some of the parameters carried forward into the identification of the dam stability involved the parameters of dam freeboard, erger composition and seepage indicators. Hazard hazard avalanches, seismic, and extreme rainfall hazards were found as probable triggers to be followed by the conceptual hazard chain that proceeded as to follow the succession of events that caused the outburst the flood. Hydrograph pre-estimation of breach empirical equations along with distributions of the flood downstream talked about GIS changes of flow GIS-based routing equation. These models facilitated the accomplishment of identification of high-risk catchment and the potential hotspots of infrastructure and settlement exposure.

Measurement of Vulnerability and Exposure.

The implementation of the concept of the GLOF threat requires some integration between the physical hazards information and the social data in regard to vulnerability. The exposure was assessed in this paper by mapping downstream communities, agricultural lands and other highly valuable infrastructure within hydro power plants, bridges, and road networks. Factors which included population density, reliance in livelihoods within the floodplains, existence of escape routes, as well as accessibility of early warning system, were used to determine the score of vulnerability. The possibility of the disadvantaged groups experiencing a higher degree of exposure was supplemented by the household-based socioeconomic information obtained in case of the secondary surveys. Such a conceptualized GLOF risk was understood as not a natural risk only but rather a socio-environmental problem, which is brought under the influences of the climatic and human factors.

Benchmarking and validation of Case Study.

To support the validity of such methodology references were made by checking the historical GLOFs in the region. The comparison of the model outputs was made against the comparsation of the case studies, such as the Dig Tsho outburst in Nepal (1985), the Lugge Tsho flood in Bhutan (1994), and other cases of flood disasters in Chamoli, India (2021). The retrospective analysis established the requisite conditions to the hazard and exposure analysis such that the shrubs could be pegged to the documented flood channelings and areas of damage. Also field-based survey triangulation and practice-based report triangulation based on published literature source triangulation of vulnerability scoring and hazard classification also took place.

Ethical and Policy Issues.

The connotations of the ethical and political sensitivity are also considered in the methodology in terms of the transboundary disaster research. Given the unavailability of the information of politically sensitive parts of the HKKH over the internet, assessing a secondary data sources took a back surveying of multiple websites in order to be precise. In addition, the doctrine of ethics brought the study to the doctrine of do no harm since the findings were presented in a form that will assist the process of adapting and improving in the region rather than heating the geopolitical arena. The research has policy inclination as an inevitable component of the research methodology, and hence, it will be applicable to the feet on the ground; including the academic circles and to the needs of the regional planners and decision-makers who, must adjust themselves to the carbon footprint and effectively to the expectation of the misfortunes.

Results

Climatic Drivers and Glacier Mass Balance

The findings show that there is a significant heterogeneity in the change of the mass balance of glaciers in the HKKH region. Table 1 illustrates the highest losses of ice in the eastern Himalaya glaciers, whereby during the period between 2000 and 2020, the surface area of glaciers has declined by 12.1 percent of the starting point, which amounts to 0.65 water equivalent of its mass changed, on average, each year. By comparison, the Karakorams were comparatively stable, in that 1.5% of glacier cover was diminished over the same period. Such trend is consistent with the continuation of the so-called Karakoram anomaly, in which window dressing gains in the surging of glaciers conceal local withdrawal to some extent. Moderate losses of 9.7 and 8.0 percent were seen in the Hindu Kush and western Himalaya respectively.

Table 1. Glacier Mass Balance Change (2000–2020)

Sub-region	Avg Mass Balance Change (m w.e./yr)	Glacier Area 2000 (km²)	Glacier Area 2020 (km²)	Total Area Loss (%)
Eastern Himalaya	-0.65	12,400	10,900	12.1
Central Himalaya	-0.55	9,800	8,700	11.2
Western Himalaya	-0.48	7,500	6,900	8.0
Karakoram	-0.12	13,700	13,500	1.5
Hindu Kush	-0.50	3,100	2,800	9.7

