Nepal Floods and Their Relationship with Glacial Lake Outburst Floods (GLOFS): Spatial Patterns, Environmental Impacts and Risk-Reduction Strategies

Birendra kumar Yadav*

Assistant Professor Department of Geography Baiswara Degree College Lalganj Raebareli

***Corresponding Author**

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ABSTRACT

Flooding is one of the most recurrent and damaging natural hazards in Nepal because of the country's steep topography, intense monsoonal rainfall, highly dissected drainage network, unstable slopes and rapidly changing Himalayan cryosphere. In the high mountain environment, conventional rainfall-induced floods increasingly interact with glacier-related processes, including glacial lake formation, glacier retreat, ice avalanches, landslides and glacial lake outburst floods (GLOFs). A GLOF occurs when water stored in a glacial lake is suddenly released, producing a high-energy flood wave that may transport large quantities of sediment, boulders, ice and debris into downstream valleys.

This paper examines the relationship between floods and GLOFs in Nepal, with particular emphasis on the role of glacier retreat, glacial-lake expansion, triggering mechanisms, downstream vulnerability and cascading hazards. The study uses a secondary-data and geospatial approach based on published literature, satellite-based glacial-lake inventories, government reports and assessments by ICIMOD, UNDP and other institutions. Historical events including the Nare GLOF of 1977, Nagma Pokhari GLOF of 1980, Zhangzangbo GLOF of 1981, Dig Tsho GLOF of 1985, Chubung GLOF of 1991, Tam Pokhari GLOF of 1998 and the Thame Valley GLOF of 2024 are examined alongside major rainfall- and river-related floods. The analysis demonstrates that Nepal's flood risk cannot be understood through a single hazard category

The study concludes that GLOF risk reduction requires an integrated approach combining remote sensing, GIS-based hazard mapping, continuous glacial-lake monitoring, early warning systems, structural mitigation, ecosystem-based measures, community preparedness and transboundary cooperation. The findings have implications for climate adaptation, mountain development planning and disaster-risk management in Nepal.

Keywords: Nepal, GLOF, glacial lakes, glacier retreat, floods, climate change, Himalaya, remote sensing, disaster risk, Thame Valley

INTRODUCTION

Nepal occupies a geographically distinctive position in the central Himalaya and contains a large vertical range extending from the low-lying Terai plains to the world's highest mountains. This extreme altitudinal variation creates diverse climatic and hydrological conditions, but it also produces considerable exposure to floods, landslides, avalanches, debris flows and other mountain hazards. Floods are particularly important because river systems originating in the Himalaya descend rapidly through steep valleys before entering the densely populated plains. During the summer monsoon, intense rainfall can generate flash floods and river floods, while in the high mountains, glacier-related processes can produce sudden and exceptionally destructive flood waves.

Flooding in Nepal therefore consists of several interconnected processes. In the Terai, riverine flooding is commonly associated with intense monsoon rainfall, high sediment loads and river-channel processes. In the

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middle mountains, steep slopes, landslides and intense rainfall contribute to flash floods and debris flows. In the high Himalaya, additional hazards arise from glacial lakes, unstable moraine dams, ice avalanches and landslides entering glacier-fed lakes. The failure of such a lake can generates a Glacial Lake Outburst Flood (GLOF).

The relationship between climate change and GLOF risk has become an important area of research. The Intergovernmental Panel on Climate Change has documented warming, glacier mass loss and retreat and changing cryospheric conditions across the Hindu Kush Himalaya. Continued glacier retreat can create or enlarge glacial lakes, while degradation of surrounding slopes and permafrost may increase the possibility of mass movements entering lakes. However, an important distinction is necessary: glacier retreat and lake expansion increase the conditions for GLOF hazard, but they do not mean that every expanding lake will necessarily produce an outburst. GLOF occurrence depends on lake morphology, dam characteristics, glacier and slope conditions, triggering events and downstream exposure.

