GLOF Disaster in Sikkim: A Case Study of South Lhonak Lake

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ABSTRACT

The Himalayan region is highly tectonically active, rendering Sikkim an ecologically and geologically fragile zone. Exacerbated by climate change, disasters like landslides, earthquakes, cloudbursts, and Glacial Lake Outburst Floods (GLOFs) have increased in frequency. Situated in seismic Zone IV, Sikkim's steep slopes and complex geological structures further elevate its vulnerability, causing severe socio-economic and ecological losses. This study aims to address these escalating threats, focusing on emerging catastrophic phenomena like GLOFs and evaluating how geospatial technologies can minimize risk. Methodologically, the paper examines recent disaster events as case studies—most notably the catastrophic Sikkim disaster of October 3, 2023—to analyze the compound effects of simultaneous heavy rainfall, seismic activity, and landslides. The findings reveal that these multi-hazard events trigger devastating, far-reaching consequences. Structurally, they cause massive destruction to critical infrastructure (roads, bridges, and dams), cutting off essential services to large areas. Furthermore, these events have transboundary consequences that severely impact low-lying downstream areas in Bangladesh, while simultaneously degrading the fragile local ecosystem and halting regional development projects. In conclusion, natural disasters in Sikkim pose a continuous threat to human life, economic stability, and environmental sustainability. To effectively manage these hazards within hostile and inaccessible mountainous terrains, the integration of Remote Sensing (RS) and Geographic Information System (GIS) technologies is crucial. Incorporating these geospatial tools into formal planning frameworks significantly enhances regional disaster preparedness, optimizes emergency response strategies, and minimizes future vulnerabilities and damages.

Keywords: Sikkim, GLOF, Disaster Management, Remote Sensing, GIS, Climate Change.

INTRODUCTION

Climate change is increasingly visible, particularly within the Himalayan belt. The hilly terrain of Sikkim is highly vulnerable to various disasters, including earthquakes, hailstorms, and landslides. Rising global temperatures are leading to a wetter climate, which is expected to increase the frequency of extreme weather events. Furthermore, the construction of multiple hydropower projects has negatively impacted the local ecosystem. The Teesta River serves as a major source for many of these interconnected hydropower projects. The state also faces unregulated commercial development and dam construction that run counter to the region's fragile geology. Because the melting glaciers feeding these rivers provide fresh water to millions of people for their livelihoods, any further environmental disruption will have catastrophic effects. Consequently, the escalating risk of Glacial Lake Outburst Floods (GLOFs) demands greater care in regional planning and execution. A recent report warned that glaciers are melting at an alarming rate and could lose up to 80% of their volume due to rising global temperatures, placing nearby communities at an exceptionally high risk of GLOFs (CNN, October 6, 2023).

About the Study Area

Sikkim transitioned into an Indian protectorate in 1950 and was formally integrated as the 22nd state of the Republic of India in 1975. Geographically positioned in the eastern Himalaya, the state extends between 27°00′46″–28°07′56″ N latitude and 88°00′58″–88°55′25″ E longitude. It shares international boundaries with the Tibet autonomous Region of China to the north and northeast, Bhutan to the southeast, and Nepal to the west, while the Indian state of West Bengal borders it to the south.

Study Area

Figure 1

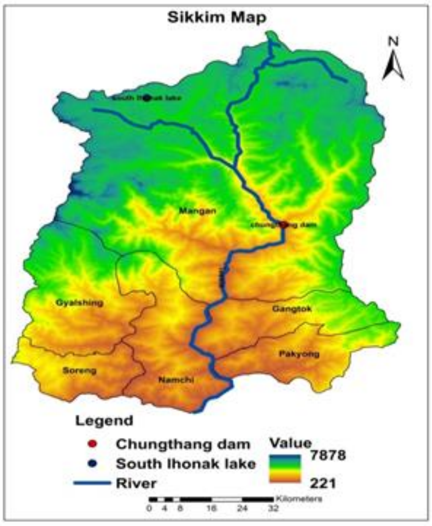


Figure 2

With a total geographical area of approximately 7,096 km² and a projected 2021 population of about 0.68 million, Sikkim is among India's smallest and least densely populated states (86 persons per km²). Administratively, it comprises six districts: Mangan, Gangtok, Namchi, Gyalshing, Pakyong, and Soreng. Gangtok, located in the southeastern sector, functions as both the political capital and principal urban center.