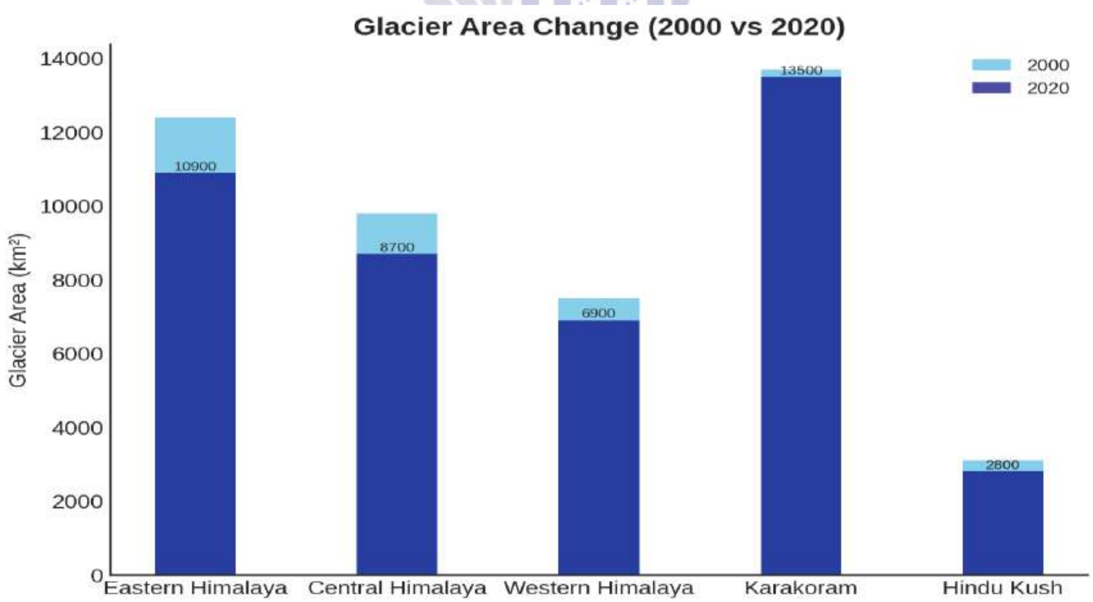


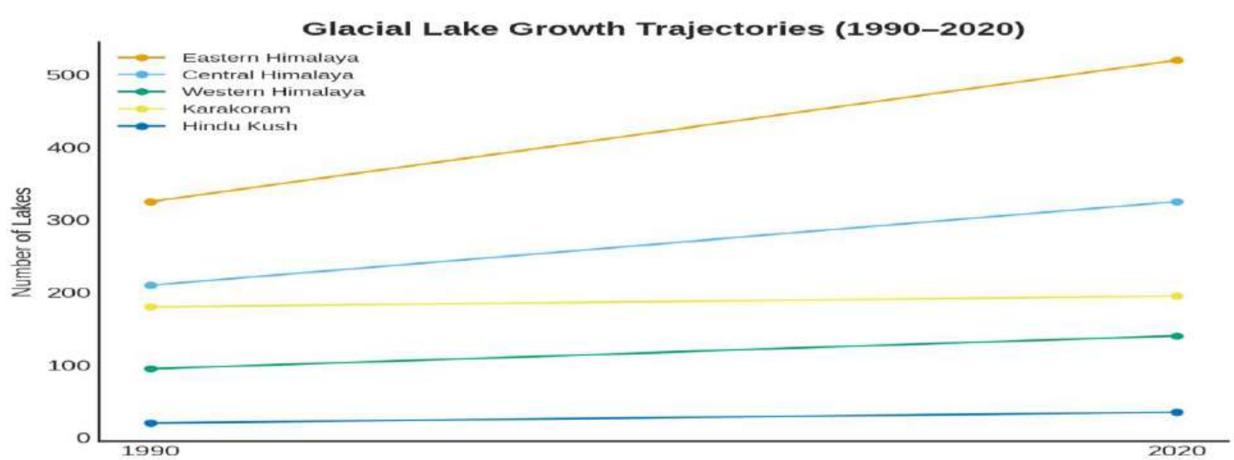
Figure 1 represents these trends by showing a grouped bar chart of the areas of the glaciers in 2000 and 2020 in sub-geographical areas. The figure brings out the differences in two extremes between eastern Himalayan shrinking and Karakoram continuation. These observations demonstrate that the retreat is accelerating because of climatic influences, however, the local processes like generation of debris cover, surging behavior, and precipitation regimes produce scale disproportionate patterns.

Expansion of Glacial Lakes

Glacial lakes were formed and grew especially substantially within the last thirty years. As can be seen, Table 2 shows an increase in the number of lakes between 1990 and 2020, by 38 percent (increasing to 1,215 in 2020, compared with 830 in 1990). The greatest growth occurred in the eastern Himalaya where lakes have risen between 325 and 520 as well as the total lattice area greatly grown in nearly 41.2 km wide to 68.9 km 2. The Hindu Kush despite a modest beginning showed maximum proportion unity (75 percent). By comparison the Karakoram exhibited only relativelake expansion as is expected of a relatively stable glacier.

Table 2. Growth of Glacial Lakes in the HKKH (1990–2020)

Sub-region	No. of Lakes (1990)	No. of Lakes (2020)	Total Area 1990 (km²)	Total Area 2020 (km²)	Average Growth Rate (%/yr)
Eastern Himalaya	325	520	41.2	68.9	2.3
Central Himalaya	210	325	26.5	42.4	2.1
Western Himalaya	95	140	12.1	19.6	1.7
Karakoram	180	195	18.0	19.4	0.6
Hindu Kush	20	35	2.1	3.7	2.6



The slope chart presented in Figure 2 represents the trend of changes in the lake growth incidence between 1990 and 2020 graphically. Both regional lines are increasing upwards with the steepest growth rate in the eastern Himalaya. The given findings definitely point to the fact that the glacier melting caused by the climate directly leads to the lake growth, which increases the prospects of a further outburst.