Historical GLOFs demonstrate the destructive potential of these events. The 1985 Dig Tsho GLOF in the Everest region damaged infrastructure, cultivated land and the nearly completed Namche hydropower project. The 1998 Tam Pokhari event similarly caused extensive downstream damage. More recently, the 16 August 2024 Thame Valley event demonstrated that contemporary GLOFs can involve complex chains of processes. According to the later ICIMOD investigation, a rock avalanche entered a glacial lake at approximately 4,900 m, generating a displacement wave and initiating successive lake breaches. An estimated 459,000 m^3 of water was released from two lakes, debris travelled approximately 80 km downstream, 25 homes were destroyed and 135 people were displaced .The significance of these events extends beyond individual disasters. GLOF-related floods can interact with normal river flows, monsoon rainfall, landslides and debris flows, producing compound hazards. A high-magnitude GLOF occurring during or immediately before the monsoon may therefore have consequences that differ considerably from an isolated high-altitude flood. The present study investigates this relationship from a geographical perspective. It focuses on the spatial distribution of potentially dangerous glacial lakes, historical GLOF events, environmental and socio-economic impacts, and strategies for reducing downstream vulnerability.

Objectives

The study has three principal objectives:

1. To examine the geographical and climatic relationship between flooding and GLOFs in Nepal.
2. To analyse the environmental and socio-economic impacts of GLOF-related floods.
3. To evaluate integrated approaches for GLOF monitoring, early warning, adaptation and disaster-risk reduction.

MATERIALS AND METHODS

The study is based primarily on secondary information and geospatial interpretation. Published scientific literature, institutional reports, government documents, glacial-lake inventories and historical disaster records were reviewed to develop an integrated understanding of GLOF and flood processes in Nepal. The principal institutional sources include the International Centre for Integrated Mountain Development (ICIMOD), Government of Nepal, Water and Energy Commission Secretariat (WECS), Department of Hydrology and Meteorology (DHM), United Nations Development Programme (UNDP), IPCC and other scientific publications.

Particular attention was given to the ICIMOD–UNDP inventory of potentially dangerous glacial lakes and the recent assessment of the 2024 Thame Valley GLOF. Remote sensing and GIS are particularly important for this research because many glacial lakes are situated in remote and inaccessible terrain. Satellite imagery allows researchers to identify changes in lake area, glacier extent, moraine-dam characteristics and surrounding slopes. Multi-temporal satellite imagery can be used to compare lake expansion over different years. Digital Elevation Models (DEMs) are useful for determining elevation, slope, drainage direction, valley morphology

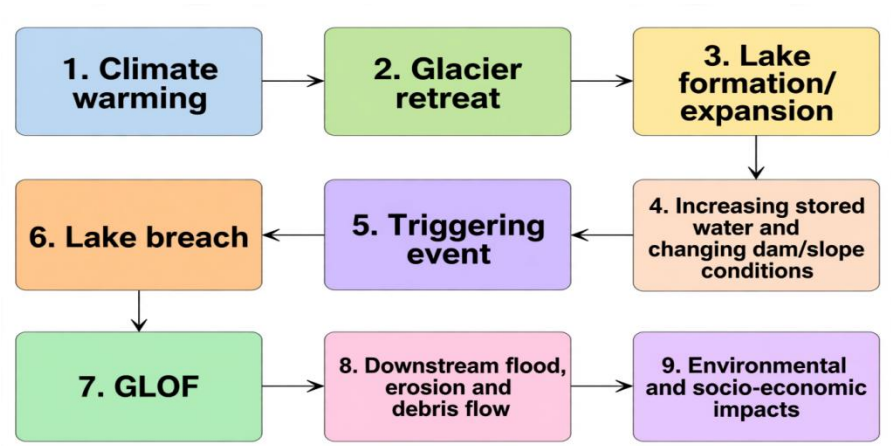
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and potential downstream flow paths. A conceptual hazard relationship was developed by linking climate change with glacier retreat, lake formation and expansion, triggering mechanisms and downstream flood impacts. Historical GLOF events were then compared with conventional flood events to distinguish cryosphere-related floods from rainfall- and river-dominated floods.