Physiographically, the state forms part of the Eastern Himalayan orogenic belt, characterized by steep altitudinal gradients ranging from subtropical valleys at 300 m to high alpine zones exceeding 8,500 m. The region hosts Kangchenjunga, India's highest peak and the world's third-highest mountain, which exerts a significant influence on regional microclimates and glaciation patterns. The drainage network is dominated by the Teesta River system—including the Rangeet and numerous glacial and snow-fed tributaries—which collectively regulates hydrological flux, sediment transport, and hydropower potential. Approximately 47–48% of the state's area remains under forest cover, reflecting high ecological integrity, while nearly 35% falls within the Khangchendzonga National Park, a UNESCO-recognized biosphere of global biodiversity significance. Consequently, the area exhibits pronounced climatic heterogeneity, ranging from humid subtropical to alpine tundra conditions that support exceptional floral and faunal diversity.

Socio-demographically, Sikkim demonstrates relatively high human development indicators, including a literacy rate exceeding 80% and an urbanization level of roughly one-quarter of the total population. The principal ethnic communities—the Lepcha, Bhutia, and Nepali—contribute to a distinctive socio-cultural landscape shaped by trans-Himalayan interactions. Infrastructure has expanded rapidly in recent years with the operationalization of the Pakyong Greenfield Airport, ongoing rail connectivity toward Rangpo–Majhitar, and the strengthening of national highway corridors such as the NH-10 and NH-717 variants. These transport interventions are strategically significant for regional integration, disaster response logistics, and economic diversification, though their implementation in fragile mountain terrain necessitates rigorous geotechnical assessments and strict environmental safeguards

Objectives

- To find out the causes of the GLOF event in the Sikkim
- To assess the damage caused by the GLOF event

DATABASE AND METHODOLOGY

This study utilizes secondary data compiled from published government reports, official portals of the Government of Sikkim, post-disaster media briefs, national seismic hazard maps of India, and empirical observations of historical events. Employing a descriptive-analytical framework, the paper evaluates the typology, causal mechanisms, and socio-ecological impacts of natural hazards in the Eastern Himalayan region, with a specific focus on Sikkim.

The analytical approach examines baseline environmental variables—including tectonic activity, structural geology, geomorphological slope profiles, and accelerated climate change—to determine their collective contribution to systemic risks such as earthquakes, landslides, Glacial Lake Outburst Floods (GLOFs), and flash floods. To illustrate the region's acute exposure to multi-hazard cascades, the catastrophic Sikkim event of October 3, 2023, is utilized as a primary case study. This compounding disaster—triggered by concurrent extreme precipitation, seismic instability, and mass wasting that culminated in a major GLOF—serves as an empirical anchor to evaluate broader Himalayan vulnerability and climate-induced risks. Furthermore, this work assesses the integration of advanced geospatial techniques, specifically **Remote Sensing (RS)** and **Geographic Information Systems (GIS)**, for predictive risk modeling and long-term mitigation management. Finally, a qualitative interpretive matrix is applied to delineate the interconnected dynamics between climate change, environmental fragility, and subsequent socio-economic consequences, evaluating the overarching implications of these events on both anthropogenic and ecological systems.