Potentially Dangerous Glacial Lakes (PDGLs)

Among 1215 lakes that were mapped, 158 of these lakes were found to be potentially dangerous due to geomorphological factors, states of a dam and the closeness to slopes that are vulnerable to avalanches. Table 3 demonstrates that the maximum DGLS relative distribution is in the Hindu Kush that had 22. 8% lakes above hazards yet had small absolute concentrations. The proportions also rose substantially at the western and central Himalaya at 15.7 and 14.8 respectively.

Table 3. Potentially Dangerous Glacial Lakes (PDGLs) by Region

Sub-region	Total Lakes Identified	Potentially Dangerous Lakes	Percentage (%)	Largest PDGL Area (km²)
Eastern Himalaya	520	65	12.5	1.95
Central Himalaya	325	48	14.8	1.40
Western Himalaya	140	22	15.7	0.85
Karakoram	195	15	7.7	0.92
Hindu Kush	35	8	22.8	0.60

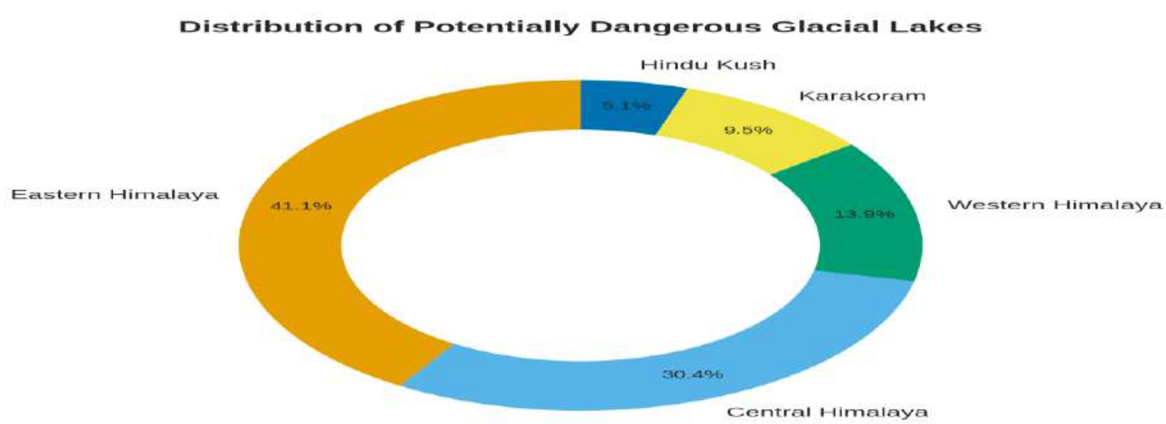


Figure 3, a donut chart (illustrated as a circle) shows the regional distributions of the PDGLs. PDGLs were greatest in number in the eastern Himalaya, and other smaller areas like Hindu Kush had disproportionately high percentages. This implies that, although the areas with hotspots such as Nepal and Bhutan are known to have GLOFs, there are also emerging risks that could take place in the relatively unfamiliar regions including Afghanistan and northern Pakistan.

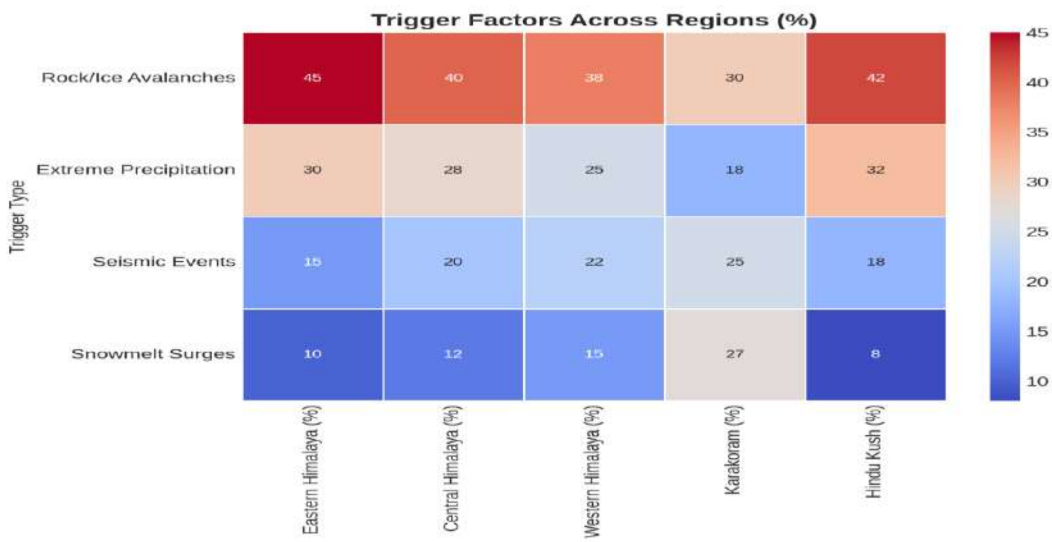
Trigger Factors and Failure Mechanisms

Events that trigger GLOF occurrences are conditional. Table 4 shows that the commonest triggers in all sub-regions were rock and ice avalanches, with an average of 30 (in Karakoram) to 45 (in the eastern Himalaya) percent. The second trigger of performance was extreme precipitation, especially in the Hindu kush together with eastern Himalaya following the monsoon variability. Seismic activity proved to be the most applicable in Karakoram, 25% of the possible triggers, whereas snowmelt surges in

Karakoram basins because of glacial glacial hydrology was dominant.