The analytical procedure consisted of the following stages:

Research problem → Literature review → Research design → Data collection → Remote sensing/GIS analysis → Historical event analysis → Impact assessment → Interpretation → Risk-reduction recommendations

Figure 1. Research Methodology Flow Chart



The methodology combines physical geography and disaster-risk perspectives. Physical processes such as glacier retreat, lake expansion, slope instability, moraine-dam failure and river response are examined together with human exposure, infrastructure, settlements, agriculture and tourism. This integrated approach is necessary because GLOFs are not only hydrological events; they are also geomorphological and socio-economic hazards.

Nepal's Flood and GLOF Environment

Flood Geography of Nepal

Nepal's flood environment varies considerably between the Himalaya, hills and Terai. In the high mountains, steep gradients produce rapid runoff and high-energy flows. The middle mountains contain narrow valleys where settlements, roads, hydropower facilities and agricultural terraces are often concentrated along river corridors. In the Terai, rivers become wider and flatter, increasing the potential for inundation when channels exceed their carrying capacity. Monsoon rainfall is the dominant seasonal driver of conventional flooding. Intense rainfall may produce flash floods, landslides and debris flows in mountainous areas and prolonged riverine flooding in the plains. The geographical concentration of population and infrastructure along river valleys increases vulnerability.

GLOF-related flooding adds another dimension to this hazard system. Unlike ordinary rainfall floods, a GLOF may originate from a high-altitude lake several tens of kilometres upstream from the affected settlement. The initial flood wave can entrain sediment, rocks, trees and other material as it moves downstream. Consequently, the eventual flood may be considerably more destructive than the volume of water released from the lake alone would suggest.

Glacier Retreat and Glacial-Lake Expansion

The Himalaya has experienced substantial cryospheric change over recent decades. Rising temperatures have contributed to glacier mass loss and retreat, while changes in precipitation and snow conditions have also

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affected glacier and lake dynamics. As glacier tongues retreat, depressions may become occupied by meltwater, leading to the formation or enlargement of glacial lakes.

Glacial lakes may be dammed by moraines, ice or combinations of ice and sediment. Moraine dams can contain large volumes of water but may have relatively complex and unstable structures. A sudden external trigger can generate a displacement wave capable of overtopping and eroding the dam.

Potential triggers include:

- ice or glacier avalanches;
- rockfalls and landslides;
- intense rainfall;
- rapid snow or ice melt;
- calving of glacier ice into lakes;
- earthquake-induced slope failure; and
- failure or progressive erosion of moraine dams.

The relationship is therefore best understood as a chain rather than a single cause:

Climate warming → glacier retreat → lake formation/expansion → increasing stored water and changing dam/slope conditions → triggering event → lake breach → GLOF → downstream flood, erosion and debris flow → environmental and socio-economic impacts.