LITERATURE REVIEW

The October 2023 South Lhonak Lake outburst flood in Sikkim underscores the critical intersection of environmental fragility and anthropogenically driven development in high-mountain ecosystems. Historical trends indicate that rising temperatures across the Indian Himalayan Region (IHR) have significantly accelerated glacial ablation and proglacial lake expansion. For instance, Sharma and Gupta (2025) note localized warming rates up to 0.16°C per year in parts of the Himalayas, which have driven a marked increase in both the volume and frequency of Glacial Lake Outburst Floods (GLOFs)—exemplified by over 45 documented events in neighboring Nepal alone.

The catastrophic failure at South Lhonak Lake, which culminated in the destruction of the Chungthang hydroelectric dam and extensive downstream socio-economic losses, had been anticipated by prior hazard modeling (Govindha Raj, 2013; Begam et al., 2018; Sattar et al., 2021). Despite these predictive risk assessments, a pronounced gap between scientific consensus and policy execution—compounded by the absence of functional Early Warning Systems (EWS)—prevented timely mitigation. This systemic vulnerability is further illustrated by historical multi-temporal satellite analyses of glacial evolution across the broader orogenic belt. Govindha Raj and Kumar (2012) utilized decades of remote sensing datasets—spanning Landsat MSS (1976) to Resourcesat-1 (2005)—to track the spatio-temporal dynamics of supraglacial features like Vasundhara Tal in the Kumaun Himalaya. Their study demonstrated how climate-induced retreat promotes the coalescence of smaller meltwater ponds into highly unstable, moraine-dammed lakes.

The cascading nature of these cryospheric hazards is well-documented across the broader Himalayan arc. Historical precedents—such as the 1926 Jammu and Kashmir deluge, the 1981 Kinnaur Valley floods, the 1985 Dig Tsho and 1994 Lugge Tsho GLOFs, alongside the more recent 2013 Kedarnath and 2021 Chamoli disasters—confirm that warming temperatures and extreme precipitation trigger mass wasting events, ice avalanches, and moraine failures. The 2021 Uttarakhand disaster, which resulted in severe structural failures at two downstream hydroelectric installations and caused at least 38 fatalities, explicitly highlighted how slope instability and rapid meltwater surges can convert localized geomorphic failures into regional disasters, particularly along steep, infrastructure-dense river corridors.

Sikkim exhibits one of the highest concentrations of cryospheric systems in India, hosting approximately 80 glaciers that are currently experiencing accelerated retreat. South Lhonak Lake, a large proglacial water body situated at the snout of a receding glacier in North Sikkim, expanded rapidly over recent decades due to heightened thermal ablation. While the October 3, 2023 outburst temporarily evacuated a significant volume of the lake, post-disaster assessments by Sattar (2023) indicate a high probability of structural re-stabilization and future water-level expansion, maintaining its long-term hazard potential.

Concurrently, empirical climatic modeling from institutions like the Indian Institute of Technology Guwahati confirms a twentieth-century trend of increasing baseline temperatures and extreme precipitation frequencies across Sikkim. These hydro-climatic changes are compounded by localized anthropogenic stressors, including deforestation, unregulated commercial urbanization, and the proliferation of run-of-the-river hydropower projects. Local communities and regional monitoring bodies, such as the International Centre for Integrated Mountain Development (ICIMOD), emphasize that addressing these compounding risks requires shifting from passive observation to active risk reduction. This includes the urgent deployment of real-time telemetry monitoring, localized early warning architectures, and community-inclusive planning frameworks before subsequent thresholds of stability are breached. The structural and chronological distribution of these regional hazards is systematized in Table 1, categorizing the specific typologies of natural disasters recorded across the Himalayan terrain throughout the annual cycle.