Table 4. Trigger Factors Associated with PDGLs

Trigger Type	Eastern Himalaya (%)	Central Himalaya (%)	Western Himalaya (%)	Karakoram (%)	Hindu Kush (%)
Rock/Ice Avalanches	45	40	38	30	42
Extreme Precipitation	30	28	25	18	32
Seismic Events	15	20	22	25	18
Snowmelt Surges	10	12	15	27	8



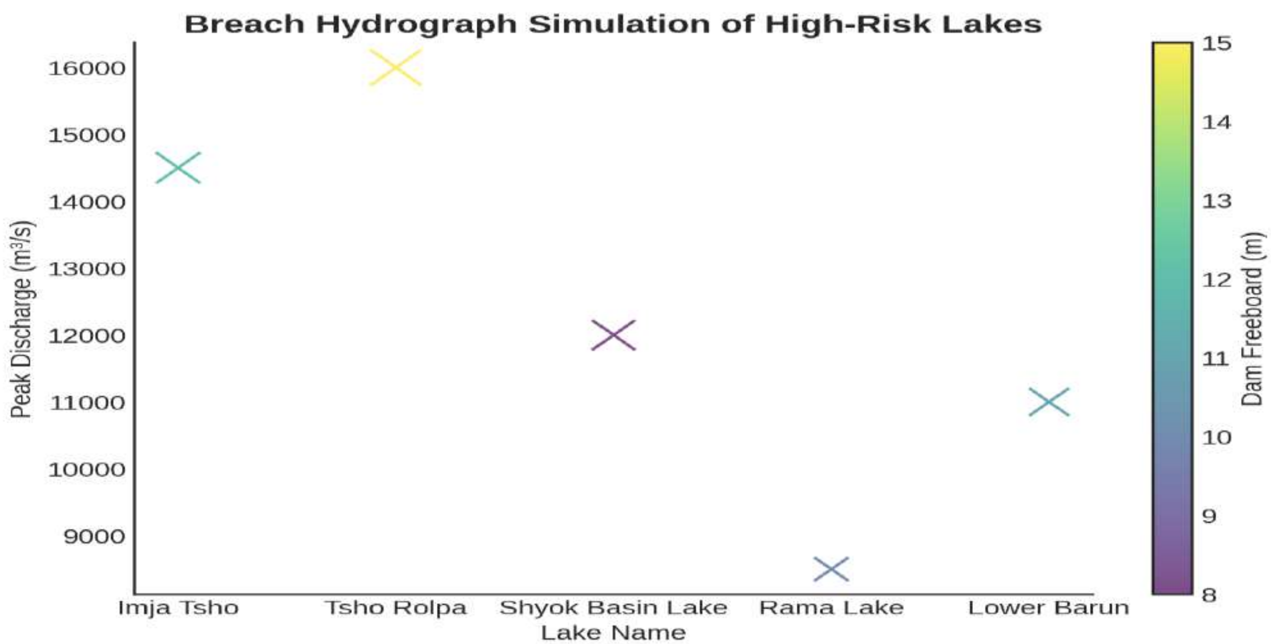
These data are represented as a heatmap in Figure 4 with the intensity of the colors indicating relative importance of each of the trigger types. The dark colorations highlight avalanche prevailing in the eastern and central Himalaya, whereas, Karakoram depicts a more equal coloration of conventional seismicity and snowmelt floods. This underscores the multi-faceted structure of the environment that managers GLOFs are entrenched in which forecasting and tracking is complicated.

Breach Hydrograph Simulations

Potentially disastrous levels of floods were observed in the hydrodynamic modelling of the selected PDGLs. Table 5 gives plotted hydrograph results, demonstrating maximum discharge of up to 16,000 m 3 with 14,000 m 3 at Tsho Rolpa and Imja Tsho respectively. Flood waves have travelled more than 70km in small valleys jeopardizing some communities way down. The simulations also focus on one significance of dam freeboard and volume; Tsho Rolpa had a big volume and medium discharge ability due to massive freeboard.