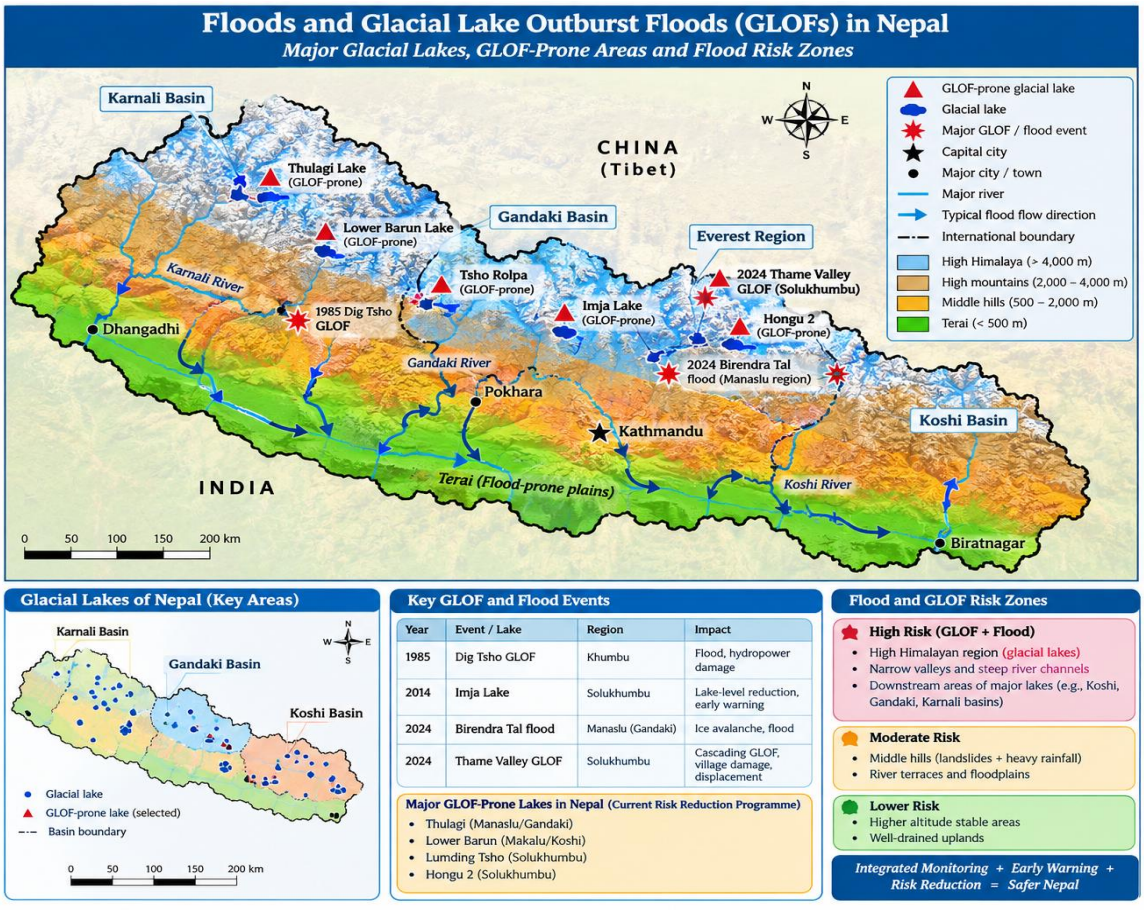


Figure 2. Map of Floods and GLOFs in Nepal

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The map illustrates the geographical relationship between major Himalayan glacial lakes, river basins and downstream flood-prone areas. The major GLOF-prone zones are concentrated in the high Himalayan portions of the Koshi, Gandaki and Karnali drainage systems. The downstream effects, however, are not confined to the immediate mountain environment because rivers transport floodwater, sediment and debris into lower valleys and plains.

Historical GLOF and Flood Events

Nepal's GLOF history extends for several decades. Events have occurred in different river basins and have varied in magnitude and triggering mechanism. The historical record also demonstrates that not all major floods in Nepal are GLOFs.

Table 1. Major Historical GLOF and Flood Events in Nepal

Year	Location/Event	Hazard Type	Major Trigger/Process	Major Significance
1977	Nare, Dudh Koshi	GLOF	Glacial-lake failure	Important early documented GLOF in the Everest region
1980	Nagma Pokhari, Tamor	GLOF	Lake/moraine failure	Significant high-mountain flood event
1981	Zhangzangbo/Cirenmacho, Bhote Koshi	GLOF	Glacial-lake failure	Damaged Friendship Bridge and Sun Koshi hydropower infrastructure
1985	Dig Tsho, Dudh Koshi	GLOF	Ice avalanche into lake	Destroyed the nearly completed Namche hydropower project and downstream infrastructure
1991	Chubung, Tama Koshi	GLOF	Lake/moraine failure	Downstream geomorphic and infrastructural impacts
1993	Central/Southern Nepal	Major monsoon flood	Extreme rainfall and river flooding	One of Nepal's major historical flood disasters
1998	Tam Pokhari/Sabai Tsho, Dudh Koshi	GLOF	Ice avalanche and moraine-dam breach	Severe downstream erosion, infrastructure and agricultural damage
2008	Koshi River, Sunsari	River flood	Embankment breach and high river discharge	Major displacement and inundation in the eastern Terai
2014	Sunkoshi, Sindhupalchok	Landslide-dam flood	Large landslide blocked river	Temporary lake formation and downstream flood risk
2017	Southern/Terai Nepal	Major monsoon flood	Intense monsoon rainfall	Widespread flooding across numerous districts