Table: 1, Various Types of Disasters in Sikkim

Disasters	**Period of Occurrence**
Landslide	June to September
Earthquake	Any Time
Flash Flood	June to September
Hailstorm	March to June
Drought	October to April
Forest Fire	March to April
Avalanche	January to March

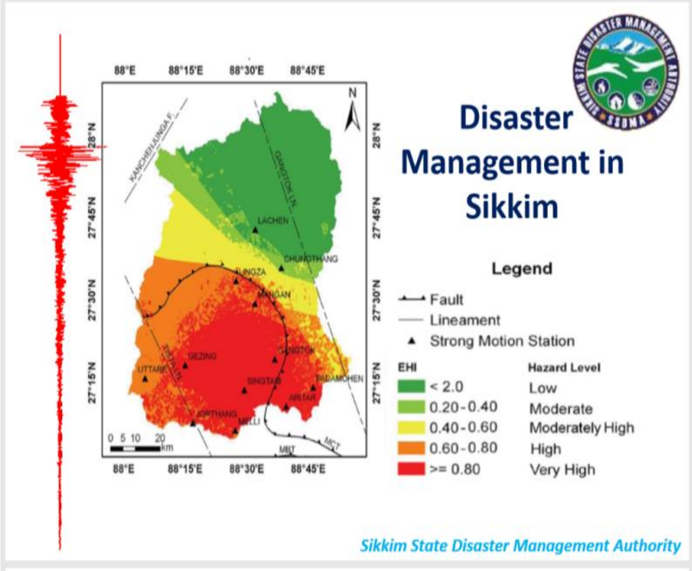


Figure 3

Source: SSDMA PPT, 2023 workshop held at Gangtok, Sikkim on 9 March 2011, CGWB, Eastern Region, Kolkata

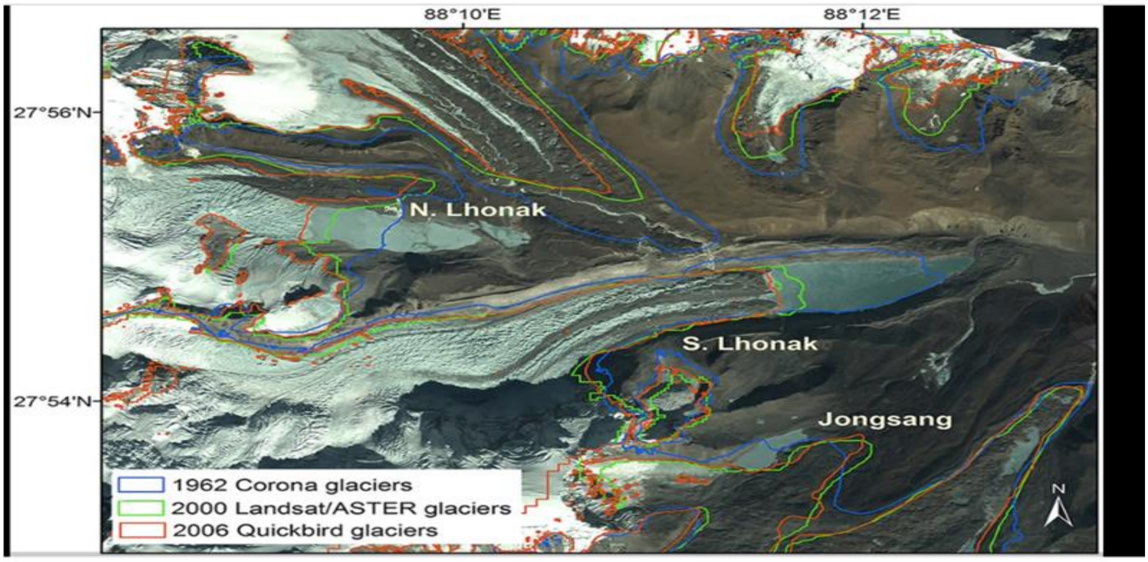
GLOF Phenomena

As global temperatures rise, accelerated glacial retreat causes meltwater to accumulate in deep depressions, forming proglacial or supraglacial lakes. These bodies of water are typically impounded by unstable, naturally occurring dams composed of loose glacial debris and ice (moraines). A Glacial Lake Outburst Flood (GLOF) occurs when this structural barrier fails or is breached, resulting in the sudden and catastrophic release of massive volumes of meltwater downstream. This failure is frequently intensified or triggered by multi-hazard cascades, including tectonic activity, displacement waves from rockfalls or ice avalanches, and extreme precipitation events that overwhelm the lake's storage capacity.