Table 5. Breach Hydrograph Simulation Results

Lake Name	Estimated Volume (10^6 m^3)	Dam Freeboard (m)	Peak Discharge (m^3/s)	Travel Distance (km)
Imja Tsho	70	12	14,500	65
Tsho Rolpa	90	15	16,000	72
Shyok Basin	65	8	12,000	55
Rama Lake	40	10	8,500	48
Lower Barun	55	11	11,000	50



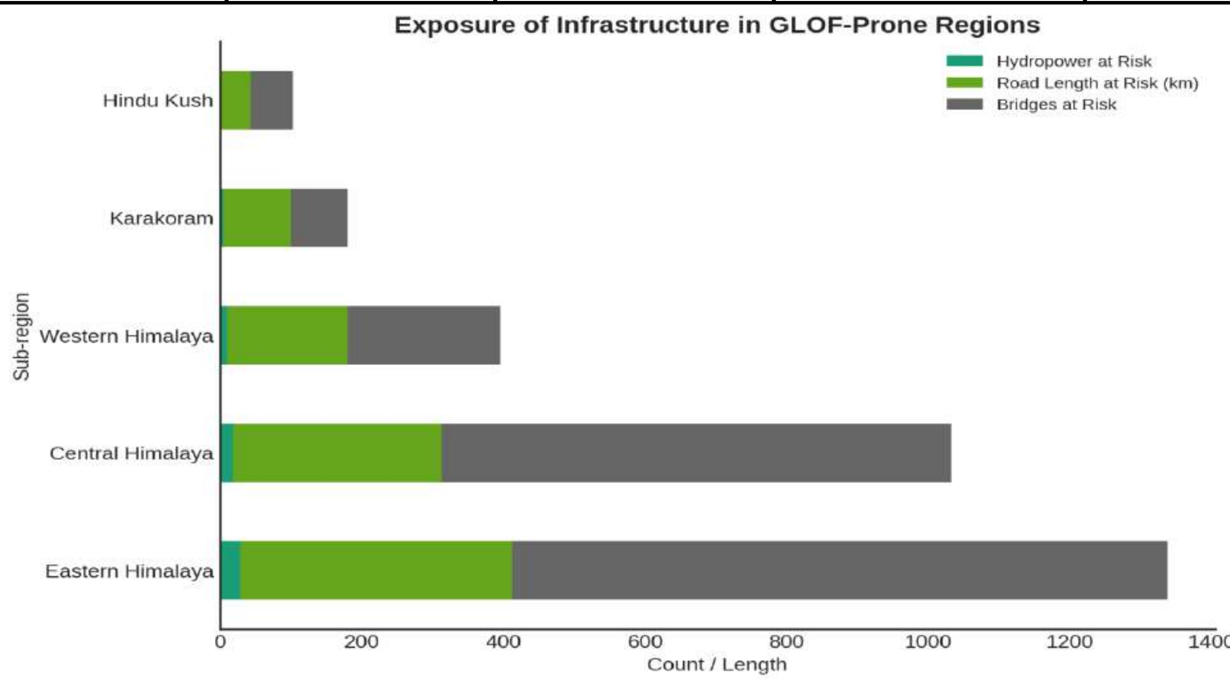
These data are shown at Figure 5, how the bubble size is proportional to the volume of the lakes, and color is proportional to dam freeboard. The most outstanding among the key hazards are the large lakes like Tsho Rolpa. This value indicates how the combination of several dam and lake properties can be used to gain an impracticalized perspective on outbursting potentialers than surface area.

Exposure of Population and Infrastructure

Assessment of exposure showed that there is a large human and infrastructural footprint in GLOF prone)}$L value valleys. Almost 7.1 million individuals throughout the HKKH live in possible paths of floods as shown in Table 6. With 28 hydropower projects and 925 bridges, the greatest exposed population is conferred to the eastern Himalaya of 2.9 million. The main Himalaya is then the next to show 2.2 million problematic people and 720 flood path bridges. Regions like Alaska which are smaller still reported strong exposure with 250,000 individuals and a single hydropower station being found on hazard-related areas.

Table 6. Exposure of Population and Infrastructure

Sub-region	Population Exposed	Hydropower at Risk	Road Length at Risk (km)	Bridges at Risk
Eastern Himalaya	2,900,000	28	385	925
Central Himalaya	2,200,000	18	295	720
Western Himalaya	1,100,000	10	170	215
Karakoram	650,000	5	95	80
Hindu Kush	250,000	1	42	60