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2017	Lower Barun Valley	Glacial-lake-related flood	Cryosphere/glacial processes	Demonstrated continuing high-mountain flood risk
2021	Melamchi, Sindhupalchok	Flash/debris flood	Extreme rainfall and mountain processes	Extensive damage to settlements and infrastructure
2024	Birendra Tal/Manaslu region	Cryosphere-related flood	Ice avalanche/glacial processes	Sudden downstream flooding in the Budhi Gandaki system
2024	Thame Valley, Solukhumbu	GLOF/cascading flood	Rock avalanche and successive lake breaches	Destruction of houses and infrastructure and displacement of residents

Source: Compiled from ICIMOD, UNDP, Government of Nepal and published historical GLOF and flood records.

The historical sequence demonstrates that Nepal's flood hazard has several distinct components. Events such as Dig Tsho and Tam Pokhari were clearly associated with glacial lakes, whereas major events such as the 1993 and 2017 floods were predominantly related to monsoon rainfall and river processes. The 2014 Sunkoshi disaster represented another category involving a landslide-dammed river. The distinction is important because the monitoring, forecasting and mitigation requirements differ between these hazard types.

Potentially Dangerous Glacial Lakes

The ICIMOD–UNDP inventory identified 21 potentially dangerous glacial lakes within Nepal. The wider inventory covering Nepal, the Tibet Autonomous Region of China and India identified 47 potentially dangerous lakes, of which 21 were located in Nepal. The Koshi basin contained the largest concentration.

Table 2. Major Potentially Dangerous Glacial Lakes and Their Locations in Nepal

S. No.	Glacial Lake	District/Region	River Basin	Approx. Elevation	Risk Significance
1	Tsho Rolpa	Dolakha	Tama Koshi	~4,550 m	Large expanding moraine-dammed lake; major downstream exposure
2	Imja Tsho	Solukhumbu	Dudh Koshi	~5,010 m	Rapidly developed and expanding lake in Everest region
3	Lower Barun Tsho	Sankhuwasabha	Arun	~4,500 m	High-altitude lake exposed to mass-movement processes
4	Lumding Tsho	Solukhumbu	Dudh Koshi	~4,800 m	Potentially hazardous high-altitude lake
5	Thulagi Tsho	Gorkha	Marsyangdi	~4,000 m	Important lake in the Gandaki system
6	Chamlang Tsho	Solukhumbu	Dudh Koshi	~4,950 m	Steep surrounding terrain and mass-movement exposure
7	Chamlang	Solukhumbu	Dudh Koshi	~4,900 m	High-altitude lake with downstream

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	South Tsho				hazard potential
8	Dig Tsho	Solukhumbu	Dudh Koshi	~4,360 m	Historically produced the destructive 1985 GLOF
9	Tam Pokhari	Solukhumbu	Dudh Koshi	~4,430 m	Associated with the 1998 GLOF
10	Nagma Pokhari	Taplejung	Tamor	~4,900 m	Historically documented potentially hazardous lake
11	Hungu Lake	Solukhumbu	Dudh Koshi	~5,180 m	High-altitude lake within the Dudh Koshi system

Source: Compiled from ICIMOD–UNDP glacial-lake inventories and associated hazard assessments. Elevations are approximate and may vary slightly among datasets.

Tsho Rolpa and Imja Tsho are particularly important examples of the changing GLOF risk environment. Tsho Rolpa has been extensively monitored and underwent lake-level lowering as a mitigation measure. Nevertheless, continued glacier retreat and lake expansion require continued monitoring. Imja Tsho is similarly important because of its location within the heavily visited Everest region and its downstream exposure.

The existence of a potentially dangerous lake does not mean that an outburst is inevitable. Risk is determined by the combination of **hazard, exposure and vulnerability**. A lake may have high physical hazard characteristics but relatively low immediate exposure, whereas another lake may have moderate hazard but extremely high downstream exposure because settlements, roads, hydropower projects and tourism facilities are concentrated along its potential flood path.