Background of South Lhonak Lake

The high-altitude terrain of the Teesta Basin contains numerous glacial lakes susceptible to climate-induced hazards. A comprehensive risk assessment conducted in 2021 identified 12 glacial lakes in this basin with a high probability of experiencing a Glacial Lake Outburst Flood (GLOF), among which South Lhonak Lake was classified as exceptionally vulnerable. Prior to this, in 2013, the National Remote Sensing Centre (NRSC) in Hyderabad issued early warnings to regional authorities regarding the rapid aerial expansion of these water bodies.

This moraine-dammed, glacier-fed system was initially identified as a small supraglacial feature in 1962 using CORONA satellite imagery (Figure 4). By 1977, Landsat MSS datasets confirmed it had evolved into a distinct, detached proglacial lake with a surface area of approximately 17 hectares. Over the subsequent four decades, accelerated glacio-dynamic retreat caused the parent glacier to recede by 1.9 km. The compounding potential threat of a catastrophic GLOF became increasingly critical as the lake's surface area expanded exponentially, reaching approximately 100 hectares by 2008.



Satellite image from 2006 showing the expansion of the lake over four decades

A. E. Racoviteanu, Y. Arnaud, M. W. Williams, W. F. Manley - A. E. Racoviteanu et. al. "Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga–Sikkim area, eastern Himalaya", The Cryosphere doi:10.5194/tc-9-505-2015

Figure 4

Risk Mitigation and Causal Mechanics of the 2023 Outburst

In 2016, a state government inspection team reported that the sub-glacial inflow of South Lhonak Lake significantly exceeded its outflow, signaling critical volume expansion. To mitigate the rising risk of a Glacial Lake Outburst Flood (GLOF), a collaborative initiative was launched in 2018 to siphon excess water from the lake, thereby artificially lowering its hydrostatic pressure. Concurrently, the Sikkim State Disaster Management

Authority (SSDMA) and the National Disaster Management Authority (NDMA), in partnership with the Swiss Agency for Development and Cooperation, initiated monitoring protocols for two high-risk lakes: South Lhonak and Shako Cho.

Despite these preventative efforts, the catastrophic failure occurred due to delays in deploying a fully operational automated Early Warning System (EWS). While the EWS at Shako Cho was successfully implemented and functional, the installation at South Lhonak experienced critical technical and logistical delays, largely attributed to its remote, high-altitude location. The system failed prior to the arrival of technical teams tasked with resolving the instrumentation issues. Geomorphologically, South Lhonak Lake is an elongated, bullet-shaped proglacial water body situated at an elevation exceeding 5,000 meters in North Sikkim, adjacent to the Indo-China international border. The parent glacier features extensive snow and ice cover that exerts immense cryospheric and static pressure on the lake's moraine snout. The catastrophic breach on October 3, 2023, was ultimately driven by a combination of severe, compounding triggers:

- **Seismic Activity:** A series of earthquakes centered in the Nepal region induced structural instability and slope failure along the lateral moraines.
- **Extreme Precipitation:** Torrential rainfall, measuring approximately five times the seasonal regional average, rapidly overwhelmed the lake’s storage capacity and triggered mass wasting events.

The resulting catastrophic multi-hazard cascade released an unprecedented volume of high-velocity meltwater downstream. The floodwave decimated the Chungthang Hydroelectric Dam within approximately ten minutes and severely impacted over 88,000 people across regional and transboundary downstream communities. Post-disaster satellite observations (Figure 5) delineate the exact zone of the structural breach along the moraine dam. The imagery confirms that significant volumes of meltwater continued to discharge from the lake three days post-burst. Consequently, the dramatic reduction in water volume has exposed a substantial portion of the dynamic shoreline that was entirely submerged prior to the event.