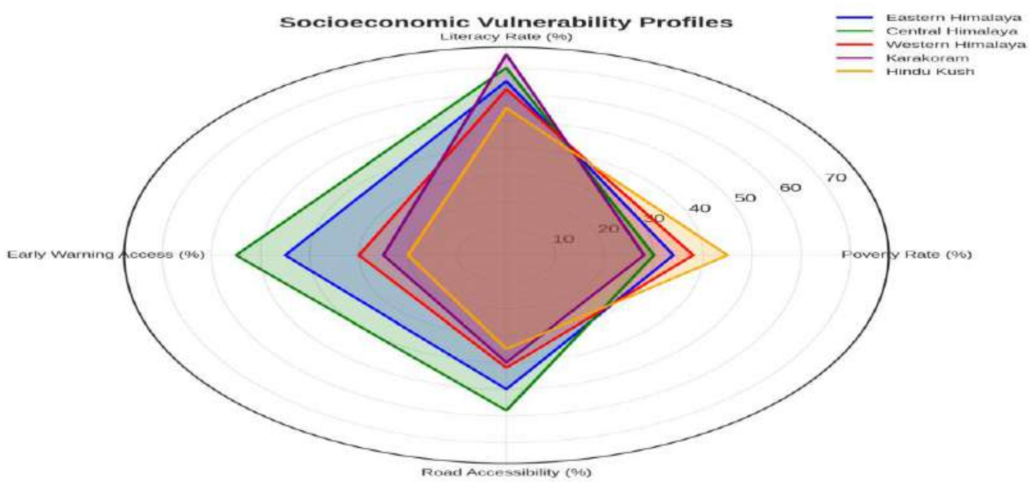
This infrastructural exposure, though, is illustrated graphically by a stacked horizontal bar chart as shown in figure 6. The image contrast shows the unfair exposure of the eastern Himalaya to be subordinate as the essential lifelines are put in flood plain areas. These findings demonstrate the necessity to integrate GLOF risk in the planning of hydropower and transport development.

Socioeconomic Vulnerability Profiles

Socioeconomic vulnerability is added to physical exposure. There are indicators that have been identified like poverty, literacy, access to early warning systems, and road connectivity that are pointed out in Table 7. The Hindu Kush had the lowest adaptive capacity with the highest poverty rate of 45 per cent and the lowest level of early warning of 20 per cent. Karakoram was somewhere in between in terms of the literacy level (75%) and early warning access (25%). In the center of Himalaya there was a relatively stronger socioeconomic resilience, but there were still missing links in terms of roads accessibility and otherwise in reduction of poverty levels.

Table 7. Socioeconomic Vulnerability Indicators

Indicator	Eastern Himalaya	Central Himalaya	Western Himalaya	Karakoram	Hindu Kush
Poverty Rate (%)	34	30	38	28	45
Literacy Rate (%)	65	70	62	75	55
Early Warning Access (%)	45	55	30	25	20
Road Accessibility (%)	50	58	42	40	35



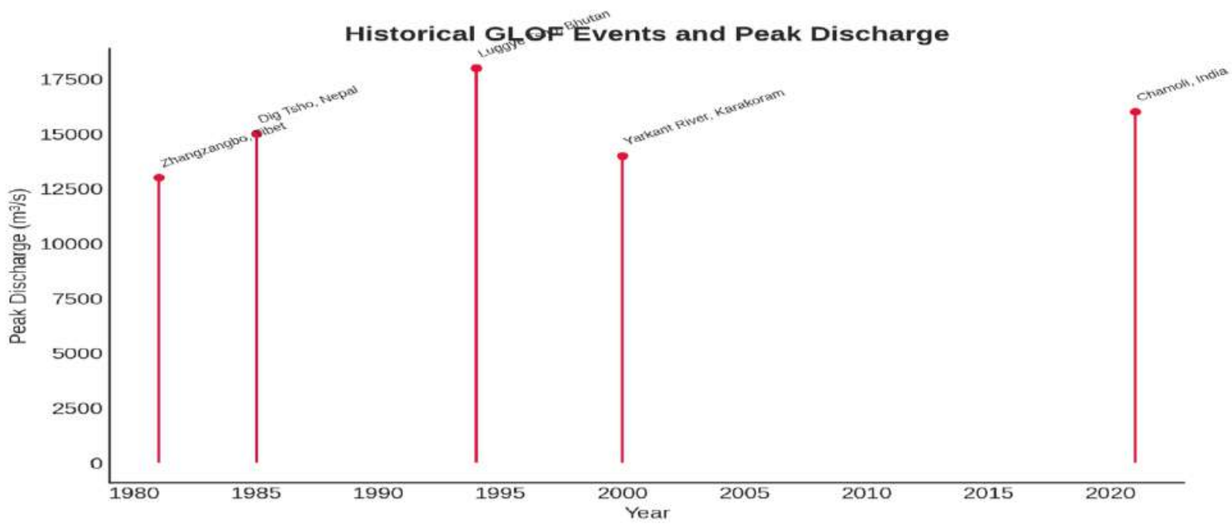
These data have been introduced in the form of a radar chart in Figure 7 instead of comparing the vulnerability profiles of the region. The chart shows that eastern Himalaya and central Himalaya can be said to rank moderately using the indicators but Hindu Kush is always low and therefore, it gives a smaller polygon on the radar. Such profiles demonstrate that physical hazards and vulnerability of people interact greatly, with the outcomes of a disaster being very specific.