Impacts and Spatial Dimensions of GLOF-related Floods

Physical and Environmental Impacts

The environmental consequences of GLOFs extend beyond the temporary rise in river discharge. A high-energy flood wave can erode valley sides, remove vegetation, transport boulders and sediment and modify river channels. Where the valley is narrow, the flood can cause deep incision and extensive bank erosion.

Sediment is particularly important. A GLOF may entrain large quantities of material from moraines, landslide deposits and riverbanks. The resulting debris-rich flow can have a destructive capacity much greater than a clear-water flood. Deposition may bury agricultural fields, block channels and alter local drainage.

River morphology can also change considerably. New channels may form, existing channels may migrate, and floodplains may be partially destroyed or newly developed. Such changes can increase long-term vulnerability because communities may continue to occupy apparently stable areas that have become geomorphologically unstable.

Mountain ecosystems may also be affected. Riparian vegetation can be removed, aquatic habitats disturbed and forest patches fragmented. However, the environmental impact varies according to flood magnitude, valley morphology, sediment availability and ecosystem characteristics.

Socio-economic Impacts

GLOF impacts become more severe where human settlements and infrastructure are located close to rivers. Nepal's mountain valleys frequently contain roads, bridges, hydropower plants, trekking trails, agricultural terraces, hotels and villages in narrow corridors. Consequently, even a relatively localized high-altitude event can generate extensive economic consequences.

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Table 3. Environmental and Socio-economic Impacts of GLOF-related Floods in Nepal

S. No.	Impact Dimension	Major Impacts	Consequences
1	Riverbank erosion	Removal of banks and floodplain material	Loss of land and destabilisation of settlements
2	Sediment/debris deposition	Deposition of boulders, gravel and mud	Burial of farmland, roads and infrastructure
3	Agricultural land	Inundation and burial of cultivated fields	Crop losses and livelihood disruption
4	Forest and ecosystems	Removal of vegetation and habitat disturbance	Ecological degradation
5	River morphology	Channel widening and diversion	Long-term floodplain instability
6	Hydropower	Damage to dams, powerhouses and transmission facilities	Electricity disruption and financial losses
7	Roads and bridges	Washing away or undermining of transport infrastructure	Isolation of mountain communities
8	Houses/public facilities	Destruction of homes, schools and health facilities	Displacement and reconstruction costs
9	Tourism	Damage to hotels, trails and trekking routes	Reduced tourism income
10	Livelihoods	Disruption of agriculture, trade and services	Household income loss
11	Displacement	Evacuation or permanent relocation	Social disruption and shelter requirements
12	Livestock/assets	Loss of livestock and productive assets	Reduced household resilience
13	Water resources	Sedimentation and water-quality impacts	Disruption of drinking-water systems
14	Cascading hazards	Landslides, debris flows and secondary flooding	Expansion of affected area
15	Long-term instability	Persistent erosion and unstable slopes	Continued exposure after the event

The 2024 Thame event provides a recent illustration. The flood damaged houses and public infrastructure, affected bridges and hydropower facilities and displaced residents. The later ICIMOD investigation found that debris travelled approximately 80 km downstream. This demonstrates that GLOF impacts can propagate well beyond the immediate vicinity of the source lake.

Tourism is especially important in this context. Several potentially dangerous lakes are located in or near major trekking and mountaineering destinations. Damage to trekking trails, bridges, accommodation facilities

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and local markets can therefore affect not only resident households but also tourism-dependent businesses and employment.

Hydropower represents another critical vulnerability. Nepal's steep river gradients provide favourable conditions for hydropower development, but many facilities are situated along rivers exposed to floods, landslides and sediment. GLOFs may therefore simultaneously damage physical infrastructure and interrupt electricity generation.

Cascading Hazard Relationship

The relationship between climate change, glaciers, glacial lakes and flooding should be understood as a cascading hazard system.