Figure 5

Figure 6

Figure 7

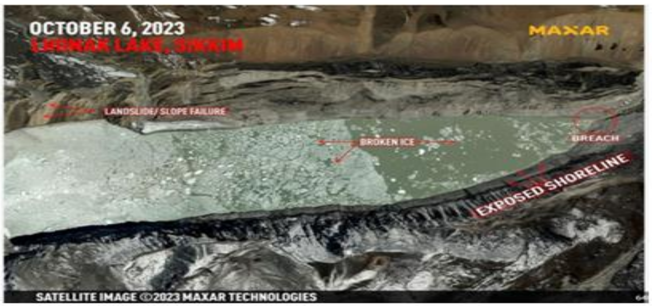


Figure 8

The exact trigger mechanism of the South Lhonak Lake breach remains a subject of ongoing scientific investigation. However, most institutional authorities attribute the initiation of the Glacial Lake Outburst Flood (GLOF) to a localized cloudburst within the high-mountain headwaters, which rapidly destabilized the cryospheric barrier. This catastrophic event validates longstanding concerns held by climatologists regarding the systemic vulnerabilities of downstream hydroelectric infrastructure situated in fragile, tectonically active alpine regions.

Multi-temporal satellite monitoring effectively captures the rapid geomorphic transformation and sudden drainage of the lake. Comparative analysis of spaceborne imagery indicates that the lake surface area spanned approximately 162 hectares on September 17, 2023, and expanded slightly to 167 hectares by September 28. Following the catastrophic breach on the night of October 3–4, post-disaster imagery revealed that the lake surface area had shrunk to just 62 hectares—representing an approximate 60% reduction in aerial extent within a single diurnal cycle.

Despite the precision of these spatial measurements, converting surface area data into precise hydrological discharge models presents significant technical limitations. As noted by Dr. Kalachand Sain, Director of the Wadia Institute of Himalayan Geology (DST), standard optical satellite datasets do not resolve bathymetric depth profiles. Consequently, calculating the exact volume of evacuated meltwater remains highly challenging without direct, in-situ physical measurements of the lake basin.