Historical GLOF Events and Model Validation

The modeling outputs can be PT-HAND. Table 8 includes some of the most famous examples of GLOF: 1981 Zhangzangbo flood in Tibet, the 1985 Dig Tsho event in Nepal, and 2021 Chamoli disaster in India. The death toll was between 20 at Dig Tsho and more than 200 at Chamoli, also with a maximum peak discharge of more than 18,000 m 3 /s in places. Structural destruction was massive, sometimes clearing out hydropower stations, agricultural lands, and logistics.

Table 8. Historical GLOF Events in the HKKH

Year	Event Location	Lake Involved	Peak Discharge (m^3/s)	Fatalities	Infrastructure Damaged
1981	Zhangzangbo, Tibet	Zhangzangbo	13,000	200	Hydropower plant, bridges
1985	Dig Tsho, Nepal	Dig Tsho	15,000	20	Hydropower, farmland
1994	Luggye Tsho, Bhutan	Luggye Tsho	18,000	21	Villages, farmland
2000	Yarkant River, Karakoram	Yarkant Lake	14,000	105	Roads, farmland
2021	Chamoli, India	Ronti Peak Lake	16,000	204	Hydropower, villages



This historical GLOF has been represented in Figure 8 as a lollipop chart to give the time vulnerability of these historical GLOFs as Annotations of these historical GLOFs run through the peak discharges. The increase in the concentration of large flows in recent decades helps put emphasis on the aggravation of risks in the twenty-first century. The visual also highlights the fact that the percentage of fatalities is more or less associated with the peak of the discharge as well as exposure and the maturity of the preparedness simultaneously within the occasion of the event.

The combined outcomes show that climate change is transforming HKKH cryosphere ice such that it has pronounced GLOF hazards, in increase and severity. Lakes are rising in size and quantity throughout glaciers and the eastern and central Himalayan areas now prove to be the most hotspots. It becomes evident through hazard model that some lakes, especially with large amounts of water and stability of the dams, are a disaster with discharge levels equivalent to some of the largest river flooding in the Asian continent.

Analyses of the exposure depict the fact that millions of people and paramount infrastructure are placed in trip-lines of vulnerability increasing the catastrophe possibilities. Significantly, vulnerability tests emphasize the fact that poverty, literacy, and access to warnings are not less important socioeconomic factors that determine the results of catastrophes than physical dangers. These insights are further validated as observed in the past where events played out as predicted by the model and the multiprodromal effect of the growth of infrastructural losses on losses.

The tables and figures taken collectively illustrate an overall risk outline, wherein the climate change, geomorphological processes, and human vulnerability overlap. The results indicate that there is a pressing necessity of specific intervention such as enhanced monitoring, preemptive alerts, community preparedness and the incorporation of GLOF risk measurement within the regional planning network and transboundary governing systems.

Discussion

Climate Change and Cryospheric Transformation

Findings of this paper highlight the fact that cryospheric change is rapidly increasing in the HKKH region and this is closely associated with global climate change. Sustained mass loss in glaciers over the past decades allows attributing the responsible role to the rapid growth of glacial lakes and the rising frequency of potentially harmful glacial lakes (PDGLs). The process aligns with the overall tendencies in the degradation of the mountain cryosphere around the world, as the glaciers fade faster than down the last hundred three centuries (Shrestha et al., 2015). The HKKH is prone to effects especially because of its location at the border of westerlies, at the border with monsoon system, which further intensifies effects of warming and varies seasonal precipitation (Salerno et al., 2017). It is this twofold climatic mechanism that forms complicated feedback mechanisms in which glaciers melt at the same time as the formation of lakes and the thawing of the permafrost, and produces compound hazards that form and are hard to predict and control.

Moreover, the augmentation of the severe natural circulation phenomena (or extremes); attributable to monsoonal variability has contributed to the increase of instability in the Lakes within the Himalayas. Recent studies indicate that the extremes of precipitation have been more frequent and magnitude more significant especially in the eastern side of Himalayan catchments, and thus, the lakes that are moraine-dammed are more susceptible to collapse (Boehner and Lehmkuhl, 2019). These results are consistent with more general data shown by the IPCC Special Report on Mountains that forecasted an increase in such extremes in the warming world (Pepin et al., 2019). This growing coupling between climate drivers and geomorphological instabilities is thus one of the hallmarks of GLOF risk in the HKKH.

Societal Exposure and Vulnerability

The extent of susceptibility and exposure is very influential in defining the extent of disaster threat, just as the physical hazard is growing. The findings demonstrate that millions of people reside in the flood prone valley and the hydropower programs, bridges and avenues are extremely concentrated in the risky regions. This observation is reminiscent with earlier literature that has suggested that infrastructural projects in the Himalaya are usually geared towards short run economic benefits at the expense of long term stability culminating into an increased vulnerability (Ives and Messerli 1989). It is also disheartening that the relyance on valley-based infrastructure has been noted because of the limited and steep nature of the terrain of the region that limits any other places of settlement and transportation pathways (Bhadra et al., 2021).