Figure 3. Conceptual Relationship between Climate Change, Glacier Retreat, GLOF and Downstream Flooding



The conceptual model begins with climatic change and glacier retreat. These processes contribute to lake formation and expansion. A triggering event, such as an avalanche, landslide, intense rainfall or ice collapse, may then generate a displacement wave or initiate moraine-dam failure. The resulting GLOF enters the river network and may transform into a sediment-rich flood or debris flow.

The hazard can become increasingly complex downstream. River morphology, channel constrictions, tributary inflow, additional landslides and human infrastructure can modify the flood wave. Thus, GLOF risk is not

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simply a question of how much water is stored in a lake. It is also a question of how that water interacts with the landscape and human environment.

Risk Reduction, Adaptation and Integrated Management

Remote Sensing and GIS-based Monitoring

Remote sensing is one of the most effective tools for monitoring glacial lakes because many are located in remote and difficult terrain. Multi-temporal satellite imagery can identify changes in lake area and shape. DEMs can be used to examine lake elevation, surrounding slope, drainage networks and potential downstream pathways.

GIS provides a platform for integrating multiple datasets, including:

- glacier boundaries;
- lake area and volume;
- slope and elevation;
- river networks;
- settlements;
- roads and bridges;
- hydropower infrastructure;
- agricultural land;
- tourism facilities; and
- population exposure.

A GIS-based GLOF susceptibility model can combine these variables to identify downstream risk zones. Hazard maps can then be used for land-use planning, evacuation planning and infrastructure design.

Early Warning Systems

Early warning systems are essential because structural mitigation cannot eliminate all GLOF risk. A functional warning system should detect changes at the source and transmit information rapidly to downstream communities.

Monitoring can include water-level sensors, automatic weather stations, seismic sensors, cameras, satellite observations and communication networks. Warning messages should be connected to clearly defined evacuation routes and community response procedures.

The experience of Tsho Rolpa demonstrates the importance of combining technical monitoring with downstream warning stations. Early warning is most effective when communities understand warning signals, evacuation routes and safe locations before a disaster occurs.

5.3 Structural and Nature-based Measures

Structural mitigation can reduce the probability or magnitude of an outburst in selected high-priority lakes. Possible measures include:

- controlled lowering of lake water levels;

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- strengthening or stabilising moraine dams;
- construction of controlled drainage channels;
- outlet improvement;
- protective barriers in selected locations; and
- reinforcement of critical infrastructure.

However, structural measures can be expensive and technically difficult at high altitude. They are therefore most appropriate for lakes where hazard and downstream exposure are both high.

Nature-based approaches should complement structural measures. Stabilisation of vulnerable slopes, protection of riparian vegetation, restoration of degraded catchments and careful management of mountain ecosystems can reduce secondary erosion and sediment transport.

5.4 Community Preparedness

Disaster-risk reduction ultimately depends on local communities. Technical warning systems have limited value if residents do not receive, understand or trust warnings.

Community preparedness should include:

1. identification of safe evacuation areas;
2. preparation of evacuation routes;
3. regular disaster drills;
4. local disaster-response committees;
5. communication systems;
6. protection of essential documents and livelihood assets;
7. awareness programmes in schools; and
8. inclusion of local knowledge in disaster planning.

Women, children, elderly people, persons with disabilities and economically vulnerable households may face greater difficulties during evacuation and should receive specific attention in preparedness planning.

Climate Adaptation and Infrastructure Planning

Climate adaptation should be incorporated into infrastructure development rather than being treated as a separate disaster-management activity. Roads, bridges, hydropower facilities, settlements and tourism infrastructure should be located using hazard and exposure assessments.

New infrastructure in GLOF-prone valleys should consider probable flood pathways, debris-flow zones, river migration and sediment deposition. Infrastructure design should incorporate appropriate freeboard and structural resilience.

The Government of Nepal's recent flood, drought and climate-change analysis also emphasise the need for proactive rather than purely reactive disaster-risk management and calls for improved guidance on flood, GLOF and landslide-dam-outburst-flood management.