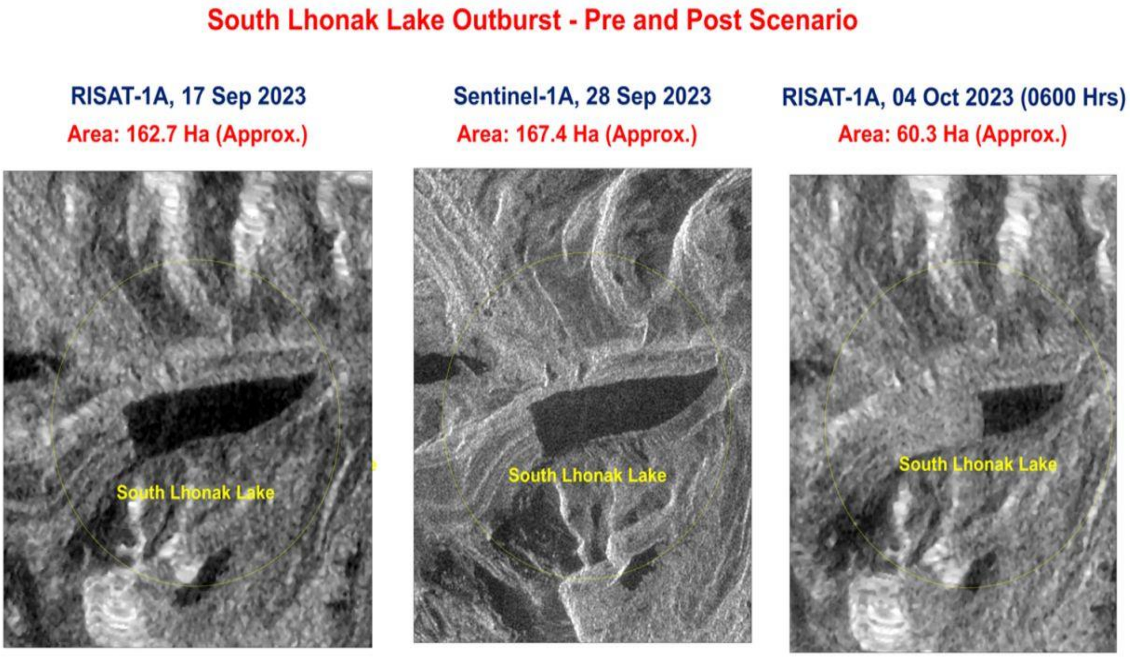


Figure 9

Source: ISRO-Temporal changes in Lhonak Lake area as of September 17; September 28; and October 4.

Analysis of Socio-Economic, Structural, and Ecological Damages

The catastrophic multi-hazard cascade initiated by the South Lhonak Lake outburst resulted in severe, wide-ranging impacts across local, regional, and transboundary jurisdictions. Although comprehensive macroeconomic evaluations remain ongoing, preliminary institutional estimates indicate that critical physical infrastructure sustained damages totaling billions of dollars (several thousand crores INR). The downstream floodwave along the Teesta River corridor peaked at an estimated 20 feet above baseline levels, completely obliterating the Chungthang Hydroelectric Dam and inundating low-lying regions.

1. Spatial Extent and Demographic Impact

The geographic footprint of the flood spanned multiple administrative boundaries:

- **Sikkim:** Severe devastation was recorded across 100 villages and wards within the Mangan, Gangtok, Pakyong, and Namchi districts, directly affecting approximately 88,400 individuals.
- **West Bengal:** Downstream inundation heavily impacted the Kalimpong, Darjeeling, Jalpaiguri, and Cooch Behar districts.
- **International Impact:** The floodwave extended into Bangladesh, causing widespread inundation across hundreds of riparian villages and vulnerable *char* (river island) ecosystems along the Teesta network.

This event represents the most severe hydrological disaster in the region since the historic 1968 deluge, which claimed over 1,000 lives. The 2023 disaster resulted in a verified death toll exceeding 100 individuals across Sikkim and West Bengal, with dozens sustaining severe injuries and scores remaining missing. Furthermore, the localized agrarian economy suffered substantial livestock depletion, with the reported mortality of 1,831 livestock animals and nearly 29,400 poultry.

2. Structural Infrastructure and Transport Logistics

The high-velocity surge decimated critical transit corridors and utility networks. National Highway 10 (NH-10) suffered catastrophic collapse, completely severing the northern districts of Sikkim from the rest of the nation. Structural damage to the housing sector was extensive, with more than 2,500 residential units recorded as either partially or fully destroyed.

The surge washed away 15 strategic bridges and rendered essential roadways impassable, trapping over 3,000 tourists across the state. This profound disruption to transport networks crippled emergency response logistics, severely impeding the mobilization of first responders and delaying the distribution of essential relief services to isolated, vulnerable populations. Communication networks were similarly compromised due to structural failures in Very Small Aperture Terminal (VSAT) Ethernet links, Bharat Sanchar Nigam Limited (BSNL) frameworks, and Optical Fiber Cable (OFC) mainlines. Military logistics were also directly impacted; out of 83 tactical vehicles submerged by the surge, only 31 were initially recovered.