The indicators of socioeconomic vulnerability go further to show the effects of poverty intensified by a lack of access to early warning systems and lack of connectivity contributes to the consequences of GLOFs. Community resilience is lower in other countries like the Hindu Kush area, where the rate of poverty is very high and the capacity of the state very low (Kattelmann, 2003). Indigenous people, minorities, and women are vulnerable populations that face it out of proportion not only due to a lack of adequate access to resources but also due to sociocultural factors limiting the mobility and decision-making (Goodrich, 2017). In such a way, the GLOFs in the HKKH cannot be perceived in the natural context of hazards; they are the sociocultural phenomena the effects of which are mediated through inequalities and gaps in governance.

Governance Challenges in a Transboundary Context

The internationalized character of the HKKH makes regulation of GLOF risk difficult. The rivers that start at the region go through Afghanistan, Pakistan, India, Nepal, Bhutan and China hence cross-border cooperation is necessary. Nevertheless, the restriction to the geopolitical tensions usually disrupts the exchange of data, collective surveillance and disaster management (Hunzai, 2010). As an example, these upstream glacial lakes in Tibet can potentially be dangerous to their downstream communities in Nepal and India, however, lack of complete information on the actual progress of the situation can arise as it is a politically sensitive issue (Xiang et al., 2014). Such ineffectiveness in collaboration undermines the effort to have early warning to occur in the region leaving the downstream populations exposed.

Falsehoods notwithstanding, there have been efforts to encourage team work. The South Asian Association of Regional Cooperation (SAARC) has been attentive to the role of the regional disaster management and the application of Himalayan Climate Change Adaptation Programme (HICAP) has aimed to address the scientific and policy gaps (Aase et al., 2017). Nevertheless, the efficacy of these programs is still limited due to lack of funds, the decentralized institutional roles and lack of establishing binding accords. Constitutionalization of transboundary hazard management governance structures is thus important particularly amidst the worst state of climate change that is increasingly cooling the cryosphere hazards of the region.

Advances in Monitoring and Risk Reduction

The creation of sophisticated skills to monitor water has raised new opportunities to minimize the GLOF risk. The remote knowledge, UAV surveys, and real-time satellite-based surveillance made an important advancement in the identification of high-risk lakes and early warned risk transferring (Fujita et al., 2013). With the help of automated algorithms, it is now possible to constantly monitor the lake area, volume and dam stability is possible and provide the assessment of the risk in close to real time. These technological advances, however, cannot be used evenly, with coverage in Nepal and Bhutan being providing at a higher rate than Afghanistan and Northern Pakistan (Sharma et al., 2019).

The pilot phase Engineering remedies have been undertaken in other countries such as Bhutan successfully, in which lowering of Thorthormi Lake was implemented by means of siphoning and controlled cutting of outlets (Komori et al., 2012). But, these interventions are expensive, labor-intensive and even political sensitive. They can also that are associated with unintended ecological effects, including the shift of downstream water supplies, or destabilizing other lakes (Mool et al., 2011). In that sense, although the structural risk mitigation does have something to contribute, the latter should be supplemented with the community-based adaptation, participatory planning and livelihood diversification.

Integrating Local Knowledge and Community Adaptation

The integration of the indigenous knowledge and the local adaptation strategies is an important aspect of GLOF risk management. It has been discovered that, Himalayan communities were continuously using their own forms of weather prediction, community notification systems, and social solidarity gaps to manage the natural hazards (McDowell et al., 2014). These approaches are often neglected in the official policy frameworks but can make the notion of a scientific observation much more effective as they offer some local contextual knowledge (Sharma and Molden, 2015).

Anticipating preparedness, such community-based disaster risk Reduction initiatives in Nepal, such as exercise, have shown how multilingual communication systems, participation mapping, and simulation exercises, can enhance preparedness (Allen et al., 2018). These strategies are able not only to decrease vulnerability, but also enable communities in taking direct action in determining their adaptation methods, which also enhances resilience long-term. The issue though is to generalize these approaches in other cultural and politically different environments and to make it inclusive and equitable.

Towards Integrated Climate Adaptation Strategies

The results of the current study reveal that combination approaches have to connect climatic adaptation as well as alleviating the climate hazards and sustainable development in the HKKH. GLOF risks have no way out of multilateral issues like poverty elimination, infrastructure design, and transboundary water management. The international schemes like the Sendai Framework on Disaster risk reduction and the Paris agreement offer a platform towards reconciliation of nationwide adaptation policies with regional hazard management (Kelman et al., 2016). Nevertheless, the globalization has left the translation of these global commitments into local working plans as a venturing issue.

Combined strategies should take into consideration multi-level governance, including national investments in monitoring infrastructure and regional collaboration on the data sharing and community involvement at the preparedness level. Moreover, it is necessary to make the usage of GLOF risk part of environmental impact assessment when building hydro-power, tourism, and road construction projects a compulsory measure in all HKKH countries (Kaenzig et al., 2016). Any development route that lacks this mainstreaming can, to put it bluntly, enhance hazard exposure and adversely affect human security and economic resilience.

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