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Transboundary Cooperation

Nepal's major rivers cross national boundaries or originate in the trans-Himalayan region. Consequently, GLOF monitoring and warning cannot always be managed exclusively within national borders.

Satellite data, hydrological information, lake monitoring and hazard warnings should be shared among relevant institutions. Cooperation involving Nepal, China and other Himalayan countries is particularly important for river systems where upstream events can affect downstream communities across political boundaries.

DISCUSSION AND CONCLUSION

The geographical relationship between floods and GLOFs in Nepal is complex. Floods cannot be treated as a single homogeneous hazard because different parts of the country experience different flood-generating mechanisms. The Terai is primarily exposed to riverine and monsoon flooding, the middle mountains experience flash floods, landslide-dam floods and debris flows, while the high Himalaya additionally faces GLOFs and other cryosphere-related hazards.

The evidence examined in this study demonstrates that climate change is modifying the physical context in which these hazards occur. Glacier retreat contributes to the development and expansion of glacial lakes, while changes in high-mountain slopes and ice conditions may influence the probability of triggering events. Nevertheless, the relationship between climate warming and GLOF frequency should be expressed carefully. Available scientific assessments provide strong evidence for glacier and glacial-lake change but do not establish a simple linear increase in the frequency of all GLOFs. GLOF risk is controlled by multiple interacting physical and human factors.

Historical events demonstrate the destructive potential of GLOFs. The 1985 Dig Tsho event remains a landmark example because the outburst caused extensive damage to downstream infrastructure. The 1998 Tam Pokhari event further demonstrated the role of ice avalanches and moraine-dam failure. The 2024 Thame event provides a particularly important contemporary example because it involved a sequence of geological and hydrological processes rather than a simple lake breach. A rock avalanche triggered a displacement wave, followed by successive lake breaches and downstream debris transport.

The spatial pattern of potentially dangerous lakes is also significant. The ICIMOD–UNDP inventory identified 21 potentially dangerous glacial lakes in Nepal, with a large concentration in the Koshi basin. The presence of these lakes, combined with dense settlement and infrastructure in downstream valleys, creates a complex risk geography.

The environmental impacts of GLOFs include riverbank erosion, sediment deposition, channel modification, vegetation destruction and habitat disturbance. These processes subsequently produce socio-economic impacts through agricultural losses, infrastructure damage, tourism disruption, displacement and livelihood insecurity. Consequently, GLOF management must address both the source hazard and downstream vulnerability.

The most appropriate strategy is therefore an integrated GLOF risk-management framework. Remote sensing and GIS should be used for continuous lake and glacier monitoring, hazard mapping and downstream exposure assessment. High-priority lakes require systematic field investigation and, where appropriate, structural mitigation. Early warning systems should be expanded and connected to community-level evacuation planning. Infrastructure development should incorporate GLOF hazard assessments, and ecosystem-based measures should be used to reduce secondary erosion and sediment impacts.

CONCLUSION

Nepal's relationship between floods and GLOFs reflects the interaction of climate, glaciers, geomorphology, hydrology and human development. GLOFs represent a specialised but potentially catastrophic component of Nepal's broader flood-risk environment. Their impacts can extend far downstream through flood waves, sediment transport, debris flows, riverbank erosion and infrastructure destruction.

The changing Himalayan cryosphere makes systematic monitoring increasingly important. However, climate change should not be viewed as the sole explanation for GLOF disasters. The final magnitude of risk depends on lake characteristics, triggering mechanisms, downstream terrain, infrastructure exposure, settlement patterns and community preparedness.

Future GLOF management should therefore move from event-based disaster response towards continuous risk management. A combination of satellite monitoring, GIS-based modelling, field observations, early warning systems, structural mitigation, ecosystem-based adaptation, community preparedness and transboundary information sharing can significantly improve resilience.

The 2024 Thame Valley event demonstrates the urgency of this approach. It shows that a high-altitude glacial hazard can rapidly become a downstream socio-economic disaster through a cascade of processes. Understanding these connections is essential for sustainable mountain development, climate adaptation and disaster-risk reduction in Nepal.

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