3. Macroeconomic and Industrial Disruptions

The compounding structural damages induced severe shocks across Sikkim’s primary economic drivers, which are structurally dependent on manufacturing (52%), services (32%), and agriculture (10%):

- **The Service and Tourism Sector:** Because the disaster coincided with the peak tourist season (October to December), the collapse of regional transport networks and hospitality infrastructure resulted in immediate and severe revenue losses within the service industry.
- **The Secondary and Industrial Sector:** Sikkim serves as a critical hub for pharmaceutical manufacturing. The flood caused extensive damage to the localized power grid and run-of-the-river hydropower infrastructure, causing widespread energy deficits. This lack of reliable power disrupted drug production lines and created profound downstream bottlenecks within national and global pharmaceutical supply chains.
- **The Agrarian Sector:** Beyond direct crop losses, the destruction of rural roads prevented local farmers from accessing regional market centers, compounding rural economic precarity.

4. Secondary Environmental and Public Health Risks

The disaster introduced complex secondary environmental hazards. The destruction of an elite military ammunition depot at Munshithang triggered significant containment concerns regarding the downstream dispersal of weapons, ammunition, and unexploded ordnances (UXOs). Concurrently, the destruction of municipal sanitation infrastructure and the contamination of regional water tables significantly elevated the risk profiles for waterborne disease outbreaks across the affected riparian communities, amplifying the baseline environmental pollution.

Rescue Operation

Figure 10

Central Government Initiative

Seeing the situation the Government released Rs 48 crores in disaster relief fund. Rescue team became active like SDRF, civil volunteers, home guard and police in flood affected part. State emergency control room opened for 24X7 monitoring. Helpline numbered issued. Adequate relief camps were opened for affected families. 4 ($4804) lakh rupees were given to those who have lost their families members. 2000 ($24) rupees immediate payment to those in relief camps.

Policy recommendations include:

- Establishing real-time glacier and lake monitoring networks**.**
- Integrating GLOF risk mapping into regional planning**.**
- Strengthening infrastructure resilience and local capacity building**.**
- Enhancing international cooperation in the Himalayan belt for data sharing and response coordination.

CONCLUSION

While precipitation is a baseline atmospheric process, anomalies in its duration and intensity frequently trigger severe multi-hazard cascades. Due to its complex high-mountain geomorphology, the state of Sikkim remains highly susceptible to diverse natural hazards. Although certain catastrophic phenomena—such as earthquakes—cannot be prevented, the risks associated with climate-induced and hydro-meteorological events can be substantially mitigated through timely intervention, robust structural planning, and modern technologies. The October 2023 disaster explicitly demonstrated how a geomorphic breach in a remote, high-altitude, and uninhabited cryospheric zone can propagate catastrophic downstream effects that devastate densely populated lower riparian environments.

This event underscores a critical disconnect between top-down infrastructure deployment and the region's intrinsic geological constraints. Sustainable and resilient development in fragile ecological zones must be inclusive, strictly respecting localized geological thresholds and incorporating community risk perceptions. The scale of the socio-economic and structural damage observed in this disaster was significantly exacerbated by the absence of fully functional automated early warning architectures, alongside a lack of cohesive coordination among institutional stakeholders, regional bureaucracies, and local communities. The resulting floodwave not only disrupted regional prosperity and caused substantial loss of life, but it also induced long-term economic shocks by destabilizing the primary tourism industry and degrading the region's rich biodiversity and fragile ecosystem.

Moving forward, robust monitoring frameworks remain imperative. Institutional bodies, such as the Indian Space Research Organisation (ISRO), continue to utilize multi-temporal satellite remote sensing to track structural and volumetric changes in high-risk proglacial lakes to provide early indicators of instability to state authorities. Modern disaster management paradigms must fully integrate these advanced geospatial techniques—specifically Remote Sensing (RS) and Geographic Information Systems (GIS)—for predictive risk modeling, hazard inventorying, and precise susceptibility zonation. Ultimately, the 2023 Sikkim disaster serves as a vital empirical lesson, demanding a paradigm shift toward risk-informed governance that harmonizes engineering interventions with the natural dynamic processes of the Himalayan landscape.

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